ABSTRACT

AGBESI, PHILLIP KODZO. The Development of Sustainable Electric Vehicle Innovation Ecosystems. (Under the direction of Prof. Rico Ruffino, Dr. Marko Hakovirta, Dr. Paul Frederik Laleicke and Dr. Stacy Nelson.)

The electric vehicle is an innovation in transportation that has gone through cycles of popularity and use throughout its history. In its early days, during the latter stages of the 19th century, it was one of the most popular energy methods for automobiles in addition to steam and gas-fueled cars. However, due to the development of the fossil fuel industry, the abundance of petroleum, and its low cost, gasoline took precedence and became the fuel of choice for automobiles. However, in the 1970s, noticeable shifts in global climate began to emerge, with scientists reaching a consensus that these changes were primarily driven by anthropogenic emissions. It became apparent that an alternative to combustion vehicles was due, and electric vehicles came to the forefront once again. Globally, over the last 10-15 years, electric vehicle ownership has risen due to developments in battery technology, design improvements, and recognition of its short-term and long-term benefits during usage. Despite these advantages, electric vehicles still have several disadvantages, both in a practical and a theoretical sense.

As a result, electric vehicles should be introduced in such a way that amplifies their benefits and decreases perceived disadvantages to ensure electric vehicles become a reliable source of transportation. For this to occur, I propose there needs to be a sufficient "innovation ecosystem". Innovation ecosystems center around an idea, concept, or innovation. In this case, the 'innovation' or 'focal point' would be the electric vehicle. In this ecosystem, the focal point is supported by ancillary stakeholders that help to ensure the innovation thrives while maintaining their self-interest. With any ecosystem, there is room for growth, and research literature emphasizes the importance of creating an environment that is suitable for growth. In addition, if we were to split the ecosystem into respective sectors, each one also has its distinctive developments, value chains, and influences.

Nevertheless, there are challenges since companies involved in the oil industry have billions of dollars' worth of investments and understandably, are hesitant to champion a product that is set to reduce their hold on the transportation landscape. At the same time consumers also have concerns that present challenges to EV adoption such as range anxiety and lack of charging

infrastructure. To combat these challenges, this dissertation seeks to propose how to construct an innovation ecosystem, look through influencing factors and find avenues for further development and novelty. In Chapter #2, I address the biggest challenge: What are the key areas for development within the electric vehicle ecosystem? Here I establish what the electric vehicle ecosystem is and briefly highlight the distinction between different ecosystem frameworks. I also provide a brief history and synopsis of EV types and charging technologies. Throughout this chapter, I systematically lay out different components of this proposed ecosystem and elaborate upon advantages, disadvantages, and opportunities for growth and novel concepts. Chapter #3 looks into challenges that stakeholders identify as these are the actors that have vested interest in the ecosystem. Here I analyze expectations through questionnaires and how their views can influence the construction of the ecosystem. Likewise, Chapter #4 takes a similar approach and views how consumers can influence the ecosystem using behavioral theories to examine different attributes that influence EV ownership and outlook. Lastly, in Chapter #5, I address possible solutions to sustainable material implementation. The typical gas station usually relies on charging canopies constructed of metal usually steel. However here I propose the prospect of thermally modified wood into the ecosystem with well-known and established but novel design methods. Concisely, this thesis provides an understanding of the dynamic and innovative elements influencing electric vehicles.

The Development of Sustainable Electric Vehicle Innovation Ecosystems

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BIOGRAPHY

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INTRODUCTION

Ecosystem Definitions

System approaches are a growing concept in academic and business environments. These systems are advantageous as they are used to view and understand concepts holistically to help solve problems by viewing the system as an interconnected entity. Within the academic literature, one of these approaches is coined the business ecosystem, which consists of multiple entities working together to create and share in collective value for a common set of ideas, concepts, or innovations. An ecosystem approach is also appropriate when considering the dynamic shifts that can bring on challenges for organizations, which can include faster innovation cycles, the shift from traditional to digital business models, and increasingly in-depth technical expertise. Nevertheless, these challenges and technologies create new opportunities for organizations to expand and grow.

From an academic viewpoint, the term business ecosystem is often conflated with other ecosystem definitions, although there are certainly similarities across the spectrum. The knowledge of ecosystem dynamics and characteristics is drawn from innovation studies, entrepreneurship research, and strategy studies, which contribute to the conceptual distinction between different ecosystems. Ecosystems can also operate at multiple levels (e.g., city, regional, national) and within multiple sectors (e.g., agriculture, health, education), and it is necessary to make delineations. Companies that utilize digital ecosystems (Amazon, Apple, and Google), and marketplace ecosystems (Etsy and eBay) are robust examples of utilizing collaboration to foster strength and growth. Others include knowledge, platform, and innovation ecosystem.
This expansion of ecosystem research has resulted in a wide range of definitions, which indicates key features, similarities, and differences between various ecosystem types (Voda et al., 2023).

a) The business ecosystem indicates companies' capabilities to co-evolve around innovation, support new product creation, satisfy clients' needs, and embrace the next

round of innovations. The system assumes joint actors' involvement in reaching common goals, with profits and benefits shared among them (Moore, 2006).

b) The innovation ecosystem focal point is the development of innovation attainable through collaboration between entities, which combine their offerings into a coherent, customer-facing solution (Adner, 2012).

c) Digital ecosystem represents a technical infrastructure that finds and connects services and information, enabling network transactions and digital object(s) distribution (Nachira et al., 2007).

d) In comparison with business ecosystems or innovation ecosystems, the concept of a knowledge ecosystem is relatively new (Jucevičius, 2022). The concept gained greater attention, especially in the context of the COVID-19 pandemic when businesses had to adapt to the crises, which determined an enhancement of the importance of knowledge sharing, development, and adaptation (Grumadaitė et al., 2022).

Motivations

The vehicle industry in the US, specifically private passenger vehicles, is a slowly evolving but dynamic environment. Combustion vehicles are currently the most popular energy storage method with a mix of gasoline, diesel, and ethanol. The electric vehicle (EV), while not a new concept, is touted as an alternative to combustion vehicles to reduce tailpipe emissions. EVs have undergone several technological advancements, which have helped decrease charging times, increase driving range and charging availability, which in turn makes them more competitive with combustion vehicles and, therefore, more desirable for consumers. EVs have grown in popularity since 2021, as the percentage of EV sales has gone up since then. Seemingly more than before, no matter the vehicle type, the vehicle industry has become more volatile and is easily influenced by national and global shifts. Changes in the presidential administration, political views, supply chain disruptions, and consumer behavior and preferences all play a part.

In such a changing environment, EVs are not as 'stable' as compared to conventional vehicles that are proven and trusted by consumers nationally, even with all the benefits that EVs possess. Additionally, conventional gas-powered vehicles typically have a different business model that focuses on the acquisition of materials, vehicle production and assembly, shipping to car dealerships, the vehicle aftermarket, and end-of-life cycle as shown in Figure 1.

Figure 1: Conventional vehicle supply chain.

While appropriate for conventional vehicles, EVs differ due to the sheer number of stakeholders and potential stakeholders that are involved in ensuring that EVs are a reliable form of transportation. For this reason, in this dissertation, I propose that EVs require an innovative ecosystem approach that considers these factors and first explores the complementarities, the synergistic nature of the ecosystem, and how different parts of the ecosystem impact one another. I also propose an idea of what this EV innovation ecosystem could look like and who the main actors within the ecosystem are. With this ecosystem framework and the evolving nature of EV, it is more important than ever before for organizations to collaborate to overcome these challenges. The idea of this association is to complement each other's resources and capabilities in very different areas, such as supply chains, digitalization, innovation, entrepreneurship, and services, among others.

Dissertation Logic

Throughout this dissertation we will discuss different subject matter that has linkages. **Chapter 2** serves as the base by tackling the following question: *What are the key areas for development within the electric vehicle ecosystem?* Here I define what the electric vehicle ecosystem is. What's more is finding out what are the main parts of this ecosystem and how can they also be developed and are there any present bottlenecks. Once laid out, there is a holistic view of the current state of affairs in the ecosystem. For example, currently in the US 60% of the electricity produced is powered by fossil fuels. With this fact there is quite a bit of cognitive dissonance, where on one hand advocates for EVs want to reduce carbon emissions but on the other hand the electricity used to charge EVs comes mainly from carbon rich sources. Throughout this chapter I discuss possible alternatives. In the next **Chapter [3]** transitions the focus toward the stakeholder perspectives. In this paper I look at what stakeholders consider to be important to the ecosystem and future expectations. Stakeholders such as manufacturers, policymakers, and utility providers are integral to shaping the trajectory of EV development.

