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Consumer Perspectives on Battery Electric Vehicles: A Literature Review

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Abstract

Electric vehicles are often considered one of the best ways to decarbonize transportation within the United States. This report reviews the battery electric vehicle adoption literature, focusing on the drivers and barriers to adoption. The first section outlines critical trends in battery electric vehicle adoption and background information about the market for electric vehicles in the United States. The second section focuses on the drivers and barriers to adoption of battery electric vehicles with emphasis on drivers and barriers relevant to the battery of a battery electric vehicle. The third section then details additional technical papers on the batteries of electric battery vehicles, including options for the end of use of the battery. The battery of an electric vehicle is one of the most expensive components, and the technology in batteries is evolving quickly, so we focus our review on papers related to the batteries of battery electric vehicles.

Keywords

Battery electric vehicle; literature review; batteries; battery passport; end of life; electric vehicle adoption; range anxiety; charging infrastructure; battery information; battery performance; battery lifetime; preowned electric vehicles.

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Acknowledgements

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1. Introduction

This introduction provides background on the current and projected electric vehicle (EV) market-related infrastructure and introduces potential concerns and considerations for adopting an EV, which will be covered in detail in the remainder of the document.

1.1. What is a Battery Electric Vehicle?

EV is a general term that includes battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). BEVs are all-electric vehicles powered by plugging into a specialized outlet and using electricity to charge a battery pack, with no gasoline engine (e.g., Tesla Model 3 or Nissan Leaf). PHEVs use a combination of a gasoline engine and battery power that can be plugged in to charge the battery component, which tends to have a limited range (e.g., Toyota Prius Prime or Jeep Wrangler 4xe). Both BEVs and PHEVs are distinct from hybrid vehicles, which use gasoline and battery power (e.g., Toyota Prius), with the battery being re-charged by driving the car and cannot be charged by plugging it in.

1.2. Electric Vehicle Market

In the United States, BEV and PHEV sales have been expanding significantly from nearly zero in 2010 to over 1 million in 2018 to almost 3.3 million in 2022, most of which (2.3 million or 70 %) are BEVs Fig. 1 [1]. As of 2020, U.S. EV sales were approximately 325 000, while U.S. EV production was 455 000, leading to net exports of 90 000 EVs (primarily driven by Tesla production and sales). The U.S. imported the most EVs from Europe and Japan, while most exports were sold in Europe and Canada. [2]. Since 2020, both domestic production and imports have risen as Tesla has continued ramping up production, and additional automakers have begun releasing more BEV and PHEV models. The U.S. is expected to remain a net exporter of EVs through 2030 [2].

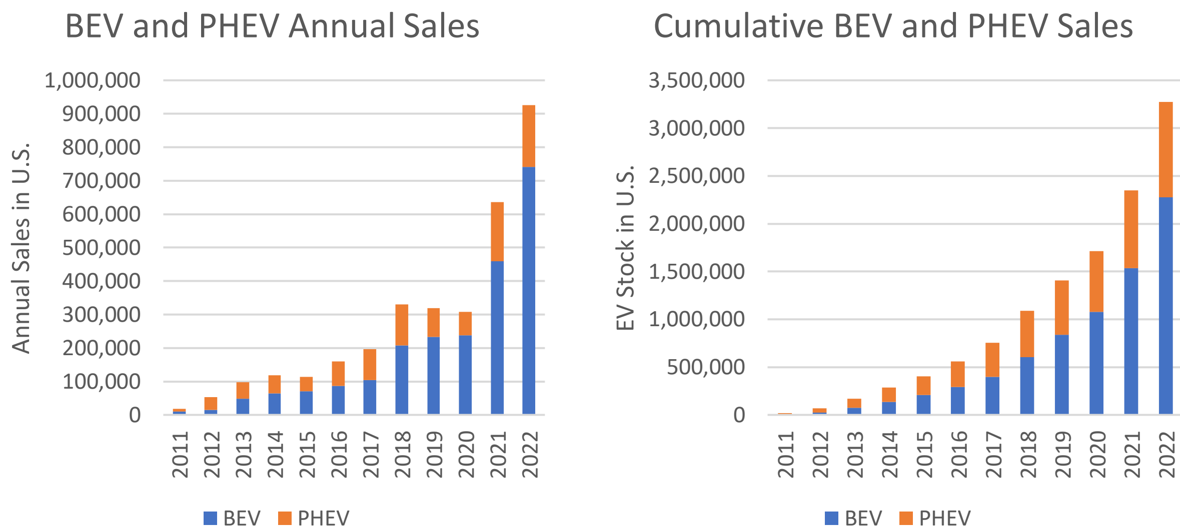

Fig. 1. U.S. electric vehicle market (2011 through 2022) [3].

U.S. sales of EVs (BEV and PHEV combined) in 2022 were primarily Tesla (64.5%), with Ford and Chevrolet accounting for an additional 7.6 % and 4.7 %, respectively Table 1. However, all manufacturers are continuing to ramp up production with 46 make-models with at least one vehicle sold in 2022 [4]. These vehicles range from compact to commercial vehicles, including pick-up trucks and vans.

Table 1. U.S. EV (BEV + PHEV) sales by manufacturer (2022)

Make	Sales	Share	Make	Sales	Share
Tesla	522 388	64.5 %	Volvo	7346	0.9 %
Ford	61 575	7.6 %	Porsche	7271	0.9 %
Chevrolet	38 120	4.7 %	Mini	3665	0.5 %
Kia	27 965	3.5 %	Lucid	2656	0.3 %
Hyundai	26 693	3.3 %	Genesis	1590	0.2 %
Volkswagen	20 511	2.5 %	Toyota	1220	0.2 %
Rivian	20 332	2.5 %	Subaru	919	0.1 %
Audi	16 177	2.0 %	GMC	854	0.1 %
BMW	15 589	1.9 %	Mazda	324	<0.1 %
Mercedes-Benz	12 421	1.5 %	Jaguar	298	<0.1 %
Nissan	12 226	1.5 %	Brightdrop (GM)	155	<0.1 %
Polestar	9322	1.2 %	Cadillac	122	<0.1 %

Projections for U.S. EV sales (BEV and PHEV) vary significantly depending on the modeled scenario and year of analysis. The EIA 2022 Reference Case projection for 2030 was under 1 million. [5], which is only slightly greater than actual sales in 2022. This estimate is conservative relative to other estimates that range from 3 million to 9 million by 2030 [6]. Aggregated manufacturer sales targets are at the high end of this range at over 8.4 million by

2030. A recently released analysis by Goldman Sachs estimates electric vehicles will account for 20 % (nearly 3 million) of all light-duty vehicle sales by 2025, 50 % (8 million) by 2030, and 85 % (almost 14 million) by 2040 [7]. Different sales forecasts vary significantly, and manufacturer EV sales targets are much higher than most forecasts (over 8 million by 2030), implying an expectation of the industry accelerating its production capacity. [6]. Regardless of how many will be sold in the U.S. over the next five years, electric vehicles will consistently become more common in new and existing cars.

1.3. Pre-owned EV Market

The secondary market for EVs (BEVs and PHEVs) has only recently existed. Pre-owned EV inventories have grown over the last two years, primarily from the resale of Chevrolet Volt and Bolt, Nissan Leaf, and Tesla Models S, 3, and Y because these were the only make-models sold in significant quantities until recently. Used EVs are beginning to account for a substantial portion of EV inventory and sales in the U.S., with approximately a third of Q1 2022 sales being used vehicles [8]. Pre-owned EV (including BEV and PHEV) inventories grew from 25 141 in January 2022 to 37 515 in January 2023, a 49 % increase year-over-year. The model year of used EVs for Q4 2022 is relatively evenly split across the last decade of production (at least 10 % come from 2013 to 2022 model years), with 2017 being an outlier of over a quarter [8]. The growth of pre-owned EV sales appears to be accelerating, with 42 753 sold in Q1 2023, twice the number sold in Q1 2021 [9]. This may be driven by the end of financed purchases of new vehicles now being resold, as drivers often upgrade to a new car after a vehicle loan is paid off. In the auto industry, 3-year to 6-year auto loans are common. Dynamics related to the pandemic may have also influenced the influx of EVs for sale (e.g., high prices for used vehicles, impact from the “work-from-home” movement). The pre-owned market will continue to grow based on the recent year-over-year growth and future projections of new EV production and sales.

1.4. Cost of BEVs

Most BEVs sold before 2022 are considered “luxury” vehicles (high-priced vehicles with high-end levels of comfort, features, equipment, and performance) or are compact cars with minimal range (less than 200 miles). However, new BEV models are being released, and the price of their base models is closer to the mass market target of $25 000, with significant range improvements. Additionally, many new models are in the high-demand SUV/crossover categories. Fig. 2 shows that models being sold in 2023 (including 2022 models for Tesla, Rivian, and Lucid) range in MSRP from $25 600 (Chevrolet Bolt) to $169 000 (Lucid Air) [10]. MSRP is the retail price of the automobile the manufacturer suggests, including manufacturer-installed options, accessories, and trim, but excluding destination fees. Most models are in the $35 000 to $75 000 range. There is no low-cost (i.e., < $25 000) BEV available in the U.S. yet, but there have been recent announcements by manufacturers targeting the mass market at this price point. Fig. 2 shows that nearly 88 % of currently available BEV models have a rated range between 200 and 350 miles per charge.

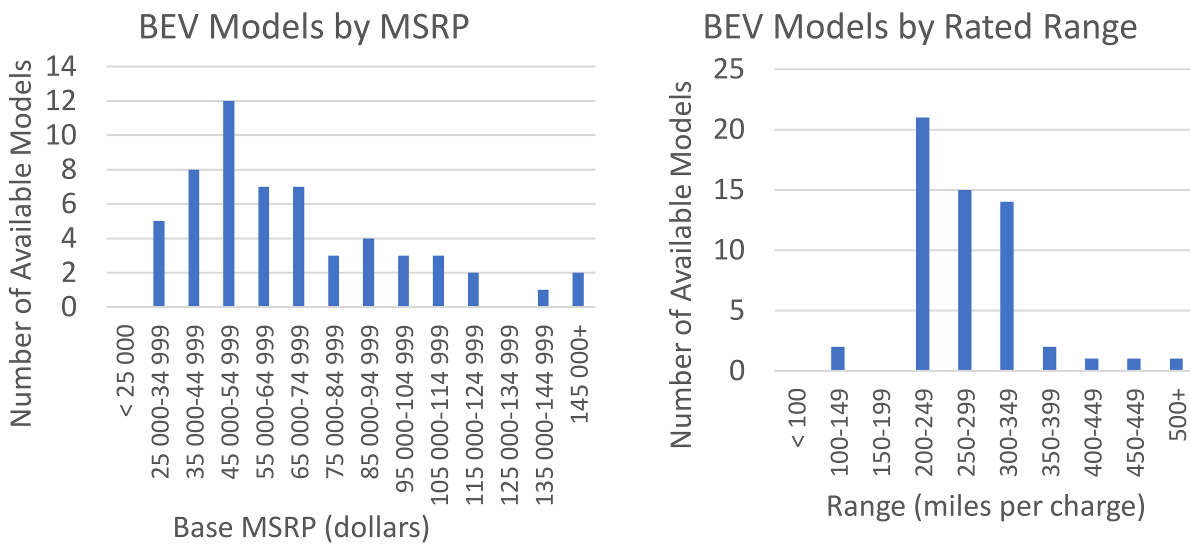

Fig. 2. EV models for sale in 2023 by starting MSRP (left) and rated range (right) [10].

Fig. 3 shows each BEV model by starting MSRP, range, and vehicle type. There is some correlation (R^2 = 0.42) between the higher-rated range and higher MSRP across all vehicles (the trend is up and to the right) because increasing battery size is a critical cost in BEVs. Still, significant variation remains due to differences in vehicle type and features provided in each base model.

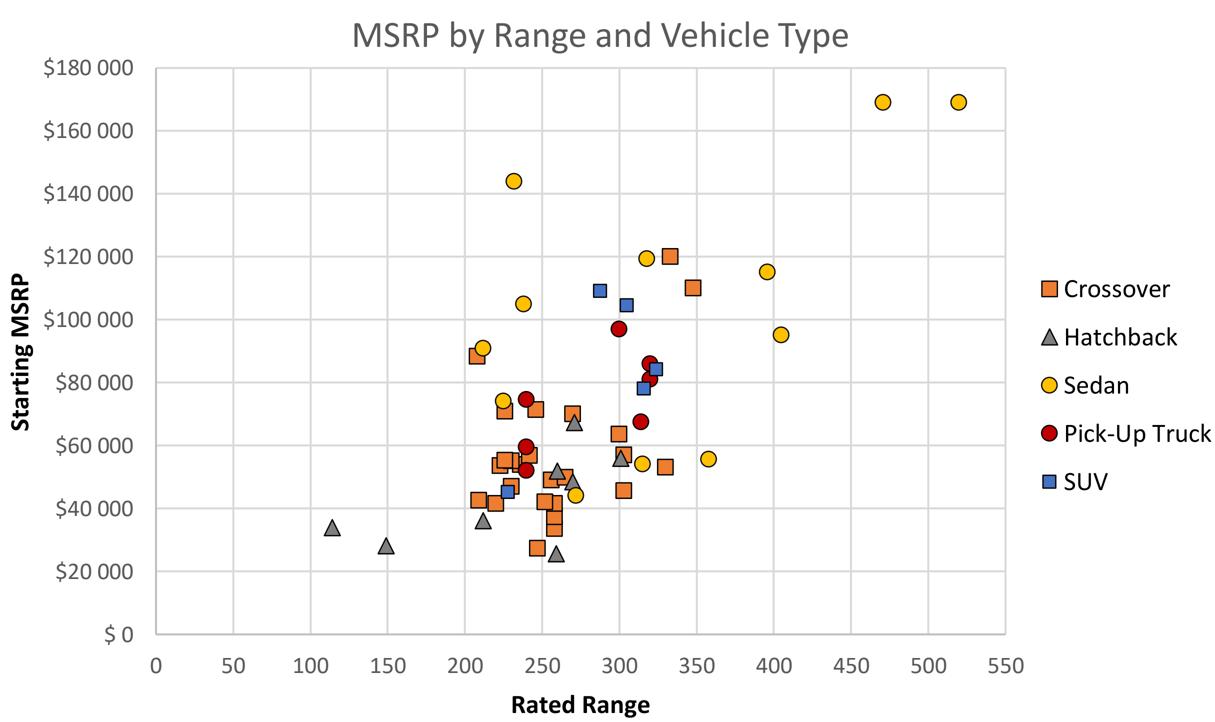

Fig. 3. BEV models for sale in 2023 by range and starting MSRP [10].

A primary concern related to EV ownership is the potential for vehicle range degradation and future battery replacement because batteries are the most expensive component of EVs. Battery replacement costs range from $5000 to $20 000 ($137/kWh to $727/kWh) depending on the battery size, technology, and vehicle model. [11]. Battery range is expected to decrease over time, but there remains uncertainty in the level and speed of battery degradation and the resulting potential replacement costs. A typical warranty for EV batteries is 70 % of capacity for eight years / 100 000 miles. There is limited data on actual battery performance beyond the initial six years of ownership because so few EVs (in terms of number and models available) have been operating for more than 5 years. However, available data has been promising. Across all models, observed degradation appears to be lower than that allowed under the warranties, with batteries performing at 93.9 % of capacity after 3 years and 87.9 % after 6 years per GeoTab's database (sample of 6000 vehicles) [12]. An assumption of linear degradation implies a two-percentage point decrease each year of operation.

Recurrent Auto analyzed vehicle range by miles driven per the odometer and found that many EVs have non-linear degradation where the initial 30 000 to 50 000 miles lead to reductions in range. Still, after that, the range performance stabilizes or degrades minimally for many miles. [13]. However, this does not control for model year, and it is reasonable to assume that newer year models will have better battery technology (different battery chemistry) and controls (optimizing battery operation). Recurrent Auto found that of approximately 15 000 EVs, 1.5 % of batteries have been replaced outside official battery recalls. The number of non-recall battery replacements is 8.5 % or less for vehicles from model years 2011-2014 (9-12 years old) [13]. Examples include the 2011 Nissan Leaf at 8.3 % and the 2013 Tesla Model S at 8.5 %.

There is additional uncertainty about the resale value of EVs as they approach the end of their warranty. Not enough EVs are resold to identify if there is a difference from ICE vehicles.

When considering a new vehicle, a purchaser should consider all the costs discussed above to determine the total cost of ownership. Total ownership costs vary based on several factors (number and type of miles driven, location, etc.). On average, EVs are less expensive to operate and maintain than non-EV vehicles, but they currently have a higher initial cost of purchase (once considering available financial incentives).

Some tools exist to assist vehicle purchasers with estimating their total cost of ownership. For example, Edmunds.com's True Cost to Own features provide a 5-year estimate of costs (assuming 15 000 mi driven annually) for a given make-model and ZIP code. [14].

1.5. Purpose, Scope, and Approach

Many factors influence EV adoption. Consumers may have vehicle preferences for vehicle performance, technology adoption, or environmental impacts. Consumer driving needs and habits (time and length of commute) may influence their choices. The economics of vehicle ownership and operation will also affect their adoption of EVs. Barriers to EV adoption are commonly driven by the battery, whether it's range anxiety (i.e., miles per charge), resale, climate-related performance issues, performance degradation, and charging access.

Consumer’s perspectives of all these factors are essential to better understanding their preferences, needs, barriers, and concerns.

The purpose of this document is threefold. First, it identifies and summarizes the research literature of studies focused on consumer perspectives on new and pre-owned electric vehicle adoption and ownership, including drivers and barriers influencing purchasing decisions. Second, it identifies what information could influence consumer decisions on new and pre-owned EV adoption, with particular interest in battery performance. Third, it identifies information, research, and data gaps that should be addressed in future work.

The literature review focuses on studies using surveys but will also supplement with other research that is considered relevant to provide as comprehensive of a review as feasible. Both academic publications and “gray” literature, which are research produced by organizations outside of the traditional scholarly publishing channels, such as reports funded by government, industry, and non-profit organizations, will be included in the review. The review will also provide a summary of information related to the EV battery that could assist consumers in making informed decisions, such as previous or projected battery performance.

2. Electric Vehicle (BEV and PHEV) Adoption and Ownership

Electric vehicle adoption has slowly been increasing in the United States and worldwide. Some factors influence or predict which individuals will adopt an electric vehicle, which we will refer to as the drivers of electric vehicle adoption. Additionally, some limiting factors prevent some individuals from adopting an electric vehicle, which we will refer to as the barriers to electric vehicle adoption. This section will focus on understanding the drivers and barriers to electric vehicle adoption.

2.1. EV Adoption Drivers

Understanding electric vehicle adoption drivers is vital for infrastructure and planning decisions. The reasons that someone purchases an electric vehicle can also inform how market shares of electric cars will change over time. Researchers have studied who buys electric vehicles and why they buy them for many years. The following sections explore electric vehicle adoption's demographic, societal, environmental, technological, and economic drivers.

2.1.1. Demographic and Societal Drivers

Early research on electric vehicle adoption focused on who would most likely be an electric vehicle owner. Carley et al. analyzed survey data of over two thousand individuals using a stated adoption intent question in 2011 [15]Respondents were asked how likely they were to purchase an electric vehicle without a gasoline engine for their next car using a ten-point scale, with a ten indicating that the individual would undoubtedly buy an electric vehicle. [15]. The average rating from each city in the survey is contained in **Error! Reference source not found.** and Columbus, Ohio and Washington, District of Columbia were not includes due to lack of responses to the survey [15]. Of the cities included the highest intent to purchase an electric vehicle is in the San Francisco and San Jose area of California with the lowest intent to purchase an electric vehicle being in the Dallas and Fort Worth area of Texas.

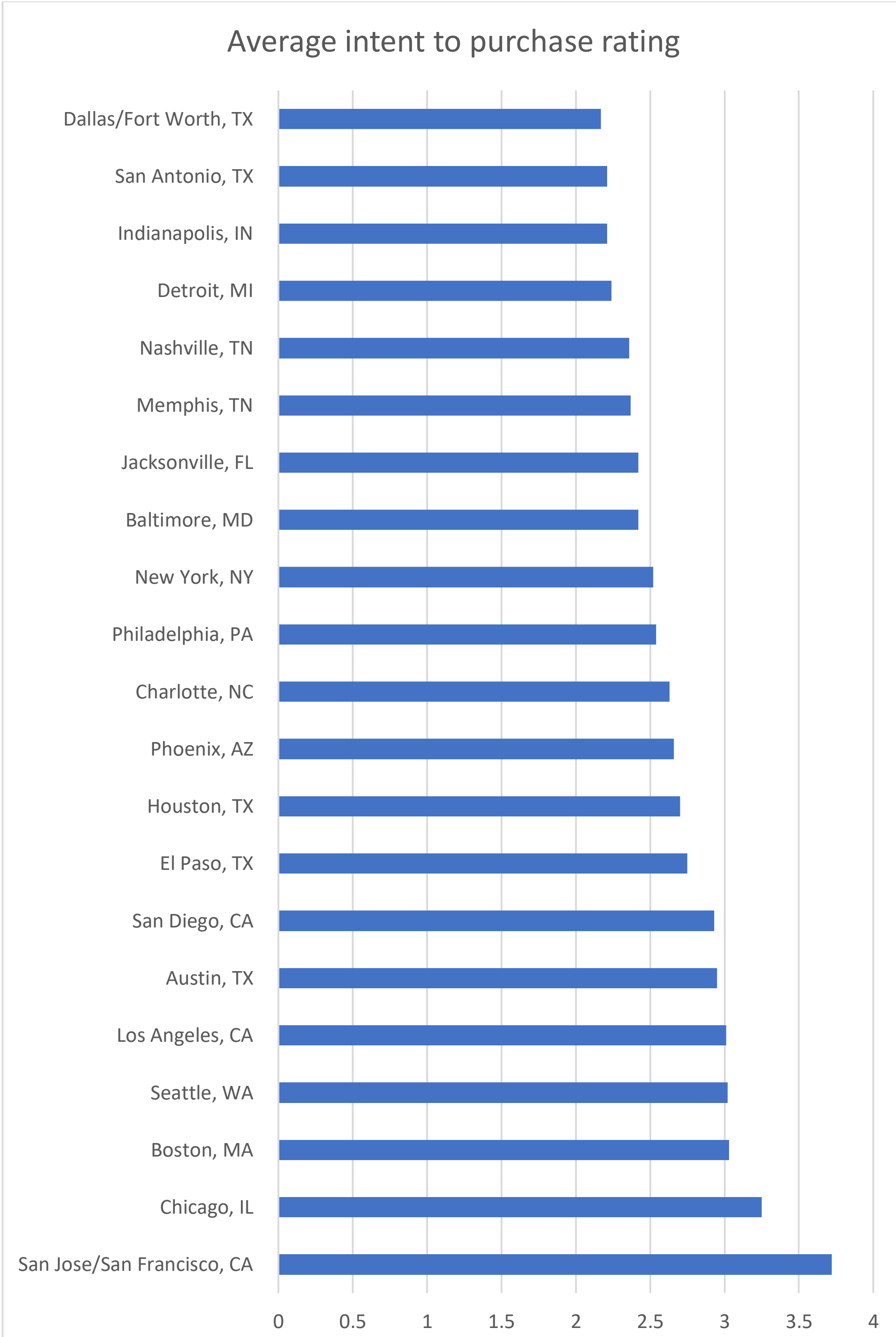

Fig. 4: Intent to purchase BEV by city from Carley et al. [15]

In addition to locations in the United States having heterogeneous electric vehicle adoption, there is high heterogeneity across different countries in electric vehicle adoption. Global demand for EVs has been growing exponentially over the last decade from essentially zero in

2010 to nearly 17 million in 2021, as shown in **Fig. 5** [16]. Total sales have been significantly greater in China and Europe than in the U.S. through 2022. Based on the top 3 BEV models sold in a given region, there is some variability in the vehicle's most significant demand [17]The China EV market has been driven more by compact vehicles (e.g., Wuling Mini EV, BYD Dolphin), although the Tesla Model Y is in the top three. Europe and the U.S. have more SUVs and sedans (e.g., Tesla Model 3, Tesla Model Y, VW ID.4, Ford Mustang Mach-E).

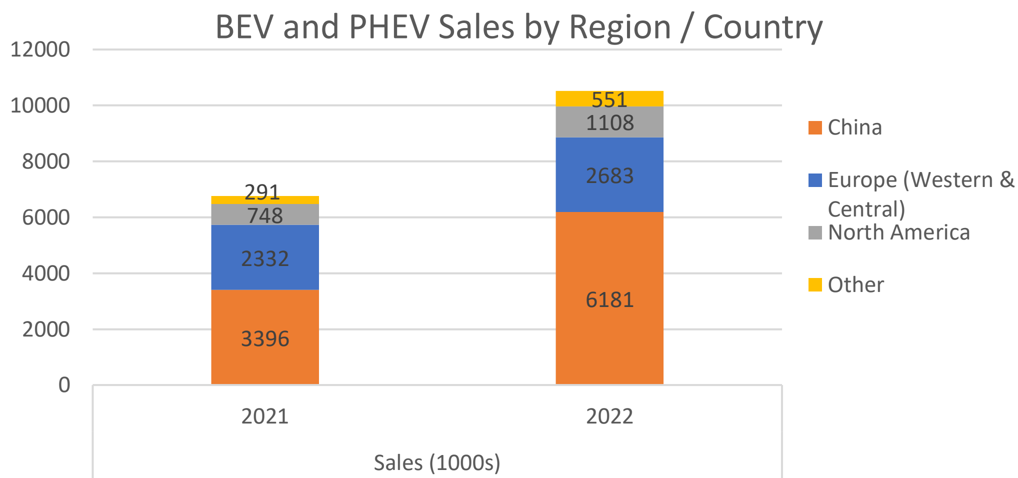

Fig. 5. Current global EV market (BEV and PHEV).

When focusing specifically on BEVs, the share of total vehicle sales varies significantly from country to country. **Fig. 6** [17]In 2022, Norway had the most significant share of vehicle sales made up of BEVs, at 79.3 %, followed by Iceland (33.4 %), Sweden (33.0 %), and the Netherlands (23.5 %). China is fifth with 21.4%, while the U.S. is 5.3%. Vehicle brand and model sales vary by country based on the vehicle market demand and vehicle manufacturers in the world region. [17]. For example, BYD models are sold in China, Australia, and New Zealand, while Škoda models are sold in Eastern and Northern Europe. The Tesla Model 3 and Model Y are prevalent in the Top 3 Model lists for countries because of their manufacturing facilities in the U.S., China, and Germany.

