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RESEARCH ARTICLE

Cost of Battery Storage: A Catalyst for Electric Vehicle (EV) Adoption

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ABSTRACT: This research paper delves into the evolving landscape of battery technology and emphasizes its pivotal role in advancing humanity toward a net-zero economy, a system in which the emissions added to the atmosphere are balanced with the amount removed. It highlights the pressing need to transition to sustainable energy sources, discusses the versatile applications of batteries, and examines established and emerging battery technologies. Most notably, this research explores the link between the cost of battery storage per kWh at the pack level and the adoption rate of electric vehicles (EVs). It suggests that achieving price parity with internal combustion engine (ICE) vehicles is the tipping point that will jumpstart the electric revolution by making EVs attractive to a broader demographic of buyers.

KEYWORDS: Earth and Environmental Sciences; Climate Change; Electrification of Transportation; Battery Storage Technology; Cost of Battery Storage.

Introduction

Climate change demands quick and decisive action:

The increasing environmental, economic, and societal costs of climate change underscore the urgent need to drastically reduce humanity's carbon footprint. In recent years, rising global temperatures have increased the frequency and magnitude of natural disasters. Hurricanes, wildfires, and droughts negatively affect vulnerable ecosystems and reduce biodiversity. Severe weather events also damage public infrastructure, reduce crop yields, and disrupt business operations, taking a substantial financial toll on communities across the globe. This impact is not evenly distributed across the socio-economic spectrum.[1] Low-income and other marginalized groups are disproportionately affected, as they lack the means to prepare for and recover from climate-related disasters effectively. This disparity exacerbates existing social inequalities and widens societal divides. World leaders agree that global warming concerns have reached a critical point. They assert that transitioning away from fossil fuels by adopting renewable energy sources and implementing sustainable practices is no longer a choice but rather an imperative. Only by rapidly pivoting to a carbon-free economy can a sustainable and equitable future for all of humanity be achieved.[2]

The scientific community asserts that humanity must halve its carbon emissions by 2030 to contain global warming to 1.5°C, a theoretical cap that, if exceeded, could trigger irreversible and catastrophic changes in the Earth's climate. Their findings reveal that, based on recent technological advancements, it is technically and economically feasible to attain a 90% clean, carbon-free electricity supply in the United States by 2035.[3] To begin with, the declining cost of wind and solar energy has fundamentally transformed the outlook for rapidly and cost-effectively expanding the share of renewable energy sources. Concurrently, battery energy storage technologies have emerged as a practical solution for integrating substantial amounts of intermittent wind and solar power into the electricity grid.

According to a 2023 report by the International Energy Agency, renewables are poised to overtake coal and become the largest source of electricity generation globally by early 2025. This shift will have profound consequences for global emissions. Since official reporting commenced in 1990, the energy sector—including electricity generation and use—has remained the largest contributor to greenhouse gas (GHG) emissions worldwide. The energy and transportation sectors are responsible for three-fourths of global GHG emissions.[4]

The fuel supply disruptions caused by the war in Ukraine have escalated the transition from oil and gas as governments across the globe are seeking to improve energy security. However, recent data suggests that the US is lagging behind other developed nations and is falling short of the CO2 targets established by the Paris Agreement.[2] While the US has made progress towards its goals, experts agree it is insufficient. In the last two years, the US economy has been less carbon-intensive overall (with fewer CO2 emissions per unit of output). However, as Figure 1 demonstrates, energy was the only sector to register reductions in GHG emissions in 2022. Instead of declining, the GHG emissions in the two biggest polluting sectors—transport and industry—increased both in 2022 and 2023.[5]

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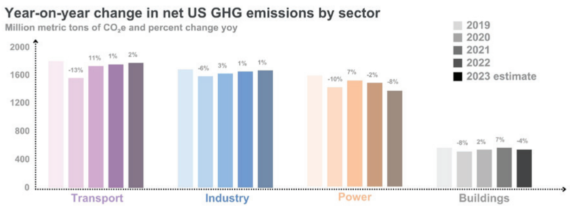

Figure 1: This figure depicts the GHG emissions by major sector in the US—year-on-year change and total emissions in metric tons. It reveals that not enough progress has been made in reducing emissions. Source: Rodium Group

Result and Discussion

Batteries are emerging as the backbone of the new carbon-free future:

Battery technology has emerged as the cornerstone in humanity's quest for a sustainable future. Their importance lies in their ability to store excess energy generated from renewable sources, bridge intermittent energy gaps, and facilitate the widespread adoption of clean energy technologies. By reshaping the way energy is generated, stored, and used, these storage devices have enabled the widespread adoption of green technologies. Furthermore, commercially viable and cost-competitive battery technologies are reducing the reliance on fossil fuels. This research paper not only underscores the critical role battery storage technologies play in the shift to clean energy by storing excess energy and enabling electric mobility but also seeks to determine the thresholds at which battery technologies become cost-competitive and rapidly displace incumbent fossil-fuel-reliant technologies.