Using structured questionnaires, I assess what can accelerate or hinder ecosystem construction. **Chapter 4** extends the analysis to the consumer level, utilizing behavioral theory to explore how individual attitudes, preferences, and decision-making patterns influence the growth of the EV ecosystem. These behavioral theories help us to understand how and why people take certain actions. This chapter helps to complement the stakeholder analysis. Although stakeholders are responsible for pushing a product or idea forward ultimately it is the consumer that influence the success of that product or idea. In **Chapter 5** there is a shift of focus toward the sustainable material design. This transition aims to turn the focus from business practices more to technical side of material implementation. In emphasizing sustainability, this chapter aims to provide a novel approach to preserving and design wood structures that could possibly be used and EV ecosystem design feature.

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The Development of Sustainable Electric Vehicle Business Ecosystems

ABSTRACT

Electrifying passenger transportation has been a topic of interest for several decades as a method of reducing carbon emissions and promoting a more sustainable society. Globally, nations are implementing policies and regulations, promoting and setting goals for carbon neutrality, lowering carbon emissions, and doing away with combustion vehicles. The electric vehicle (EV) industry has seen significant growth over the past few decades due to increased environmental awareness, political influences, and economic benefits. Even so, before they can become a reliable mode of transportation, significant changes need to be implemented to improve the EV ecosystem. Previous literature has explored issues such as lack of charging infrastructure, charging times, and range anxiety that hinder the mass adoption of EVs. However, to our knowledge, there is no literature that discusses the interdependencies of the EV ecosystem holistically and how many of the aforementioned elements interact. Additionally, there is little discussion on sustainable materials which could be instrumental to EV ecosystem development. This paper attempts to discuss many ecosystem components, present trends, difficulties, and possible frameworks for sustainable advancement. Through this research we found that the EV ecosystem development will be a collective effort and will rely on the collaboration of multiple actors.

1. INTRODUCTION

Electric vehicle (EV) usage presents an excellent opportunity to reduce urban air pollution and greenhouse gas emissions (Temporelli et al., 2020). Traditional internal combustion engine vehicles (ICEV) rely on fossil fuels which emit gases such as carbon oxides, hydrocarbons, and nitrogen oxides that pollute the atmosphere and are harmful to the environment (Z. Li et al.,

2019). In the past few decades, there has been a steady transition from fossil-based fuels to electric-based transportation, and this shift is expected to advance rapidly. The rapid development of the EV industry has taken place globally and is being promoted by national policies. Countries like Norway, Finland, Germany, and France have committed to banning the sale of combustion vehicles in the next 10-25 years. China has similar goals within that time span and plans to cease the use of combustion vehicles entirely by 2050 (R. Hou et al., 2022). The United States has also committed itself to electrification by investing $7.5 billion to build a national network of EV chargers throughout the United States as part of the Bipartisan Infrastructure Law (whitehouse.gov, 2021a). EV sales have also continued to rise over the past decade. In 2021, more than 6 million EVs were sold globally, accounting for nearly 9% of the global automotive market (Paoli & Gül, 2022). This growth can be attributed to increased environmental awareness, political incentives, and falling prices of vehicle production (Nykvist & Nilsson, 2015). Most recent developments include the price hike of petroleum products and the new oil supply threat due to the ongoing crises in Ukraine. Although such events have temporarily impacted the EV supply chains, interest in EVs have surged, and issues such as energy security, energy independence, sustainability and renewables have become even more prominent. These global developments could further accelerate EV sales across the US and EU (Electrive.com, 2022; Europe Commission, 2022; Ewing & Gandel, 2022; Jin, 2022). While EVs are recognized as the most feasible technological option to decarbonize transportation, many barriers hinder the mass deployment and adoption of EVs despite the regulatory and financial support from the government. These barriers include but are not limited to lack of knowledge, doubt and uncertainty of potential consumers, lack of EV infrastructure and technology, relatively low range, cold climate performance, and long recharging times. For EVs to successfully penetrate society, optimal business models and ecosystems should be centered around developing charging networks, infrastructure, battery, and vehicle development. The past linear business and supply chain models used for combustion engine vehicles are unsuitable for EVs. To take full advantage of EV potential, appropriate business models and EV ecosystems need to be constructed, as the EV ecosystem will require the integration of diverse independent actors (*Business Model Innovation in the EV Ecosystem*, 2021). These actors must also make an effort to introduce new technologies and transition to electrification sustainably. In doing so, it ensures that the EV ecosystem can be sustained and that the advantages of EV penetration are

realized and greater than those of combustion vehicles. Over the years, the meaning of sustainability has broadened and expanded outside of environmental factors and considers the economic and social aspects (Cricelli & Strazzullo, 2021). As for the EV ecosystem, it is critical for there to be continuous progress in air quality, human health, job opportunities, energy independence, energy, and cost savings. The topic of sustainable development has grown significantly over the last several years, as noted by (Centobelli et al., 2021). In Reinhardt et al.'s (2019) work, the authors concluded that business models with multiple stakeholders in mind have an awakened view of sustainability compared to traditionally firm-centric models. Additionally, providing a framework of the complexities of the ecosystem can benefit academics and practitioners, as sustainable business models provide examples that present the diffusion of new and clean technologies, social innovations, and organizational solutions (Reinhardt et al., 2020).

Business ecosystems are defined as closed systems that involve the collaboration of members of the system to ensure its stability and overall benefit (Sarafin, 2021). Business ecosystems are full of interdependencies; one component's growth and success often depend on the others' success, growth, and development. Adner (2017) makes a distinction, as the term "ecosystem" can have different meanings. The one most applicable to the EV ecosystem is the "ecosystem-as-affiliation," which views ecosystems as communities of associated actors defined by their networks and platform affiliations. Jacobides et al. (2018) further state that ecosystems are distinct forms of organizing economic activities linked by specific types of complementarities. To continue, the authors identify three distinct ecosystem streams and define them as the following. A "business ecosystem" stream centers on a firm and its environment; an "innovation ecosystem" stream focuses on a particular innovation or new value proposition and the constellation of actors that support it; and a "platform ecosystem" stream considers how actors organize around a platform (Jacobides et al., 2018). Of the three, the innovation ecosystem stream seems to be the most appropriate description of how the proposed EV ecosystem operates. However, throughout the paper, we still refer to the ecosystem as the EV business ecosystem. Note that the 'business ecosystem' stream definition provided by Jacobides et al. (2018) should not be confused with the definition used by Sarafin (2021). Throughout the

remainder of the text, any reference to the "business ecosystem" includes the "innovation" scheme, as one does not rule out the other.

The ecosystem approach for matters pertaining to EVs is important and is not a new concept. Existing literature often discusses and analyzes individual components of the EV industry and its ecosystem, whether related to commercial charging infrastructure (Davies et al., 2022), home charging infrastructure (Ma et al., 2021), or smart grids (Chan & Zhou, 2014). Other relevant literature about innovation and business ecosystem development discusses the proposed models for EV ecosystems (Giesecke, 2014); comparisons of different innovation ecosystems (Valta et al., 2018); and the exploration of international business ecosystems (C. Lu et al., 2014a; Shang & Shi, 2012). However, to our knowledge, current research does not discuss innovation for the EV ecosystem holistically and presents a literature gap. To illustrate the interdependencies of the EV ecosystem, we provide an example of the challenges in the supply chain and other issues based on a framework similar to the one used in Adner & Kapoor's (2010) work. In the EV ecosystem, auto manufacturing brands like Tesla, BMW, and GM serve as the focal firm. As auto manufacturing brands continue to expand in the EV market, there are challenges in constructing batteries and car bodies for EVs. Beyond the challenges of constructing the vehicles are the suppliers that attain the raw materials and must look to fulfill the needs of the original equipment manufacturers (OEM). Other suppliers must also deal with materials and parts shortages (including semiconductors), labor shortages, wars, and sanctions that put a halt to the supply chain. Afterward, the OEM faces the difficulty of integrating the different components into the vehicle. Once constructed, EVs will rely on a charging network, both commercial and residential levels, that can charge EVs quickly, reliably, and safely. Power and utility companies must adapt and invest in the power grid to ensure that electricity production can keep up with the increasing demand for EVs and societal needs. Additionally, those entities must face the challenge of upgrading to a smart grid that integrates renewable energy sources to phase out fossil fuels and reduce carbon emissions. Communication and data management will be increasingly important as 5G, and the Internet of Things (IoT) become more embedded in the EV ecosystem. Constant communication between vehicles, charging stations, smart meters, smart grids, and homes will increase user reliability and optimize the ecosystem. However, such connectivity leaves the ecosystem susceptible to cybersecurity issues, which must also be assessed. The inclusion of

EVs creates an opportunity for adopters of green technology to take advantage of off-grid renewable energy like solar roofs that can supplement power to homes. Vehicle to Grid (V2G) becomes an effective tool for those with home charging systems and solar roofs as a means for energy storage in emergency situations. As illustrated, the EV ecosystem is complex, and it is necessary to explore the complexity. In addition, there are literature gaps in the development of the EV ecosystem. To explore the gaps and complexities, we use the following research questions:

RQ1: What are the key areas of development for the EV ecosystem in the U.S.?
RQ2: What are the current and future trends of the EV ecosystem in the U.S.?