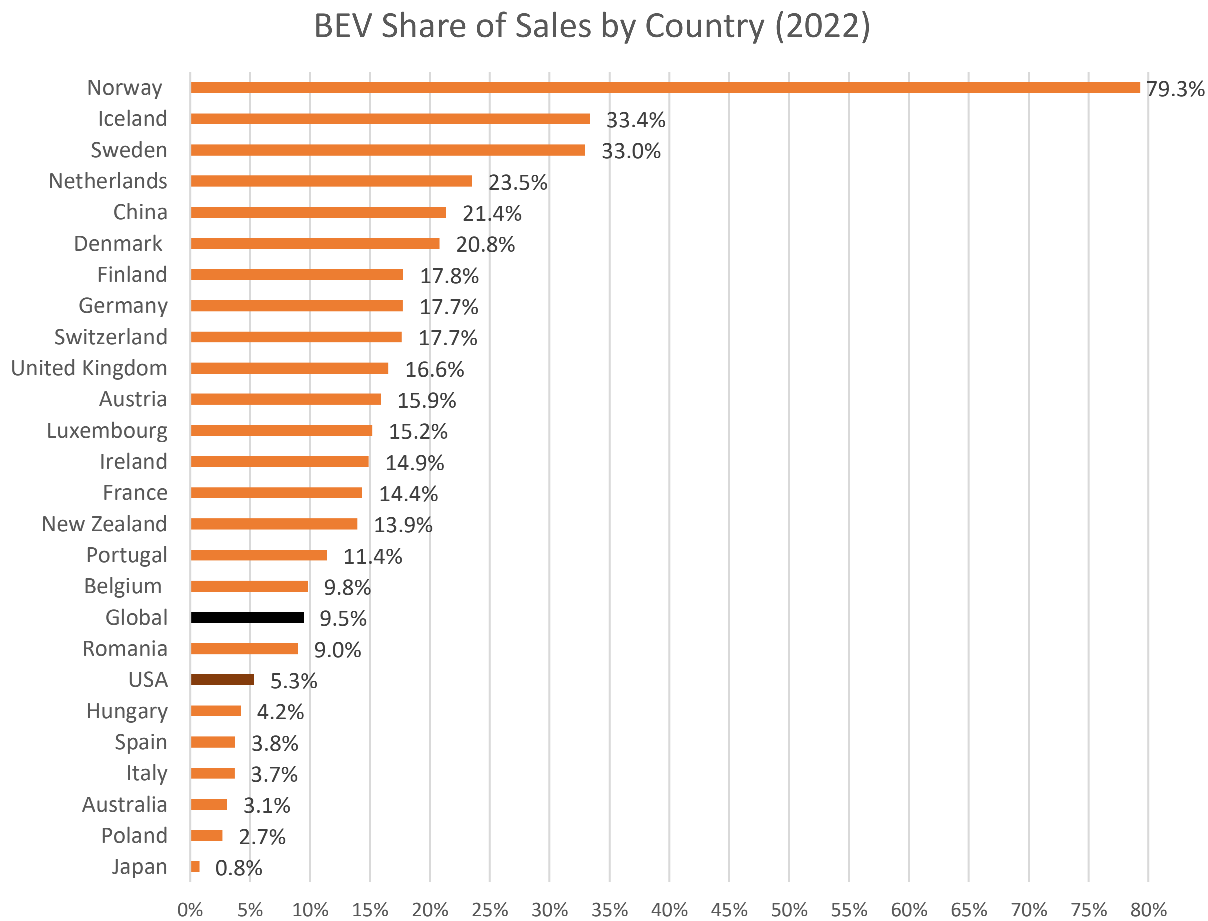

Fig. 6. BEV share of vehicle sales by country – 25 largest BEV markets (2022).

There is a strong correlation between counties with high BEV shares of total vehicle sales and the size of the financial incentives provided for their purchase, including a combination of income, purchase, and value-added tax credits, import tariff exemptions, and grants/rebates/subsidies. Norway has been providing possibly the most significant financial incentives for BEV purchases (totaling $10 700 in 2021) of any country in the world. [18]Additionally, some of these incentives were reduced starting January 1, 2023. This may have led to a pull-forward of BEV sales to 2022, causing a dramatic differential in EV shares relative to all other countries.

Further investments in EVs will continue with cumulative announced investments totaling $867 billion as of Q3 2022: (Europe at $238 billion, United States at $210 billion, Asia (Ex-China) at $210 billion, China at $199 billion, and $10 billion outside of these regions (including Mexico, Canada, and Australia)) [19].

The global BEV and PHEV stock projections show continued expansion in the coming decades, with BEVs maintaining a more significant EV market share. **Fig. 7** provides one such projection based on the IEA's Sustainable Development Scenario [20]. The global light-duty electric vehicle stock of all EVs (BEV and PHEV combined) is projected to grow from 23 million in 2023 to nearly 200 million by 2030, with growth across all regions.

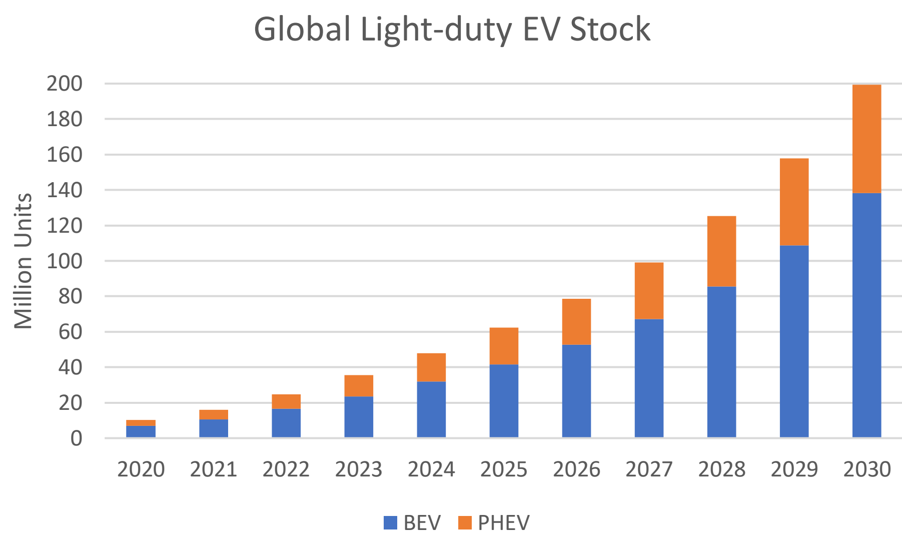

Fig. 7. Global electric vehicle market projection through 2030 (IEA Sustainable Development Scenario).

Additionally, Carley et al. analyze the impact of demographic questions on intent to purchase an electric vehicle in a sample of individuals from the United States. [15]. The paper finds that men are 11.5% more likely to purchase an electric vehicle than women. Age is also a significant predictor; each year older, an individual decreases their likelihood of purchasing by 0.42% within the linear estimation in Carley et al. [15]. Educated individuals are likelier to show a stated intent to purchase an electric vehicle. Within this paper, income is not a predictor of stated adoption intention. The number of cars owned does not predict the stated adoption intent; however, this paper uses a linear assumption for the number of vehicles owned rather than testing if being a multicar household impacts adoption intent. Additionally, concern surrounding dependence on foreign oil increases electric vehicle adoption intent by 21.58%. Peters and Dütschke find that multi-car households are more likely to purchase a BEV because purchasers want an additional vehicle for travel that is not hindered by the limited range of the BEV. [21].

2.1.2. Environmental and Technology Interests

Carley et al. use an additive index of four questions to evaluate if environmental preferences impact stated electric vehicle adoption intent [15]. The statements are presented in **Table 2**, as well as if the statement was coded positively or negatively. Each positive statement that an individual responded to with a strong agreement added two points to their environmental index. Suppose the selected individuals agree to a positive statement that adds one point to their ecological index. For negative statements, two points were added for a strongly disagree and one for a disagree selection. The paper finds that a one-point increase in the environmental index results in a 5.38% increase in the stated electric vehicle adoption intent.

Table 2: Question text to measure environmental beliefs from Carley et al. [15].

Statement	Positive or Negative
People need to change their lifestyles to protect the environment	Positive
Climate change is a severe problem.	Positive
Climate change is a result of human actions	Positive
Environmental problems facing humankind have been greatly exaggerated	Negative

Krupa et al. surveyed in 2011 of one thousand survey participants in the United States. [22]. This survey collected data on individual's demographics, purchasing decisions, vehicle acquisition, environmental attitudes, attitudes on PHEVs, and discounting questions. Participants were asked about their comfort level surrounding PHEVs and told to assume that the PHEV had all their desired features. The answer choices were 1 = ''not at all''; 2 = ''a little''; 3 = ''somewhat''; 4 = ''a lot''; and level 5 = ''a deciding factor''. **Table 3** presents the results from the environmental and technology-related questions. Approximately half of respondents responded that they would be more comfortable with a PHEV that could significantly cut greenhouse gas emissions. Only one-fourth of participants view owning a PHEV as a robust environmental value statement, and even fewer participants view a PHEV as an indicator that someone is at the forefront of technology innovation. It is important to note that these responses were collected in 2011 and that the perception of electric vehicles is continuing to evolve and change.

Table 3: Deciding factors in BEV purchase questions from Krupa et al., [22].

Percent of participants who state the following factors would increase their comfort in purchasing or leasing a PHEV by ''a lot'' or would be ''a deciding factor'' (assuming the PHEV had all their desired features and was within budget)	
Realizing a PHEV could cut greenhouse gas emissions significantly (potentially to zero)	55.1%
Owning a PHEV would make a statement of one's solid environmental values	25.0%
Owning a PHEV would make a statement that one is at the forefront of new technology	17.0%

White and Sintov explore how symbolism impacts BEV adoption intent and how that compares with demographics correlated with BEV adoption intent [23]. They find that the strongest predictor of stated BEV adoption intent is environmental symbolism, social innovation symbolism, and demographic characteristics. The questions used to measure environmental symbolism and social innovator symbolism are included in **Fig. 8**. This construct differs from other research that examines the self-identity of individuals by looking at symbolism specifically. Due to this, their results can be interpreted as the leading driver of BEV adoption intent is showing that you make environmentally responsible decisions to others.

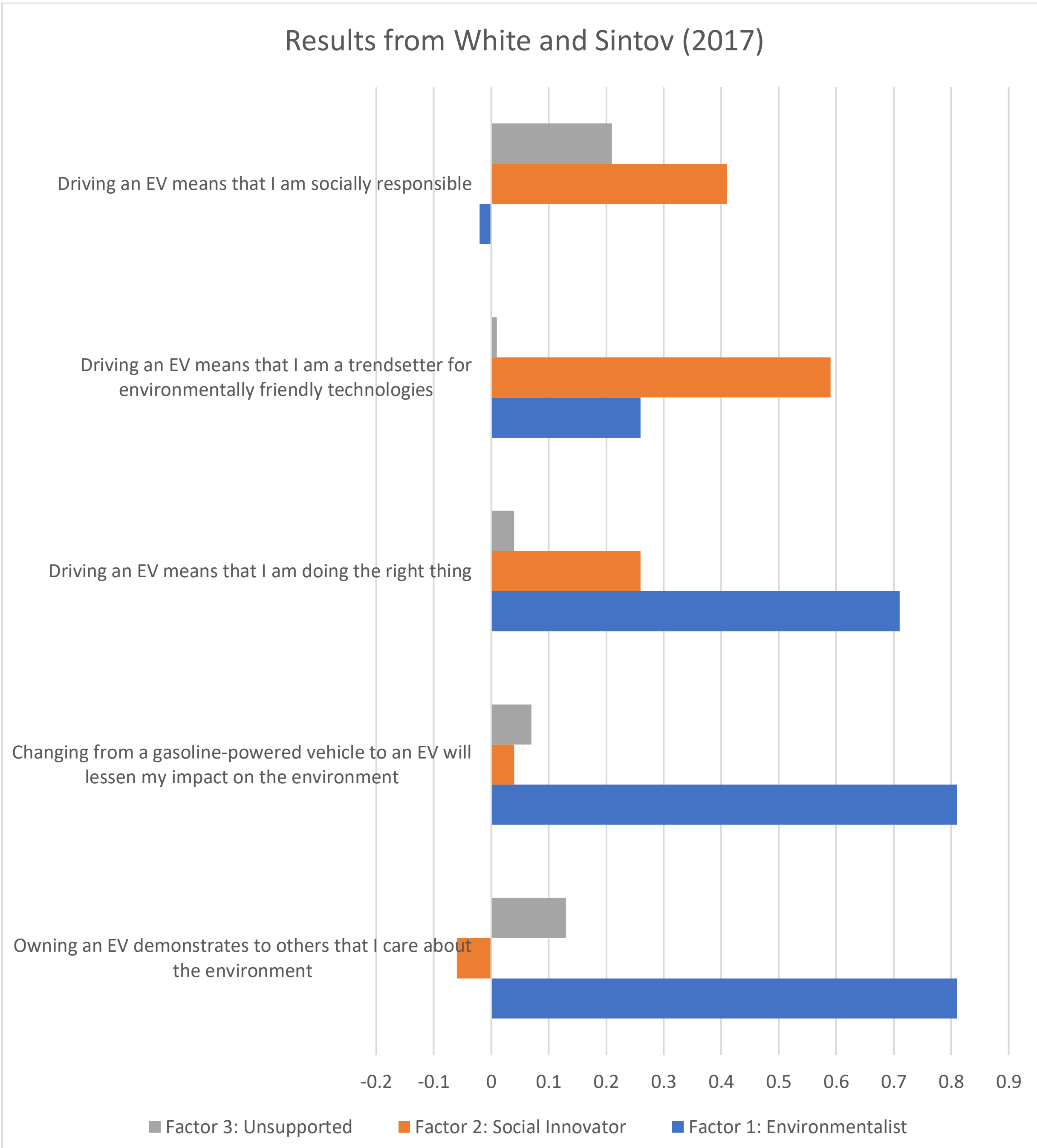

Fig. 8: Questions from White and Sintov to measure environmentalism and social innovation [23].

Additionally, Gore extends the research on environmental motivations for adopting a BEV by estimating the willingness to pay for a BEV given different emissions scenarios using an information experiment embedded within a discrete choice experiment. [24]The author finds that individuals are willing to pay the highest premium for the vehicle with the lowest emissions, even when that vehicle is a hybrid instead of a BEV. Additionally, the willingness to pay increases the amount of carbon dioxide equivalent emissions reduced by the BEV, further showing that one of the main driving factors for BEV adoption concerns reducing one's environmental impact.

2.1.3. Cost of Ownership

The total cost of ownership is a term used to refer to the summation of all the costs incurred by owning a vehicle, including the purchase price, fuel costs, depreciation, and more. The purchase price of a BEV is typically higher than that of a similar conventional vehicle. Still, the operational costs of a BEV are generally lower than the operational costs of a traditional car. Breetz and Solon compare three vehicles with different fuel types to calculate the total cost of ownership differences for a BEV, hybrid, and conventional vehicle [25]. The traditional vehicle has the lowest total cost of ownership without a subsidy. The hybrid generally has a lower total cost of ownership than the BEV, but that does not hold for all scenarios studied. The difference in the total cost of ownership for a BEV and a conventional vehicle is less than the price difference for the purchase prices. Since part of the price differential between a BEV and a traditional car is offset by the lower operational costs, Dumortier et al. find that giving consumers more information about the total cost of ownership leads to a higher preference for a hybrid or BEV [26].

Letmathe & Suares examine the market adoption rates of alternative powertrains in Germany, focusing on battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs) [27]. The core of the research is a comparative analysis of the total cost of ownership (TCO) for BEVs, HEVs, and traditional ICEs. The approach includes enhancing current consumer-oriented TCO models to evaluate electric vehicles' economic feasibility more accurately than ICEs. This involves accounting for variables such as the potential resale value of batteries and the effect of governmental financial incentives. The findings indicate that BEVs with a leased battery option are more cost-effective than those with purchased batteries. However, owning a battery may offer additional opportunities, especially concerning the recycling and repurposing of batteries after their primary use. Therefore, the eventual resale value of these batteries and their secondary market are significant determinants in the TCO calculations for BEVs. Another study by Hagman et al. highlights the complexities in constructing a consumer-centric TCO model for BEVs, emphasizing the difficulties in estimating cost factors like depreciation and fuel costs due to their unpredictable nature. [28]. It notes that while some costs, such as interest, insurance, maintenance and repair, and taxes, are relatively stable, depreciation can vary significantly due to various market factors, and fuel costs are subject to global market volatility and discrepancies between official and real-world fuel consumption rates. Using real-world data, the study found notable discrepancies between TCO and purchase price among sample vehicles, with the BMW i3 having the lowest TCO despite its high purchase price. This is attributed to its lower running costs and significant government subsidies. The study's findings challenge prevalent assumptions regarding the cost-effectiveness of BEVs, given the common perception that BEVs are prohibitively expensive due to their higher upfront costs.

The federal BEV and PHEV tax credits may also assist with the initial costs, updated by the U.S. Inflation Reduction Act of 2022. The Inflation Reduction Act of 2022 changed the rules for this credit for vehicles purchased from 2023 to 2032. New guidance from the IRS was provided in April 2023, and this has led to some BEVs and PHEVs losing their tax credit starting April 18, 2023, due to the battery's critical mineral and assembly requirements. The credit is available to individuals and businesses. To qualify, individuals must purchase it for their use and primarily use it in the U.S. In addition, their modified adjusted gross income (AGI) for the year the vehicle is put into service or the year prior (whichever is less) may not exceed $300 000 for married couples filing jointly, $225 000 for heads of households, or $150 000 for all other filers [29].

For EVs (BEV and PHEV) placed in service from January 1, 2023, through April 17, 2023:

- $2500 base amount
- Plus $417 for a vehicle with at least 7 kilowatt hours of battery capacity
- Plus $417 for each kilowatt hour of battery capacity beyond 5 kilowatt hours
- Up to $7500 total
- In general, the minimum credit will be $3751 ($2500 + 3 times $417), the credit amount for a vehicle with a minimum 7 kWh of battery capacity.

For vehicles placed in service on April 18, 2023, and after:

Vehicles will have to meet all of the same criteria listed above, plus meet new critical mineral and battery component requirements for a credit up to:

- $3750 if the vehicle meets the critical minerals requirement only.
- $3750 if the vehicle meets the battery components requirement only.
- $7500 if the vehicle meets both.
- A vehicle not meeting either requirement will not be eligible for a credit.

To qualify, a vehicle must:

- Have a battery capacity of at least 7 kWh.
- Have a gross vehicle weight rating of less than 14 000 pounds.
- Be made by a qualified manufacturer.
- a qualified manufacturer does not require FCVs to be eligible. See Rev. Proc. 2022-42 for more detailed guidance.
- Undergo final assembly in North America
- Meet critical mineral and battery component requirements (as of April 18, 2023).
- The sale qualifies only if:
    - The vehicle is purchased new.
    - The seller reports the required information to the buyer at the time of sale and to the IRS.
- The vehicle's manufacturer suggested retail price (MSRP) cannot exceed:

- $80 000 for vans, sport utility vehicles, and pickup trucks
- $55 000 for other vehicles

Qualifying models-trims of BEV and PHEV as of April 17, 2023, are shown in **Table 4** [30]Of the 21 model trims that still qualify, 15 are BEVs, and 6 are PHEVs, while 13 qualify for the full credit ($7500) and eight qualify for the partial credit ($3750). Qualified model trims may change as manufacturers modify their battery material and manufacturing sources.

Table 4. Currently qualifying model U.S. EV sales by manufacturer

Vehicle Description	Type	Credit	MSRP Limit		Vehicle Description	Type	Credit	MSRP Limit
Cadillac Lyriq	BEV	$7500	$80 000		Jeep Wrangler PHEV 4xe & Grand Cherokee 4xe	PHEV	$3750	$80 000
Chevrolet Blazer, Bolt, Bolt EUV, Equinox, & Silverado	BEV	$7500	$55 000		Lincoln Aviator Grand Touring	PHEV	$3750	$80 000
Chrysler Pacifica PHEV	PHEV	$7500	$80 000		Lincoln Corsair Grand Touring	PHEV	$7500	$80 000
Ford F-150 Lightning	BEV	$7500	$80 000		Tesla Model 3 Rear Wheel Drive	BEV	$3750	$55 000
Ford Escape Plug-In Hybrid	PHEV	$3750	$80 000		Tesla Model 3 Performance	BEV	$7500	$55 000
Ford Mustang Mach-E Standard, Mach-E Extended & E-Transit	BEV	$3750	$80 000		Tesla Model Y AWD, Long Range, & Performance	BEV	$7500	$80 000
Note: Qualified vehicles as of April 17, 2023 (Source: https://fueleconomy.gov/feg/tax2023.shtml).								

In addition to the federal tax credit, various state incentives for EV owners have been adopted. The most common is a state tax credit (of varying sizes) for purchasing an EV, which currently exists in California, Colorado, Connecticut, Delaware, Illinois, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, Texas, and Vermont. [31].

The future operational costs of owning and operating a vehicle include fuel, maintenance, repair, and vehicle component replacement costs. Relative to traditional cars, EVs have been found to have lower future costs for all three cost categories.

The fuel cost of BEVs tends to be lower per mile driven than conventional (ICE) vehicles. Per American Automobile Association (AAA), as of March 28, 2023 the average price of gasoline in the U.S. was $3.44/gal, with state averages ranging from $3.19/gal to $4.82/gal. [32]. Across all 2023 models, EPA-rated fuel efficiency of gasoline-consuming vehicles (including hybrids) ranges from 12 miles per gallon (MPG) to 57 MPG. [33]. Excluding hybrid vehicles, the maximum rated efficiency is 39 MPG. Assuming the national average gasoline cost, the cost per 100 miles is as low as $6.04 for hybrid vehicles and ranges from $8.82 to $28.67 for conventional gasoline vehicles. As of January 2023, the average electricity price in the U.S. was 15.5 ¢/kWh, and state average electricity prices ranged from 9.4 ¢/kWh to 45.0 ¢/kWh [34]The 2022 and 2023 BEV models' rated fuel efficiency ranges from 24 kWh/100 mi to 53 kWh/100 mi. [35]. Assuming the national average electricity price, the cost per 100 miles ranges from $3.72 to $8.22. Based on these calculations using national average fuel costs and EPA-rated fuel efficiencies, all BEVs have lower fuel costs than any conventional gasoline vehicle, and many BEVs have lower fuel costs than hybrid vehicles. Carley et al. do not find that expectations around gasoline price impact stated electric vehicle adoption intent. [15].

To get a direct comparison, it is essential to compare vehicles with the same characteristics (vehicle size, performance, features, etc.). **Table 5** shows two comparable cars: the 2022 Ford F150 Pickup 4WD (6cyl 2.7L) and the 2022 Ford F-150 Lightning 4WD BEV [36, 37]. Based on national average fuel costs and rated fuel efficiencies, the Ford F-150 gasoline vehicle gets 19 city/24 highway MPG, which works out to $14.33/100 mi to $18.10/100 mi, while the Ford-F-150 Lighting BEV gets 44 city/56 highway kWh/100 mi, which works out to $6.82/100 mi to $8.68/100 mi (less than half the fuel cost). Based on starting MSRPs, the Lighting EV is $4089 more expensive. Depending on their income, a buyer may qualify for up to $7500 in federal tax credit and state incentives depending on their location.

Table 5. Example Comparison of Fuel Costs [37]

Vehicle Description	Starting MSRP	Tax Credit	Fuel Price	Rated Range (city/hwy)	Fuel Cost Per 100 mi
2022 Ford F150 Pickup 4WD 6cyl 2.7L Automatic (S10)	$35 885	-	$3.44/gal	19/24 MPG	$14.33 to $18.10
2022 Ford F-150 Lightning 4WD Automatic (A1) EV	$39 974	$7500*	$0.155/kWh	44/56 kWh/100 mi	$6.82 to $8.68
* If AGI is below limits Note: Example uses defaults for DOE AFDC's Vehicle Cost Calculator (https://afdc.energy.gov/calc/)					

In addition to saving money on lower fuel costs, BEVs typically require less maintenance and repairs and, therefore, have lower maintenance costs because (1) BEV battery, motor, and electronics require little (or no) regular maintenance; (2) BEVs have fewer fluids (e.g., engine oil), requiring regular maintenance; (3) brake wear is significantly reduced due to BEV using regenerative braking; and (4) BEVs have fewer moving parts relative to a conventional fuel engine. [38]. ANL estimates that BEVs have maintenance and repair costs that are 33 % to 53 % lower than traditional internal combustion engine (ICE) vehicles, depending on the vehicle type (car, SUV, pick-up) [39].

To understand consumer preferences related to total cost of ownership, Krupa et al. included questions relating to the different aspects of the total cost of ownership of PHEVs [22]. Respondents were asked about their comfort level for purchasing a PHEV with the answer options being 1 = ''not at all''; 2 = ''a little''; 3 = ''somewhat''; 4 = ''a lot''; and level 5 = ''a deciding factor''. **Fig. 9** contains the list of questions participants were asked as well as the percentage of participants who responded with a lot or a deciding factor as their answer. 86% of participants responded that having significant savings on fuel costs would make them a lot more comfortable or would be a deciding factor in their purchase of a PHEV. Additionally, over 80% of individuals listed a subsidy as increasing their comfort levels with purchasing a PHEV. Additionally, battery related questions have a large impact on comfortability in purchasing a PHEV.