First and foremost, batteries enable the efficient integration of renewable energy sources like wind and solar power into the electric grid. Because these energy sources are inherently intermittent, batteries serve as a buffer, holding surplus energy during periods of high output and releasing it when demand rises or supply dwindles. This battery storage capability ensures a stable and reliable energy supply, regardless of weather or time. In doing so, batteries are instrumental in reducing reliance on fossil fuels and advancing the transition towards a cleaner, more sustainable energy grid.[6]

Battery storage systems are also instrumental in revolutionizing how electricity is managed and distributed. Namely, by storing excess energy during off-peak hours and discharging it during periods of high demand, they reduce strain on the grid and optimize energy use. Additionally, energy storage systems enhance grid resilience by providing backup energy during power outages and allowing for the integration of decentralized, renewable energy sources. This resilience is critical amidst increasing infrastructure vulnerability due to climate-related natural disasters. Hence, batteries, as the core component of energy storage systems, play a pivotal role in enhancing the reliability and flexibility of the energy infrastructure.

Finally, batteries enable the transition towards electric mobility and, as a result, transform the transportation sector, the second largest GHG emitter both in the U.S. and worldwide. EVs are becoming more affordable and practical, primarily due to improvements in battery technology. High-capacity, long-lasting batteries have enabled longer driving ranges and shorter charging times. These crucial advancements have transformed EVs from a novelty to a viable mainstream alternative to traditional ICE vehicles. The transition to electric mobility will reduce carbon emissions, lessen the dependence on fossil fuels, and mitigate the impact of oil price fluctuations. Batteries are the driving force behind the electrification of transportation, paving the way for a cleaner, greener world.

The world of battery technology is rapidly changing:

A battery comprises one or more electrochemical cells that store chemical energy and convert it to electrical energy.[7] Through a chemical reaction, a battery creates an electrical circuit and produces a flow of electrons, which can be used to power devices. A battery has four basic components: the anode (negatively charged electrode), which undergoes oxidation during cell discharge; the cathode (positively charged electrode), which undergoes reduction during cell discharge; the electrolyte, a medium for ion transfer—typically a liquid—through which ions move between electrodes during cell charge and discharge; and a separator, a semi-permeable barrier that blocks the flow of electrons inside the battery. An ionic species, the electrolyte salt, is dissolved in the electrolyte to enhance battery performance. Lithium-ion systems make up 90% of the installed stationary battery capacity. Also, almost all new battery storage installations and long-range EVs rely on lithium-ion batteries.[4]

What is a lithium-ion battery, and how does it work?

The invention of the rechargeable battery dates back to 1859. The first rechargeable batteries utilized lead-acid chemistry. This chemistry continues to be widely used in car batteries for ICE vehicles. The journey towards the modern lithium-ion battery began in 1970 with the publication of the foundational work that laid the groundwork for this promising new technology. It took more than two decades to produce the first commercially viable lithium-ion cells, an important milestone that enabled significant breakthroughs in energy storage innovation. In 2019, John B. Goodenough, M. Stanley Whittingham and Akira Yoshino were awarded the Nobel Prize in Chemistry for their contributions to the invention of the modern lithium-ion battery.[8]

Lithium-ion batteries store and release energy by moving lithium ions between the cathode and anode. During the discharge cycle, the electrolyte carries positively charged lithium ions from the anode to the cathode, and during the charge cycle, the lithium ions travel in the opposite direction. Because the movement of the lithium ions generates free electrons in the anode, it creates a charge at the positive battery terminal. The resulting electrical current, which has a direction opposite to that of the flow of electrons, travels from the positive to the negative battery terminal through an electric circuit.

The lithium salts dissolved in the electrolyte enable the efficient movements of the lithium ions and eliminate the need for individual particles to travel the entire distance between the two electrodes during the charge and discharge cycles. Its small atomic weight and radius, 6.94 g/mol and 167pm, makes lithium perfect for this application. Larger only than hydrogen and helium, lithium is small enough to move through the electrolyte and the separator easily and to support a sufficiently high voltage and charge storage per unit of mass and volume.[9] Figure 2 illustrates the charging and discharging cycle of a lithium-ion battery.