By answering these questions, we can determine what is necessary to make EVs a reliable form of transportation and help sustainably accelerate electrification. To answer these questions, we propose an ecosystem model that highlights eight distinct areas of development. The EV business ecosystem is a complex network that is influenced by several components necessary for EVs to be a reliable method of transportation. Business ecosystems differ from and expand upon traditional value and supply chains. The EV ecosystem is influenced by the automotive industry, battery manufacturers, charging infrastructure companies, local and federal governments, academic and private researchers, and businesses such as restaurants, hotels, and rental car companies. As EVs continue to penetrate society, not only will the landscape of the automotive industry change but there will be an impact further beyond. In the supply chain, companies that produce specialized batteries essential for EV operation, electric vehicle charging stations (EVCS), and those in the semiconductor sector are in great positions for growth (Putnam Investments, 2021). The low maintenance requirements for EVs will change how vehicles are serviced and financed as auto dealers, mechanics, and the automotive aftersales market find alternative ways to bring in revenue. As EVs continuously evolve, novel technologies and ideas like automation and artificial intelligence will require high-tech suppliers, IT and data management solutions. Electrification of the private passenger fleet will also catalyze the development of greener options for other transportation vehicles like public buses, school buses, and light and heavy-duty vehicles. To emphasize sustainability, the extraction, reuse, and

repurposing of car materials will also need to be rethought and considered to address current supply chain issues in the lithium and metals market. Additionally, the use of wood-derived and other bio-based sustainable materials to construct elements of vehicles and other applicable components should be considered and could be a significant pathway in the ecosystem. Such a great electricity demand will require sufficient power grid capabilities, adequate charging stations, and renewable energy sources. In addition, the skills and knowledge required to repair and maintain ICEVs will slowly become obsolete, and EVs will require new skills and knowledge to maintain, repair, and manage at its end-of-life stage. This paper will outline several components of the EV ecosystem, including current business models, international EV markets, the specific types of EVs and the automotive industry, charging technology and stations, the relation and impacts of EVs to the power grid, the implementation of renewable energy sources, sustainable materials, and the social impacts. From this article, readers should gain insight into the complexity of EVs and their associated components and the environmental and social benefits of EVs.

2. EV market review

The history of electric cars dates back to the early to mid-19th century, but it was not until the late 19th century that the first electric cars were produced and sold in the US. Prior to this, motorized carriages carrying batteries could not be recharged. Entering the 20th century electric cars were popular among car owners and represented 38% of the car market (Guarnieri, 2012). It is important to note that the electric cars of this time did not have the capabilities of current EVs. At the time, EVs held distinct advantages over steam and gas vehicles in terms of reliability, being odorless, and being easier to start (Guarnieri, 2012). However, the electric cars of the time suffered from severely limited range and a lack of charging infrastructure. Fast forward a decade later, gas-powered vehicles started to become more advantageous Starting in 1908, gasoline vehicles, namely the Ford Model T, started to be mass-produced, significantly lowering the price of said vehicles. Charles Kettering invented the electric starter in 1912, which removed the need for a hand crank to start gasoline-powered vehicles (Yong et al., 2015). Adding to this, the availability of cheap petrol made gasoline-powered vehicles cheaper to operate than EVs, and gas could be carried around in a container that extended the vehicle's mobility (Situ, 2009; Yong et al., 2015). It would not be until the 1970s that emission and energy independence issues

sparked an interest in EVs again. Governments began to implement regulations to reduce air emissions and promote electric and hybrid vehicle development (Yong et al., 2015). In the 1990s, several well-known auto manufacturers like Chrysler, Ford, and General Motors began developing EVs. The EVs of this time primarily relied on lead-acid batteries, and most had a range from 70 - 95 miles. However, as EV development continued, lighter weight and higher energy battery chemistries were introduced into the marketplace in large numbers (Idaho National Laboratory, n.d.). Current EVs primarily run-on lithium-ion batteries and, on average, have a range of 150 – 300 miles.

2.1 EV Types

The Alternative Fuel Data Center (AFDC) categorizes EVs into three categories (Alternative Fuels Data Center, 2022b). There are three main types of EVs: hybrid electric vehicles (HEV) rely on an electric motor that uses stored battery energy and gasoline to operate internal combustion engines. The battery is charged though regenerative braking. When power demand for the HEV is low, energy from the battery is used, which reduces fuel consumption. Plug-in hybrid electric vehicles (PHEV) share similarities to HEVs in that they also rely on an engine and electric motor. The difference is that the PHEV can operate in an all-electric mode and can be recharged with charging equipment. Before operating on gasoline PHEVs typically can travel between 20 to 40 miles on electricity. All-electric vehicles, also referred to as pure electric vehicles (PEV) or battery electric vehicles (BEV) have a battery that is charged by plugging the vehicle into charging equipment and typically have driving ranges from 150 to 300 miles (Alternative Fuels Data Center, 2022b). These vehicle ranges are also dependent on road conditions, climate, battery type, and age (Un-Noor et al., 2017a). Some of the bestselling BEV models are the Tesla Model 3 and the Mustang Mach-E by Ford (White, 2022). Close to 1.8 million EVs were registered in the U.S. as of 2020 (IEA, 2021a). Globally, in spite of the COVID-19 pandemic, EV car sales rose while overall car sales declined. The global electric car stock surpassed more than 10 million at the end of 2020, up over 40% from 2019. By 2030 that number could jump up to almost 145 million (IEA, 2021a). Europe saw the largest number of registrations with 1.4 million and was the world's leading electric car market, followed by China with 1.2 million registrations and the United States with 295,000 (IEA, 2021a; Molliere, 2022). Seeing such growth indicates that people view EVs as better technology and look to benefit from

them. As of 2021, more than 40 EV car manufacturers exist in the US, and several internationally based car manufacturers have a substantial market in the U.S. (B2BEV, 2022). EV sales and adoption momentum saw tremendous growth in 2021. Nearing the end of that year, Tesla, Rivian, and Lucid were the three most valued pure EV manufacturers. They had a combined market capitalization of $1.3 trillion, even surpassing the combined market capitalization of traditional car manufacturers like Toyota, Volkswagen, and Nissan, while having significantly fewer vehicle deliveries (Richter, 2021b). Millions of dollars are being invested into EV companies as businesses look for durable vehicle alternatives to reduce their carbon footprint. Amazon for example has invested at least $1.3 billion in Rivian and in 2030, plans to have at least 100,000 electric delivery vans on the road (Stinson, 2019).