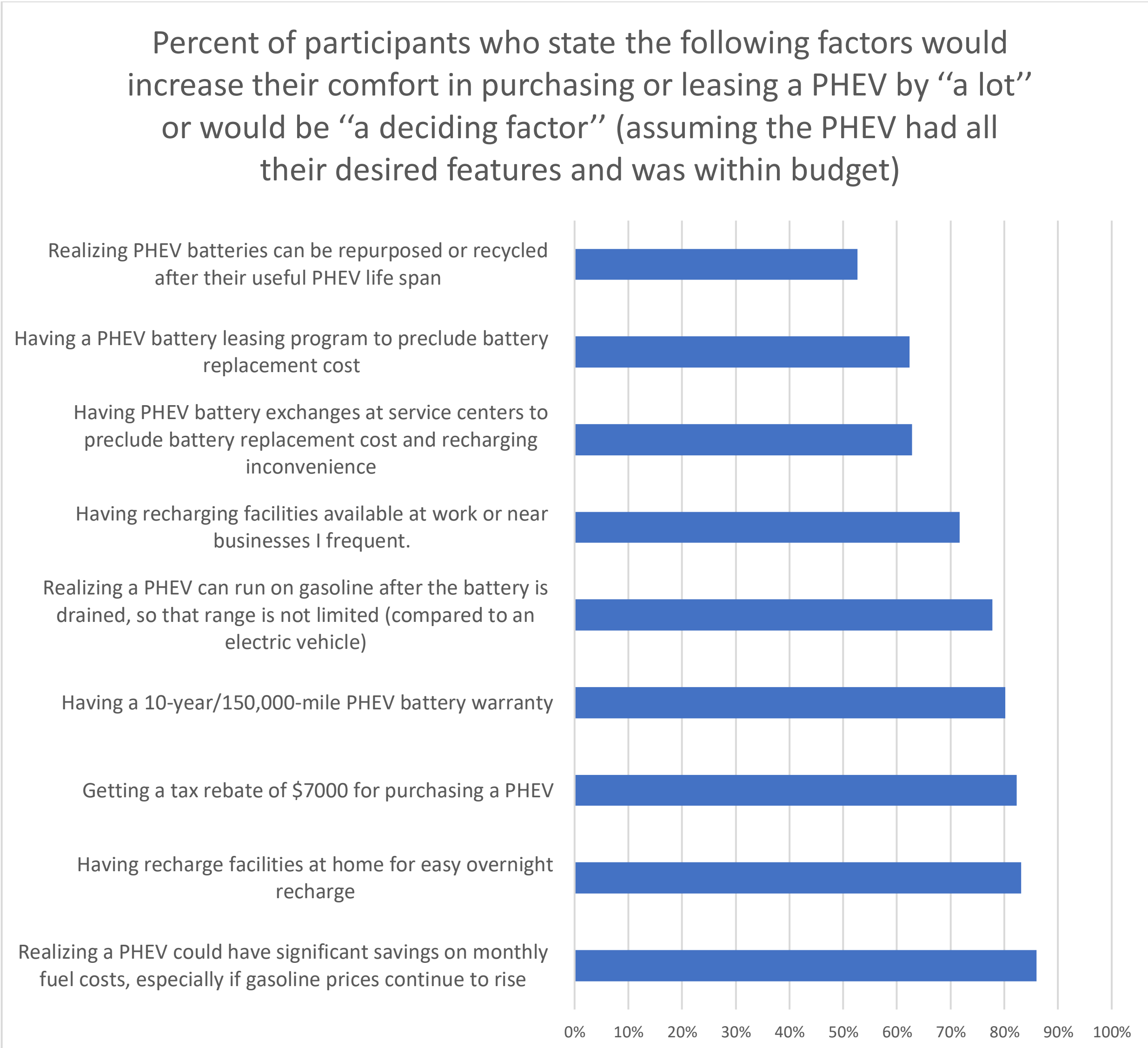

Fig. 9: Increasing comfort in owning a PHEV from Krupa et al., [22].

One of the most significant components of the total cost of ownership for a battery electric vehicle (BEV) is the battery itself. The price of a BEV could drop significantly as battery technology continues to improve. The battery's longevity also impacts how long a BEV is expected to be on the road. The third section of this report will focus on the battery of BEVs since it is such a vital component.

2.2. EV Adoption Barriers

Identifying common barriers to electric vehicle adoption is essential to reducing those barriers and increasing electric vehicle adoption. This section includes obstacles to electric vehicle adoption, including battery performance, charging access, and range anxiety. This report is focused on the barriers related to a BEV's battery specifically, but there are other barriers to BEV adoption, including technological and social barriers.

2.2.1. Battery Performance

In Krupa et al., participants were asked about their level of concern surrounding PHEVs and were told to assume that the PHEV had all of their desired features [22]. The answer choices were 1 = ‘‘not at all’’; 2 = ‘‘a little’’; 3 = ‘‘somewhat’’; 4 = ‘‘a lot’’; and level 5 = ‘‘a preventative factor’’. **Fig. 10** contains the percentage of respondents who selected that their level of concern would be a lot or a preventative factor. Factors relating to the battery performance had high levels of reported concern in the results. The highest level of concern among participants was for the cost of replacing the battery if it failed with almost 80% of participants responding that their level of concern was a lot or preventive of purchasing a PHEV. Additionally, 70% of participants are concerned about the battery lifetime. The least concern among participants was for the ecological cost of battery disposal and the ecological and/or political cost of manufacturing. Additionally, Egbue and Long focuses on the impact that the range of a BEV has on likelihood of adoption [40].

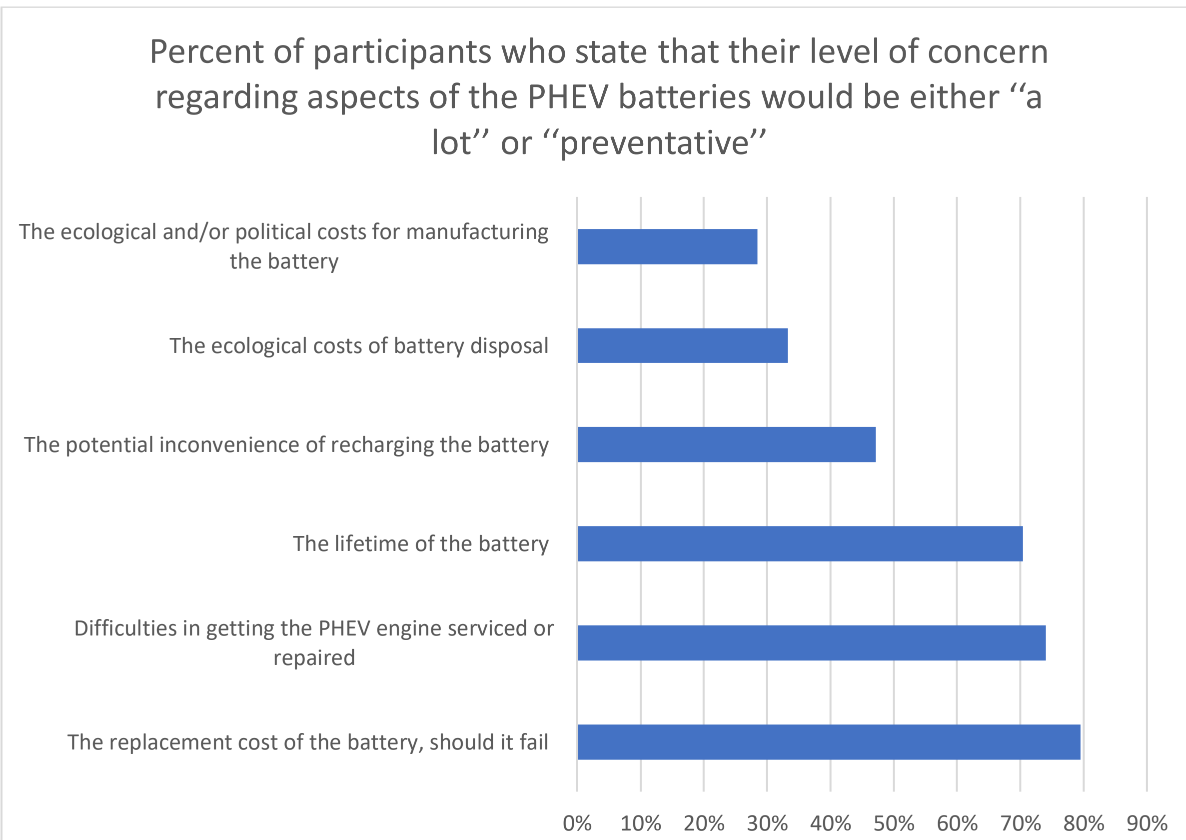

Fig. 10: Concern surrounding battery of BEV from Krupa et al., [22].

Charging

Access to charging stations is essential in BEV adoption since they depend entirely on charging. Krupa et al. found that 47.2% of respondents said that the potential inconvenience of recharging the battery would be a lot or a preventative factor in their decision to purchase a

PHEV. [22]. Axsen and Kurani conducted two surveys on access to residential charging infrastructure. [41]. They found that households living in detached homes with garages have much more access to an electrical outlet near their vehicle parking spot. Additionally, Carley et al. find charge time to be a disadvantage of electric vehicle adoption, with some stating that charging time is a significant disadvantage, leading to a 16.89% decrease in stated adoption intent. [15].

The infrastructure for electric vehicle charging has expanded across the U.S., with the greatest concentration of chargers in the largest cities. **Fig. 11** and **Fig. 12** show the number of public charging outlets by county as of March 2023 [42]The number of charging outlets per county shows higher density on the East and West Coasts and large population centers. Although not shown here, charging outlets tend to be located along the federal interstate system.

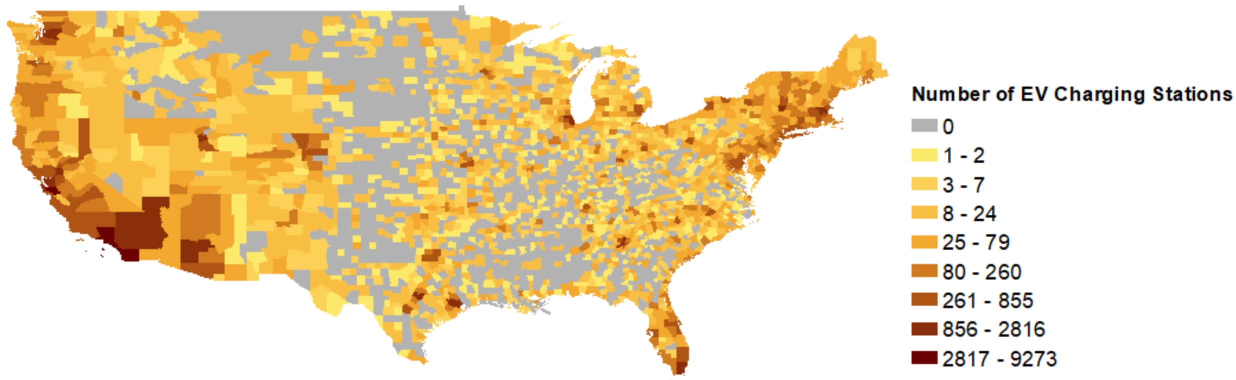

Fig. 11. Public electric vehicle charging outlets by county [42].

Much of the country (36.2 % of all counties) has no public charging outlets. Of the counties with at least one charging outlet, 80.2 % have 25 or fewer, while other areas have significant density. [42]. For example, one county (Los Angeles County) has over 9000 charging outlets. Most (77.2 %) current chargers are Level 2, while 22.2 % are Level 3 (DC Fast Charging) and 0.6 % are Level 1.

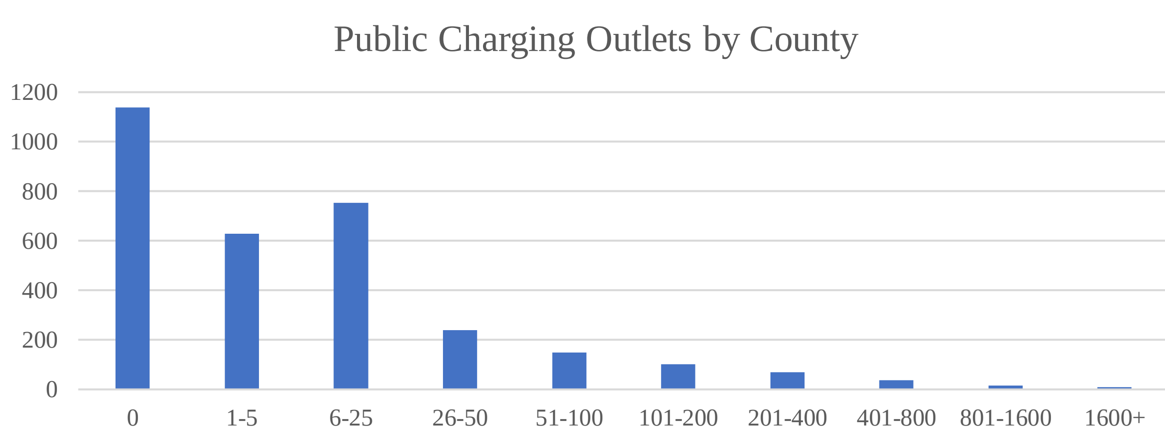

Fig. 12. Public electric vehicle charging outlets by county [42].

Potential EV adopters have identified access to chargers as a significant barrier. Additional investments in charging infrastructure will be necessary for the ever-growing share of vehicles, both BEVs and PHEVs. There are 51 804 public EV charging "stations" with 133 503 outlets (ports) across the U.S. as of March 28, 2023, with few being standalone locations like most gas stations. Instead, charging stations are in parking lots/garages for large retailers, shopping malls, airports, car dealers, hotels, hospitals, schools, etc. This may hinder EV owners from quickly finding a charging station while away from their residences. Additionally, 82 % of these stations have two or fewer charging outlets, limiting the volume of vehicles that can be charged at any time. For perspective, there are 145 000 fueling stations across the United States [43] that typically have 6 to 12 pumps each.

The infrastructure needed for mass electric vehicle adoption will look different from the existing network of gas stations. Instead of requiring a charging station to be located, many owners will complete most of their charging at their residence and/or workplace. Public charging will likely be needed occasionally. One estimate of the required number and level of charging outlets is provided in [6], which leverages NREL's EVI-Pro Lite tool [44]. The U.S. will require charging ports totaling 12.9 million by 2030 with the following breakdown:

- Public fast charging (Level 3) = 0.14 million (1 %)
- Public Level II = 2.01 million (16 %)
- Workplace Level II =1.21 million (9 %)
- Home & Multi-family Dwelling Level II = 9.52 million (74 %)

To meet such infrastructure needs, significant investment will be required. Future investment in charging infrastructure is being led by federal funding to create a national network of 500 000 electric vehicle chargers by 2030 [45]. There is $7.5 billion for EV charging, $4.2 billion of which is being allocated for states to install EV charging stations along designated Alternative Fuel Corridors [46]. Additional funding totaling over $5.3 billion includes over $3.0 billion from electric companies that have received state regulatory approval and over $2.3 billion from Electrify America (a Volkswagen subsidiary) and Environmental Mitigation Trust resulting from the Volkswagen emissions settlement. [6]. Other auto manufacturers (e.g., Tesla, BMW, Nissan, GM) and their partners (e.g., ChargePoint, EVgo) are also building charging infrastructure.

2.2.2. Range Anxiety

One common concern of vehicle buyers when considering a battery electric vehicle (BEV) is the range of that vehicle. Buyers are often worried that they will run out of range and be unable to complete the trips they want to because of the limited range of a BEV. This concern surrounding the range of a BEV has been called 'range anxiety.' Carley et al. find that individuals who see the range as a significant disadvantage of an electric vehicle are 16.78% less likely to adopt an electric vehicle [15].

Franke et al. document the impact of range anxiety before and after potential vehicle buyers test a BEV for three months. [47]. The article finds that range anxiety is positively correlated with an increased preference for a BEV with a higher range. As drivers gained more experience with the BEV, their desired range decreased and was more related to their daily driving patterns and mobility needs. **Table 6** includes the question text that was used to measure range anxiety in Franke et al., [47]. The analysis used a combination of an open-text question coded by hand and three questions on a Likert scale to measure range anxiety in the participants.

Table 6: Questions used to measure range anxiety in Franke et al., [47].

Question	Scale
"How have you experienced the range of the EV?"	Qualitative analysis
"The range was sufficient for everyday use."	1 (completely disagree) to 6 (completely agree)
"While driving, I was often worried about the range."	1 (completely disagree) to 6 (completely agree)
"I am more worried about the range in an EV than in a conventional combustion engine vehicle."	1 (completely disagree) to 6 (completely agree)

Although range anxiety has been documented as a barrier to electric vehicle adoption, range anxiety in BEV owners has also been evaluated. Yuan et al. study the impact of range anxiety on BEV owners. [48]. The range anxiety measures, as well as the scale, mean, and standard deviation, are in **Table 7**. Most BEV owners reported being content with their vehicle's range and trusting the remaining range displayed by their vehicle. They also reported behaving decisively and that their emotions did not impact their driving. While the range is a limiting factor of a BEV, owners of BEVs did not seem to experience much anxiety or concern surrounding the range of their vehicles.

Table 7: Range anxiety measures from Yuan et al., [48].

Statement	Scale	Mean (SD)
"I am content with my BEV's range."	1 (strongly disagree) to 5 (strongly agree)	3.41 (1.185)
"It is convenient to recharge my BEV."	1 (strongly disagree) to 5 (strongly agree)	3.54 (1.100)
"I trust my BEV's range remains display."	1 (strongly disagree) to 5 (strongly agree)	3.64 (1.135)
"I behave decisively when driving."	1 (strongly disagree) to 5 (strongly agree)	3.87 (0.913)
"Emotions hardly affect me when I am driving."	1 (strongly disagree) to 5 (strongly agree)	3.55 (0.989)

3. EV Resale and Battery End-Of-Life Decisions

With the rise of pre-owned BEV sales, there is increasing concern and interest in expected battery life and replacement options for BEV batteries. BEV batteries have a typical warranty of 8 to 10 years with some level of expected degradation. Given that the first mass-production BEVs are just reaching the end of their warranty period, it is likely to see an expansive focus on the performance of batteries at the end of service life in a BEV. Additionally, the length of time vehicle owners keep a vehicle has risen on average to over ten years. Unknown long-term battery life could be a deterrent to adoption. Different battery technologies could influence the expected lifetimes. Due to a combination of supply constraints and price volatility of the rare earth elements required in lithium-ion batteries, there has been a shift toward lithium iron phosphate (LFP) batteries starting in 2021 in lower price point vehicles because it lowers cost with a trade-off in power density that reduced vehicle range.

3.1. Pre-owned EVs

The transition toward decarbonizing personal transportation depends on the emerging pre-owned electric vehicle market. However, this market faces unique challenges, such as concerns over battery reliability, alongside typical used car market issues like model availability and vehicle condition uncertainties. Pedrosa and Nobre highlight the impact of battery quality on consumer acceptance and the valuation of used battery electric vehicles (BEVs) [49]. Their findings, derived from semi-structured interviews with seventeen conventional vehicle drivers, reveal nuanced perspectives on the willingness to invest in second-hand EVs, stressing the importance of battery condition and after-sales assurances.

Pedrosa and Nobre's findings are significant as they reveal the varied willingness among participants to engage in the second-hand BEV market [47]. The participants' willingness to pay for a second-hand BEV over their conventional vehicle budget varied significantly, with eight individuals willing to pay more for a BEV than their conventional vehicle budget by an average of 50% more. The proposition of a refurbished second-hand EV equipped with a new battery and dealership warranty elicited unanimously positive reactions. Statements from participants such as "It would bring more confidence in the purchase" (Participant 2) and "As long as there is a warranty by the dealership... I see no other problem" (Participant 5) underscore the heightened perceived value and confidence provided by a new battery and warranty. Post-introduction of the refurbished option, the study noted a distinct shift in participants' valuation: six maintained their initial willingness to pay, while eight indicated a willingness to pay a higher amount for the refurbished BEV than previously when given no information about the BEV. This willingness to increase their budget for a refurbished BEV highlights the substantial impact of battery replacement and warranties on consumer decision-making in the second-hand BEV market. Further, **Fig 13** details the responses received by the authors during the interview.

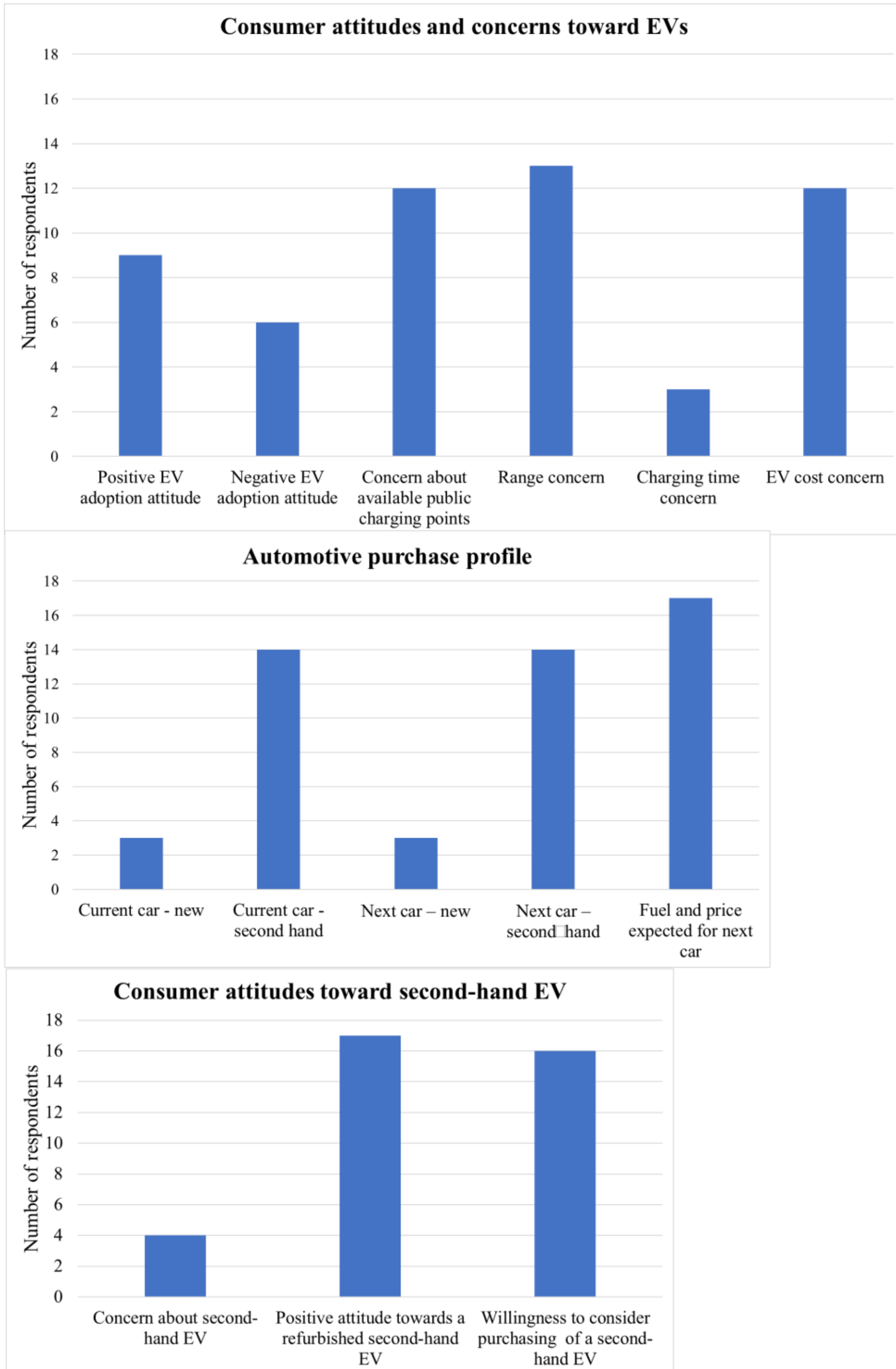

Fig 13. Responses received by Pedrosa and Nobre's semi-structured interview [49]

Christensen et al. complement these findings by delving into the dual-edged nature of Lithium-ion Battery (LIB) technology's rapid adoption [50]. The authors outline the environmental and safety challenges stemming from global incidents, regulatory standards, industry reports, and environmental impact assessments. They identify the BEV production phase, particularly battery production, as more carbon-intensive than its fossil fuel-powered counterparts. This discrepancy is attributed to factors such as the sourcing of battery materials, manufacturing locations, battery chemistry, capacity, and structural materials in modules and packs. The safety risks are also significant, especially to first responders, the public, and the environment. Christensen et al. call for developing a robust educational framework and legal standards to address these challenges. Moreover, they highlight a knowledge gap regarding the total carbon footprint of the LIB industry, advocating for detailed life cycle assessments (LCAs) to quantify and mitigate environmental impacts.

3.2. Battery Performance and Lifetime

Battery performance and longevity are vital in the consumer's willingness to adopt a BEV. [49]. Charging costs and infrastructure are highlighted as immediate barriers to the adoption of BEV. [51]. Battery performance and longevity directly impact charging frequency, which can be disrupted by charging costs and infrastructure.

Several studies have investigated charging frequency, charging patterns, and driving patterns that impact battery health and longevity. Bashash et al. explore the possibilities of optimizing charging patterns for PHEVs that use lithium-ion batteries while reducing operational costs. [52]. The study focuses on anode-side resistive film formation as a significant factor in battery wear. By combining the theoretical modeling of battery degradation, simulations of on-road power management, and considering the variation in the actual electricity prices in Michigan, the study addresses the inherently conflicting idea of reducing the operational cost while extending the battery life in electric vehicles. The research identifies four solutions that balance energy cost and battery longevity enhancement. The **Table 8** summarizes the solutions mentioned by the authors.

Table 8: Selected solutions proposed by Bashash et al., [52].

Choice	Preference	Solution proposition
1. PHEV operates as a conventional HEV	Least battery degradation	No external charge is added to the battery, so the battery packs' State of Charge (SOC) remains at its lowest.
2. Trade-off between energy and battery health	Battery health	A charge of about 50% is added to the battery before the first trip only. The charging is delayed until before the start of the journey to avoid unnecessary degradation due to storage at high SOCs. The best way to achieve this is to deplete the battery soon after charging.
3. Trade-off between optimization and energy cost	Energy cost	In a two-trip scenario, both trips include charging. The first trip receives a full charge (65%), while the second trip receives a 30% added charge. The first charging is delayed until the first trip's departure time, and the second charging is delayed until the

		transition to on-peak electricity pricing. Therefore, charging takes place only during off-peak hours.
4. Charge pattern leading to the least energy cost	Energy cost	This solution mirrors the third one, except the PHEV is fully charged before each trip.