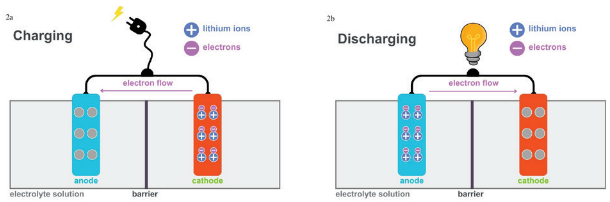

Figure 2: This diagram depicts the charging (2a) and discharging (2b) cycle of a lithium-ion battery. Source: Australian Academy of Science

Since charging and discharging lithium-ion batteries is repeatable, it allows for efficient and long-lasting use in various applications, from powering smartphones to EVs to energy storage systems.

Key metrics of battery performance:

Voltage measures the difference in electric potential between two points in a circuit. It represents the energy required to move a charge unit through a circuit and is measured in volts (V).

Current is the electric charge in a battery flowing through the external circuit per unit of time. It is directly proportional to the number of electrons and is measured in amperes (A).

Power is the rate at which electrical energy is transferred or used. It is the product of voltage and current measured in watts (W). In the context of a battery, it represents the rate at which it can deliver energy to a device or system.

Capacity refers to the total electric charge a battery can store and deliver. It represents how long a battery can provide a specific current before it is depleted. Capacity is measured in ampere-hours (Ah).

Energy density measures the energy a battery can store relative to its volume or weight. It is measured in watt-hours per liter (Wh/L) or watt-hours per kilogram (Wh/kg) and indicates the energy storage efficiency of the battery.

Charge rate refers to the speed at which a battery can be charged. It is usually expressed as a current (in amperes) or a multiple of the battery's capacity (C-rate). A higher charge rate means the battery can be charged faster.

Cycle life is the number of charge-and-discharge cycles a battery can undergo before its capacity significantly degrades. It is an important factor in determining a battery's longevity and durability. Cycle life can vary considerably between different battery chemistries and designs.

Different applications demand different battery technology solutions:

Batteries have become ubiquitous in our modern world, powering electronic devices and systems, from smartphones to EVs to renewable energy systems. Their versatility is a testament to the enormous advances in battery technology. It is important to recognize, however, that batteries are not interchangeable. For example, the materials used for a battery's electrodes will affect both the battery's properties and costs. Consequently, depending on each application's energy density, lifespan, and cost requirements, different battery technologies and chemistries have emerged as the winners.

Consumer electronics, such as smartphones, laptops, and tablets, require energy-dense batteries to ensure prolonged usage without adding excessive weight. Lithium-ion batteries, known for their high energy-to-weight ratio, have become the standard for these applications. More specifically, lithium cobalt oxide ($LiCoO_2$ or LCO) is the battery of choice in consumer electronics.

Renewable energy generation relies on battery storage technologies to counter the intermittent nature of solar and wind energy. In this application, the focus is on large-scale systems with high capacity and a long life cycle. Lithium-iron phosphate ($LiFePO_4$ or LFP) batteries have gained popularity due to their unique combination of low cost, extended cycle life, and safety.[10] Lower energy density, their main disadvantage, is not a primary concern in grid applications. Additionally, new low-cost technologies, such as sodium-ion batteries, garner substantial interest from scientists and investors alike.

Electric vehicles require energy-dense batteries for extended driving ranges and rapid charging capabilities. Lithium-nickel-manganese-cobalt oxide ($LiNiMnCoO_2$ or NMC) and LFP batteries have emerged as the two leading chemistries in the EV space. The higher-energy density NMC batteries are best suited for longer-range models, and the LFP batteries are the winning cost-effective solution in the compact vehicle segment.[11] Experts predict that by 2026, NMC and LFP batteries will account for over 80% of the EV battery market.

Promising new battery storage technologies are also emerging:

Ongoing advancements in lithium-ion technology are propelling the adoption of EVs and the seamless integration of renewable energy sources into the electric grid. While lithium-ion technologies will continue to dominate the battery storage market for the foreseeable future, most experts also recognize that this technology will eventually reach its theoretical limits. As a result, researchers are already working hard on the next generation of energy storage solutions. As expected, the most promising new battery storage technologies are attracting much attention and healthy capital investments. While the next generation of technologies will encompass a wide range of solutions, from new chemistries to radically new approaches, they all share consistent goals: higher energy density, faster charging, improved safety, cycle longevity, and lower cost.[12]

Lithium-sulfur is emerging as one of the most promising new battery chemistries. Adding sulfur to lithium-ion batteries can increase energy density, theoretically doubling the EV range and lowering the cost of lithium-ion batteries, as sulfur is more abundant than the metals used in current commercial lithium-ion chemistries.[13] Researchers also claim that sodium-ion technologies and solid-state batteries, two of the most promising novel solutions, have the potential to offer higher energy density, extended lifespans, and enhanced safety. Sodium-ion batteries, which are already making commercial inroads, are poised to provide a cost-effective alternative, particularly for energy storage applications where energy density is not a primary concern. Solid-state batteries, which rely on a

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solid instead of a liquid electrolyte, have the potential to revolutionize the world of battery storage by drastically improving both energy density and charging speed. These emerging technologies are set to play a critical role in reducing the world's dependence on fossil fuels and lowering GHG emissions.[14] Figure 3 highlights the advantages and disadvantages of the three new technologies discussed above.