2.2 EV Charging & Energy Storage Methods

The most popular energy storage method used in EVs today by far are lithium-ion batteries which rely on vehicle chargers to recharge when depleted (Zablocki, 2019). An EV charger is a device or equipment that supplies electrical power for charging plug-in electric vehicles, and EVCS is a key infrastructure for expanding EV adoption (Pardo-Bosch et al., 2021). Range anxiety, a fear of the vehicle battery having insufficient energy storage, is a key concern within the present EV ecosystem. Having optimally and enough placed charging stations is essential to eliminate these concerns. Plug-in charging is currently the most popular method of supplying energy to EVs, but other energy restoration methods like battery swapping and wireless charging exist. In the U.S. there are over 45,000 public plug-in charging stations (Alternative Fuels Data Center, 2022b). EVCS stations can be categorized differently, but in general, there are three main level stations: residential (Level 1), public (Level 2), and DC Fast or ultra-fast charging stations (Level 3) (Alternative Fuels Data Center, 2021a). The default connector (also called plug) for level 1 and 2 charging in North America is the J1772 connector, except for Tesla, which has a unique connector. Non-Tesla charging equipment can be used on Tesla vehicles with a J1772 adapter (Alternative Fuels Data Center, 2021a). Nearly 100 EV charging companies exist in North America (B2BEV, 2022). Investments in the charging industry have also helped fuel its growth, and governments and utility service are encouraged by the current market potential of EVs and the potential to reduce greenhouse gas (GHG) emissions (Levinson & West, 2018). The U.S. Department of Energy constructed over 17,000 charging stations throughout various regions

of the U.S. between January 1, 2011, and December 31, 2013 (Levinson & West, 2018; Smart & Salisbury, 2015). Even with the current expansion, it is essential to increase fast-charging infrastructure to match the convenience of traditional fueling stations, especially considering the current cost of EV charging equipment and installation. As of 2015, according to a report funded by the Department of Energy, the cost of a single port EV charging unit can range from $300-$1,500 for Level 1, $400-$6,500 for Level 2, and $10,000-$40,000 for DC fast charging. Installation costs vary with a range of $0-$3,000 for Level 1, $600- $12,700 for Level 2, and $4,000-$51,000 for DC fast charging (Smith & Castellano, 2015).

Various energy storage systems exist and are used in EVs to store electrical energy, but batteries are the most widespread energy storage device. Of the different battery types that exist and are suitable for road transportation, lithium-ion batteries (LIB) are the most promising and most popular. This is because of their advantages, such as high energy density, light weight, no memory effect, and no in-use environmental concerns (Z. Li et al., 2019). These qualities make lithium highly desirable for not only electric vehicles but consumer products such as laptops and smartphones. The largest lithium producers in the world are Australia, Chile, and China who accounted for 86% of worldwide lithium production in 2020 (Visual Capitalist, 2022). In the same year, the lithium battery market globally was valued at $53.6 billion and is expected to grow by 19% from 2020 to 2028 (Grand View Research, 2021). This growth can be mainly attributed to the growing demand for EVs powered by lithium and battery makers are looking to meet the projected demand. In fact, during 2020, six of the top ten EV battery manufacturers supplied 89 percent of the batteries for EVs (Ulrich, 2021). While LIB batteries can help to achieve a cleaner and more sustainable solution for transportation, there are downsides to this technology. The extraction of the raw materials needed for the batteries, mainly lithium and cobalt, requires large quantities of energy and water (Nature, 2021). There are also several social issues associated with mining lithium and other metals, including violation of human rights, discrimination, and restriction of access to communal land and water (Agusdinata et al., 2018). Additionally, the high demand for lithium in EVs, laptops, digital cameras, and mobile phones make it a limited resource. The future of lithium use depends on the discovery of new lithium sources, lithium recycling, and cost of the material. Due to limited supply, economic and social issues, research on sodium-ion batteries (SIB) as potential replacements for LIBs is underway.

Major EV manufacturers like Tesla and Volkswagen are set to experiment with SIBs in upcoming vehicle models. Sodium shares similar chemical characteristics to lithium and its abundance make this material much lower in cost than lithium (S.-W. Kim et al., 2012). While not as energy dense as LIBs, SIBs offer better performance and can operate at a wider temperature range, working more functionally and efficiently in cold environments compared to LIBs. The cost difference is remarkable as it costs about $150 per ton to extract and purify compared to lithium's $15,000 per ton (Holzman, 2020). When compared to LIBs, the production cost of SIBs is also significantly lower since cells can be manufactured with inexpensive metals such as iron and manganese. LIBs on the other hand, require cobalt which is a highly expensive mineral to obtain and is the most expensive component of current EV batteries. Tesla has voiced concerns about lithium pricing in the past due to the slow extraction and refinement process, which hinders the growth of EV production.

2.3 EV Car Classifications

The popularity and demand of vehicle models vary from country to country. In addition, it should be noted that the vehicle classification schemes vary depending on the country. From this point, the U.S. EPA Classification scheme, as seen in Table 1, will be used to refer to any vehicle type. The data used to create the classification scheme seen in Table 1 is compiled from (EPA, 2022; Ou et al., 2019). The most popular EV worldwide in 2021 was the mid-size Tesla Model 3, with 501,000-unit sales. Followed by that were the Wuling HongGuang Mini EV, Tesla Model Y, Volkswagen ID.4, and the BYD Qin Plus PHEV(Statista, 2022). Two of the vehicle models are Chinese brands, the Wuling HongGuang Mini EV and BYD Qin plus PHEV, and due to the population of China, such vehicles will experience a high sales volume. Specific to China, mini-compact cars are quite popular, and in general small cars (mini-compact, subcompact, and compact cars) dominate the EV market totaling between 60 – 80%. In contrast, in the U.S., midsize and large sedans account for more than 60% of EV models (Ou et al., 2019). Across Europe, the top five bestselling combustion vehicles are compact and subcompact cars. However, in the EV sector, it seems that consumers are purchasing bigger vehicles with more compact and SUV models. This trend is likely occurring since bigger vehicles typically have longer ranges due to bigger batteries. The bestselling EVs in Europe were the Tesla Model 3, Renault Zoe, Volkswagen ID 3, Hyundai Kona, and the Volkswagen eGolf (Best-Selling-

Cars.com, 2022). Differences in vehicle class popularity are likely due to driving patterns, income, and charging infrastructure (Ou et al., 2019). Cultural and social differences also dictate the popularity of vehicle types. The U.S. is quite a vast country, where people are accustomed to personal space, and things in general (e.g., houses, supermarkets, and even the width of the roads) are larger in the U.S., so it makes sense that people tend to gravitate towards larger vehicles. This is opposed to smaller and densely populated countries in Europe and large metropolitan cities in China, where there are regions where space is limited, or in some cases, the current road infrastructure is not suitable for large vehicles.

Table 1: Car classification scheme.

CATARC Classification		Euro Car Segment	U.S. EPA Classification	Combustion Vehicle Example	Electric Vehicle Example	*EV Cost (Base Price)
Sedan/Car	A00	A-segment mini cars	Mini-compact	Fiat 500	BMW i3	$44,450
	A0	B-segment small cars	Subcompact	Ford Fiesta	Honda e	$37,088
	A	C-segment medium cars	Compact	Toyota Corolla	Nissan Leaf	$27,000
	B	D-segment large cars	Mid-Size	Audi A4	Tesla Model 3	$49,990
	C	E-segment executive cars	Large Size-Car	Chevrolet Impala	Mercedes EQS	$102,310
SUV		J-segment sport utility cars	Standard SUV	Hyundai Santa Fe	Tesla Model Y	$53,990

The following classification scheme was compiled from tables used in (EPA, 2022; Ou et al., 2019). *Price data acquired from (Mark, 2021).

2.4 Lightweighting Market

Current EVs are quite heavy when compared to ICEVs. The primary reason for this is the battery, which is the heaviest component of an EV. The weight of a battery for a PEV can vary depending on the battery capacity and the energy density, but typically the battery pack can weigh anywhere from 100 kg to 544 kg. The battery is essential for the function of the vehicle, and it is difficult to reduce the weight of the battery pack without sacrificing the range and storage capacity of the vehicle. Considering that the heavier a vehicle is, the more energy it takes to move it, EV manufacturers look to lighten the weight of EV components outside of the battery

to improve vehicle efficiency and increase range. Aside from the battery, vehicle weight has also increased from improvements in vehicle safety, emissions control, and comfort features. Government regulations on fuel economy and emission controls, high vehicle production, overall availability and increased use of lightweight materials are some of the factors that have the biggest influence on the global automotive lightweight materials market (Faruk et al., 2017). According to the Market Research Future, the lightweight materials market size will reach USD 276.50 billion by 2027 (Market Research Future, 2021). Many lightweight materials are now in production, such as high-strength steels, aluminum alloys, plastics, and composites (Office of Energy Efficiency and Renewable Energy, n.d.).