Another comprehensive analysis conducted by Neubauer et al. in 2012 applies the Battery Ownership Model (BOM) to examine the sensitivity of BEV economics to 'drive patterns,' 'vehicle range,' and 'charge strategies.' This analysis includes a high-fidelity battery degradation model, financially justified battery replacement schedules, and two different means of accounting for a BEV's unachievable vehicle miles traveled (VMT). [53]. Unachievable miles refer to the difference in miles driven between a conventional and a battery electric vehicle. One key finding from applying the BOM is the strong impact of the valuation of unachievable VMT with a BEV. This valuation significantly influences the optimal range, charge strategy, and battery replacement schedule, highlighting the complex interplay between BEV utilization and cost. The study emphasizes the high sensitivity of BEV cost competitiveness to specific drive patterns, highlighting the need to consider individual or household driving behaviors in economic evaluations. Changing the drive pattern can increase the BEV to conventional vehicle cost ratio by up to a factor of 3.6. For instance, nearly 25% of the drive patterns demonstrate that a 75-mile-range BEV in the household could be more cost-effective than an additional conventional vehicle when the unachievable miles can be completed at low cost using a range-unlimited conventionally powered vehicle available within the household. Thus, the study highlights that the total cost of ownership (TCO) largely depends on the driving pattern, and comparing the TCO of a conventional vehicle with that of a BEV is not as simple because it invariably delves into the complexities of driver behaviors and driving patterns.

A study conducted by Yang et al. highlights that the variability in battery life expectancy across the U.S. ranges from as low as 5.2 years in Florida to as high as 13.3 years in Alaska, under a 30% battery degradation threshold [54]. The variations are attributed to ambient temperatures, driving patterns, annual travel demand, and driving conditions. A compromised battery condition can result in higher energy consumption, increasing greenhouse gas (GHG) emissions for each kilometer traveled. The authors highlight that the energy consumption and GHG emissions from EV operations in the U.S. are generally increasing by 11.5–16.2% at the recommended 30% battery degradation limit. In their 2015 study, Neubauer et al. also demonstrate this cycle of impact through their research of select high-wear cases, particularly for high-mileage drivers in hot climates; the average battery temperature during initial use—primarily influenced by the climate—is the single most critical factor affecting the battery's residual value for secondary applications. [55]. Both studies demonstrate the impact of climate on BEV battery degradation and their second-life usage.

Complementing the studies conducted by Yang et al. and Neubauer et al., the research undertaken by Martel et al. evaluates the long-term management of battery degradation and its impact on operational costs, particularly in the context of PHEVs equipped with advanced battery and fuel cell technologies [56]. This is done by assessing the feasibility and economic implications of a preemptive battery replacement strategy for plug-in hybrid electric vehicles (PHEVs). The results of this study highlight that, over time, as a battery in a PHEV gets worn out, the importance shifts from using the battery for power to using fuel. This happens because the battery does not perform as well, and it's not economically wise to keep it in a state that prevents wear and tear from using fuel. The analysis also reveals that while preemptive replacement of the PHEV battery pack might seem like a viable strategy to counter late-stage battery degradation, the economic benefits are minimal. The slight variations in lifetime expenses (between 4% and 7%) suggest that preemptive PHEV battery replacement is not cost-effective.

3.3. Battery Reuse Alternatives

End-of-life battery management is critical in EVs (BEVs and PHEVs), which may not be as thoroughly researched as user-centric factors such as charging infrastructure, range, and battery life. Given the chemistries involved in manufacturing EV batteries, improper disposal or after-life management could negate the environmental benefits gained during the EV's operational lifetime. Although some studies have investigated the post-use applications of EV batteries, this area could benefit from further exploration.

A study conducted by Skeete et al. examines the challenges and opportunities associated with the end-of-life management of Battery Electric Vehicles (BEVs) [57]. The authors studied the dynamic stockpile of obsolete lithium-ion batteries (OLIB) between 2011 and 2018 in the United Kingdom. They projected the United Kingdom's dynamic stockpile of OLIB through 2025 using forecasted BEV registrations. The results of the OLIB forecast reveal a potential stockpile exceeding 100 000 battery packs by 2025 or 42 000 t of lithium-ion battery waste. Thus, the study underscores a critical need for developing sustainable recycling technologies and policies. The analysis also reveals a gap in current recycling capabilities, particularly for batteries with varied chemistries and form factors, emphasizing the necessity for innovative recycling processes that can adapt to these challenges. The findings from Baars et al. continue the conversation on resource sustainability and end-of-life battery management, specifically by researching the escalating demand for cobalt due to the wide adoption of lithium-ion batteries in EVs and its implications for the automotive industry's supply chain. [58]. Baars et al.'s conclusions resonate with Skeet et al.'s findings by highlighting that technology-driven circular economy strategies with efficient recycling systems hold the most promise in significantly reducing cobalt reliance. Jiao and Evans also find that repurposing end-of-life (EOL) BEV batteries presents a promising avenue for enhancing the sustainability of BEVs. Still, it is not a remedy for all environmental challenges associated with the industry. [59]. Some key factors identified in the study include the critical role of battery ownership in managing the lifecycle of batteries, the importance of fostering inter-industry partnerships for scaling up battery second-use applications, and the need for supportive government policies to create a conducive environment for such initiatives. These elements are crucial for overcoming the current hurdles and maximizing the value of used BEV batteries, thereby reducing the cost barrier for BEVs and improving the overall sustainability of the technology.

Another study by Heymans et al. assesses the viability of repurposing BEV batteries as residential energy storage systems (ESS) [60]. The primary research question centers on whether decreased electricity rates or auxiliary fees would incentivize Ontario homeowners to adopt second-use battery packs for load shifting. The findings indicate low potential savings, with the maximum annual household benefit from an ESS estimated at $38. The study also notes that an ESS made of used battery could lead to a 6 to 7% rise in energy use, equating to an annual increase of 390 kWh. Despite this uptick in consumption and potentially low savings, the research supports the repurposing of EOL EV batteries for residential ESS, pointing to economic incentives that could improve feasibility. Significant savings and cost recovery for the initial investment in ESS are possible if auxiliary fees are eliminated and off-peak electricity rates are cut by 75%. The elimination of auxiliary fees is identified as the most effective savings strategy. The study acknowledges that a 6 to 7% increase in energy consumption could necessitate an additional 57 900 MW for Ontario's power grid if 1 in 20 detached homes adopted the technology. The study makes it clear that this consumption would be distributed throughout the day, potentially reducing the load on the power generation system and possibly lowering GHG emissions through the increased utilization of Ontario's low-cost, low-emission nuclear energy.

A study by Neubauer et al. conducted in 2015 explores the viability and methodology of repurposing used plug-in electric vehicle (PEV) batteries for secondary applications, specifically focusing on energy storage. [55]. The examples of PEVs authors give are BEVs like Chevrolet Volt and Nissan LEAF. This concept, termed Battery Second Use (B2U), aims to extend the utility of PEV batteries beyond their initial automotive use. The study's findings highlight that properly managed repurposed PEV batteries could effectively serve in secondary roles, such as energy storage for peak shaving, for ten years or more. It underscores the significant impact of capacity fade from automotive use on the value and performance of batteries in their second life.

A similar study by Zhu et al. evaluates the feasibility of reusing retired BEV lithium-ion batteries in less demanding applications while offering economic and environmental benefits. [61]. The study highlights that with the increase in BEV usage, many batteries are expected to retire due to reduced capacity and performance, failing to meet the stringent demands of vehicular use. The paper discusses various disposal methods for lithium-ion batteries and highlights ‘repurposing’ as a preferred option where retired batteries are used in less demanding applications like energy storage for low-speed electric vehicles, residential energy systems, street lighting, and as backup power for large buildings. The study also conducted an economic feasibility assessment of battery repurposing by comparing the costs of refurbishing batteries against the cost of manufacturing new ones. The study states that the production of new batteries is becoming cheaper due to technological advances and increased production to scale. The paper mentions forecasts suggesting that new lithium-ion batteries might drop below $100/kWh in the coming decade, setting a benchmark for the refurbishment costs to beat. It is noted that the refurbishing costs could be reduced to as low as $20/kWh with practical strategies. The study highlights that the economic feasibility of repurposing retired BEV batteries hinges on the ability to refurbish and reuse them at a competitive cost compared to producing new batteries, along with creating favorable market and regulatory conditions that can sustain such business models. The authors also highlight other challenges, such as the lack of standardization procedures for assessing and refurbishing used batteries and safety concerns associated with reusing batteries that have degraded over time. Thus, the authors advocate for increased research, development, and regulatory framework improvements to support the second-life battery industry, emphasizing that overcoming these challenges could lead to substantial economic and environmental benefits.

3.4. Battery Information

Tracing and maintaining comprehensive information on batteries is crucial for facilitating informed end-of-use decision-making, ensuring environmental sustainability, and optimizing resource recovery. To achieve this, the implementation of a Digital Battery Passport (DBP) can play a pivotal role. This tool provides a digital record of a battery's lifecycle, including its manufacturing details, usage history, and recycling information, thereby enhancing transparency and efficiency in battery management. DBP establishes digital twins for the batteries that could provide valuable information about the battery's life cycle and support sustainable battery management during the battery's end-of-life period. A study conducted by Bai et al. provides an extensive review of lithium-ion battery (LIB) recycling technologies and details the concept of the Battery Identity Global Passport (BIGP) [62]. The authors highlight that BIGP could serve as a significant enhancement to facilitate the efficient sorting and recycling of batteries as it serves as a tool that could lead to streamlined recycling processes by providing recyclers with immediate access to detailed information about the batteries like battery's chemistry, origin, state of health, and chain of custody accessed through scanning devices used by recyclers. Moreover, BIGP could potentially overcome challenges posed by proprietary concerns, as battery manufacturers might be hesitant to share detailed formulation data. Therefore, cooperation between stakeholders, including manufacturers and recyclers, is essential to implement the BIGP effectively. This cooperation would be facilitated by global agreements and regulatory frameworks that support the integration of such digital tools into the battery manufacturing and recycling ecosystem.

In their 2022 study, Berger et al. detail the development of a Digital Battery Passport (DBP) for electric vehicle batteries (EVBs) to identify and categorize the necessary data points that would enable a more sustainable and circular approach to EVB management [63]. The researchers used SCOPIS (Supply Chain-Oriented Identification Process) methodology to identify potential DBP users within the EVB value chain. This included an initial systematic literature review using PRISMA guidelines to create a value chain diagram, validated and adapted through expert feedback. Based on stakeholder mapping and systematic literature review inputs, 54 specific data points were structured into four main information categories, reflecting the needs across the EVB lifecycle from production to end-of-life. The DBP information categories devised were labeled as (1) battery, (2) sustainability and circularity, (3) diagnostics, performance, and maintenance, and (4) value chain actors. Further, the paper highlights four uses of the DBP concept, covering the entire life cycle of the battery. (1) an OEM (representing the beginning-of-life phase); (2) a vehicle user (representing the middle-of-life phase); (3) a recycler (representing the end-of-life phase); and (4) a regulatory body (representing a stakeholder group which may exert influence over the entire product life cycle). In another study, Berger et al. explore how DBPs could impact various stakeholders in the Electric Vehicle Battery (EVB) value chain, focusing on the data needs and sustainability performance management (SPM) [64]. Using focus groups, interviews, and expert consultation, the authors highlight that the stakeholders need data transparency and traceability for effective decision-making. It also highlights that stakeholders at various points in the EVB value chain—manufacturers to end-users and recyclers—have differing priorities and, thus, different informational needs. Although the need for data is variable, the data available to each stakeholder varies dramatically. For instance, manufacturers might have complete access to production data. Still, this information often does not flow freely to downstream stakeholders such as maintenance providers or second-life battery users, leading to potential inefficiencies or suboptimal decisions based on incomplete data. The fragmentation of the value chain, lack of standardization of data documentation and data sharing, and reluctance to share information could directly impact circular economy strategies. Thus, the authors [64] recommend incorporating the stakeholders' varying requirements into a DBP for sustainable battery management.

4. Recommendations for Future Research

This report has focused on electric vehicle adoption research, specifically on battery-related considerations. The battery of a BEV is one of the most expensive components, but it also has a shorter lifespan than the rest of the vehicle's components. The engine in a BEV experiences less damage while running the car than a typical combustion engine, which could allow BEVs to be on the road longer than their conventional vehicle counterparts. The battery lifespan of a BEV battery is only approximately 8-10 years, which is a constraining feature of the vehicle's lifespan unless the battery is replaced. Additional concerns surrounding the battery of a battery electric vehicle include how to reuse or recycle the battery most efficiently if it is replaced and what information would be needed to make that process more efficient.

One under-explored research area is related to how range anxiety is different between BEV and non-BEV owners. While the impacts of range anxiety have been measured in both groups, direct comparisons are limited by the ways questions have been asked. The different constructs for measuring range anxiety are not easily comparable across different population groups, preventing comparisons between the two groups. Additionally, the impact of range anxiety does change with familiarity with a BEV, so more information about how range anxiety changes over the length of ownership of a BEV would be a fascinating additional exploration to see if the size of experience impacts range anxiety or if having experience is the only impact.

Additionally, battery degradation experienced by BEV owners is an under-researched area of the BEV literature. The amount of battery degradation experienced varies considerably based on driving, weather, charging, and more. Understanding how BEV owners experience degradation and how that impacts their driving and charging behavior is critical. The slight range changes may also affect the range anxiety that BEV owners experience as the range they can travel on a single charge decreases over time.

As more BEVs are sold on the pre-owned market, understanding how the batteries degrade over the vehicle's lifetime will become more critical to user experiences. Additionally, how this information is communicated to pre-owned vehicle purchasers will matter for the stability of the pre-owned market. At the time of publishing, there are not currently any papers that investigate the impact of battery health information or the source of that information on consumer decisions in the pre-owned electric vehicle market. As more BEVs are bought and sold in the new vehicle market, having a well-functioning market with complete information in the pre-owned market will become increasingly important.

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Appendix A. Annotated Bibliography

Axsen, Jonn, and Kenneth S. Kurani. "Who can recharge a plug-in electric vehicle at home?" ***Transportation Research Part D: Transport and Environment*** **17.5 (2012): 349-353.**

The availability of electrical infrastructure for recharging is essential for the adoption of plug-in electric vehicles (PEVs). Two consumer surveys of new vehicle buying households provide insights into residential recharge access at Level 1 (110/120 V) and Level 2 (220/240 V) charging. The first study, which surveyed 2373 US households in 2007, found that 52 % had access to Level 1 charging at home. Detached homes and garages were positively correlated with access, but only one in six apartment dwellers had access. There were also significant regional differences in Level 1 access.

The second study assessed Level 1 and Level 2 charging access among 548 new vehicle buyers in San Diego County, California, in 2011. It found that access to both charging levels was higher for respondents living in detached homes or parking their vehicles in a garage or driveway. Among respondents with potential to install a Level 2 charger, interest in purchasing a PEV and willingness to pay for installation were higher for those facing lower installation costs. Overall, 20 % of the San Diego sample wanted their next new vehicle to be a PEV and were willing and able to install a Level 2 charger.

These studies indicate that around 50 % of new car buying households in the US have the potential to recharge a vehicle at home using Level 1 service. Access to Level 1 charging is positively correlated with single-family dwellings and private garages. In San Diego, Level 1 access depends more on living in an attached or detached home and having a private garage or driveway. For Level 2 access, 28 % of respondents faced only the cost of the recharging appliance, while 45 % faced additional installation costs, mostly below $4000.

The findings highlight the importance of consumer-informed estimates for understanding PEV demand, usage, and energy impacts, as well as prioritizing recharge infrastructure development. Combining consumer information with their observations can replace assumptions and proxies. Approximately 50 % of US new vehicle buyers have Level 1 home access suitable for smaller battery vehicles, while one-third in San Diego County have access to Level 2 home charging for larger battery vehicles, with 20 % willing to pay for the installation costs.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H. E., & Heidrich, O. (2020). Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nature Sustainability, 4(1), 71–79. https://doi.org/10.1038/s41893-020-00607-0

The paper addresses the escalating demand for cobalt due to the wide adoption of lithium-ion batteries in electric vehicles (EVs) and its implications for the automotive industry's supply chain. It explores how circular economy strategies (CES) can mitigate the primary raw material extraction challenges, focusing on cobalt supplies within the European Union. The main research questions include how CES can reduce reliance on primary cobalt extraction and what are the impacts of these strategies on the automotive supply chain.

The data utilized in this research encompasses a mix of secondary data sets from governmental statistics, company reports, and primary data from interviews and site visits to recyclers. This comprehensive data collection is aimed at analyzing current and future cobalt flows embedded in EV batteries specifically within the EU context. The data spans a historical overview of cobalt demand from 2017 and projects future demand up to 2050, considering the evolving landscape of EV adoption rates, battery chemistries, and potential secondary supply routes.

The study employs Material Flow Analysis (MFA) to examine the stocks and flows of cobalt in EV batteries, spanning from 2017 to 2050, under various circular economy strategies. These strategies include technology-driven substitution and reduction, business models for battery reuse/recycling, and policy-driven recycling initiatives. A static MFA is utilized to analyze the global flow of cobalt from mining to production, as well as its journey from consumption to the end-of-life stage for EVs registered in 2017. To forecast future cobalt flows, a dynamic MFA is conducted, outlining a reference scenario that assumes minimal changes in institutional conditions and end-of-life management from 2017, yet incorporates expected technological advancements.

To calculate cobalt flows for 2017, vehicle-specific details were gathered, including battery size, chemistry, and material content data, informed by diverse data sources such as the European Environmental Agency and the Argonne National Laboratory. The model further distinguishes between different types of battery chemistries based on the nickel content which affects specific energy. The cobalt content per vehicle model is then derived based on these chemistries and the battery size.

For future projections, the dynamic MFA incorporates expected sales of BEVs and PHEVs, regulatory CO_2 targets, population projections, and potential battery chemistry and capacity shifts. Future vehicle and battery characteristics are segmented by vehicle type, with assumptions about specific energy improvements and market share projections for various battery chemistries. This approach allows for a nuanced understanding of how changes in technology, policy, and market dynamics might influence cobalt demand and the opportunities for recycling and secondary use of batteries.

Results indicate that technology-driven strategies hold the most promise in reducing cobalt reliance significantly but could lead to increased demand for other materials like nickel. The findings suggest a significant potential for CES to mitigate primary cobalt consumption, with technology developments and efficient recycling systems playing crucial roles. However, the paper also outlines several limitations, including the dependence on accurate future EV adoption rates, battery chemistry transitions, and the assumption of consistent vehicle and battery lifespans. Future research is recommended to explore the implications of increased nickel demand, the viability of novel battery technologies, and the economic and environmental impacts of expanding EU battery recycling capacities. This study underscores the urgent need for more ambitious circular economy strategies to address the supply chain challenges posed by the growing EV market.

Bai, Yaocai, et al. "Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport." ***Materials Today*** **41 (2020): 304-315.**

This study investigates the potential of direct recycling as an energy-efficient and environmentally sustainable lithium-ion battery (LIB) recycling strategy. The research question focuses on addressing the challenges associated with direct recycling and the development of LIB recycling technologies to promote a circular economy.

A Battery Identity Global Passport (BIGP) is a proposed digital system that provides crucial information about batteries, such as their chemistry and manufacturing details, to manufacturers and recyclers. This system could significantly ease recycling efforts by streamlining sorting and separation processes.

The current state of battery recycling involves three primary methods: pyrometallurgical, hydrometallurgical, and direct recycling. The methods used in this study include discharging, dismantling, electrolyte recovery, and regeneration of electrode materials. Data is collected on the recovery yield and chemical purity of all recovered materials, with a focus on the cathode. Data reveals that the NMC cathode material is around 10 times more valuable than an equivalent number of pure metals, suggesting direct recycling has both economic and environmental benefits. Results indicate that direct recycling can effectively recover manufacturing scraps and batteries produced by manufacturers who recycle their products.

Future work will address the limitations of direct recycling, such as improving the quality and consistency of regenerated materials and recovering current collectors in a cost-effective and environmentally friendly manner. Furthermore, the study will explore the development of Battery Identity Global Passports (BIGP) to streamline the sorting and separation processes for efficient recycling. Research will also focus on promoting a circular economy for LIBs, considering the recycling prospects of solid-state batteries, and designing new technologies for recycling.

One limitation of the current research is that direct recycling is still at the lab scale. More research is needed to validate small-scale experimental results and recover other materials to expand recycling revenues. Evaluating the recycling cost of direct recycling processes and identifying their economic and environmental viability is essential for future development. Collaboration between academia, industries, governments, and end-users is necessary to accelerate the development of LIB recycling technologies and ensure the success of direct recycling and the circular economy.

Bashash, S., Moura, S. J., Forman, J. C., & Fathy, H. K. (2011). Plug-in hybrid electric vehicle charge pattern optimization for energy cost and battery longevity. Journal of Power Sources, 196(1), 541–549. https://doi.org/10.1016/j.jpowsour.2010.07.001

The study is an exploration of optimizing charging patterns for plug-in hybrid electric vehicles (PHEVs) that utilize lithium-ion batteries. It aims to minimize energy costs and battery health degradation. Addressing the inherent conflict between reducing operational costs and extending battery life, the study employs a Non-dominated Sorting Genetic Algorithm II (NSGA-II) for multi-objective optimization, the research utilizes a mid-size sedan PHEV model alongside an established on-road power management strategy, simulating realistic driving scenarios inclusive of both morning and afternoon trips. This approach allows for an examination of the complex dynamics between vehicle operation, charging decisions, and battery health.

Central to the study is the degradation of lithium-ion batteries, with a particular focus on anode-side resistive film formation as a significant factor in battery wear. By combining simulations of on-road power management with theoretical modeling of battery degradation, the research offers a novel perspective in the field of PHEV charging optimization. It further considers daily variations in electricity prices by incorporating the pricing policy of the DTE Energy Company in Michigan, adding a layer of real-world applicability to the optimization process.

The research identifies four distinct charging solutions, each presenting a different balance between energy cost reduction and battery longevity enhancement. These range from no charging, where the PHEV functions as a conventional hybrid electric vehicle, to strategic charging before trips and delayed charging to minimize degradation or reduce costs, particularly emphasizing the benefits of off-peak electricity usage. One of the notable findings is the illustration of the charging process through a “Constant Current – Constant Voltage” (CC-CV) charging strategy, showcasing an initial slow increase in input power followed by a rapid decline. Looking forward, the study outlines future research directions that include extending the optimization and analysis framework to cover various battery sizes, drive cycles, and pricing policies. The study highlights that a significant goal of the future studies could be to apply the optimization approach to assess the collective impact of multiple PHEVs on the power grid, forecasting potential challenges and opportunities for energy providers and vehicle users alike. In conclusion, the paper significantly contributes to the PHEV charging strategy. The application of an electrochemistry-based model for analyzing battery degradation marks an advancement in the study, positioning it as an effort in optimizing PHEV charge patterns for enhanced battery longevity and energy cost efficiency.

Bauer, Gordon, Chih-Wei Hsu, and Nic Lutsey. "When might lower-income drivers benefit from electric vehicles? Quantifying the economic equity implications of electric vehicle adoption." ***Work. Pap*** **6 (2021): 1-21.**

The paper analyzes the financial and equity impacts of electric vehicles (EVs) adoption, specifically targeting lower-income households. To answer their research question - when will EVs reach cost parity with gasoline vehicles across different socioeconomic groups, the authors have used data from the 2017 National Household Travel Survey (NHTS) and 2018 Consumer Expenditure Survey (CEX) as well as key vehicle specs and projected cost inputs. They examined vehicle purchase cost, fuel, insurance, and maintenance as significant components of car ownership. Additionally, they projected the trends for both EVs and gasoline vehicles up to 2030. The study acknowledges that the current fast-paced EV technology improvement leads to higher EV depreciation rates, which indirectly benefits the used EV market due to reduced prices.

The results suggest that, by 2028, the average upfront price parity between battery electric vehicles (BEVs) and gasoline vehicles will be reached across all income groups. Total cost parity, accounting for purchase, insurance, fuel, and maintenance, is expected to be achieved by 2030. Lower-income households might witness these benefits slightly later due to their tendency to buy older vehicles, but the gap is negligible. Moreover, by 2030, the average household could save $1400 per year by replacing all their vehicles with EVs. The paper concludes that, despite expected cost savings and wider EV affordability, there is a need for additional policy action to ensure equal EV access for all income groups. Future work is necessary to analyze supply of affordable used EVs, market dynamics, shorter-range EVs, and the cost of charging infrastructure, which were limitations in this study.

Berger, Katharina, et al. "Data needs and requirements of digital battery passports as enablers of circular battery value chains. A stakeholder perspective." (2022).

The study explores how Digital Battery Passports (DBPs) impact various stakeholders in the Electric Vehicle Battery (EVB) value chain, focusing on the data needs and sustainability performance management (SPM). To address this research question, the authors use focus group workshops, interviews, and expert consultations to collect perspectives and insights from different stakeholders. The data gathered helps identify the importance of specific data points, such as carbon footprints, and the varying needs of stakeholders when it comes to data granularity and sharing.

The results show that stakeholders, including process suppliers, Original Equipment Manufacturers (OEMs), and others, need data transparency and traceability for effective decision-making. However, some may be reluctant to share information due to competitive drawbacks or a lack of legal pressure. The study also reveals that defining information flows is challenging because the EVB value chain is continuously evolving, and new technologies are emerging.

Various actors in the EVB value chain have unique data needs, and the importance they assign to sustainability indicators differs. While current regulations mainly focus on environmental performance, other aspects like social sustainability performance and life cycle assessment-related indicators are often overlooked. The research also highlights the significance of circularity and recycling in the EVB context, and the challenges and barriers associated with implementing DBPs.

In conclusion, this study contributes to the scientific debate around DBPs and SPM, offering valuable insights for regulators and industry stakeholders. Although the research acknowledges its limitations, such as potential biases in the empirical material, it encourages future research to focus on specific stakeholder groups and examine the implications of using DBPs in a rapidly changing landscape.

Berger, Katharina, Josef-Peter Schöggl, and Rupert J. Baumgartner. "Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases." *Journal of Cleaner Production* 353 (2022): 131492.

The study investigates the potential of a Battery Passport, which aims to provide essential information to consumers and stakeholders regarding electric vehicle batteries (EVBs), including longevity and capacity. This information is particularly valuable for used BEV buyers, allowing them to make well-informed decisions.

The Battery Passport covers various aspects, such as product details, sustainability and circularity-related factors, product status, and value chain actors. The study highlights determining the second life of an EVB, emphasizing the importance of this information for different stakeholders, including Original Equipment Manufacturers (OEMs), Electric Vehicle (EV) users, recyclers, and regulatory bodies.

Using a mixed-methods approach, researchers examine four use cases related to the Digital Battery Passport (DBP) concept in the context of Sustainable Product Management (SPM). For each use case, they assess how the DBP addresses the informational needs of the stakeholders. Key findings demonstrate that incorporating real-time estimates of sustainability and circularity-related impacts, as well as product health information, can improve the Battery Passport's user-friendliness and effectiveness.