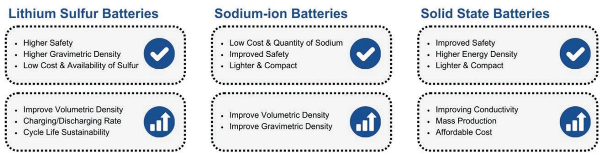

Figure 3: This figure highlights the key advantages and areas for improvement for the three most promising new battery technologies. Source: Ganesh Sankaran and S. Venkatesan 2022 IOP Conf. Ser.: Earth Environ. Sci. 1042 012012

The pace of innovation and the drivers of carbon-free mobility:

Adopting EVs is essential in humanity's path towards a more responsible transportation future. As costs rapidly decline and technology advances, EVs are increasingly becoming technologically superior to ICE vehicles and more affordable. With longer driving ranges and faster charging times, the current generation of EVs is already offering consumers a better driving experience and a lower ownership cost than ICE vehicles. These advancements are making EVs increasingly practical and attractive to a broader range of consumers.[15] Experts agree that a convergence of technological innovations, such as drastic improvements in photovoltaic and energy storage technologies, has already set the clean energy disruption in motion.[16] Some even argue that governed by the economics of increasing returns, the EV adoption and clean energy transition, in general, will not follow a linear path but rather the exponential growth trajectory of revolutionary tech companies, such as Apple, Google, and Intel, that have transformed entire industries. The disruptive technologies responsible for this swift transition are knowledge-based, environmentally responsible, and cost-effective. These new technologies will enable humanity to leave behind the industrial age of energy and transportation, which has been heavily reliant on fossil fuels, and move into the era of information technology.[17]

EVs are following the typical adoption curve of new technologies:

The adoption rate is the pace at which a new technology penetrates the market. The adoption curve, illustrated in Figure 4, provides a framework for breaking down customers into five segments.

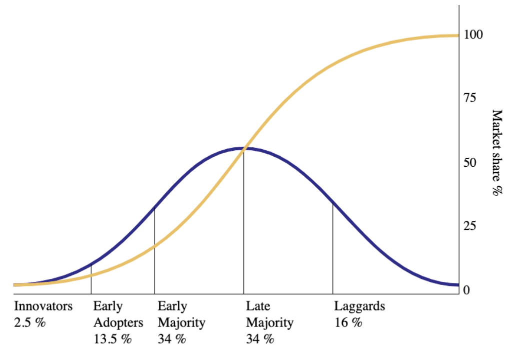

Figure 4: This figure depicts the typical adoption curve of new technologies—percent breakdown of customer segments and market share penetration.

The innovators, accounting for about 2.5% of consumers, embrace new technology despite its initial high cost. Early adopters, accounting for 13.5%, are more risk-averse but play a crucial role as thought leaders and influencers. The early majority, which makes up 34% of the market, adopts technology after thorough vetting, considering the experiences and insights of innovators and early adopters. The late majority (34%), typically risk-averse, waits until the technology is well established before adopting it. Finally, the laggards (16%) are the last to adopt when the technology has become mainstream.[18]

While the adoption curve and the laws of normal distribution provide guidelines for the percentage breakdown by customer segment, the adoption rate or the pace at which each innovation moves through the customer segments depends on several factors, the chief amongst which is cost.

EV sales are gaining momentum:

Unit sales of EVs reached 10 million in 2022, accounting for 14%, or 1 in 7 vehicles sold globally. What is more impressive is that this figure represents a 10-fold increase over the number of EVs sold only five years earlier. In the U.S., the third largest EV market after China and Europe, EV sales grew 55% and reached an 8% share of new car sales in 2022.[19] The EV Sales Tracker from EVadoption estimates that EV sales reached 1.2 million vehicles in 2023. At 8.8% of the total car market, this figure signals that the U.S. EV market has reached the tipping point, the threshold at which the technology is advanced and the price is competitive enough to enable broader market penetration. This is the stage at which the market shifts towards the early majority and reaches the steep part of the adoption curve, enabling growth at scale. Demand proliferates during this adoption phase, and for revolutionary new technologies, it typically grows significantly faster than any of the models predict.