2.5 Electricity Demand

As more EVs enter the global market, the global demand for electricity and power consumption will increase. Electricity demand is also dictated by population growth, urbanization, and increasing everyday demand for heating, cooling, lighting, refrigeration, and operating appliances and machinery. Such demand will require sufficient energy sources and rely on electricity utility providers to produce the electricity from reliable sources. Globally, electricity consumption had grown steadily each year since 2010 except in 2020, when there was a slight reduction due to the COVID-19 pandemic. However, as conditions improve, the growth trend will resume. Interestingly despite the pandemic, renewables were the only energy source to increase in demand (IEA, 2021b). This trend can be seen in Figure 2 and is measured by terawatt. In addition, the renewables in the global power mix are expanding as there was a 28.7% increase in the share of renewables for G20 nations (Enerdata, 2021). In particular, wind and solar power generation have grown substantially, especially across the US, China, and the EU. In the US, approximately 3,300 electricity utility providers are responsible for the distribution and generation of electricity. Most of them rely on some combination of fossil fuels and renewable energy sources like solar, wind, geothermal, and hydroelectric power to produce electricity delivered to their customers. Now more than ever, utility companies such as Duke Energy, NextEra Energy, and Dominion Energy are committed to investing in new infrastructure for a sustainable future. As seen, there will be challenges ahead for the future power grid. In addition to new infrastructure and renewables, grid modernization is required for sufficient storage, management, and efficient electricity production. Governments worldwide are focusing on

implementing smart grids that can help manage energy consumption. The smart grid allows the communication of data from the utility to its customers. It is a developing network of tools, computers, and automation that work together to make the grid more reliable, secure, and greener (SmartGrid.gov, 2019). One of the many benefits of the smart grid to the EV ecosystem is smart charging capabilities that help minimize charging costs and increase the efficiency of the electricity supply. Estimates indicate that the global smart grid market is expected to grow from an estimated $43.1 billion in 2021 to $103.4 billion by 2026 (Markets and Markets, 2021). Over the course of the next 20 years, trillions of dollars will be used to update the electric grid in preparation for increased vehicle electrification and renewables (Levering et al., 2021).

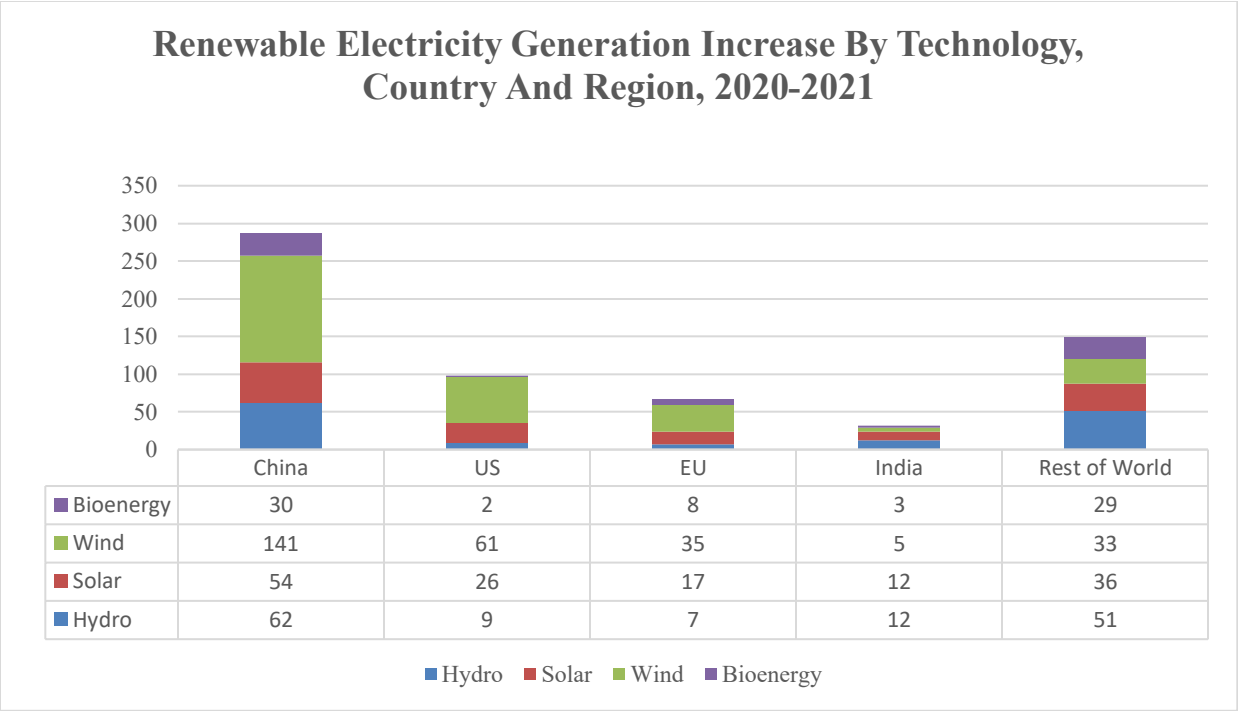

Figure 2: Renewable Electricity Generation Increase by Terawatt hour. (TWh). Source: Based on IEA data from the IEA (2021) Renewables, https://www.iea.org/reports/global-energy-review-2021/renewables. All rights reserved. (IEA, 2022b)

2.6 EV Software

The importance of software in the overall EV systems cannot be undermined. Installed software enables many of the capabilities within EVs to operate. For example, current software monitors the battery's health and offers connectivity, navigation, and maintenance (Britton, 2021). ICEVs

typically rely on updates to be made in a workshop but with EVs over the air (wireless), updates can be made. These updates help to enhance the functionality, safety, and security of the vehicle. In addition, frequent automatic software installation ensures that EVs can maintain optimal performance (Britton, 2021). The automotive software market and electrical and electronic components are expected to thrive in the next decade. Autonomous driving is one of the leading developments in this sector and as a whole the automotive sector is expected to grow from $238 billion to $469 billion between 2020 and 2030 (Burkacky et al., 2019). The embedded software systems in EVs are essential for proper function and several of the capabilities such as self-parking and advanced-voice control. As of now, EVs have plenty of software embedded in parts of the vehicle, and this trend will be greater in future EVs. For example, EV manufacturers are incorporating high-resolution displays, touchscreens, automatic wipers, and lights which requires more software and connectivity.

3. Global EV Business Ecosystems

3.1 Asia

3.1.1 Japan

Several international markets have succeeded in constructing a well-built EV ecosystem. This can be attributed to a combination of incentive measures, policies from the government, and an overall desire for energy security and a low carbon society. However, there are also underlying motivating factors that differ from country to country. The early success in the EV industry is related to the business model creation and associated ecosystem built to facilitate sustained growth in the future. The EV market in Japan is one of the most prominent markets globally in terms of sales. A combination of innovative OEMs (Nissan, Mitsubishi, Toyota) and leading battery and energy companies headquartered in Japan led to the development of a competitive EV market and created the second-highest levels of EV sales globally from 2005 to 2013 (Weiller & Neely, 2015). Japanese EV ecosystem development has been quite forward-looking. Weiller & Neely (2015) explored some of the reasons behind Japan's EV industry success. TEPCO (Tokyo Electric Power Company) is the largest public electric utility in Japan, and in the mid-2000s, it started to promote EV charging development. TEPCO recognized the value of fast charging availability and how it can help reduce consumer range anxiety and support EV adoption through its research (PBS News Hour, 2011; Weiller & Neely, 2015). The team developed a fast charger called CHAdeMO, which allowed a 100-mile EV to fully recharge in 30

minutes. Since 2011 the CHAdeMO charger has been in use in over 1800 stations in Japan and more than 3000 worldwide, and there are more than 57,000 CHAdeMO compatible EVs on the road as of October 2013. The Japanese government also played an essential role in developing the EV charging infrastructure network (Åhman, 2006). Here the government's goal was not to prioritize companies over others but to provide support through research and development in the automotive, energy sector, and smart city projects. In addition, the Japanese government provided 1-billion-yen ($10 M) funding for slow and fast-chargers. The government's assistance helped create a competitive landscape with four major industrial consortia, each having different services, membership offerings, and a network of chargers. The diversity of entrants and pricing models in EV charging helped stimulate growth in the market and ultimately increase consumer welfare (Weiller & Neely, 2015). To add, the government of Japan set a target for the year 2035, where all new cars sold will either be BEVs, PHEVs, or fuel cell electric vehicles (FCEVs). The government will also offer a subsidy on qualifying vehicles to help with the purchase price (International Trade Administration, 2021a). Japan has experienced progressive expansion and growth in the EV industry. However, while Japan has set target years, offered subsidies, and seemed to have a distinct advantage or head start in the EV space, Toyota has lagged behind current competition in the EV industry. In late 2021 Toyota announced that 30 all-electric vehicles would be coming to the brand by 2030 (Lambert, 2021). Still, the company looks to redo its EV strategy to compete with other EV auto manufacturers and has halted some work on existing EV projects (Shirouzu, 2022). All the reasons to why the reboot is occurring are unclear, but Toyota representatives do reiterate that there is still a commitment to carbon neutrality. Representatives also express that buyers that may not be ready to shift to fully electric vehicles can use hybrid vehicles and may be a better short term solution (Eckert, 2022). Honda another prominent Japanese auto manufacturer shares the same uncertainty (Automotive News, 2022).