For OEMs, the Battery Passport can facilitate sustainable and circular value chain development efforts, helping them identify areas for improvement. EV users can benefit from the transparency of the EVB's health and performance data when considering buying a used BEV. Recyclers can use the Battery Passport to determine the most suitable recycling process for an EVB, while regulatory bodies can monitor compliance and assess the overall environmental impact of the EVBs.

However, the research also highlights challenges in achieving value chain transparency and gathering data from different stakeholders. Some actors might be reluctant to share information, fearing potential competitive disadvantages or reputational damage.

In conclusion, developing a Battery Passport for EVBs has the potential to support SPM and contribute to a circular economy. To advance this concept, more research is needed to validate its effectiveness, address data availability and accessibility, and explore key factors for successful implementation. By including information on determining second life and addressing the use cases of various stakeholders, the Battery Passport can become a powerful tool for promoting sustainable practices in the electric vehicle industry.

Berkeley, Nigel, David Jarvis, and Andrew Jones. "Analysing the take up of battery electric vehicles: An investigation of barriers amongst drivers in the UK." ***Transportation Research Part D: Transport and Environment*** **63 (2018): 466-481.**

This paper investigates the barriers to electric vehicle (EV) adoption among internal combustion engine (ICE) vehicle drivers in the UK and seeks to provide practical suggestions to address the EV uptake problem. To achieve this, the study relies on data from a survey conducted by the Automobile Association (AA) Motoring Panel, which measures the level of concern for various barriers using a 5-point Likert scale. The researchers employ exploratory factor analysis (EFA) and multivariate regression analysis to identify the extent to which barriers are influenced by driver characteristics.

The survey includes responses from 26 195 ICE vehicle drivers in the UK. Results show that high purchase price and availability of charging stations are the principal barriers to EV adoption. The study also reveals that addressing individual barriers may not be sufficient to promote mass EV adoption, and a holistic approach is needed. EFA results in two factors: 'economic uncertainty' and 'sociotechnical issues'. The multivariate regression analysis demonstrates associations between economic uncertainty and age and geography, and to a lesser extent between socio-technical issues and gender.

The most significant concerns for EV adoption include high purchase price, availability of public charging stations, time taken to offset the higher purchase price, anxiety over resale values, battery performance, and the availability of maintenance, service, and repair infrastructure. Battery-related concerns are mainly focused on performance and durability.

Future research identified by this paper includes concentrating on understanding regional differences in perception when implementing policies, addressing misinformed perceptions and economic uncertainties, and exploring the connections between intentions and behaviors. One limitation of the study is that it does not provide a clear explanation for the reasons behind economic uncertainty being a barrier outside of London, which requires further investigation.

Bognar, L., Brave, S., Klier, T., & McGranahan, L. (2023). ***Charged and Almost Ready—What Is Holding Back the Resale Market for Battery Electric Vehicles?*** **Federal Reserve Bank of Chicago.** https://doi.org/10.21033/wp-2023-35

This paper investigates the dynamics and characteristics of the used battery electric vehicle (BEV) market in comparison to internal combustion engine (ICE) vehicles, hybrids, and vehicles with mixed powertrain options, focusing on the United States. The core research questions address why BEVs are absorbed into the resale market at a slower rate than other vehicle types and how vehicle miles traveled (VMT) influence the transition of BEVs from new to used status. Additionally, the study explores the potential impact of increased BEV utilization on their presence in the used vehicle market.

This study harnesses an extensive dataset from Experian Automotive's Auto count database and the Wards Intelligence data center, spanning vehicle registrations from model years 2010 to 2022, with registration dates from January 2009 to December 2022. By categorizing vehicles into four distinct powertrain types—internal combustion engines (ICE), hybrids (including plug-in hybrids, PHEVs), mixed powertrain options, and purely battery electric vehicles (BEVs)—the research covers 278 979 072 matched registrations, enabling a comprehensive analysis of the used vehicle market dynamics across these categories. A significant methodological innovation of this research is the development of the used prevalence ratio (UPR), which estimates the proportion of new vehicles sold into the used market, offering insights into the resale market dynamics specific to BEVs in comparison to other powertrain technologies. Key findings indicate that BEVs are absorbed into the resale market at a significantly slower rate and accumulate fewer vehicle miles traveled (VMT) than their ICE and hybrid counterparts.

Utilizing Pseudo Poisson Maximum Likelihood (PPML) estimators to analyze used vehicle registration counts, the research identifies notable behavioral differences in how BEVs versus ICE vehicles are utilized and subsequently resold. A counterfactual exercise adjusting for average VMT across vehicle types suggests that these utilization differences could account for 10 to 30 % of the disparity in resale market penetration between BEVs and ICE vehicles, underscoring the potential of increased BEV utilization to bolster their presence in the used vehicle market.

However, the research acknowledges limitations and areas for future inquiry. It highlights that a significant portion of the difference in market absorption rates remains unexplained by VMT alone, suggesting that factors beyond utilization, such as owner characteristics and preferences, may play a critical role. The study calls for further exploration into these aspects to better understand the dynamics of the BEV resale market. Additionally, the reliance on administrative data, while providing a large and detailed sample, limits the ability to capture the motivations behind vehicle resale decisions directly from owners, presenting another avenue for future research.

Breetz, Hanna L., and Deborah Salon. "Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 US cities." ***Energy Policy*** **120 (2018): 238-249.**

This study compares the cost-effectiveness of the Nissan Leaf (BEV), Toyota Prius (hybrid electric vehicle), and Toyota Corolla (internal combustion engine vehicle) under various electricity and gasoline prices and battery electric vehicle (BEV) subsidies. The Leaf performs better with free electricity and in cities with high subsidies. The cost premium of the Leaf does not change significantly with different discount rates. Leaf and Prius owners may drive more than average due to lower operating costs but achieving cost parity with a Prius or Corolla requires driving a Leaf more than most owners typically do. Depreciation rates for the Leaf are higher than for the Corolla and Prius, but future BEVs might depreciate less. The total cost of ownership (TCO) is lowest for the Corolla, and the Leaf becomes less expensive than the Prius only with free electricity over longer ownership periods.

To achieve unsubsidized cost parity, the Leaf's price must drop significantly, which could happen through automaker discounts or manufacturing cost reductions. The study suggests that current BEVs may be competitive without federal subsidies if several favorable conditions are assumed. However, this study finds large-scale subsidies are not sustainable in the long term, and alternative policies will be needed to support BEV adoption once these are phased out. Small policy options, such as reduced tax rates and low-cost charging, could help make BEVs cost-competitive without federal subsidies.

The results are affected by policy changes, price fluctuations, and vehicle choices. The analysis is based on the initial model year of the Nissan Leaf, and future BEV cost competitiveness may change due to innovation and automakers' strategic decisions. Policymakers should consider alternative policies and regulatory measures, such as energy-based taxes and state Zero Emission Vehicle (ZEV) mandates, to support BEV adoption.

Brückmann, Gracia, Michael Wicki, and Thomas Bernauer. "Is resale anxiety an obstacle to electric vehicle adoption? Results from a survey experiment in Switzerland." *Environmental Research Letters* 16.12 (2021): 124027.

The primary objective of this study is to examine the influence of resale anxiety on the adoption of battery electric vehicles (BEVs) and to compare the depreciation and resale value of BEVs with conventional cars. Using an experimental design integrated into three surveys carried out in Zurich, Switzerland, researchers randomly adjust BEV prices and apply the experiment to both current BEV owners and conventional car owners. Linear and quadratic age terms are used to predict vehicle resale values. A vignette experiment is also conducted to gauge the perceived resale value of various car types.

Data collected from three Swiss population samples found inconsistencies between its findings and other research concerning resale anxiety's role as a barrier to BEV adoption. The study also discovers evidence of a possible correlation between the absence of BEV adoption policies and insufficient support for BEV resale.

The results show a notable premium on the expected resale value of BEVs compared to other car types. BEVs depreciate less than other car types, with a 7 % difference between BEVs and petrol cars. Additionally, the perceived depreciation of BEVs is lower among their owners.

Despite these findings, the study recognizes limitations in terms of generalizability since it is focused on a single country and has a relatively small sample size. The surveys measuring resale anxiety might also display an upward bias. Future research could investigate how car dealers set leasing rates for BEVs compared to non-BEVs and how these influences expected resale values. Moreover, additional exploration is needed to assess the impact of technological risks, shifting social norms, and policy signals on the perceived depreciation of BEVs.

Carley, Sanya, et al. "Intent to purchase a plug-in electric vehicle: A survey of early impressions in large US cites." ***Transportation Research Part D: Transport and Environment*** **18 (2013): 39-45.**

This paper investigates early consumer interest in plug-in electric vehicles (PEVs) by conducting an online survey of 2302 licensed drivers from 21 large urban areas in the U.S. The survey gathers information on consumer perceptions of plug-in vehicles, general vehicle preferences, car-purchasing behavior, travel behavior, and awareness of public policies promoting plug-in vehicle ownership or use. Regression analysis was used to estimate the relationship between intent to purchase and factors influencing consumer interest in PEVs.

Results reveal that the intent to purchase PEVs among U.S. urban drivers was low in 2011, primarily due to perceived disadvantages such as high cost, long recharging times, and limited driving range. Demographic factors, such as age, gender, and education level, were strong predictors of intent to purchase. The study also identified variations in electric vehicle interest across major US cities, suggesting a more cost-effective approach would be to concentrate marketing resources and recharging stations in receptive cities.

Future work could address consumers' concerns about perceived disadvantages by highlighting the economic advantages of electric vehicles in marketing and policy campaigns, increasing the number and visibility of public charging stations, and promoting more efficient technologies such as superfast charging systems or battery pack swaps. However, the study's limitations include the use of a dependent variable that reflects consumer openness to purchasing a PEV, rather than actual purchasing behavior, and the data collection in 2011, which may not fully represent current consumer perceptions and interests in the electric vehicle market.

Carrel, A. L., White, L. V., Gore, C., & Shah, H. (2022). Subscribing to new technology: Consumer preferences for short-term ownership of electric vehicles. Transportation.
https://doi.org/10.1007/s11116-022-10353-1

The literature review synthesizes existing research on the adoption of battery electric vehicles (BEVs) and the burgeoning interest in vehicle subscription models, with a focus on discerning consumer preferences and fostering a transition from traditional vehicle ownership to subscription models. It is premised on the hypothesis that vehicle subscriptions, particularly those for BEVs, offer a lower-commitment pathway for consumers to engage with new automotive technologies, which are crucial for mitigating climate change impacts. This approach is aimed at understanding the factors that influence consumer preferences for vehicle subscriptions over purchases, underscoring the diversity in decision-making processes and quantifying the willingness to pay for flexible BEV subscriptions across different consumer segments.

The review delves into the distinction between BEVs, which rely exclusively on battery power, and other electric vehicles such as hybrid-electric vehicles (HEVs) and plug-in hybrid-electric vehicles (PHEVs), each with unique charging requirements. It acknowledges the varied demographic and psychological traits of early adopters, emphasizing the perceived benefits and risks associated with BEVs. Particularly, it highlights the importance of self-identity, notably among environmentalists and technology enthusiasts, as a predictor of adoption intent. By leveraging the diffusion of innovation theory, the review posits that a specific subset of consumers, characterized by their enthusiasm for technology and environmental values, will show a preference for BEV subscriptions. Exploring the concept of flexible BEV subscriptions (BEV+), the review hypothesizes that risk-averse consumers may favor this option to alleviate range concerns and seamlessly integrate BEVs into their mobility needs. This comprehensive overview sets the stage for investigating vehicle subscriptions as a viable strategy to enhance BEV adoption and support environmental sustainability goals.

Employing a sophisticated survey design and a robust discrete choice model, including integrated latent class and latent variable choice models, this research analyses consumer preferences for vehicle subscriptions versus purchases, with a particular focus on BEVs. The study, conducted among 1567 participants across three U.S. metropolitan areas, uses a stated preference (SP) survey to explore various vehicle acquisition scenarios under different pricing structures and subscription terms, capturing the nuanced preferences of consumers and the impact of technology enthusiast and environmentalist self-identities on decision-making processes. To mitigate hypothetical bias, the study introduced a "cheap talk" script before the choice tasks, encouraging respondents to make realistic decisions between purchasing a vehicle or opting for a subscription. The methodology integrates a discrete choice model with latent class analysis and choice and latent variable models, providing a multifaceted framework for understanding consumer preferences. This approach accounts for heterogeneity among respondents by incorporating latent constructs reflecting technology enthusiasm and environmentalist self-identity and segments the sample into distinct classes based on preferences and behaviors.

The results identify three distinct consumer classes—change-oriented, ownership-oriented, and cost-oriented—each with unique preferences for vehicle subscriptions. The change-oriented class, driven by environmental and technological enthusiasm, significantly favors BEV subscriptions, validating the hypothesis that a segment motivated by sustainability and innovation exists. Conversely, the ownership-oriented class prefers traditional ownership, indicating resistance to subscription models, while the cost-oriented class, influenced by economic considerations, displays a greater openness to BEV and HEV subscriptions, emphasizing cost as a decisive factor.

This nuanced understanding of consumer segments suggests that targeted marketing strategies could effectively enhance the attractiveness of BEV subscription models. The study underscores the potential of subscription models to appeal to a broad consumer base, including technology enthusiasts and environmentally conscious individuals, as well as those hesitant about the upfront costs and technological uncertainties of BEVs. Subscriptions offer a lower-commitment method to experience and adopt BEVs, potentially increasing their attractiveness and adoption rates. Future policy and market strategies should consider supporting subscription models to expand BEV accessibility and appeal, addressing both environmental goals and consumer hesitancy towards new vehicle technologies, thereby significantly contributing to the broader adoption of sustainable transportation solutions.

Casals, Lluc Canals, B. Amante García, and Camille Canal. "Second life batteries lifespan: Rest of useful life and environmental analysis." *Journal of environmental management* 232 (2019): 354-363.

The study investigates the potential for reusing EV and PHEV batteries in stationary applications through a project called Sunbatt. The focus is on four scenarios: fast EV charge support, self-consumption, area regulation, and transmission deferral, with methods involving literature review, environmental and economic considerations, and simulations. Data is collected from the project's operations, the Spanish electricity generation mix, and the estimated efficiency of the charging and discharging process.

Results indicate varying lifespan outcomes. Fast EV charge support shows the longest battery life, at nearly 29 years. Self-consumption offers a Remaining Useful Life (RUL) of 11.6 years, while area regulation and transmission deferral scenarios provide shorter lifespans. Importantly, environmental benefits appear more achievable in self-consumption scenarios, with a 9 % reduction in emissions compared to grid power. Limitations include the need for significant oversizing of renewable power sources for certain applications and the study's regional focus on Spain. The study suggests further exploration of second-life EV battery uses, presenting them as a viable alternative to new lithium batteries.

Casals, Lluc Canals, Mattia Barbero, and Cristina Corchero. "Reused second life batteries for aggregated demand response services." *Journal of cleaner production* 212 (2019): 99-108.

The paper explores how batteries from electric vehicles (EVs) can be used for a "second life" once they are no longer effective for powering cars. The study focuses on one potential second-life use: acting as an energy storage system (ESS) for stationary applications, such as powering buildings. The authors suggest that when an EV battery's capacity drops to about 70 to 80 % of its original state, it can be repurposed for this second-life use. This approach extends the lifespan of the batteries by 35 % and creates a new market niche for lower-cost, second-life EV batteries. Yet, the effectiveness and profitability of this strategy can depend heavily on battery costs and market conditions.

In the study, a second-life EV battery is used to store energy generated from solar panels installed on a public library in Montgat, Spain. The battery also takes advantage of electricity tariff differences. In terms of market services, these batteries are found to be ideal for Frequency Containment Reserves (FCR) and Frequency Restoration Reserves (FRR), due to their fast response and good power-to-capacity ratio. However, participating in these secondary markets could potentially accelerate the aging of the battery. Despite the limitations, the study concludes that second-life batteries could potentially reduce the effective price of EVs, and their life cycle impacts, offering a promising avenue for future research and development.

Christensen, P. A., Anderson, P. A., Harper, G. D. J., Lambert, S. M., Mrozik, W., Rajaeifar, M. A., Wise, M. S., & Heidrich, O. (2021). Risk management over the life cycle of lithium-ion batteries in electric vehicles. Renewable and Sustainable Energy Reviews, 148, 111240.
https://doi.org/10.1016/j.rser.2021.111240

The study explores the role of Lithium-ion Batteries (LIBs) in driving the decarbonization of transportation and energy sectors. It examines the growing integration of LIBs into these sectors, highlighting their indispensable attributes such as high energy density, high voltage, stability, low discharge-rate and long lifecycle which underpin their utility in electric vehicles (EVs) and as storage for renewable energy. The research highlighted the dual-edged nature of LIBs' rapid adoption: while they are central to reducing carbon emissions and fostering renewable energy use, their safety, environmental impact, and lifecycle management present unresolved challenges. The authors have gathered that the electric vehicle (EV) production phase (as opposed to its whole life cycle) is more carbon intensive than its fossil counterpart. More specifically, the impact of battery production significantly depending on where the battery materials are sourced, the place of battery manufacturing, the chemistry and capacity of the battery pack as well as structural materials used in modules and packs. Through an in-depth analysis of global case studies, regulatory frameworks, and incident reports, the paper navigates the complex terrain of LIB safety issues, end-of-life (EoL) management, recycling practices, and the potential environmental ramifications of their widespread use.

The research methodology incorporates a wide array of data sources, including global incidents, regulatory standards, industry reports, and environmental impact assessments. This approach facilitates a nuanced understanding of the risks associated with LIBs, particularly focusing on safety concerns that may arise throughout their lifecycle—from production and usage to disposal and recycling. Although the study does not specify the exact time frame of data collection, it references forecasts and developments up to 2040, indicating an extensive review that spans both historical data and future projections.

Central to the analysis is the categorization of safety risks and the evaluation of existing and potential regulatory mechanisms aimed at mitigating these risks. The paper underscores the importance of developing robust educational frameworks and legal standards to manage the safety risks posed to first responders, the public, and the environment. It identifies a
The call for establishment of comprehensive regulatory standards highlights critical areas for future research, policy development, and industry practices.

The conclusions drawn from the study emphasize the critical yet complex role of LIBs in the transition toward a low-carbon future. While recognizing the essential contributions of LIBs to decarbonization efforts, the paper sheds light on the urgent need for a holistic approach to addressing the safety, environmental, and lifecycle management challenges associated with their rapid adoption. The authors advocate for a multi-stakeholder collaboration to close the existing knowledge and regulatory gaps, suggesting that the development of clear guidance, enhanced safety protocols, and environmental standards is paramount for harnessing the full potential of LIB technology without compromising public safety or environmental integrity.

Corradi, C., Sica, E., & Morone, P. (2023). What drives electric vehicle adoption? Insights from a systematic review on European transport actors and behaviors. Energy Research & Social Science, 95, 102908. https://doi.org/10.1016/j.erss.2022.102908

The study comprehensively explores electric vehicle (EV) adoption in Europe, emphasizing the role of regime actors—including consumers, industry actors, policymakers, and civil society (citizens, workers, trade unions, environmental organizations, NGOs). Utilizing a systematic literature review of 44 publications concerning the road transport regime actors in the European continent from 2015–2020, it investigates the dimensions and complex interdependencies affecting EV integration into the market. This approach underscores the collective influence of these varied groups on the socio-technical systems of EV adoption, aiming to shed light on the layered transition towards electric mobility within European contexts.

Employing the Multi-Level Perspective (MLP) to examine the roadblocks hindering the shift towards electric mobility within the road passenger transport sector, MLP conceptualizes sustainability transitions as non-linear processes across three tiers: niche innovations, socio-technical regimes, and the landscape level. It highlights the dynamics of building momentum within niches, the pressure these innovations and landscape changes exert on regimes, and the ensuing opportunities for disruption. The integration of psychological and sociological theories with MLP underscores the critical influence of individual and organizational behavior on sustainability transitions, emphasizing collaboration and actor interplay for successful transitions.

The literature review delves into the multifaceted dynamics of the EV transition in Europe, guided by the PRISMA protocol. It highlights the deterrent effect of high purchase costs and limited range on consumer adoption, notwithstanding a general preference for EVs, and notes the significant role of government incentives in fostering acceptance. Consumer behavior is further influenced by cognitive biases, social norms, and personal experience with EVs. The review identifies a demographic profile of typical EV owners and points out gender differences in the valuation of EVs. Industry actors, including manufacturers and suppliers, initially resisted EV adoption due to technological lock-in and market uncertainties, with some shifting focus towards R&D for EVs amid regulatory pressures. Policymakers emerge as pivotal in shaping EV-friendly policies, emphasizing economic incentives and addressing technological barriers. Civil society's concerns center on fossil fuel dependency, energy security, and the equitable distribution of the benefits and burdens of EV adoption.

This literature review synthesizes findings on the behavior of regime actors and their impact on the EV transition in Europe, emphasizing resistance factors and facilitators of change. It underscores the stabilizing role of regime actors in maintaining the status quo within the passenger car regime, highlighting resistance to change as a predominant theme. Key insights include the need for tailored information to address consumers' psychological distance and cognitive biases regarding EV adoption. Consumer acceptance may be enhanced by focusing on environmental concerns and leveraging social and personal norms to promote EV diffusion. The review also identifies industry inertia, cost-benefit considerations, and infrastructure challenges as barriers to EV adoption by manufacturers and suppliers. Policy recommendations include maintaining incentive schemes, investing in charging infrastructure, and supporting new market entrants to foster competitive dynamics and accelerate the transition. Additionally, addressing concerns related to job loss, ethical material sourcing, and social disparities is crucial. This review suggests integrating psychological concepts into the MLP for a deeper understanding of individual behaviors and their collective impact on the transition towards sustainable mobility, highlighting the importance of a comprehensive approach that considers the multifaceted interactions within the socio-technical system.

Davis, L., Li, J., & Springel, K. (2023). Political Ideology and U.S. Electric Vehicle Adoption (p. 59). Energy Institute at Haas.

The study employs a comprehensive methodological framework to analyze the correlation between political ideology and electric vehicle (EV) adoption in the United States. The study involves the utilization of county and state-level new vehicle registration data from 2012 to 2022 retrieved from the Experian Auto Registration Database. This encompasses both purchases and leases of new vehicles. This longitudinal dataset allows for an in-depth analysis of trends over a significant period, capturing shifts in consumer behavior concerning political landscapes. The study used the measure “EV Share” (share of all new vehicle registrations that are EVs) from the Experian database as a primary measure of EV adoption. The EVs considered for the scope of the study include both battery EVs (like all Tesla models) and plug-in hybrid EVs (like the Prius Plug-In Hybrid). The primary measure of political ideology is the Democrat vote share from the state and county for the 2012 U.S. presidential election obtained from the MIT Election Lab. Due to the lack of county-level data in the state of Alaska, the state dropped from the county-level analysis. In some specifications the following variables were controlled; medium household income (because EVs are expensive than their conventional counterparts making them more accessible to higher income households), population density (primarily because densely populated urban areas tend to have robust charging infrastructure encouraging the urban dwellers to buy EV among other reasons) and gasoline prices (previous studies have shown that vehicle buyers base their purchase decision on the gasoline price).

The model used in the core study is least squares regressions, adding control variables progressively. These regressions are conducted with a comprehensive dataset of a little over 34 200 observations, highlighting the robustness and extensive nature of the study. A key feature of the study's methodological approach is the use of different models to assess the impact of various factors. For instance, separate models evaluate the influence of county median household income, population density, and gasoline prices, both individually and in combination. This allows the researchers to dissect the relative contribution of each factor to EV adoption rates and to understand how political ideology interacts with economic and demographic variables.

The results, presented across several regression models, consistently indicate that political ideology is a significant predictor of EV adoption, even after accounting for various control variables. The coefficients for the Democrat vote share are positive and statistically significant across different model specifications, highlighting a strong positive relationship between Democratic political leaning and higher rates of EV adoption. The analysis was also conducted excluding the three West Coast states (California, Washington, and Oregon), which have large Democratic vote shares and high EV adoption rates. The findings remained consistent, showing a clear positive correlation, with households in majority Democrat states being about twice as likely on average to adopt an EV compared to households in majority Republican states. The study also reveals growth in EV adoption during the sample period. In the early years of the sample, it is evident that the EV shares are near 0 % in most states, and below 5 % everywhere. Adoption increases sharply year after year with particularly notable growth in 2018, 2021, and 2022. By the end of the sample period, EVs represent more than 5 % of the market in most Democratic states, while still less than 5 % in most Republican states. The state-level scatterplots generated in the study show a strong and enduring relationship between EV adoption and political ideology. The authors highlight that based on the figures, it was hard to conclude whether political ideology matters more or less in 2022 than it did in 2012, but it does matter throughout the sample period.

The authors also identified the top 20 counties with EVs, most of which are urban, high-income, and in Democratic states. California features prominently in the list with nine of the top ten counties. Strikingly, the top four counties are all in California's Bay Area. Counties from outside California mostly include urban left-leaning cities. The identified twenty counties were responsible for 40 % of all U.S. EV adoption over the study period while representing only 12 % of all U.S. vehicle registrations.

In conclusion, the study provides compelling evidence that political ideology significantly influences EV adoption in the U.S. This is notable despite the strong presence of the EV market in the U.S. for over a decade and a half, along with a diverse range of models available. The researchers employed a methodological approach that meticulously accounts for a variety of potentially confounding variables. Utilizing a large, longitudinal dataset and conducting rigorous statistical analysis, their findings are robust, offering valuable insights while also suggesting avenues for future research. Specifically, they highlight the need to understand the mechanisms behind the observed correlations. The authors also outline a forthcoming study in which they plan to conduct a nationally representative survey in the U.S. This survey will involve showing respondents images of different EV and non-EV models and asking them to identify whether each vehicle is an EV. Vehicles that 90 % of respondents can identify as an EV will be deemed "conspicuous," whereas those only 10 % can identify will be considered "inconspicuous." An intriguing aspect of the future study will be to examine whether responses vary between Democrats and Republicans, further exploring the intersection of political ideology and perceptions of EVs.

Dumortier, Jerome, et al. "Effects of providing total cost of ownership information on consumers' intent to purchase a hybrid or plug-in electric vehicle." *Transportation Research Part A: Policy and Practice* 72 (2015): 71-86.