When examining historical data of EV sales across 17 individual countries, it can be concluded that the rate of EV adoption to date has been consistently exponential.[20] In an exponential model, the rate of change of a given quantity $n_E^{(exp}(t)$, the change of that quantity over period t, is proportional to the quantity itself. The following differential equation can represent this relationship:

$$\frac{dn_E^{(exp)}(t)}{dt} = an_E^{(exp)}(t)$$

Where $a > 0$ is the parameter denoting the growth rate

Solving the equation yields the exponential model:

$$n_E^{(exp)}(t) = exp\big(a(t - t_0)\big) \qquad t > t_0 > 0$$

Where t_0 represents the temporal offset

A prediction for future EV sales can be made by extrapolating the historic exponential trend. This data would suggest that the US and world markets will undergo a much faster system-wide adoption than most economic models have predicted. Under this model, most new vehicle sales in the US and world markets will be electric by 2030 (see Figure 5). It is predicted that many regions in the developed world will double their EV fleet every 15 months.[20]

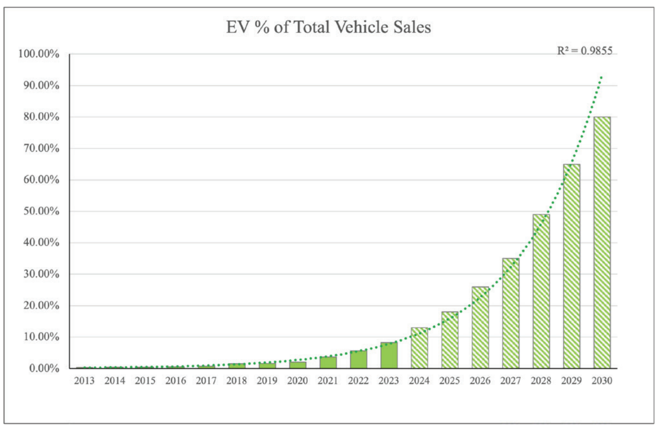

Figure 5: This figure uses an exponential growth model to project U.S. EV market penetration (% of total vehicle sales) through 2030. Historical data source: Statista, Bloomberg Finance

While the exponential model is well-suited for projecting growth during the initial and growth phases of adoption, it has limitations. Namely, it fails to consider the idea of ultimate market saturation. Therefore, a more accurate model of the late phases of adoption is logistic growth. The logistic model introduces the saturation limit by adjusting the growth rate proportionally to the difference between the quantity at any given time and the limit, which is full market penetration. Introducing this limit results in the following differential equation:

$$\frac{dn_E^{(log)}(t)}{dt} = an_E^{(log)}(t)\left(1 - n_E^{(log)}(t)\right)$$

The logistic model for EVs as a function of time follows as a solution to the equation:

$$n_E^{(log)}(t) = \frac{L}{1 + exp\big(-a(t - t_0)\big)} \qquad L, a, t_0, t > 0$$

Where a, t_0, and L represent the initial growth rate, the time offset, and the saturation limit, respectively.

While many factors are responsible for disrupting incumbent technologies, in this case, ICE vehicles, numerous research studies and historical data have demonstrated that cost is often the single most important underlying driver governing consumer behavior and choice. This report seeks to analyze the relationship between the cost of battery storage at the pack level and EV sales.

Falling battery storage costs are driving down EV prices and fueling demand:

With technological advancements fueled by healthy investments in research and development and economies of scale, the cost of battery storage has declined to a fraction of its original value. Illustrated in Figure 6, the cost per kWh of battery storage at the pack level has decreased at an average annual rate of 15% over the last ten years. In fact, according to Bloomberg New Energy Finance, lithium-ion battery pack prices fell by 85 percent from 2010 to 2018. Moreover, technological innovations continue to unlock superior performance, which drives faster adoption and higher demand, creating a self-reinforcing feedback loop that brings about further price decreases and performance improvements.

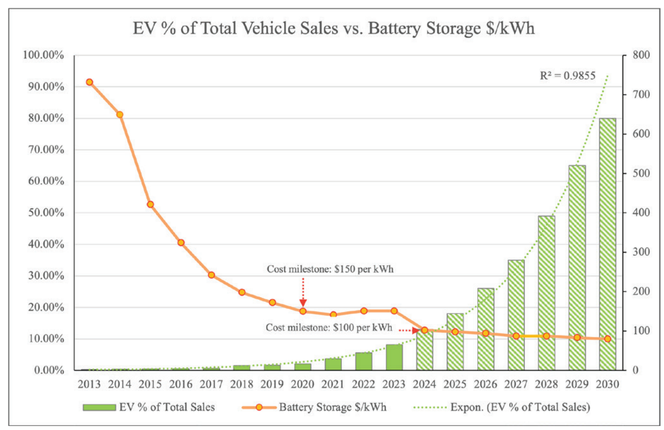

Figure 6: This figure displays the strong negative relationship between EV market penetration (% of total vehicle sales) and battery storage cost ($/kWh) and highlights two critical cost milestones that accelerate the adoption process. Historical data source: Bloomberg Finance, Statista