3.1.2 China

China has also made improvements to its EV market and looks to increase EV uptake. China is the world's largest energy consumer, and energy consumption in the transport sector has mainly consisted of petroleum-based fuels (L. Zhang & Qin, 2018). In addition, China is the leading emitter of GHGs annually in the world (Center for Climate and Energy Solutions, 2021; Friedrich et al., 2020; Shan et al., 2020). Such high energy consumption in China led to rapid

socioeconomic development but has produced a large amount of emissions, and has resulted in environmental pollution in China that has become increasingly serious (M. Song et al., 2018). Pollution issues, namely urban air pollution issues, are also increasing in severity throughout China, and research results show that tailpipe emissions are the primary source of urban air pollution, especially PM2.5 (Q. Wang et al., 2021). Motivated by this, China's new energy vehicle (NEV) program, which has existed since the 1980s, became official policy in 2009. Since 2010, many policies have been designed to support the development of NEVs, and the focus of the program is to make China a leader in EV technology. Battery electric vehicles, plug-in hybrid electric vehicles, and hybrid electric vehicles can be classified as NEVs. These policies included regulation, financial incentives, and improving charging infrastructure. These policies helped to rapidly increase the production and sales of NEVs as they stood at 1.366 million and 1.367 million in 2020 (X. Wang et al., 2021). The EV industry's rapid development has helped to foster and propel many EV companies in China. Top-selling Chinese companies include SAIC, BYD, Chery, and Changan. In addition, new Chinese EV start-ups like Nio, Xpeng, and Li are becoming increasingly popular as they release new models and make more vehicle deliveries. Targets for Chinese EV companies can be seen in Table 2.

Table 2: Chinese automobile manufacturers' EV sales target.

Chinese Electric Vehicles Auto Manufacturers' Sales Targets		
Company	**Sales Target**	**Target Year**
SAIC Motor	1 million NEV sales	2023
BYD Auto	1.2 million NEVs	2022
Changan	3 million vehicles	2025
	4.5 million vehicles	2030
All EV	**Delivery Target**	**Target Year**
Nio	153,000	2022
	239,000	2023

The sales target for Chinese-based traditional car and EV manufacturers. (Armental, 2022; Chinese Automaker Changan Aims to Sell 3 million Cars Annually in 2025, 2021; Kane, 2022; P. Zhang, 2022)

3.2 Europe

For the first time, in 2020 Europe emerged as the largest car market surpassing China, and this trend has been influenced by new standards set by the EU (IEA, 2021a). This growth in Europe

was primarily influenced by the need to adhere to stricter EU CO_2 standards for new passenger cars and vans (Paltsev et al., 2018). The EU is committed to creating a low carbon society, and in 2021 the EU Commission set a target for CO_2 emissions from new cars with a reduction target of 37.5% in 2030 and 100% by 2035, effectively ending the sale of ICEV within the next two decades (Hampel, 2021). Furthermore, the EU plans to be climate neutral and reduce GHG emissions by 80% - 95% (Colmenar-Santos et al., 2019; European Commision, n.d.). National and local actions within Europe vary and impact the EV market regarding adoption rates, types of vehicles, and convenience of owning an EV. When it comes to automotives, Germany, France, the UK, and Italy are the most prominent national markets in Europe; however, Nordic countries are the leaders in Europe when it comes to EV sales (Plötz & Dütschke, 2020).

3.2.1 Norway

Norway, for example, has seen success in the EV market as it is the world's largest market for EVs compared to the total vehicles sold (Saele & Petersen, 2018). The market has steadily grown from 42 percent of new sales in 2019 to 54 percent in 2020. In 2021, according to the Information Council for the Road Traffic in Norway, of the 176,276 first-time registered new passenger cars, 113,715 were electric cars which accounted for 65 percent of the sales for that year (Norwegian Road Federation, 2022). High sales can be attributed to incentive measures that are put in place by the government and include access to free parking and public bus lanes, road toll waivers, free EV charging, and tax benefits (Mersky et al., 2016). The success of the EV market is no accident, as its success can also be attributed to the development phases used in Norway to push towards electromobility. The idea of introducing EVs into Norway started in the 1970s with the development of EV prototypes. The 1990s went through test phases and continued into the early market phases from 1999 to 2009. During this time frame, the most important incentives introduced were the VAT exemption and access to bus lanes. Such attractive measures caused some buyers to purchase EVs, trading aspects of comfort for access to the bus lanes, free parking and no road tolls (Figenbaum & Kolbenstvedt, 2013).

3.2.2 Germany

Germany, a country known for its success in the car industry, is Europe's largest vehicle market (Hall, 2020). Renowned German companies like Audi, BMW, Mercedes, Porsche, and Volkswagen have been successful and have a large international presence. In fact, three-quarters

of German-produced cars are exported, with the US, United Kingdom, and China as key importers. However, up until 2018, when compared to other major car markets like the U.S. and China, the sales share of EVs in Germany was lackluster. The EV market sales share up until 2014 was less than 0.5% and has since surpassed 2% after financial subsidies from the German government became available and more EV models were introduced (Plötz & Dütschke, 2020). Germany's focus now is to become a world leader in electric mobility and has a goal of having 7-10 million registered electric vehicles on German roads by 2030 (Automotive News Europe, 2021). In 2020 Germany experienced record EV sales growth selling nearly 400,000 vehicles with a 263% sales increase from 2019 (Richter, 2021a). Its federal government has helped increase adoption through incentive measures that have greatly contributed to its current growth. Energy companies also give incentives for purchasing and installing home chargers or from city and state governments to businesses to install charging stations (Wallbox, 2020). German manufacturers also have goals of switching their fleets to all-electric, and the EV goals as seen in Table 3. Mercedes, for example, is committing $68 billion toward luxury cars and vans from 2022 to 2026, and more than $40 billion is going towards electrification (Wilkes, 2021). Volkswagen is already the most popular EV maker in Europe, and its popularity could soon extend into the American market to overtake Tesla as the leading EV brand (Singh, 2022).

Table 3: German car manufacturers and EV target years.

Car Brand	All Electric Target Year	EV Sales Target
Mercedes Benz	2030	Undisclosed
Volkswagen	50% by 2030 100% by 2040	Undisclosed
BMW	50% by 2025	2 million by 2025
AUDI	1/3% by 2025	800,000 by 2025

German targets for EV sales percentage. (Audi, n.d.; Mercedez-Benz, 2021; Reuters, 2018, 2021; C. Taylor, 2021)

3.2.3 United Kingdom

By sales volume, the United Kingdom (UK) is Europe's third-largest electric vehicle market (Hall, 2020). The UK passenger car market has seen rapid growth in electrification and looks to

accelerate EV adoption throughout the nation even more. UK auto manufacturers Rolls Royce and Aston Martin are internationally well-known luxury car brands and have plans to electrify models in 2023 and 2026, respectively. In 2018, the UK government initially announced a ban on new combustion vehicle sales by 2040 (International Trade Administration, 2021b). In November 2020, this plan was fast-forwarded to 2030 as part of the "10-point plan for a green industrial revolution." Even more so, this plan called for the end of sales of hybrid cars and vans after 2035 (International Trade Administration, 2021b). By 2030, the UK government anticipates there will be up to 10 million battery-electric vehicles on the road. It is also reported that there will be a minimum of 300,000 public charge points throughout the country (United Kingdom DOT, 2022).

3.2.4 Other European Nations

Other European countries like France, Italy, the Netherlands, Portugal, and Spain, are experiencing steady growth in the EV market (Hall, 2020). Expectedly most of the market share for EVs occurs in major cities like Paris, Barcelona, Rome, and Madrid, to name a few. The most popular EV models vary from country to country. A 2020 report from the International Council on Clean Transportation (ICCT) showed several of the most popular EV models in European countries. The Tesla Model 3 is the most popular model in Austria, Belgium, Denmark, and the Netherlands. The Renault Zoe is the most popular model in France and is substantially popular in Italy, Germany, Portugal, and Sweden (Hall, 2020).