This study investigates the challenges of energy-efficient technologies, which have high initial costs and delayed financial benefits, and proposes a solution: total cost of ownership (TCO) information. To evaluate the impact of TCO and fuel cost savings information on consumer preferences for different types of vehicles, the authors conducted an online survey of 3199 U.S. consumers in late 2013. The survey included information on gasoline, conventional hybrid, plug-in hybrid, and battery electric vehicles, with a focus on small/mid-sized cars and small sport utility vehicles, as these were considered practical options. Respondents were randomly assigned to one of three groups: control, treatment 1, and treatment 2. Treatment 1 received additional five-year fuel savings information, while treatment 2 received TCO information. Results show that TCO information increases the likelihood of consumers preferring to acquire a conventional hybrid, plug-in hybrid, or battery-electric vehicle, but only for small/mid-sized cars, not small sport utility vehicles. These findings align with previous studies in behavioral economics and suggest that further research is needed to evaluate the impact of providing TCO information on consumer decision-making.

To calculate TCO and fuel savings information, the authors used generic EPA labels that provided data on various technology types and vehicle sizes, allowing for comparisons between vehicles with similar functionality, size, and interior volume. The authors used incremental cost calculations to determine the differences in propulsion systems and drivetrains, and calculated purchase price, five-year fuel expenditure and cost savings, and monthly TCO for each vehicle. The fuel savings information was calculated over five years, while the TCO information was calculated over a lifetime of 10 years. All prices and costs were adjusted to 2013 U.S. dollars using the Consumer Price Index (CPI). The authors used a rank-ordered logit model to analyze the data and answer research questions, as this method provides additional information by utilizing the ordinal ranking of all items in the choice set to estimate parameters. Results indicate that TCO information is statistically significant for all new technology vehicles in the small/mid-sized car category, particularly plug-in hybrid and battery electric vehicles. The study also found that the impact of fuel savings information might be greater when presented on a standard car label rather than promotional materials, and its effect varied by vehicle type and size, being significant for small and midsized cars but not for small SUVs. However, there are several non-economic factors that may influence consumer purchasing decisions, such as range anxiety and charging infrastructure issues, that need to be considered in future research.

Egbue, Ona, and Suzanna Long. "Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions." *Energy policy* 48 (2012): 717-729.

This study examines concerns and opinions about electric vehicles (EVs) and factors influencing their adoption. The top three concerns for EVs are battery range, cost, and charging infrastructure. There is an association between gender and concern, with a larger number of males concerned about battery range and a larger number of females concerned about cost.

There is no evidence of differences in concerns based on age, education, income, or between students and non-students.

In a survey of 395 people, the average amount respondents are willing to pay for gasoline before switching to an EV is calculated to be $5.42, with a mode and median of $5.00. When gasoline prices rise, a significant number of people consider purchasing an EV. The main factor governing the decision to purchase an EV is not cost but rather car range.

Sustainability perceptions are varied among respondents, with 77 % believing that EVs are more sustainable than traditional vehicles, and 16 % believing they are less sustainable. Individuals who consider sustainability before purchasing a vehicle are more likely to adopt EVs with an average gas price willingness to pay of $5.20 compared to $6.30 for individuals who do not.

In terms of public opinion, the main barrier to EV adoption is low public confidence. Current incentives such as tax credits and fuel taxes have little effect because consumers lack confidence in the technology. Policies to increase the market share of EVs could include education, investment in technology, charging infrastructure, and warranties. Future research aims to explore differences in opinions of EVs among various demographics and compare the cost of purchasing EVs in Europe and the United States.

Farkas, Z., Hyeon-Shic Shin, and A. Nickkar. "Environmental attributes of electric vehicle ownership and commuting behavior in maryland: Public policy and equity considerations." ***Mid-Atlantic Transportation Sustainability University Transportation Center. Retrieved April*** **20 (2018): 2019.**

The paper explores the factors that influence electric vehicle (EV) adoption and travel patterns in Maryland, with a focus on the impact of political affiliation. The survey design uses geographic classifications to examine the socio-demographic characteristics and travel patterns of EV owners. 4282 EV (non-fleet) owners were identified, and the EV survey was administered from July 1, 2016, through August 19, 2016, and 1323 responses were received (30.9 % response rate).

The results indicate that EV owners typically consist of white, educated, affluent, older males who are environmentally conscious. However, the primary motivation for purchasing an EV is efficiency and performance. Younger individuals tend to buy EVs to express their political beliefs, while older individuals are more concerned about environmental issues. Notably, the study discovers that 70 % of EV owners use their vehicles for work commutes, and 97 % drive their EVs more than three days a week.

About political affiliation, EV owners with Republican affiliations prioritize price and status when buying an EV. In contrast, EV owners with liberal affiliations are more likely to consider environmental concerns. Additionally, the study found that EV drivers are more likely to live in suburban areas than in city or rural areas.

The survey's methodology emphasizes the importance of understanding the motivations behind EV adoption. For example, EV owners with fewer household members and vehicles are more likely to prioritize efficiency and performance when purchasing an EV. Moreover, individuals with lower education and income levels are more concerned about the price and status of the EV.

In summary, the study offers insight to the demographic profiles and motivations of EV adopters in Maryland, highlighting the role of political affiliation in EV adoption decisions. These findings can assist policymakers and stakeholders in developing well-informed strategies to support sustainable transportation options and increase EV adoption across socio-demographic groups.

Franke, Thomas, and Josef F. Krems. "What drives range preferences in electric vehicle users?" *Transport Policy* 30 (2013): 56-62.

This study investigates the range preferences of potential electric vehicle (EV) customers with hands-on EV experience and the factors influencing these preferences. The study involved 80 participants from the Berlin metropolitan area who used an EV for three months. The findings show that their range preferences were higher than their average daily range needs but similar to their weekly maximum daily range needs. Usual range needs, familiar conventional vehicle range, and experienced range anxiety positively affected range preferences.

As participants gained more experience with EVs, the connection between usual range needs and range preferences grew stronger, while overall range preferences decreased. The study suggests that a one-week travel pattern analysis is enough to estimate average range preferences for future EV markets with more experienced users. Addressing range anxiety is crucial in closing the range discrepancy gap, as those experiencing more range anxiety might need extra support to accept lower range values.

This study is one of the first to examine factors influencing range preferences among potential EV customers who have actual experience with EVs. However, the field study design limits causal inferences, and the results are based on early EV adopters who may not represent all car buyers. Additionally, the study didn't consider factors like recharging infrastructure and alternative mobility options, which could affect range preferences. Future research should focus on these factors and investigate the changes in range preferences due to EV experience more comprehensively.

Graham-Rowe, Ella, et al. "Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: A qualitative analysis of responses and evaluations." *Transportation Research Part A: Policy and Practice* 46.1 (2012): 140-153.

The study discusses various barriers to electric vehicle (EV) adoption. It highlights that drivers find it hard to adapt to EVs due to long charge times, limited public charging stations, and changes in driving dynamics, like silent operation. Furthermore, drivers consider EVs as a work in progress, awaiting improvements in performance, safety, and charging infrastructure before buying. Although some drivers value the environmental benefits of EVs, many prioritize cost, performance, and convenience. The study suggests that positive imagery and cost minimization strategies, such as government subsidies, could help increase EV adoption. Further research is encouraged to explore these barriers and potential solutions in-depth.

Gore, C. (2021). What drives battery electric vehicle adoption? Willingness to pay to reduce emissions through vehicle choice. Ohio State University.

The study by Gore et al. (2024) provides a nuanced analysis of the factors influencing the adoption of battery electric vehicles (BEVs), focusing on the impact of regional energy production mixes and the willingness of individuals to pay for carbon emission reductions. The research delves into consumer preferences and the trade-offs they are willing to make, particularly in terms of paying a premium for reduced emissions.

The methodological approach involves a survey conducted between May 2019 to January 2020. The survey systematically captures the nuances of consumer behavior and the monetary value they place on reducing emissions. These individuals, who were considering the purchase of a new car within the next five years, provided insights through a survey that highlighted significant consumer behaviors and preferences regarding BEVs.

The survey included a discrete choice experiment in which 1658 individuals across five U.S. metropolitan areas (Los Angeles, California; Atlanta, Georgia; and Cincinnati, Cleveland, and Columbus, Ohio) were asked to indicate what vehicle they would purchase under different hypothetical settings. In the discrete choice experiment, respondents selected a conventional vehicle, a hybrid, and a BEV based on varying purchase prices, annual fuel (or fuel-equivalent) costs, and emissions levels, with BEV emissions reflecting indirect emissions from power production. Participants answered eight stated preference questions in two blocks: the first block presented vehicles with national average emissions, varying in price and annual costs. The second block assigned individuals to scenarios with either a greener energy mix, reducing BEV emissions, or a fossil fuel-dominant mix, increasing the BEV emissions.

Utilizing a mixed multinomial logit model, the choice analysis was confined to three vehicle types (conventional gasoline vehicle, a hybrid vehicle, and a BEV), explicitly excluding the "status quo" option ("Even if these were my best options, I would not choose any of these vehicles."), leading to estimations based solely on selections among these alternatives. This model incorporated eight variables: purchase price, annual fuel cost, and specific constants for hybrid and BEV options, alongside binary indicators for low- and high-emissions scenarios, which were tailored to the fuel types of hybrids and BEVs. While the purchase price coefficient was consistent across respondents, other coefficients varied at the individual level, allowing for a nuanced understanding of consumer preferences within the vehicle choice context.

The findings reveal that indirect emissions from BEV charging significantly influence consumer purchase decisions, with an average willingness to pay $225 per ton of CO_2 avoided. This is about 4X the current social cost of a metric ton of carbon used by the US federal government $51. While the study does not delve into the specific reasons behind individuals' willingness to pay a higher amount for emissions reductions, the author proposes that this willingness is context dependent. Specifically, in the realm of vehicle choice, opting for a hybrid or BEV offers a straightforward means to lower emissions without significantly altering one's lifestyle. This availability of nearly perfect substitutes for conventional vehicles may lead individuals to value emissions reductions more highly in this context than they might in situations where equivalent alternatives are not available.

This underscores the importance of considering indirect emissions in BEV adoption strategies and highlights a previously underexplored factor that may be affecting BEV adoption rates in the U.S. The study suggests that regional differences in energy production significantly impact BEV attractiveness, pointing towards a cooperative relationship between BEV adoption and investments in renewable energy sources. Despite its comprehensive analysis, the study indicates the need for further research into how energy production methods, technological advancements, and infrastructural developments could shape BEV adoption trends. The study also highlights the need for understanding why people are willing to pay significantly higher amounts to abate emissions in the realm of vehicle ownership.

In conclusion, the work contributes significantly to the discourse on sustainable transportation, emphasizing the complex interplay between environmental policies, consumer preferences, and the automotive market. The research provides a solid foundation for future studies aimed at expanding on the factors influencing the transition towards more sustainable vehicular technologies and underscores the importance of policy measures in accelerating this transition.

Hagman, J., Ritzén, S., Stier, J. J., & Susilo, Y. (2016). Total cost of ownership and its potential implications for battery electric vehicle diffusion. Research in Transportation Business & Management, 18, 11–17. https://doi.org/10.1016/j.rtbm.2016.01.003

The paper addresses the adoption dynamics of battery electric vehicles (BEVs) within the Swedish market, with a specific focus on the concept of Total Cost of Ownership (TCO) as a pivotal determinant in consumer vehicle purchase decisions. Despite the acknowledged potential of BEVs to significantly reduce CO_2 emissions, their market penetration remains notably low. This phenomenon underscores the importance of understanding not only the economic but also the societal and technological factors influencing consumer behavior towards BEVs. The research aims to analyze the components contributing to the TCO for BEVs and compare them against those for Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs), thereby offering a nuanced perspective on the economic viability of BEVs.

The methodology employed in this study leverages publicly accessible contemporary vehicle and market data. This model is applied to a small yet representative sample comprising a petrol and a diesel version of one of the most sold vehicles in Sweden, the Volvo V40, together with the Toyota Prius Hybrid and the BMW i3 (BEV), enabling a focused analysis of TCO across different vehicle technologies. Chosen vehicles share similar size, equipment and performance, which have been critical in sample choice, leaving little room for more samples due to availability on the current market. The authors also acknowledge that equipment needs will vary for individual buyers, which could have a significant effect on the TCO results. Such a methodology not only ensures the relevance and applicability of the findings to the contemporary Swedish market but also facilitates a detailed exploration of the cost dynamics associated with vehicle ownership over time. The variables utilized in formulating the total cost of ownership (TCO) of the car are purchasing price (PP), resell price (RP) at the end of ownership, depreciation (PP-RP), fuel cost (FC), total kilometers driven (TKD), monthly interest rate (r), amount borrowed (P), number of monthly interest payments (N), insurance cost (IC), maintenance and repairs cost (MR) along with government taxes (T) and subsidies (S). The study omits the usage of opportunity cost of car ownership while calculating the TCO and acknowledges the possibility of significant opportunity cost differences between considered models.

The study addresses the complexities involved in constructing a consumer centric TCO model for vehicles, highlighting the difficulties in estimating cost factors like depreciation and fuel costs due to their unpredictable nature. It notes that while some costs such as interest, insurance, maintenance and repair, and taxes are relatively stable, depreciation can vary significantly due to various market factors, and fuel costs are subject to global market volatility and discrepancies between official and real-world fuel consumption rates. The study suggests that financial institutions should adopt less conservative depreciation estimates for Battery Electric Vehicles (BEVs) compared to Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs). Using real-world data, the study found notable discrepancies between TCO and purchase price among sample vehicles, with the BMW i3 having the lowest TCO despite its high purchase price, attributed to its lower running costs and significant government subsidies.

The findings of the study serve to challenge prevalent assumptions regarding the cost-effectiveness of BEVs. Contrary to the common perception that BEVs are prohibitively expensive due to their higher upfront costs, the study reveals that the BEV in the sample (BMW i3) exhibits the lowest TCO when all factors of ownership are considered over time. This revelation positions BEVs as a potentially more economical choice for consumers in the long term, especially when government subsidies and the inherently lower operating costs of BEVs are factored into the TCO equation.

The study explores the creation and application of a consumer-centric Total Cost of Ownership (TCO) model, highlighting the challenges involved due to the necessity for relevant data and assumptions about future conditions. Despite these challenges, the constructed TCO model, when applied to current vehicles, shows significant potential for informing both theory and practice. The findings reveal a disparity between the purchase price and TCO across different vehicle drivetrains, with BEVs exhibiting substantially lower running costs than ICEVs and HEVs, thereby offering a competitive TCO. It also addresses the energy paradox, noting that most vehicle buyers traditionally undervalue operational costs in their purchasing decisions, which may contribute to the slow diffusion of BEVs. The study suggests a need for further research to understand the prevalence of TCO analysis among consumers and to identify potential shortcomings in current TCO computations due to limited vehicle samples and assumptions. It underscores the importance of developing credible, accessible tools for TCO comparison and experimenting with information campaigns and business models, to potentially influence government policies aimed at increasing BEV uptake and to assist manufacturers in highlighting the cost benefits of BEVs.

Heymans, C., Walker, S. B., Young, S. B., & Fowler, M. (2014). Economic analysis of second-use electric vehicle batteries for residential energy storage and load-leveling. Energy Policy, 71, 22–30. https://doi.org/10.1016/j.enpol.2014.04.016

The article explores the feasibility and economic benefits of repurposing electric vehicle (EV) batteries for residential energy storage. The main research questions focuses on assessing if reducing electricity rates or auxiliary fees would encourage home owners in Ontario to purchase second-use battery pack as a load shifting energy storage system (ESS).

The study uses a simulated dataset generated via MatLAB, which includes specifications of current Li-ion EV batteries in North America, electricity cost based on the time of day for Southern Ontario, Canada, and residential load profiles sourced from the International Energy Association (IEA). Additional scenarios are explored to identify ways to decrease energy costs for residential consumers. These scenarios examine the impact of reduced energy rates and supplementary charges for consumers who participate in off-peak energy storage, thereby lowering peak time demand. With an assumed ten-year lifespan for the Energy Storage Systems (ESS), the study conducts a ten-year present worth analysis that considers both capital and maintenance costs to compare the economic viability of each option. The results indicate that shifting consumption from medium to low price periods is economically unsound due to the minimal price difference and battery inefficiencies. The analysis calculates the maximum annual savings from utilizing a battery for household energy storage at approximately $38. This limited benefit leads to the exploration of additional incentives to enhance the economic appeal of energy storage systems (ESS). The study also finds that introduction of an ESS increases energy consumption by 6 to 7 percent, equating to an annual increase of 390 kWh. Applying this to 1 in 20 detached homes in Ontario would necessitate an additional 57 900 MW for the grid, distributed across the load profile, potentially easing the strain on the generation system and enabling reduced greenhouse emissions by leveraging Ontario's nuclear energy during off-peak hours.

The paper concludes that the best potential for savings and recuperating initial ESS investment costs comes when auxiliary fees are waived, and off-peak electricity rates are reduced by 75 percent. Under such conditions, the average energy user could see savings of 132 percent. Eliminating auxiliary fees presents the most effective strategy for realizing saving. However, the study also identifies limitations and suggests areas for future research. These include the need for detailed technical analyses of safety risks associated with battery use and the exploration of fiscal incentives such as capital cost reductions, tax incentives, and increased rates for selling energy back to the grid. The research highlights the importance of developing strategies to encourage the adoption of ESS technologies, especially in unregulated energy markets where greater economic benefits may be realized. The study concludes that significant savings and incentives for adopting energy storage technology would require not only reductions in energy rates but also the elimination of auxiliary fees or a combination of both to make the implementation of such systems economically viable.

Jensen, Anders Fjendbo, Elisabetta Cherchi, and Stefan Lindhard Mabit. "On the stability of preferences and attitudes before and after experiencing an electric vehicle." ***Transportation Research Part D: Transport and Environment*** **25 (2013): 24-32.**

This paper explores how individual preferences and attitudes towards electric vehicles (EVs) change after experiencing an EV in daily life. Researchers use a joint hybrid choice framework, a latent variable model that considers individual attitudes and vehicle attributes. They collect data from surveys conducted before and after individuals test an EV for three months, resulting in a sample of 369 individuals with 5904 stated choice observations.

The results reveal that factors like purchase price, fuel costs, and carbon emissions negatively impact preferences, while car performance and charging options have positive effects. Driving range emerges as a crucial factor for EVs, with the value of an extra kilometer being much higher for EVs than for internal combustion vehicles (ICVs). After the EV experience, preferences change for top speed, fuel cost, battery life, and charging in city centers and train stations. Smaller car classes are preferred, and people with higher environmental concerns show a greater preference for EVs.

While the study provides valuable insights, it has some limitations, such as the sample being drawn from local advertisement respondents and only considering individuals who have bought or plan to buy a car within a specific time frame. Future research could investigate additional factors influencing EV preferences, such as government incentives, charging infrastructure expansion, and the role of marketing and public opinion.

Jia, Wenjian, and T. Donna Chen. "Are Individuals' stated preferences for electric vehicles (EVs) consistent with real-world EV ownership patterns?" ***Transportation Research Part D: Transport and Environment*** **93 (2021): 102728.**

This study investigates factors influencing electric vehicle (EV) adoption by comparing consumer stated preferences from a survey and aggregate EV ownership analyses in Virginia. The survey is implemented through Qualtrics and consists of five parts: 1) household socio-economic characteristics; 2) future vehicle purchase plans and household vehicle fleet inventory; 3) materials to familiarize respondents with different vehicle powertrain technologies and EV technical characteristics, costs, and policies; 4) choice experiments where respondents select the one vehicle they would most likely purchase from four alternatives (ICEV, HEV, PHEV, and BEV) based on hypothetical scenarios; and 5) respondents' experiences and attitudes towards EVs.

Respondents choose the vehicle body type before engaging in choice experiments, making the experiments more relevant to them. The study divides vehicle body types into five categories: subcompact/compact car, mid/full-size car, small/medium SUV, standard/large SUV or minivan, and pick-up truck. Responses to questions about body type preferences and estimated annual VMT are crucial for designing tailor-made choice experiments for each respondent. The survey uses a full factorial design, resulting in a large number of choice scenarios, which are then divided into blocks and assigned to respondents. The D-efficiency of the design is 100 %, indicating a balanced and orthogonal design.

A pilot survey was conducted in February 2018 with 15 respondents, including both EV owners and non-EV owners, to gather feedback on the survey's duration, language, and presentation. The survey was then revised and distributed from March to May 2018 using a two-prong approach targeting both general respondents and EV-specific respondents. A total of 5022 observations were used for estimating the individual vehicle choice model.

The findings suggest that being male and having a higher educational attainment positively impact EV adoption. Additionally, the importance of DC fast charging infrastructure, especially for battery electric vehicle (BEV) adoption, is highlighted, while the effects of AC (Level 1 and Level 2) charging stations appear to be weak. Age effects show mixed results, with older individuals having negative stated preferences for EVs, but counties with more elderly populations registering more EVs. The study also compares preferences for various vehicle-related attributes between EV owners and non-EV owners, revealing that EV owners are more sensitive to battery range and DC fast charging infrastructure availability, while non-EV owners are more sensitive to monetary attributes.

Jiao, Na, and Steve Evans. "Business models for sustainability: the case of second-life electric vehicle batteries." ***Procedia Cirp*** **40 (2016): 250-255.**
https://doi.org/10.1016/j.procir.2016.01.114

In addressing the sustainability challenges within the electric vehicle (EV) industry, particularly concerning the high costs and environmental impacts associated with battery disposal, the paper delves into the potential of repurposing retired EV batteries. By integrating these batteries into energy storage systems for renewable energy sources, the research highlights that such a practice could not only extend the usefulness of EV batteries but also contribute significantly to making EV technology more sustainable. The essence of this investigation lies in exploring innovative business models that can accommodate the reuse of EV batteries, thereby fostering a more sustainable EV ecosystem. The research employs a qualitative methodology, drawing from semi-structured interviews with stakeholders across various sectors of the EV industry, complemented by an analysis of industrial reports and academic literature. This approach aims to uncover insights into the enablers and barriers of battery second use and its implications for business model innovation within the sector.

The study's core research questions revolve around the mechanisms through which battery reuse can lead to business model innovation aimed at sustainability within the EV industry. It critically examines the influence of factors such as battery ownership, the necessity of inter-industry partnerships, and the role of policy support in facilitating the secondary use of batteries. Moreover, the paper seeks to understand how battery reuse could serve as a pivotal linkage between the transport and energy sectors, potentially acting as a catalyst for reconfiguring business models to align more closely with sustainability goals.

Utilizing a case study approach that focuses on four distinct EV stakeholders, the research adopts a multi-stakeholder perspective to increase the reliability and richness of the data collected. The qualitative data, derived from interviews and secondary sources, provides a comprehensive view of the current landscape of battery reuse within the EV industry, highlighting innovative practices and challenges faced by various actors. The sample size, though limited to four case studies, offers valuable insights into the complexities and potential of battery reuse as a strategy for sustainable development in the EV sector.

The study's findings underscore that while repurposing end-of-life (EOL) EV batteries presents a promising avenue for enhancing the sustainability of EVs, it is certainly not a remedy for all environmental challenges associated with the industry. Key factors identified include the critical role of battery ownership in managing the lifecycle of batteries, the importance of fostering inter-industry partnerships for scaling up battery second-use applications, and the need for supportive government policies to create a conducive environment for such initiatives. These elements are crucial for overcoming the current hurdles and maximizing the value of used EV batteries, thereby contributing to the reduction of the cost barrier for EVs and improving the overall sustainability of the technology.

However, the paper also acknowledges significant limitations, notably the nascent state of the EV market which restricts the availability of batteries for secondary applications and poses challenges for large-scale implementation of battery reuse practices. The research suggests avenues for future exploration, emphasizing the need for further studies on stakeholder involvement and the development of business models that facilitate the mutual promotion of EVs and battery second use. This recommendation points to a broader discourse on the interplay between technological innovation, business model development, and sustainability in the EV industry, highlighting the potential for repurposed batteries to act as a catalyst for systemic change.

Kim, Sukhee, et al. "Analysis of Influencing Factors in Purchasing Electric Vehicles Using a Structural Equation Model: Focused on Suwon City." *Sustainability* 14.8 (2022): 4744.

The study investigates factors influencing electric vehicle (EV) adoption. Key findings indicate that government subsidies, charging services, battery performance, and safety positively impact EV adoption decisions. In contrast, charging infrastructure and operating conditions negatively affect the decision to purchase EVs. However, information shortage and EV recognition show no significant correlation with EV adoption decisions.

The study also reveals that public charging infrastructure plays a crucial role in EV adoption. Consumers concerned about the availability and accessibility of charging stations are less likely to purchase an EV. As a result, it is essential to install more charging stations in high-demand locations, such as public parking lots, gas stations, and residential areas, to address these concerns and encourage EV adoption.

Furthermore, battery performance and safety are critical factors for potential EV buyers. One-time charging distance and the ability to maintain performance under varying temperature conditions are essential considerations for consumers. To boost EV adoption, manufacturers should focus on enhancing battery performance, safety, and temperature resilience while offering more affordable options for consumers.

To increase EV adoption, improvements in battery performance, safety, charging infrastructure, and government subsidies are needed. The study's limitation is its focus on Suwon city, making it difficult to generalize the findings to other locations. Further research should analyze consumer choice factors and decision-making processes affecting EV purchases in different areas for effective policy development.

Krupa, Joseph S., et al. "Analysis of a consumer survey on plug-in hybrid electric vehicles." ***Transportation Research Part A: Policy and Practice*** **64 (2014): 14-31.**

This paper aimed to study consumers' willingness to consider Plug-in Hybrid Electric Vehicles (PHEVs) and understand their concerns about the price and other features of PHEV technology. A survey was conducted on Amazon Mechanical Turk (AMT) in July 2011, involving 1000 US participants aged 18 or older. The survey covered demographics, purchasing decisions, vehicle acquisition, environment and energy concerns, attitudes towards PHEV technology, and discounting questions. Data was analyzed using different statistical methods such as logistic regression models, Spearman rank correlations, and odds ratios.

Out of 1000 surveys, 911 were considered reliable and included in the analysis. The data was quite representative of US demographics, with some observed differences in daily driving distances, income, education levels, age, gender, and political affiliations. The study found that factors like the type of vehicle, price, miles per gallon (MPG), and performance had the highest impact on participants' recent purchase decisions and were expected to be even more important for future purchases. Factors that made people more comfortable with PHEVs included saving money on monthly fuel costs, at-home charging facilities, and a $7000 tax rebate.