In 2022, battery cell costs increased for the first time due to global raw material shortages and supply chain disruptions. Recent data suggests that this deviation from the long-term trend has already been corrected. As of the summer of 2023, reports indicate that cost reductions have offset the temporary spike and reverted to the trend. Global survey data with battery manufacturers reports that the weighted average cell costs for lithium-ion batteries in 2023 will fall below projections. This cost will be below $100 per kWh for some parts of the world.[21] More importantly, in the next decade, with exponential growth in EV demand and economies of scale, the cost of lithium-ion batteries will continue to decline steadily. The next critical milestone for battery and EV manufacturers is projected in 2025, when the cost per kWh at the pack level will consistently fall below $100 in most markets.[22]

Not surprisingly, data analysis reveals a negative correlation between the cost of battery storage per kWh at the pack level and EV sales. Furthermore, it is evident that demand growth

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escalated significantly after achieving the first milestone, cost per kWh at or below $150, and is forecasted to do so again once the second important milestone, cost at the pack level below $100 per kWh, is achieved. This relationship supports the thesis that declining battery storage costs coupled with improving technology is a key driver responsible for the robust growth projected in EV sales. This claim is further supported by consumer survey data, which reveals high upfront costs and range anxiety as two of the top three reasons for hesitancy in switching to EVs, with the third factor being an inadequate charging network.[23]

It is also important to clearly define what constitutes cost. Although EVs became more cost-competitive on a lifetime basis than ICE vehicles in 2017, this did not result in any evident spike in EV sales, demonstrating that typical customers evaluate cars based on purchase price.[24] Thus, it is important to analyze the cost competitiveness of EVs based on upfront costs. Specifically, it is important to compare the purchase price of EVs with that of ICE vehicles in the three main segments—compact car, midsize SUV, and pickup truck— while considering the maturity of the new technologies.

Comparative analysis of the cost breakdown of EV and ICE vehicles reveals that the powertrain accounts for 51% of the overall cost of EVs and 25% of ICE vehicles.[25] This shows that the battery pack cost is the single most expensive component in an EV and drives the cost differential with ICE vehicles. To achieve cost parity, therefore, the cost of battery storage must drop sufficiently to bring the overall cost of the EV powertrain to that of an ICE vehicle.

By assuming a typical EV range in each car segment and dividing that range by vehicle efficiency, one can compute the required battery size and the target battery storage cost. Comparing the ICE vehicle MSRP and powertrain cost by class with the EV motor plus inverter cost allows for calculating the target battery storage cost.[25,26] The calculation in the table below reveals that the cost of battery storage per kWh at the pack level needed to achieve parity with ICE vehicles for compact cars, SUVs, and pickup trucks is $96, $88, and $68, respectively.

Conservative cost projections for battery storage suggest that without incentives, in the U.S., cost parity for the three highest sales segments—compact, midsize SUV, and pickup truck— would be achieved in 2025, 2027, and post-2030, respectively.

Table 1: This table calculates the target battery storage cost per kWh required to achieve cost parity with ICE vehicles. It underscores the impact of government incentives on cost targets.

	Compact Car	Midsize SUV	Pickup Truck
ICE Vehicle MSRP	$25,000	$40,000	$50,000
ICE Powertrain Cost (25%)	$6,250	$10,000	$12,500
EV Range in mi	200	300	350
Efficiency in mi/kWh	4.5	3.5	2.5
Battery Size in kWh (Range/Efficiency)	44	86	140
EV Motor plus Inverter Cost	$2,000	$2,500	$3,000
Target Battery Storage Cost	$4,250	$7,500	$9,500
Battery Pack Cost per kWh for Parity (No Incentive)	$96	$88	$68
Battery Pack Cost per kWh for Parity ($7500 Tax Credit)	$138	$125	$90

Inflation Reduction Act (IRA) incentives will accelerate the adoption timeline:

With the generous incentives offered under the Inflation Reduction Act (IRA), including point of sale incentives ($7,500 off the transaction price on qualifying models and makes) and direct subsidies to car companies for batteries and battery materials produced in the U.S. (subsidy of $35 per kWh at cell level and additional $10 per kWh at pack level), this timeline will be fast-tracked.[27] Consequently, EV models fully compliant with the IRA requirements in all three car segments will become cost-competitive with ICE vehicles as early as 2024. See Figure 7.