3.3 United States

The U.S. is currently the third-largest market behind China and Europe. The U.S. Department of Transportation and Energy announced that nearly $5 billion over a period of 5 years will be used to help states create a network to build out a national electric vehicle charging network in an effort to make EV charging accessible to all Americans (US DOT, 2022). Multiple automakers and subsidiaries in the U.S. (such as Nissan and Volkswagen) also invest in charging infrastructure (Slowik & Lutsey, n.d.). The EV market in the U.S. is projected to grow from $28.24 billion in 2021 to $137.43 billion in 2028 (Fortune Business Insights, 2022a). Innovation for U.S. car companies is at an all-time high. General Motors (GM), the largest auto manufacturer in the country, is introducing the Ultium Platform, a vehicle battery system that is optimized for range, power, and flexibility and fit GM's various vehicle types (General Motors,

n.d.). It is an essential element of General Motors' plan to offer 30 new EVs globally by 2025. In addition, the company plans to introduce electrified versions of popular U.S. models like the Chevrolet Silverado, GMC Hummer EV, and the Cadillac LYRIQ. Up and coming luxury car brand, LUCID Motors flaunts the most extended vehicle range, up to 520 miles on a single charge (Lucid Motors, 2021). Rivian, another US-based EV company, primarily focuses on electric sport utility vehicles and pickup trucks and, upon IPO, raised $13.5 billion (Pangarkar, 2021). Individually Tesla, Rivian, and Lucid are the most valued EV companies globally. Even with such a commitment, EV market penetration varies from state to state, and EV adoption has not occurred evenly in all regions.

California, for example, has the largest EV car market representing 42% of the sales in the US. The total amount of registered EVs in California can be seen in Table 4 and this data was retrieved from the AFDC (Alternative Fuels Data Center, 2022c). In 2013, an executive order was issued by Governor Brown to put 1.5 million "Zero Emissions Vehicles" (ZEVs) on California roads by 2025 (and 5 million by 2030) with a goal by 2030 to reduce emissions from transportation by 50% (Alternative Fuels Data Center, 2022d). Twelve other U.S. states—Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont, have adopted California's Zero Emission Vehicle plan (Government of Vermont, n.d.). California has considerable subsidies for purchasing EVs, spending nearly $900 million on the state-wide vehicle subsidies. Subsidies and EV registrations vary in other states, as seen in Table 4. Ownership and registrations seem to be tied to population density and the prevalence of large metropolitan areas. Examples include Los Angeles, Miami, Philadelphia, and Atlanta, where EV registrations are higher than average (Slowik & Lutsey, n.d.). Targets for the phasing out of ICEVs are found in Table 5.

Table 4: USA EV registrations by state.

Electric Vehicle Registrations by State	
State	**Registration Count**
California	425,300
Florida	58,160
Texas	52,190
Washington	50,520
New York	32,590
New Jersey	30,420

The six states with the highest EV registration numbers as of 2021. (Alternative Fuels Data Center, 2022c)

Table 5: Targets for phasing out the sale of ICE vehicles.

Government	Year	Vehicle category	Target vehicle types
Norway	2025	Passenger cars, light commercial vehicles, urban uses	New vehicle sales 100% zero-emission
United Kingdom	2035	Passenger cars, light commercial vehicles	No sales of new gasoline, diesel, or hybrid vehicles
France	2040	Passenger cars, light commercial vehicles	No sales of new fossil fuel vehicles
Germany	2050	Passenger cars	New vehicle sales 100% zero-emission
California (United States)	2035	Passenger vehicles, light-duty trucks	New vehicle sales 100% zero-emission
Connecticut, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont, Washington (United States)	2050	Passenger cars	New vehicle sales 100% zero-emission
Hainan (China)	2020	Government and car-sharing vehicles, light-duty trucks	New vehicle sales 100% electric

Note. Adapted From Growing Momentum: Global Overview Of Government Targets For Phasing Out Sales Of New Internal Combustion Engine Vehicles by Wappelhorst & Cui, 2020 Copyright 2021 by International Council on Clean Transportation.

3.3.1 Testing Future EV Markets in the United States

Based on the previous models discussed, there is a trend that shows that government investments are necessary for a flourishing EV market. Ultimately governments must see the benefit of EVs in society whether it is for sustainability purposes, job creation, or energy independence. The government can help to facilitate EV penetration with expansion projects like the “Ten Cities, Thousand Vehicles” program used in China, with a goal for ten cities to add 1,000 NEVs

annually over three years (X. Zhang et al., 2014). Successful EV markets also have a long history, meaning there was a plan for the electric transition decades before implementation. This gave room for development and research on EVs and prototypes and a knowledge base to build on as the years progressed. Incentives encourage consumers to adopt EVs and are necessary because it takes a while for society to change certain habits, like driving patterns and refueling methods. That said, the most effective incentives will differ from country to country. For example, lane access incentives are provocative but would only be available in certain states and applicable in certain areas. Regarding incentives in the US, it is unclear if the general public outside of EV owners is aware of such benefits or if they make EVs worth switching towards. Interestingly a novel incentive method rewarded users with cryptocurrency to encourage customers to charge vehicles at certain times (T. Zhang et al., 2018). The rising prevalence of NFTs and cryptocurrencies could foster a rapid spike in EV interest and adoption, but such a concept is still in its infancy.

The idea of testing EVs in small cities and municipalities is not a new concept, and these tests have been conducted in places like Durham, NC (*Alternative Fuel Implementation Tool Kit Case Study on Electric Vehicles: City of Durham and Durham County, North Carolina*, 2015) and Vermont (Wagner et al., 2016). Test programs are a great way of identifying what works best in a local EV market. For example, Hawaii is the most petroleum-dependent state in the US, and due to the state's remoteness and distance from oil production regions, high shipping, and labor costs are attached to oil prices (Ku, 2015). In 2018 the average cost for a gallon of gas in Hawaii was between $3.50 - $4.00 compared to the U.S. average, which hovered between $2.50 – $3.00 (EIA, 2022; Wee et al., 2020). While Hawaii does not have an established EV ecosystem, its abundant renewable energy potential has promise to be a viable alternative to fossil fuel dependence. Opportunities exist for Hawaii to serve as a testing site for battery storage and the feasibility of vehicle-to-grid (V2G) technology. Additional opportunities exist to harness geothermal, solar, and wind energy and experiment with laws and policies that increase EV adoption rates. Hawaii and Japan share similarities as both are islands and are high tourist destinations. Using lessons from the 2010 "Eco-Resort Island Okinawa Promotion Project," similar mobility as a service (MaaS) models can be deployed on the Hawaiian Islands. In the Japanese case study, 200 EVs were deployed by car rental companies on Okinawa Island to help

lead the way in the spread of EVs to reduce the effects of tourism on the environment (Nissan, 2011; Weiller & Neely, 2015). Geotab defines MaaS as "a consumer-centric model of people transportation. It is an on-demand, real-time platform that can include any combination of transport methods such as car and bike sharing, taxis, and car rentals/leases and provides everything for the consumer, from travel planning to payments" (Geotab, 2018). Uber is a popular MaaS app, and Uber Green is a ride option that connects users with hybrid and fully electric vehicles (Uber, 2022). Uber could deploy a fleet of EVs and offer incentives for locals in the area to drive these cars and receive higher pay, free parking, and initial sign-up bonuses. Riders in turn, would be incentivized with faster service, lower ride prices, and higher reward points.

4. The Future of the EV Business Ecosystem

The global EV ecosystem is comprised of a different number of components that come together and provide the necessities for EVs to be a reliable method of transportation. In expanding access to EVs and EV chargers, interactions between drivers, vehicles, and charging times need to be considered. Integrating EV infrastructure into communities successfully will consider the following; a knowledge of the types of residencies and businesses in each neighborhood; the existing EV charging network; and the time residents spend at different services are essential (City of Vancouver, 2016). The EV ecosystem can support innovation in the following areas: business models, manufacturing and delivery, charging infrastructure, and sustainability. These areas holistically address how EVs are made, how EV makers make a profit, how customers operate EVs, and how EVs are handled at the end of their life cycle (Venkateswaran et al., 2021). EVs are recognized as the most feasible option to decarbonize passenger transportation but currently have an unfavorable business model compared to combustion vehicles (Y. Huang & Kockelman, 2020). The current EV business ecosystem needs to expand and improve upon multiple facets, from mobility and energy to infrastructure and battery development. An area where the unfavorability lies is within the charging infrastructure, mainly availability and convenience. On average refueling at a gas station typically takes less than three minutes. Compare that to EVs, where the fastest charging times are reported at 30 minutes and can only be achieved at Level 3 (superchargers or DC fast current) charging stations. Even in those cases, batteries are often not charged to full capacity within that period and depending on the duration

and destination of the trip this could prolong travel. Combustion vehicles are also more convenient to own and refuel since traditional refueling stations are abundant. According to the American Petroleum Institute, there are more than 150,000 fueling stations throughout the United States (American Petroleum Institute, 2021). In comparison, there are approximately 47,000 public charging stations located throughout the country. Almost 90% of which are Level 2 charging stations, which can take upwards of 4 hours to deliver a substantial charge to the vehicle (Alternative Fuels Data Center, 2022a). Depending on the region of the country, EVs can be unsuitable for long road trips and require planning and heightened awareness of the battery level (C. Wang et al., 2019).