Battery-related concerns, such as replacement costs, difficulties in servicing or repairing the engine, and battery lifetime, were also found to be significant factors. People's political views and environmental concerns influenced their likelihood of considering a PHEV purchase, with left-leaning individuals and those concerned about climate change being more open to PHEVs.

However, most participants were not willing to pay much more upfront for long-term benefits framed in terms of climate change mitigation.

The paper calls for more research by other scholars, as the full survey and individual responses are publicly accessible. Despite the relatively small sample size, the study found that participants were representative of US demographics. However, the data showed some differences, such as slightly shorter daily driving distances, higher income and education levels, younger ages, more females, and more left-leaning politics and Democrats. Additionally, the study highlights that the ranking of factors based on different statistical methods often differs from the ranking based on individuals' stated importance, which may impact the interpretation of the results.

Letmathe, P., & Suares, M. (2017). A consumer-oriented total cost of ownership model for different vehicle types in Germany. *Transportation Research Part D: Transport and Environment*, *57*, 314–335. https://doi.org/10.1016/j.trd.2017.09.007

The paper analyzes the progression of market penetration by alternative powertrains, specifically battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs), in Germany. It assesses whether the 2020 target of one million registered electric vehicles (EVs) is achievable given the current slow pace of adoption. The primary research quest revolves around comparing the total cost of ownership (TCO) for BEVs, HEVs, and internal combustion engine vehicles (ICEVs). This comparative analysis is enriched by incorporating the resale value of batteries for their second use, a factor not thoroughly examined in previous studies. The methodology involves refining and advancing existing consumer oriented TCO_C models to accurately reflect the economic viability of EVs in contrast to ICEVs, considering factors like battery resale value and the impact of government subsidies.

The study's data utilizes statistics from the German Federal Motor Transport Authority, encompassing the ten most frequently registered BEVs and HEVs alongside their ICEV counterparts. This selection represents a significant portion of the passenger vehicle market in Germany, offering a robust basis for the TCO_C calculations. The research delves into existing datasets and employs a dynamic investment appraisal method, including Monte Carlo simulations. This approach allows for the analysis of the TCO_C under various annual mileage profiles and market scenarios, presenting a detailed comparison of cost-efficiency across different vehicle types and segments.

The findings from this analysis reveal that without subsidies, only a select few BEVs and HEVs are cost-effective compared to their ICEV counterparts across all considered scenarios. BEVs are competitive to some extent at lower annual mileages in the small and large vehicle size classes. This economic landscape shifts slightly with the introduction of government subsidies, although the effect is marginal, indicating that substantial cost barriers still exist for broader EV adoption. Specifically, the study highlights the mini and medium vehicle segments as areas where achieving cost competitiveness for EVs remains challenging, pointing to a need for targeted policy and industry efforts to enhance the attractiveness of EVs in these segments.

Furthermore, the research identifies the resale value of batteries for second use as a critical factor that could potentially offset some of the initial investment costs associated with EVs. However, the paper also acknowledges limitations, such as the reliance on current data and projections, which may only partially capture future technological advancements, policy changes, or shifts in consumer behavior. The authors suggest future research avenues, including exploring the effects of providing consumers with detailed TCOC information on their purchasing decisions and refining the TCOC model to adapt to emerging automotive trends.

Lim, Michael K., Ho-Yin Mak, and Ying Rong. "Toward mass adoption of electric vehicles: Impact of the range and resale anxieties." ***Manufacturing & Service Operations Management*** **17.1 (2015): 101-119.**

This research examines the electric vehicle (EV) market, focusing on the impact of consumer anxieties on different business models. The study calibrates a model based on data from the San Francisco Bay Area and evaluates performance measures such as the firm's profit, consumer surplus, adoption size, and emission savings.

The paper discusses two methods for enhancing EV infrastructure: enlarging the battery's driving range and enhancing the charging model. The paper also assesses the impact of various anxieties on the performance of four business models in the EV industry, particularly in relation to leasing versus owning and range enhancement strategies. It finds that range and resale anxieties can harm the firm's profit but can also lead to larger investments in charging stations, increasing adoption size and consumer surplus.

Leasing models generate higher profits for firms, but battery leasing can lead to smaller adoption sizes and reduced consumer surplus, especially when anxiety levels are low. Comparatively, offering range enhancement through larger battery capacity can increase a firm's profit while enhancing charging infrastructure can lead to higher adoption rates and greater consumer surplus.

The authors suggest that social surplus, which includes the firm's profit, consumer surplus, and emission savings, is an essential factor in evaluating the sustainability of the EV industry. Policymakers are urged by the authors to provide favorable policies to promote models that offer the highest social surplus.

Liu, F., Li, J., Zhang, J. Z., Tong, Z., & Ferreira, J. (2023). Optimal strategy for secondary use of spent electric vehicle batteries: Sell, lease, or both. Annals of Operations Research.
https://doi.org/10.1007/s10479-023-05380-9

The paper explores the best marketing strategies for the secondary use of spent electric vehicle batteries (EVBs) within a recycling supply chain framework. It specifically investigates whether selling, leasing, or a combination of both (hybrid strategy) is most beneficial for attracting secondary users and maximizing profit.

In the context of electric vehicle battery (EVB) recycling and remanufacturing, the study explores a supply chain framework involving sorters and gradient remanufacturers, engaged in handling retired EVBs for secondary use. Sorters collect spent batteries and categorize them based on quality into high-quality (for remanufacturing) and low-quality (for recycling or landfill). The government encourages sorter operations through subsidies per battery. High-quality batteries are sold to gradient remanufacturers, who repair and reassemble them for secondary use, with the cost of remanufacturing inversely related to battery quality. The remanufacturer offers secondary users the option to buy or lease refurbished batteries, expanding the EVB secondary market. Three marketing strategies are considered: selling only, leasing only, and a hybrid approach. The supply chain dynamics are analyzed through a Stackelberg game framework, with the sorter as the leader and the remanufacturer as the follower, influenced by Extended Producer Responsibility (EPR) regulations and recycling efficiency. This setup reflects the evolving landscape of EVB recycling, where collaboration and strategic pricing play critical roles in enhancing recycling rates and promoting sustainable secondary-use markets.

The theoretical modeling and numerical experiments used in the analysis suggest that diversified option strategies, especially when leasing options include fixed and per-time leases, outperform single-option strategies. The study further emphasizes the critical role of new battery manufacturing costs and the quality of spent batteries in determining the recycling battery supply chain's effectiveness. It suggests that remanufacturing costs and government subsidies could act as mechanisms to facilitate coordination among supply chain members, thereby improving the overall efficiency of the recycling process.

This paper presents a constrained model focusing on scenarios where the supply of collected batteries consistently meets the demand for secondary use, without addressing potential supply-demand mismatches. It treats government subsidies as an exogenous variable and limits its scope to a single type of EVB and two quality levels. These assumptions offer avenues for future research to explore more comprehensive implications by considering supply-demand dynamics, treating government subsidies as an endogenous factor, and incorporating multiple types of EVBs and a broader spectrum of quality levels. Moreover, the study's theoretical framework may need to fully encapsulate the complexities of real-world market dynamics and consumer behaviors. Future investigations could benefit from empirically validating the theoretical models, delving deeper into consumer preferences, and assessing the environmental impacts of various secondary use strategies for spent EVBs. These directions promise to enrich the understanding of the recycling battery supply chain's efficiency and its sustainability implications.

MacArthur, John, Michael Joseph Harpool, and Daniel Scheppke. "Survey of Oregon Electric Vehicle & Hybrid Owners." (2018).

This study presents the findings of a survey on the demographics, motivations, and concerns of electric vehicle (EV) owners, including plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV). The survey respondents were predominantly white, highly educated males with an annual household income above $100 000, revealing an underrepresentation of

African Americans and low-income households in the EV market. Most respondents were homeowners, employed, and politically identified as Democrats.

The top motivations for purchasing an EV were reducing environmental impact, saving money on fuel, and interest in new technology. Least-reported motivations included workplace incentives and lease deals for electric vehicles. In terms of concerns, the study found that battery range, running out of charge, and insufficient public charging infrastructure were the primary issues for both EV and non-EV owners. However, after purchasing an EV, concerns related to range anxiety and battery longevity significantly decreased, while concerns about public charging infrastructure and resale value increased.

The study also examined respondents' charging habits and satisfaction with public charging infrastructure. Most EV owners charged their vehicles at home, with about two-thirds doing so daily or multiple times a day. While respondents were generally satisfied with the quantity of Level 2 chargers, there was a desire for more public fast chargers, particularly among BEV owners.

To increase EV adoption and address identified concerns, the study suggests improving public charging infrastructure, promoting informative and supportive public policies, and focusing on outreach and awareness programs in low-income minority communities. Future research could explore social and economic barriers to EV adoption, work incentives, changes in travel behavior, and the significance of EVs in rural households. By addressing these barriers and providing targeted incentives, the EV market could expand at a greater rate, leading to wider acceptance and adoption.

Martel, F., Dubé, Y., Jaguemont, J., Kelouwani, S., & Agbossou, K. (2017). Preemptive degradation-induced battery replacement for hybrid electric vehicles in sustained optimal extended-range driving conditions. *Journal of Energy Storage*, *14*, 147–157.
https://doi.org/10.1016/j.est.2017.09.001

This research delves into the feasibility and economic implications of a preemptive battery replacement strategy for plug-in hybrid electric vehicles (PHEVs), specifically focusing on the long-term management of component degradation and its impact on operational costs. The main research question centers on whether such a preemptive strategy could align with economic and performance efficiency goals throughout the vehicle's lifecycle, particularly in the context of plug-in hybrid electric vehicles equipped with advanced battery and fuel cell technologies. At its core, the study verifies if replacement of battery packs in PHEVs, before reaching terminal end-of-life (EoL) conditions, could mitigate escalating operational expenses attributable to the inherent degradation of lithium-ion batteries and polymer electrolyte membrane fuel cells (PEMFCs).

The methodology employed in this investigation is the numerical optimization, utilizing discrete dynamic programming (DDP) to simulate the operational dynamics of a mid-sized sedan PHEV over an extended period. The simulation integrates detailed models of the vehicle's lithium-ion battery pack and PEMFC, alongside Markov chain-generated driving cycles that extend to a 100-

mile scenario, to project the degradation patterns of these key components and their consequent impact on operating costs. The data utilized in this research, therefore, is not derived from empirical collection but from a theoretical model that generates a comprehensive dataset simulating the vehicle's performance and degradation over time. This approach enables a macroscopic exploration of the vehicle's operational efficiency and the cost-effectiveness of the preemptive battery replacement strategy over the vehicle's useful life.

The findings underscore a shift from relying on battery to fuel consumption as the battery undergoes degradation, pinpointing the economic drawbacks of keeping a highly degraded battery's state of charge (SOC) high with the support of fuel-based secondary energy sources. Contrary to potential expectations, preemptive replacement of the PHEV battery pack, as a strategy to combat late-stage battery degradation, offers marginal economic advantages. The study notes minor differences in lifetime costs (ranging between 4 % and 7 %), indicating that preemptive battery replacement does not emerge as a financially viable option. Moreover, the research illustrates through simulation how an optimized management solution can substantially prolong a battery's operational lifespan compared to simpler, rule-based approaches. Nonetheless, as the battery reaches the later stages of its lifecycle, the economic benefits of mitigating degradation lessen, highlighting the diminished value of using fuel cell-based load sharing for reducing battery wear.

Conclusively, the study asserts that while optimal energy management strategies can extend the lifespan of PHEV batteries, preemptive battery replacement fails to offer significant economic incentives. However, the study is not without its limitations, chiefly its reliance on numerical models and simulations that may not fully capture the complexities of real-world driving conditions and component degradation behaviors. The authors acknowledge these constraints and suggest that future research could explore more dynamic models of degradation, incorporate environmental factors like temperature, and assess the strategy's viability under varied operational scenarios. Furthermore, extending the analysis to include the active management of battery temperature could provide a more nuanced understanding of how external energy carriers might influence degradation and operational efficiency.

Mothilal Bhagavathy, Sivapriya, et al. "Impact of charging rates on electric vehicle battery life." ***Findings*** **2021.March (2021).**

The paper provides an in-depth analysis of the effects of charging speed and patterns on the degradation of electric vehicle (EV) batteries. The authors aim to encourage EV adoption by offering comprehensive information on battery types, lifespan, charging times, and rates for popular EV models. They use a variety of methods to study battery lifespan and degradation, emphasizing the influence of charging speeds and patterns.

The study finds that charging speeds significantly impact the lifespan of EV batteries. However, the impact of rapid and ultra-rapid charging on battery life is minimal due to battery management systems that limit the charge rate. Therefore, while the research acknowledges that regular rapid and ultra-rapid charging can reduce battery life, it concludes that the effect is not significantly detrimental due to the protective measures in place in EVs.

Neubauer, J., Brooker, A., & Wood, E. (2012). Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. *Journal of Power Sources*, *209*, 269–277. https://doi.org/10.1016/j.jpowsour.2012.02.107

This paper, developed by the National Renewable Energy Laboratory (NREL), delves into the complexities of comparing the economics of battery electric vehicles (BEVs) with conventional vehicles (CVs). The crux of the analysis is the Battery Ownership Model (BOM), a total cost of ownership (TCO) calculator designed to dissect the nuances of vehicle economics across various scenarios. The Battery Ownership Model is applied to examine the sensitivity of BEV economics to drive patterns, vehicle range, and charge strategies when a high-fidelity battery degradation model, financially justified battery replacement schedules, and two different means of accounting for a BEV's unachievable vehicle miles traveled (VMT) are employed. To study the interplay of three vehicle ranges (50-100 miles), three maximum SOCs, three charge timing schedules, and two alternative means of accounting for unachievable VMT with 398 drive patterns recorded for 3 months, the authors simulate 21 438 unique cases. One of the key findings from applying the BOM is the strong impact of the valuation of unachievable vehicle miles traveled (VMT) with a BEV. This valuation significantly influences the optimal range, charge strategy, and battery replacement schedule, highlighting the complex interplay between BEV utility and cost. The study further elucidates the high sensitivity of BEV cost competitiveness to specific drive patterns, emphasizing the necessity of considering individual or household driving behaviors in economic evaluations.

The study has interesting findings in terms of the level of impact that the cost of unachievable VMT has on economics and cost-optimal operational strategy. The study infers that for nearly 25 % of the drive patterns, a 75-mile-range BEV in the household could be more cost effective than an additional conventional vehicle, when the unachievable miles can be completed at low cost using a second, range-unlimited conventionally powered vehicle available within the household. The 50-mile-range BEV studied suggested higher cost savings for a larger proportion of drive patterns, but the frequency at which an alternative means of transportation must be employed may be high enough to make this vehicle less cost-effective than predicted in the study. The authors also have observed that changing the drive pattern can increase the BEV to CV cost ratio by up to a factor of 3.6, and that this sensitivity is a function of vehicle range, charge strategy, and the cost of unachievable VMT.

Future research directions are suggested to refine the model's accuracy and applicability. These include incorporating more dynamic models of battery degradation and expanding the analysis to encompass a broader range of operational conditions and charging infrastructure scenarios. In conclusion, the research underscores the nuanced economics of BEV ownership, driven by multiple factors including drive patterns, vehicle range, charging strategies, and battery degradation. By employing the BOM, the study provides valuable insights into the conditions under which BEVs can be economically competitive with conventional alternatives, while also laying the groundwork for future investigations aimed at enhancing our understanding of BEV adoption implications.

Neubauer, J. S., Wood, E., & Pesaran, A. (2015). A Second Life for Electric Vehicle Batteries: Answering Questions on Battery Degradation and Value. *SAE International Journal of Materials and Manufacturing*, *8*(2), 544–553. https://doi.org/10.4271/2015-01-1306

The study explores the viability and methodology of repurposing used plug-in electric vehicle (PEV) batteries for secondary applications, specifically focusing on energy storage. Termed as Battery Second Use (B2U), this concept aims to extend the utility of PEV batteries beyond their initial automotive use. The overarching goal of B2U, as supported by the research, is to evaluate how these used batteries can serve as a cost-effective solution for energy storage needs across various sectors, thus enhancing the total value derived from the lifecycle of PEV batteries.

Central to the research are several pivotal questions regarding the degradation, lifespan, and valuation of PEV batteries throughout their lifecycle, both in automotive and secondary uses. The inquiry delves into understanding the longevity of these batteries within their primary automotive application, their condition upon exit from this phase, their potential lifespan in secondary service roles, and the methodologies to accurately forecast their performance and value in these subsequent uses. Addressing these questions is essential not only for establishing the feasibility of B2U strategies but also for identifying the factors that most significantly influence the residual value and performance of repurposed batteries.

The analytical foundation of the study rests on data derived from simulations, notably employing the Battery Lifetime Simulation Tool (BLAST) developed by the National Renewable Energy Laboratory (NREL). This approach enables a detailed examination of battery degradation patterns across various operating conditions, focusing on a specific lithium-ion battery chemistry. While the exact period of data collection is not specified, it is implied that the simulation leverages contemporary data reflective of current battery technologies and usage scenarios. The study does not delineate a specific sample size but indicates a comprehensive analysis designed to yield generalizable insights across different usage patterns and climatic conditions.

Methodologically, the research employs a semi-empirical life model to predict battery degradation, incorporating both cycling-based and calendar-based mechanisms into its analysis. This model is instrumental in quantifying the relative impacts of various operational stresses on battery health over time. Coupled with BLAST-V, an advanced vehicle simulator, the study offers predictions on battery wear and potential second-use lifespans under assorted driving patterns, vehicle platforms, and climates. This integrative methodological approach facilitates a nuanced understanding of the factors influencing battery degradation and the practicalities of repurposing PEV batteries for secondary applications.

The study's findings highlight that properly managed repurposed PEV batteries could serve effectively in secondary roles, such as energy storage for peak shaving, for ten years or more. It underscores the significant impact of capacity fade from automotive use on the value and performance of batteries in their second life. Moreover, the analysis reveals that the average battery temperature during initial use—largely influenced by the climate—is the single most critical factor affecting the battery's residual value for secondary applications. These insights not only contribute to the body of knowledge on battery repurposing but also underscore the potential economic and environmental benefits of B2U strategies.

However, the study also acknowledges certain limitations, particularly regarding the precision of current models in forecasting battery degradation and valuation for secondary use. It suggests future research directions, including the development of on-board diagnostic capabilities that could significantly enhance the efficiency and reliability of battery repurposing efforts. By improving the accuracy of predictions regarding battery health and second-use value, these advancements could facilitate more sustainable and economically viable uses for retired PEV batteries.

Pamidimukkala, A., Kermanshachi, S., Rosenberger, J. M., & Hladik, G. (2023). Evaluation of barriers to electric vehicle adoption: A study of technological, environmental, financial, and infrastructure factors. Transportation Research Interdisciplinary Perspectives, 22, 100962.
https://doi.org/10.1016/j.trip.2023.100962

The study conducted by the authors aims to investigate the barriers to electric vehicle (EV) adoption by examining technological, environmental, financial, and infrastructure challenges. The research questions are designed to understand how these barriers impact consumers' intentions to adopt EVs and to identify the causal relationships between them. To answer the research question, the study hypothesizes that technological, financial, environmental, and infrastructure barriers negatively impact EV adoption intentions. The data used in the statistical analysis was gathered from a survey that the authors conducted in March 2023 at the University of Texas at Arlington.

The authors analyze survey data collected from 733 respondents of age over 18 years affiliated with the university. This demographic includes students, faculty, and staff with parking permits. Participants were also allowed to express their concerns and preferences by responding to an open-ended question at the end of the survey. Since the data was collected from a single source and relied on a survey questionnaire, the researchers analyzed the potential for common method bias. Harman’s single-factor test was utilized to complete this, and the result revealed the absence of common method bias in the data.

The model development process in the study consists of a measurement model that defines the interrelationships between factors, and a structural model that is used to examine the causal relationships between the factors. Based on the survey responses, the confirmatory factor analysis (CFA)/measurement model was developed and verified to evaluate the interconnected nature of a group of factors and to assess the degree to which a given dataset conforms to a causal model. Further Structural Equation Modeling (SEM)/structural model was conducted, which analyses latent factors and is recognized for its flexibility in examining the direct, indirect, and interactive relationships among complex, interrelated variables. The maximum likelihood estimate was employed to test the relationships, results show that the model fit was found to be satisfactory.

The findings support the hypotheses for technological (the limited driving range and long charging times), financial (the cost of EVs typically exceeds that of traditional gasoline-powered vehicles), and infrastructure (insufficiency of public charging infrastructure) barriers, indicating a considerable negative impact on adoption intentions. However, the environmental barriers (pollution generated while producing batteries and electricity necessary for EVs and the lack of adequate recycling infrastructure for the used batteries disposal) do not show a significant deterrent effect, suggesting that these may not be primary concerns for consumers or that the perceived environmental benefits of EVs are already well recognized.

This research provides valuable insights for policymakers and industry stakeholders to develop strategies addressing technological, financial, and infrastructure barriers to EV adoption. It also indicates a potential area for re-evaluating consumer education and marketing strategies to better highlight the benefits of EVs beyond environmental advantages. The authors note limitations in their study, including a focus on intentions rather than actual purchasing behavior and the potential for limited generalizability outside the United States. They suggest future research directions to examine actual purchasing behaviors, differentiate between EV types, and expand the study's geographical reach.

Pedrosa, G., & Nobre, H. (2018). Second-hand electrical vehicles: A first look at the secondary market of modern EVs. *International Journal of Electric and Hybrid Vehicles*, *10*(3), 236. https://doi.org/10.1504/IJEHV.2018.097378

The study explores several critical questions regarding the acceptance and valuation of second-hand electric vehicles (EVs) in the automotive market. The research questions revolve around how consumers perceive second-hand EVs, including their willingness to pay, concerns about battery life, and the appeal of warranty options.

The study utilizes qualitative data gathered through 17 in-depth interviews with drivers of conventional fuel vehicles, aiming to understand their attitudes towards purchasing second-hand EVs. The data was collected through phone interviews, allowing for a broad geographical reach and the inclusion of participants from various backgrounds. The interviews were designed to capture detailed information about participants' views on EVs, their current automotive purchasing profiles, and their openness to considering second-hand EVs in the future.

Analytically, the study employs qualitative data analysis to dissect and categorize the responses from the interviews. This method facilitated the identification of key themes and attitudes toward second-hand EVs, including concerns about vehicle range, charging time & infrastructure, and the initial cost of EVs. Significantly, the research highlights a general willingness among the participants to consider purchasing second-hand EVs, especially if concerns regarding battery condition and warranties are addressed satisfactorily.

The results of the study reveal a mixed but generally positive attitude towards second-hand EVs. Participants expressed a clear interest in the environmental and cost-saving benefits of EVs especially in terms of cost per kilometer traveled, albeit tempered by concerns over range, charging times, and the upfront cost. The study suggests that a significant number of participants would be willing to pay a premium for a second-hand EV, particularly if it comes with a new battery and a dealership warranty, highlighting the critical role of perceived reliability and vehicle longevity in consumer decision-making. The study also highlights that refurbishing second-hand EVs with new batteries will reduce consumers' concerns and increase acceptance, alleviating some concerns regarding the battery life in the second-hand EV market.

However, the study acknowledges its limitations, including the small and demographically narrow sample size and its focus on a single country, Portugal, thus limiting the ability to generalize the results. The study also lacked samples from older demographics as their sample had participants aged between 20-40 years of age. This limitation suggests the need for further research that encompasses broader demographics and explores the secondary EV market in different cultural and economic contexts. Additionally, the study points to future research directions, such as investigating the impact of brand loyalty on second-hand EV purchases and the potential of refurbished EVs to attract buyers.

Pevec, Dario, et al. "A survey-based assessment of how existing and potential electric vehicle owners perceive range anxiety." ***Journal of Cleaner Production*** **276 (2020): 122779.**

The study focuses on understanding the preferences of drivers, both EV and non-EV owners, when it comes to the distance between neighboring charging stations. This information is crucial for decision-makers to develop a charging infrastructure that meets the needs of drivers and reduces range anxiety. Range anxiety is the concern drivers have over whether their vehicle has enough battery charge to reach the next charging station. Non-EV owners tend to prefer fewer gas stations, with greater distances between them. On the other hand, EV owners prefer more charging stations located closer together.

In this research, it was found that the average desired distance between neighboring charging stations for non-EV owners is about 8 km. For EV owners, the preferred distance is closer. The variance in preferred distances is influenced by settlement hierarchy levels, suggesting that in larger cities with well-developed traditional refueling infrastructure, people might have a less flexible mindset when it comes to the distance between charging stations. This finding highlights the need for a tailored approach to charging infrastructure development depending on the location and type of settlement.

The study also analyzed range anxiety among drivers. Non-EV owners experienced greater range anxiety than EV owners, with the remaining distance being a more significant concern than the state of charge (SoC). Interestingly, the experience of owning an EV greatly affects range anxiety, with EV owners showing similar trends to non-EV owners but being less sensitive to key EV parameters. Most non-EV owners are likely to charge when the SoC drops below 15 %.

These findings have important implications for green transportation and can be used in various decision support systems. For example, if the results presented in this paper are taken into consideration when deploying new charging stations, they could potentially influence a potential EV owner's decision to buy an electric vehicle. This could lead to increased adoption of electric vehicles, which is essential for reducing greenhouse gas emissions and promoting sustainable transportation.

In the future, the authors plan to refine their research by customizing the survey for each group of EV owners and using more complex statistical analysis methods. They also aim to gather a more geographically balanced set of participants to ensure a better understanding of drivers' preferences across different regions. This will help create a more comprehensive and accurate picture of the factors that influence the development of charging infrastructure and the adoption of electric vehicles.

Picatoste, Aitor, Daniel Justel, and Joan Manuel F. Mendoza. "Exploring the applicability of circular design criteria for electric vehicle batteries." ***Procedia CIRP*** **109 (2022): 107-112.**

This study focuses on assessing the potential implementation of circular economy (CE) design criteria in lithium-ion batteries (LIBs) for battery electric vehicles (BEVs). Stakeholders from the H20020 LIBERTY project engaged in identifying stakeholder priorities, challenges, and opportunities based on importance and viability. A four-step methodology is used, which involves selecting and adapting the CE design assessment tool (CIRCit) for the context of LIBs in BEVs, engaging stakeholders from the H2020 LIBERTY project, prioritizing the CE design criteria based on importance and viability, and conducting a critical assessment of the CE design criteria.