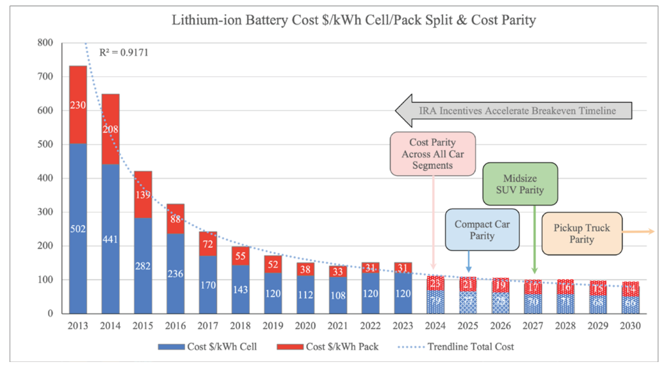

Figure 7: This figure displays historical and projected battery storage cost ($/kWh for cell and pack). It highlights the effect of IRA point-of-sale incentives and direct subsidies on the timeline for achieving cost parity with ICE vehicles. Source: Statista, Bloomberg Finance, E Source

Moreover, some states offer additional incentives to EV buyers, which can be quite generous. For example, New Jersey provides a tax rebate anywhere from $2,000 to $8,000 depending on the make and model, and under their Xcel program, Colorado gives qualifying EV buyers $5,500 upfront towards the purchase of a new EV and $3,000 towards a used one, and Massachusetts offers up to a $3,500 rebate on new EV purchases. Considering these generous rebates and subsidies, it is unsurprising that 2024 and the following years are projected to register the highest growth in EV sales. EV sales in the US are projected to almost double in 2024 and 2025.

Other parts of the developed world are making an even swifter transition. Accounting for half of global EV sales, China has already achieved 30% EV market penetration and exceeded its 2025 goals. In 2022, China was responsible for 60% of global EV sales. European countries, where one in every five cars sold is electric, are also making significant inroads, with Norway leading the pack with EVs accounting for 88% of its vehicle sales in 2022.[11]

Consumers can choose from a growing number of EV models:

The availability of EV models by manufacturer is also an important consideration. As expected, the number of EV models consumers can choose from is rapidly growing both in the U.S. and globally. The number of 2022 model year light-duty, long-range EVs has reached 14, nearly triple that of the 2021 model year.[28] See Figure 8 below. That number is expected to continue to increase for 2023 and subsequent model years. The number of EV models for the 2023 model year in the U.S., including long- and short-range EVs, reached 40.

The number of EV models available globally in 2022 reached 500, double that of only four years earlier. While the number of EV models is still significantly lower than that of ICE vehicles, which some argue is inadequate to fuel mass market adoption, the trend is clear—the number of EV models is growing exponentially. The number of new ICE models has stalled.

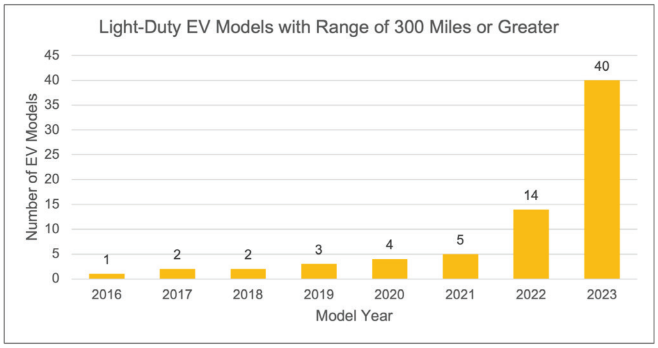

Figure 8: This figure shows the change in the number of light-duty EV models with range of 300 miles or greater in the U.S. market. Source: www.Fueleconomy.gov

The US charging network is rapidly expanding:

Charging is another key concern when buyers consider EVs. The charging network and fact-charging infrastructure in the US, in particular, are lacking. The U.S. Department of Energy's Alternative Fuels Data Center reports around 50,000 public EV charging points. However, only 6,600 are classified as DC Fast Charging, the rest being level 2 chargers incapable of supporting uninterrupted long-distance travel. Experts and consumers alike agree that building a sufficient charging network is essential for supporting the mass adoption of EVs. From an economic standpoint, this relationship creates a two-sided market with network effects. That is to say, a more extensive charging network will stimulate EV sales, and more EVs in the driving fleet will encourage more investments in charging infrastructure.[29]