Data was collected through stakeholder engagement, with eight companies participating from the H2020 LIBERTY project. Stakeholders provided scores for each circular criterion based on their technical know-how and involvement. The results show that the top five implementable criteria for circular design are as follows:

1. Focus on functionality and quality performance, ensuring batteries meet consumers' expectations in terms of range, charging time, and driving performance, rather than prioritizing aesthetics.
2. Consider and anticipate legislation by designing LIBs that adhere to current and future regulations regarding recycling rates, material recovery, and environmental standards.
3. Utilize digitalization, information, and communication technologies (ICT), and internet of things (IoT) solutions to improve battery performance, monitor usage, and potentially facilitate easier dismantling and recycling.
4. Avoid toxic materials and substances by exploring alternatives to critical materials in battery composition, aiming to maintain performance while reducing environmental and health risks.
5. Favor cleaner production processes, implementing environmentally friendly manufacturing methods, including the use of recycled materials and energy-efficient techniques, to minimize the overall environmental impact of battery production.

However, the study has some limitations. The stakeholder analysis may be limited due to the involvement of battery manufacturers who are not waste managers. Additionally, the study only analyzed the top five criteria and not all 53 criteria present in the CE design tool. Future work could include analyzing the effect of CE design criteria on circular business models and value chains and understanding their impact on resource consumption and environmental implications of LIBs.

Propfe, Bernd, et al. "Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values." ***World Electric Vehicle Journal*** **5.4 (2012): 886-895.**

The paper explores the importance of considering resale value when assessing the life cycle cost of a vehicle. The researchers develop a new model to estimate the resale values of alternative vehicles. They use factors such as purchase price, powertrain type, vehicle age, vehicle-miles-traveled, and technology costs as input parameters in this model.

In the first step, the model analyzes resale values of conventional internal combustion engine vehicles based on historical German data. It uses multiple regressions to identify functional dependencies between these input parameters and the resale value. The second step involves applying these results to new powertrain architectures while taking into account varying lifetime expectations and their impact on utilization costs.

The model reveals that the resale value of conventional vehicles has a linear relationship with both annual vehicle miles traveled and the initial purchase price. Analyzing limited data on hybrid vehicles, the researchers observe that after a holding period of 4 years, hybrid vehicles have a higher resale value than their conventional counterparts.

However, the resale value of battery electric vehicles (BEVs) is expected to be lower than that of conventional vehicles, with values ranging from 10 % to 44 % lower. This discrepancy is primarily attributed to uncertainties around the life cycle expectations of the traction battery and the associated risks. The model's calculations for resale values after a 4-year holding period are based on a linear regression model, with specific parameters set for the total cost of ownership analysis.

Rezvani, Zeinab, Johan Jansson, and Jan Bodin. "Advances in consumer electric vehicle adoption research: A review and research agenda." ***Transportation research part D: transport and environment*** **34 (2015): 122-136.**

This study aims to provide a comprehensive overview of the drivers and barriers to consumer adoption of plug-in electric vehicles (PEVs) and identify gaps and limitations in current research, focusing on understanding consumer behavior toward these disruptive innovations in transportation technology. A systematic literature review approach is employed, focusing on empirical studies with consumer data to understand actual consumer intentions and behaviors.

The data reveals that the theory of planned behavior (TPB) is commonly used to study consumer EV adoption, with factors such as consumer attitude, perceived behavioral control, and subjective social norms playing crucial roles.

The compatibility of EVs in consumers' everyday lives, the symbolic meanings they hold, and the emotions they evoke are key aspects of consumer EV adoption. Governments can improve compatibility by creating suitable charging infrastructure, while companies can explore options like separating battery and car ownership. The study also emphasizes the need to explore the role of justifications in alleviating consumer regret and the impact of different justifications on resolving the EV obsolescence issue. Moreover, understanding the symbolic meanings of EVs and the influence of self-identity on adoption intentions can inform marketing strategies.

The role of emotions in EV adoption is also significant, as positive emotions like "feeling good" and "less guilt" are correlated with consumer attitudes and intentions to adopt EVs. Further research should investigate the antecedents and consequences of emotions in consumer EV adoption to enhance understanding and inform communication, education, and policy.

Five key themes are identified in the literature: planned, emotional, and symbolic behavior; consumer knowledge and skills; policy perception; social norms and neighborhood effects; and attitudes and behavior. Addressing methodological limitations, focusing on actual adoption behavior, and examining interventions to close the attitude-behavior gap is essential for future research. Understanding consumer knowledge and skills, policy perception, social norms, and neighborhood effects can help design effective policies for pro-environmental behavior. The study also suggests exploring the adoption of EVs by fleet managers and the potential influence of driving an EV at work on private car adoption.

Riexinger, Günther, et al. "Integration of traceability systems in battery production." *Procedia CIRP* 93 (2020): 125-130.

This research explores the role of traceability in lithium-ion battery production, a critical factor in optimizing processes and reducing environmental impact. Traceability, which links production data with performance indicators, provides a detailed understanding of the product lifecycle, supporting the production of more sustainable battery systems.

The study's approach includes a morphological analysis, which helps identify potential solutions for integrating identification technologies in battery production. This analysis is supplemented by an in-depth exploration of current industry practices.

The results suggest potential strategies to bridge information gaps in the production process. However, additional tests are needed to ensure the introduced markers do not impact the battery cells' quality.

While the research presents promising techniques, it acknowledges there's no universal solution for traceability in battery production. Yet, the study underlines traceability's importance, demonstrating its role in enhancing production efficiency and sustainability in lithium-ion battery manufacturing.

Schoettle, Brandon, and Michael Sivak. "Resale Values of Electric and Conventional Vehicles: Recent Trends and Influence on the Decision to Purchase a New Vehicle." (2018).

This research examined how resale value affects consumer purchasing decisions, concentrating on battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) as opposed to internal combustion engine (ICE) vehicles. Data was gathered from the EPA website and Kelley Blue Book for 11 pairs of BEV and ICE vehicles and 9 pairs of PHEV and ICE vehicles. The analysis revealed that BEVs generally have a lower resale value than ICE vehicles, with a 6-year-old ICE retaining a similar resale value to a 4- or 5-year-old PEV. The average difference in retained resale values between ICEs and PHEVs was -8.5 % throughout the years.

Surveys conducted among gasoline, diesel, and light truck owners found that purchase price, fuel economy, and fuel costs were the most crucial aspects for buyers of gasoline or diesel passenger cars and light trucks. In contrast, maximum battery range, purchase price, and safety were the most significant factors for plug-in electric passenger cars. Resale value was only a factor for a small portion of respondents. However, people tended to prioritize expected resale value when buying a plug-in electric passenger car or light truck.

The study’s limitations include having a small sample size and collecting data from a single source. Future research can investigate the impact of other factors, such as battery degradation, charging infrastructure, long-term maintenance costs, fuel economy and fuel costs, and vehicle design, on consumer decision-making.

Singer, Mark. *Consumer views on plug-in electric vehicles--National Benchmark Report*. No. NREL/TP-5400-67107. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.

The study found that respondents who are aware of PEV charging stations have a higher percentage of positive views towards PHEVs. People who had personal experience with PHEVs also had a positive view towards them. The sample sizes for respondents that fit into additional segments were generally small, with new vehicle purchasers having the highest sample size of 241.

Regarding EVs, 45 % of respondents reported positive views towards them, with new vehicle purchasers having a more positive view than used vehicle purchasers. Respondents who bought or planned to buy a vehicle in the next year also had more positive views of EVs.

Those who were able to plug in their vehicles at home were slightly more likely to consider purchasing an EV. Those who were aware of PEV charging stations were the most likely to consider an EV, with 20 % of respondents saying they would consider purchasing or leasing an EV in the next year. However, there were some differences between groups of respondents who were more or less likely to consider purchasing an EV. The sample sizes for the respondents that fit into additional segments were generally small, with able to name one of the nine top selling PEVs having a sample size of 217.

Skeete, J.-P., Wells, P., Dong, X., Heidrich, O., & Harper, G. (2020). Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. *Energy Research & Social Science*, *69*, 101581. https://doi.org/10.1016/j.erss.2020.101581

This paper conducts an examination of the challenges and opportunities associated with the end-of-life management of Battery Electric Vehicles (BEVs) (and does not include HEV oe any other alternative fuel vehicles) in the UK, with a specific focus on lithium-ion batteries. The primary research questions delve into forecasting the UK's dynamic stockpile of obsolete lithium-ion battery (OLIB) packs by 2025 and exploring the environmental, economic, and policy challenges arising from this accumulation. The study utilizes data from historical car registration records and manufacturer warranties to project the future stockpile of end-of-life lithium-ion batteries. The data spans from 2011 to 2018, with projections made up to 2025, using the forecast of new car registrations along with three possible trajectories based on low (4 %), medium (8 %) and high (24 %) rates of BEV market penetration.

The sample size includes the entirety of publicly available BEV registrations within the forecast period from the UK Driver and Vehicle Licensing Agency (DVLA) and Society of Motor Manufacturers and Traders (SMMT). The methodology combines quantitative forecasting with document analysis, drawing on official records, academic literature, and industry reports to contextualize findings within broader environmental and regulatory frameworks. Although challenging, the new car registrations in the UK between 2019-2025 was projected to be over 2 million in 2025, but during the time of the study, there were ongoing uncertainties about the Brexit the UK's unknown trading status afterwards, primarily with the EU. Thus, the two million was estimated assuming less-than-ideal trading conditions, down from 2.3 million at the end of 2018.

The results highlight a significant impending challenge in managing the end-of-life phase of BEVs, particularly the recycling and disposal of lithium-ion batteries. Projections indicate a potential stockpile exceeding 100 000 battery packs by 2025 or 42 000 t of lithium-ion battery waste, underscoring a critical need for developing sustainable recycling technologies and policies. The analysis reveals a gap in current recycling capabilities, particularly for batteries with varied chemistries and form factors, emphasizing the necessity for innovative recycling processes that can adapt to these challenges.

The paper identifies several limitations and areas for future research, including the need for improved data on BEV scrappage rates and the potential impact of emerging battery technologies on recycling processes. The discussions around policy implications and the establishment of a circular economy for BEVs in the UK are particularly insightful, suggesting that both technological innovation and regulatory frameworks will be crucial in addressing the challenges of lithium-ion battery disposal and recycling.

Thananusak, Trin, et al. "Factors affecting the intention to buy electric vehicles: Empirical evidence from Thailand." ***International Journal of Electric and Hybrid Vehicles*** **9.4 (2017): 361-381.**

The paper delves into the factors affecting the intention to purchase electric vehicles (EVs) in Thailand, highlighting performance, environmental concern, and price premium as crucial aspects. Performance factors include elements like safety, driving range, power, recharging time, and reliability, emphasizing the need for car manufacturers and government agencies to focus on these aspects. Real-world experience with EVs, such as test drives and exposure at motor shows, is found to significantly increase the intent to purchase.

Interestingly, the study indicates that the factors often deemed critical in other contexts, namely infrastructure and financial elements, don't significantly influence Thai consumers' intentions to buy EVs. This might be due to an anticipation that adequate charging facilities will be available by the time of their EV adoption and a lack of comprehensive understanding of the total cost of EV ownership.

The research also underscores the value of environmental concern as a driving force for EV adoption. However, it notes that despite a high level of concern for the environment, Thai consumers' willingness to pay a premium price for EVs decreases. This suggests that while consumers are willing to contribute to sustainability, the burden of high cost weakens this intent. Therefore, to increase EV adoption, the authors recommend increasing the social status reward from conspicuous conservation and providing incentives to offset the perceived burden of the price premium.

In future, the authors suggest further exploration of the gap between intent and actual EV adoption, retesting these relationships over different time frames, and researching the optimal price-premium range to encourage EV adoption.

White, Lee V., and Nicole D. Sintov. "You are what you drive: Environmentalist and social innovator symbolism drives electric vehicle adoption intentions." ***Transportation Research Part A: Policy and Practice*** **99 (2017): 94-113.**

This study looks at how people's self-image and what they believe about electric vehicles (EVs) affects if they want to use them. It also checks how much people care about climate change, messages that encourage them to use EVs, and other factors. The authors use an online survey to get answers from 481 people in California. After removing incomplete data, they have a final group of 355 people. The survey asks about their thoughts on EVs, who they are, what they like, how they feel about the environment, and if they want to use EVs. The authors use different ways to understand the information they get.

The study shows that if people think EVs are good for the environment and match their image, they are more likely to want to use them. The authors also find out that if people see themselves as creative and innovative, they are more willing to try EVs. The study finds that people's care for the environment and their ideas about EVs are connected.

The authors talk about some problems with the study, like how people might not give true answers, the group of people is not perfect, and they don't look at everything about EVs. They suggest that future research should fix these problems by using real EV sales data, better groups of people, and studying more about EVs. Also, they recommend that future research should think about how people feel about the distance EVs can go before needing to charge. The study suggests that to encourage more people adopt EVs, needed is a better match between their values and how they are perceived by others. They are also concerned about EV range, cost, and ability to charge.

Wicki, M., Brückmann, G., Quoss, F., & Bernauer, T. (2023). What do we really know about the acceptance of battery electric vehicles? – Turns out, not much. Transport Reviews, 43(1), 62–87. https://doi.org/10.1080/01441647.2021.2023693

The study examines the factors influencing consumer acceptance of battery electric vehicles (BEVs) through a systematic review of 94 peer-reviewed journal articles published between 2010 and 2019. The main research questions focus on the reliability of studies on BEV acceptance in terms of replicability, generalizability, and survey design, as well as identifying the causal effect of facilitators affecting consumers' preferences regarding BEV acceptance. The data used comes from various surveys and experiments detailed within these studies, covering a wide range of socio-demographic, technical, contextual, and attitudinal variables.

The review highlights several key findings: the evidence on what drives BEV acceptance is mixed and context-dependent, with few studies designed to identify causal effects of facilitators and obstacles. It also notes the limited availability of replication data, which raises concerns about the replicability of existing studies. Moreover, the paper points out the geographical concentration of studies in North America and Europe, questioning the generalizability of findings globally.

The study employs the PRISMA framework for systematic reviews and meta-analyses to assess the 94 selected studies that utilize survey methods for understanding BEV (Battery Electric Vehicle) preferences and uptake. The analysis reveals inconsistent findings across key determinants of BEV acceptance, suggesting a limited understanding of what drives BEV uptake. These determinants are grouped into seven main categories: technical (e.g., motor power, driving range, etc), contextual (e.g., charging infrastructure, environmental impact, etc), cost-related (e.g., purchase price, operational costs, etc), sociodemographic (e.g., income, education level, etc), attitudinal and behavioral (e.g., environmental attitudes, technology acceptance, etc), BEV-specific experience (e.g., familiarity with BEVs), and social factors (e.g., social norms, neighborhood effect, etc). These determinants highlight the multifaceted nature of BEV acceptance, emphasizing the importance of addressing each factor through targeted policymaking and marketing strategies to enhance BEV adoption. The study points out the inconsistencies in findings across these determinants, further underscoring the complexity of understanding BEV uptake and the need for more nuanced and comprehensive research in this area.

The study concludes with a call for more robust, internationally coordinated research efforts, emphasizing the need for pre-registration of study designs and full accessibility of replication data to build a reliable evidence base on BEV acceptance. It highlights several limitations in existing research, including a lack of studies from diverse geographical contexts, the challenge of generalizing findings due to the heterogeneity of study designs and populations, and the necessity of employing causal identification strategies to understand the factors influencing BEV acceptance better.

Woo, JongRoul, and Christopher L. Magee. "Forecasting the value of battery electric vehicles compared to internal combustion engine vehicles: the influence of driving range and battery technology." International Journal of Energy Research 44.8 (2020): 6483-6501.

The study presented explores the future of Battery Electric Vehicles (BEVs) and Internal Combustion Engine Vehicles (ICEVs), specifically focusing on their respective developments and how this affects consumer preferences. The main takeaway is that, despite technological advancements in BEVs, a total substitution of ICEVs by BEVs by 2050 may not occur. This assertion has limitations, such as the accuracy of the simulation models used and the focus on U.S. market data, and it assumes the automotive market structure remains similar to the current one over the next 30 years.

The research only focuses on Li-ion BEVs, leaving out other technologies like Capacitor Electric Vehicles, which may potentially outperform ICEVs. It's pointed out that any unexpected change in market structure, such as extreme carbon taxes or political system alterations, may also affect the forecast. Lastly, the forecast itself has inherent uncertainties, including the introduction of new technologies that offer greater performance

Yang, F., Xie, Y., Deng, Y., & Yuan, C. (2018). Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation. *Nature Communications*, *9*(1), 2429. https://doi.org/10.1038/s41467-018-04826-0

The study explores the relationship between electric vehicle (EV) battery degradation and its consequential impacts on energy consumption and greenhouse gas (GHG) emissions. This investigation is important in the context of the global push towards electric mobility as a strategy to mitigate climate change by reducing GHG emissions from the transportation sector. The primary research questions aim to uncover the extent to which battery degradation affects the operational efficiency of EVs and, subsequently, their environmental benefits. By focusing on a typical 24 kWh lithium-manganese-oxide–graphite battery pack, used in popular EV models such as the Nissan Leaf and Chevrolet Volt, the study endeavors to quantify how the sophisticated degradation processes of EV batteries influence their energy consumption rates and GHG emission levels across different U.S. states.

To conduct this analysis, the study leverages a robust dataset that includes information from the U.S. Federal Highway Administration, National Household Travel Survey, and experimental data from Argonne National Laboratory and FleetCarma. These datasets encompass a wide array of variables, including traffic volumes, travel frequencies, ambient temperatures, and specific EV performance metrics under varying driving conditions. Although the paper does not specify the exact period of data collection, it is inferred that the data represent a comprehensive snapshot of real-world EV usage, driving patterns, and environmental conditions across the U.S., thereby providing a solid foundation for the study's predictive models and analyses.

Methodologically, the study employs a multi-physics electrochemical model integrated with empirical equations to simulate the degradation processes occurring within EV batteries. This includes modeling both cycling and calendar capacity losses, which are influenced by a myriad of factors such as the number of charge/discharge cycles, ambient temperatures, and the battery's state of charge over time. These models are validated against existing literature and data, ensuring their reliability in projecting the impacts of battery degradation. The analysis is further enriched by considering state-level variations in driving demands, electricity mixes, and ambient temperatures, offering a granular view of how regional differences influence EV performance and environmental impacts.

The driving ranges of a mid-sized EV with a 24 kWh LMO–graphite battery, as reported from 2013 Nissan Leaf on their actual driving in the U.S., are ranging between 64 and 193 km under different driving patterns and temperatures which significantly affect the battery cycling capacity loss and associated GHG emissions during EV driving based on the largely different GHG emission factors (CO_2,eq k Wh^{-1}) across the U.S. One of the key results highlights the variability in battery life expectancy across the U.S., ranging from as low as 5.2 years in Florida to as high as 13.3 years in Alaska, under a 30 % battery degradation threshold. This variation is attributed to differences in ambient temperatures, annual travel demand and driving conditions, which significantly influence the rate of battery degradation. Moreover, the study estimates that battery degradation could lead to an increase in energy consumption and GHG emissions per kilometer driven by 11.5 to 16.2 % at the 30% capacity loss mark. Due to the regional variations in factors affecting the battery degradation rate, the study highlights that states with large GHG emission reductions should be provided with enhanced incentives for promoting more EV deployment, while those states with small or no GHG emission reductions should be provided with less or no incentives for EV deployment.

Despite its comprehensive approach, the study acknowledges several limitations that suggest avenues for future research. The analysis is specific to a particular type of EV battery, and the use of average state-level data may not capture the full spectrum of variability in driving patterns and ambient conditions. Future research could benefit from exploring the impacts of extreme weather conditions, variations in driving behavior, and advancements in battery and vehicle technologies on EV performance and environmental outcomes. Furthermore, the study points to the potential for more detailed investigations that could inform targeted policy measures and incentives for EV adoption, tailored to regional characteristics and needs.

Yuan, Quan, et al. "Investigation on range anxiety and safety buffer of battery electric vehicle drivers." ***Journal of Advanced Transportation*** **2018 (2018).**

This study investigates the concept of range anxiety in Battery Electric Vehicle (BEV) drivers and its impact on their driving behavior. Utilizing a questionnaire approach, data was gathered from 208 valid respondents through the Autohome forum. The questionnaire assessed both demographic information and range anxiety levels using Likert scale questions. Statistical methods such as Cronbach's Alpha and Chi-square tests were employed to test the reliability of the questionnaire and examine the correlations between influential factors, safety buffer, and driving behaviors. The results showed significant correlations between driving experience, satisfaction with recharge accessibility, and resistibility to emotions, and the safety buffer maintained by drivers. Experienced drivers and those with high resistibility to emotions tended to maintain larger safety buffers. Moreover, drivers adapted their behaviors based on the remaining range and trip length, with speed reduction and seeking nearby charging piles being the common strategies.

However, the research has several limitations. It could not cover all situations where range anxiety can occur, and the current driving style measurements might not fully capture a driver's driving style. Also, the net safety buffer was found to fluctuate around 15 km, which could limit the generalizability of the findings. The study's focus was solely on BEV drivers, excluding potential insights from non-BEV owners. Considering these limitations, future research directions were proposed. These include field experiments with varied trip mileages, exploring the impact of energy consumption during winter due to heater usage, and investigating the range anxiety of non-BEV owners to provide insights for BEV manufacturers.

Zhang, Xiang, and Chenguang Zhao. "Resale value guaranteed strategy, information sharing and electric vehicles adoption." ***Annals of Operations Research*** **(2021): 1-15.**

This paper dives into the effectiveness of a Resale Value Guarantee (RVG) strategy to mitigate resale anxiety in the Electric Vehicle (EV) market. The authors use real-world parameters and analytical models to demonstrate that under certain conditions, an RVG strategy can enhance supply chain performance and increase EV adoption. Specifically, the research establishes that key factors such as the degree of resale anxiety (β), reliability of the manufacturer's decision (I), and the trade-in cost (η or $\eta\xi$ as total trade-in costs) are pivotal to the success of an RVG strategy, especially in scenarios with asymmetric information where the dealer has more knowledge of the consumers' resale anxiety.

Numerical experiments conducted with data from Audi's all-electric e-tron 55 quattro further validate the theoretical propositions. The findings reveal that both traditional and RVG-based supply chains' total profits are impacted by changes in resale anxiety, decision reliability, and trade-in cost. However, a unique advantage of the RVG strategy is its capacity to alleviate consumer resale concerns, making it a promising solution to drive higher EV adoption rates. The paper concludes by suggesting that companies in the EV market should seriously consider implementing an RVG strategy, keeping in mind the significance of resale value on consumer demand.

Zhao, Xin, Otto C. Doering, and Wallace E. Tyner. "The economic competitiveness and emissions of battery electric vehicles in China." Applied Energy 156 (2015): 666-675.

This analysis evaluates the economic viability of Battery Electric Vehicles (BEVs) in comparison to Internal Combustion Engine Vehicles (ICEVs) within the Chinese market, from both individual and societal perspectives. The research uses a benefit-cost analysis methodology, examining data on pricing, subsidies, specifications, fuel and electricity prices, maintenance costs, and vehicle resale values, among other factors. The study indicates that BEVs, despite their higher resale values and lower ownership costs, have significantly higher initial costs compared to ICEVs. It's found that the life-cycle private cost (LCPC) of BEVs is approximately 1.4 times higher than that of ICEVs, suggesting that BEVs aren't currently economically competitive with ICEVs.

The study also incorporates environmental external costs, showing that the benefits of emission reductions from BEVs are insufficient when weighed against government subsidies and the cost disparity between the two vehicle types. Despite projected decreases in the life-cycle purchase costs (LCPCs) up to 2031, BEVs are not anticipated to surpass ICEVs economically in the foreseeable future. However, future advancements in battery technology and electricity generation may influence this outcome. The study concludes with policy recommendations, advocating for technology improvements, revision of government subsidies based on environmental benefits, and a reduction in the carbon intensity of electricity generation in China. Limitations of the study include assumptions about battery life and set resale values, and a lack of comparable data for the social cost of emissions in China.

Zhu, Juner, et al. "End-of-life or second-life options for retired electric vehicle batteries." ***Cell Reports Physical Science*** **2.8 (2021).**

The research discusses the emerging interest in the second-life applications of retired electric vehicle (EV) batteries. Potential uses include repurposing for less demanding vehicles, stationary energy storage systems, street lighting, and renewable energy generation. This recycling approach could potentially reduce the economic and environmental costs of battery disposal while catering to different energy needs. However, the ability to repurpose these batteries relies heavily on their remaining capacity, which can be challenging to accurately determine due to varied battery chemistries and a lack of comprehensive data on battery degradation.

The study also points out significant technical challenges. There's a conspicuous absence of standard procedures for handling retired EV batteries. Factors such as different form factors, designs, and cell chemistries make it impossible to develop a one-size-fits-all procedure. The dearth of detailed technical procedures and battery degradation data in open literature compounds this challenge. Therefore, the study emphasizes the importance of data collection on battery health and advocates for collaboration among companies, possibly through initiatives like a 'battery passport' proposed in the European Union, to facilitate a circular economy.

Appendix B. List of Symbols, Abbreviations, and Acronyms

4WD: Four Wheel Drive
AAA: American Automobile Association
AGI: Adjusted Gross Income
BEV: Battery Electric Vehicle
BIGP: Battery Identity Global Passport
B2U: Battery Second Use
BOM: Battery Ownership Model
DBP: Digital Battery Passport
EOL: End-of-Life
EPA: Environmental Protection Agency
EV: Electric Vehicle
ESS: Energy Storage System
EVB: Electric Vehicle Battery
GHG: Greenhouse Gas
HEV: Hybrid Electric Vehicle
ICE: Internal Combustion Engine
IEA: International Energy Agency
kWh: Kilo Watt Hour
LCA: Life Cycle Assessment
LIB: Lithium-Ion Battery
LFP: Lithium Iron Phosphate
MAGI: Modified Adjusted Gross Income
MSRP: Manufacturer Suggested Retail Price
MPG: Miles Per Gallon
OEM: Original Equipment Manufacturer
OLIB: Obsolete Lithium Ion Battery
PEV: Plug-in Electric Vehicle
PHEV: Plug-in Hybrid Electric
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SCOPIS: Supply Chain-Oriented Identification Process
SOC: State of Charge
SPM: Sustainability Performance Management
TCO: Total Cost of Ownership
VMT: Vehicle Miles Travelled