President Biden's administration, in collaboration with the U.S. Departments of Transportation and Energy, has committed a $5 billion investment over five years to establish a nationwide EV charging network. The National Electric Vehicle Infrastructure (NEVI) Formula Program allocates over $1.5 billion in funding for states to develop their EV charging networks. As of 2023, all 50 states, along with Washington, D.C., and Puerto Rico, have submitted and obtained approval on their electrification plans. The charging network funded through this program is expected to cover approximately 75,000 miles of highways throughout the United States.[30]

Additionally, with over 50,000 superchargers worldwide, Tesla owns and operates the largest charging network in the world, and it keeps growing. As of 2023, Tesla had more than 1,600 charging stations and 17,000 individual Superchargers in the United States. The company has Supercharger stations in all 50 states and Puerto Rico. In a very important move in 2023, the majority of vehicle manufacturers in the US announced a switch from the CCS charging connector to the native NACS connector (aka Tesla connector), along with deals with Tesla to access its Supercharger network in late 2024. Tesla has committed to making at least 7,500 Tesla chargers available to outside manufacturers by the end of 2024. This number includes about 3500 250-kW Superchargers along main highways and 4000 additional Level 2 chargers at public places, such as hotels and restaurants.[31]

While the U.S. lags behind Europe and China in fast-charging infrastructure, there is growing recognition of the need for significant investments in charging stations to support the increasing number of EVs on the roads. Efforts are underway to bridge this gap and enhance the accessibility and efficiency of fast-charging networks nationwide. The combination of cost-competitive, long-range EVs and the ongoing investment in developing a robust DC fast-charging network will go a long way in alleviating the range anxiety of EV skeptics.

EV and clean energy synergies are unlocking mutual benefits:

While renewable energy and electric vehicles emerged as separate markets, they have become closely intertwined. Their interdependence has and will continue to create powerful synergies to boost technological advancements further and speed up adoption. More specifically, the investments in automotive battery technologies have reduced battery costs, which has made storing solar and wind energy more affordable. Further growth in energy storage will, in turn, continue to stimulate investments and foster innovation and cost reductions in both markets. This cycle of growing demand, investment, and innovation will lower costs and enhance quality in both the clean energy and clean transportation sectors, leading to the convergence of batteries for transportation and grid storage.

Moreover, as many critics astutely point out, the EVs are as clean as the electric energy used to manufacture and recharge them. On one hand, EVs are 2-3 times more efficient than ICE vehicles, making them less energy-intensive over the vehicle's lifecycle. On the other hand, the manufacturing process of automotive batteries is more energy-intensive than manufacturing ICE vehicles. To effectively mitigate the GHG emissions of the transportation sector, the electric grid supporting EVs must be powered by renewable sources. Otherwise, the source of pollution will shift from transportation to energy generation with only minimal gains, which is insufficient to achieve the ambitious GHG emission reduction targets established by the Paris Agreement. This underscores the importance of making simultaneous progress with both EV and clean energy adoption and utilizing clean energy throughout the entire lifecycle of EVs.[32]

Many new EV models also support vehicle-to-grid (VTG) and vehicle-to-home (VTH) technology, allowing the EV battery to seamlessly integrate into the electric grid and serve as a backup power supply or additional storage for home solar systems. Electric companies and homeowners can easily tap into the electricity stored in the EV's batteries and use it to balance the electric grid or power homes during power outages. With new smart technologies, EV charging schedules can also be managed to help with grid balancing and lower the charging cost for the vehicle owner. This trend of integrating EVs as energy sources in people's homes will further accelerate the transition from liquid-energy transportation to electric transportation.[33]

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Lastly, EV batteries can power various tools at remote construction sites where grid power isn't readily available. This application showcases the adaptability and utility of EV technology in addressing energy needs beyond transportation. Leveraging EV batteries for powering tools in remote construction sites enhances operational efficiency and underscores the potential for sustainable energy solutions in diverse and off-grid environments.

Conclusion

While the path to a world without ICE vehicles is not without its obstacles—such as establishing a reliable charging network and overcoming consumer skepticism about the new technology—the rapidly declining cost of battery storage, combined with substantial technological improvements, has ignited the electric revolution. With EVs fast becoming both cost-comparable and technologically superior, the US and world markets will likely follow an exponential growth trajectory and transition to a fully electric fleet much quicker than traditional models originally predicted. Fueled by generous government incentives, renewable energy and electric transportation reinforce a virtuous cycle that promises to reduce the world's dependence on fossil fuels drastically. Healthy investments in alternative green solutions will also diversify and further accelerate the transition to sustainable transportation. Benefiting from revolutionary new technologies such as self-driving, smart grid, and vehicle-to-grid systems, the two highest polluting sectors globally are poised to transform their environmental footprint and change the face of humanity's future.

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