4.1 Sustainable Energy Storage Improvements

Various energy systems are used to store and generate electrical energy and mechanical energy; however, not all the systems are suitable for PEVs either because of installation requirements or exceedingly high cost (Z. Li et al., 2019). Batteries are the most widespread energy storage system in EVs, particularly lithium-ion batteries (LIB). LIBs are the most promising and popular due to their high energy density, light weight, and no environmental problems. The lifetime of the li-ion battery storage system is a crucial parameter if batteries are going to be the main source of energy storage for EVs (Hu et al., 2020). Martinsen (2016) notes the importance of battery lifetime in applications. Capacity fade often set to 20 – 30 %, determines the lifetime of the battery. After reaching the fade threshold, the battery is best suited for secondary applications. The capacity fade relies on several factors such as cycle depth and state of charge during resting time. Since LIBs are the most important cost item for EVs, for the purpose of economic sustainability, minimizing capacity fade and maximizing its lifetime is key (Martinsen, 2016).

Hydrogen fuel cell vehicles show great potential as well. Hydrogen has been used as a fuel in several applications due to its high energy density (Manoharan et al., 2019). While the combustion of hydrogen creates zero harmful emissions, the production cost involved with hydrogen makes it three times more expensive than petroleum refining (Manoharan et al., 2019).

Supercapacitors store energy between electrolyte ions and electrodes in a double charge layer (*Difference Between Capacitor and Supercapacitor / Ultra-Capacitor*, 2019). Supercapacitors can be recharged very quickly and release a large amount of power. Although their energy

capacities are increasing, they have a short duration and a high self-discharge rate which is the reason why supercapacitors cannot be used alone as the energy source and are more appropriate for battery hybrid applications (Burke & Zhao, 2015; Horn et al., 2019; Z. Li et al., 2019).

4.2 EV Business Strategies

Apart from charging infrastructure, one of the major disservices to EVs is that they are often manufactured in the same way as traditional cars (Zarazua de Rubens et al., 2020). Business models should be created with more of an emphasis on highlighting EV capabilities outside mobility to set them apart from traditional vehicles. Examples include connectivity to the digital world through the internet and mobile apps, high-resolution intelligent displays, and V2G capabilities. Newer EV companies with little or no bias towards the value chain model for traditional vehicles should establish these new and more favorable business models. Companies should ensure that consumers know and reap the benefits of purchasing an EV instead of being viewed as simply a replacement for an older vehicle. This can be highly disruptive for established entrants as they must now interface with electricity and infrastructure providers and create alternative business models (Nieuwenhuis, 2018).

The profitability of EVs is a crucial aspect for any company. Across the board, professionals and OEMs agree that the business case for EVs is unprofitable for the following reasons: It requires a high initial investment, which leads to lower sales volume, high battery cost, high production costs and a lack of after-sales revenue. In addition, while beneficial for consumers, the low maintenance of EVs affects overall profitability, as big companies depend on consumers returning to the dealerships for service and maintenance of the vehicles (Dombrowski & Engel, 2014; Zarazua de Rubens et al., 2020). Furthermore, industrial investments are affected by EV development, and companies are hesitant to fully commit to EVs due to the assets within the ICEV sector.

Automotive brands that traditionally relied on the sale of combustion vehicles will have different strategies and approaches to integrating EV development into their business sales model. In the past, auto manufacturers concentrated solely on design and final assembly. However, during the COVID-19 pandemic relying on outside suppliers became troublesome as supply chains were

disrupted. Ewing (2022) loosely describes many of the impacts of the pandemic on the supply chain, including disruptions and reductions in shipping, shipping container shortages, increases in shipping costs, and labor shortages. Tesla and its vertical integration strategy were key for resisting many supply chain issues that negatively impacted other auto manufacturers. Vertical integration is a strategy that allows a company to take direct ownership of various stages of its production process instead of external contractors or suppliers (Hayes, 2022). Tesla has focused not only on constructing vehicles but has ventured into commercial and home charging, solar roof offerings for homeowners, solar-powered commercial chargers, and giga factories (Lambert, 2022a, 2022b). Tesla has also ventured into land acquisition for purposes of mining as a key strategy to secure materials that would otherwise be sourced from China or other geopolitically sensitive regions (Global Data, 2022). During the pandemic, a computer chip shortage proved problematic for GM and Ford, who rely on outside sources for software and computing expertise. In contrast, Tesla, which writes its own software and creates its own circuit boards was able to meet its needed demand (Ewing, 2022; H. Jin, 2022). As a result, in 2021, Tesla deliveries rose by 87% to a record high. The success of Tesla and the vertical integration strategic approach is a lesson and could change the approaches of several automakers in the future. Already major OEMs are purchasing equity in advanced battery companies.

Other EV tech startups and companies have also been influential in the EV automotive sector and have looked to take advantage and gain ground in the EV sector where possible. Unlike established automotive brands, EV start-ups are more likely to experiment with designs and approaches to constructing EVs and components. Chinese companies like Xpeng, Nio, and Li have introduced many unique components to their vehicle fleets. Xpeng for example, introduced the XPeng P5 which is the first LiDAR-equipped vehicle for mass production (XPENG, n.d.). Light Detection and Ranging (LIDAR) relies on sensors and lasers to map the surrounding environment and can be a potent tool in autonomous vehicles, a feature which other EV companies have shied away from. Nio is unique as it is the only company with a well-established swapping station network. US-based startups Rivian, Canoo, Brightdrop also create specialized vehicles with unique designs that appeal to different consumers. They have also increased their exposure by partnering with corporations to deliver and manufacture trucks that suit their needs. In turn, corporations like Walmart, FedEx, and Amazon look to these startups to help enhance

and further sustainability goals rather than partner with well-established automotive companies. As noted by the Bocconi Students Investment Club (2021) EV startups have more expertise and knowledge in the battery and software segments over traditional manufacturers. As a result, most EV company vehicle offerings have longer vehicle ranges and better software. The newer EV companies also have more success when selling products online compared to traditional automakers which still very much rely on car dealerships for car sales.

The incentive to innovate may also be key for OEMs lagging behind in the EV industry. The incentive to innovate refers to the incentive for firms to increase competitive capabilities by introducing innovations (Wesseling et al., 2015). The authors state that firms with substantial competitive advantages have less incentive to innovate than companies with inferior competitive advantages. As a result, disadvantaged companies are more likely to introduce more radical innovations to overcome the lack of competitiveness. To set an example, the Inflation Reduction Act introduced an EV tax credit scheme aimed to make EVs in the U.S. more affordable and promote domestic development. Vehicles with battery components manufactured or assembled in North America are eligible for $3,750; and a vehicle with critical minerals extracted and processed in the U.S. or with a country that has a free trade agreement is eligible for another $3,750. Additionally, for vehicles to qualify for the credit, vans, sport utility vehicles and pickup trucks cannot exceed $80,000, and other vehicles cannot exceed $55,000 to be eligible (IRS, 2022; Plug In America, 2022). With these stipulations, weaker OEMs have a grand opportunity to manufacture vehicles that meet the standards and allow these OEMs to undercut stronger competitors and possibly sell vehicles at a faster rate. Of course, established companies that do not meet the mentioned qualifications will still be able to sell vehicles in the U.S., but consumers will likely opt for vehicles that meet the caveats to take advantage of the credit.

4.3 Proposed EV Business Ecosystem

Figure 3 is an image of the proposed EV ecosystem, the eight areas of advancement, and existing companies that could be or are already involved in developing the EV ecosystem. The areas:

1. Smart Grid – Network that allows a two-way flow of electricity and data (*Smart Grids*, n.d.)
2. Power Sources – Electric utility providers and renewable energy sources

3. Home Charging – Supplies energy to electric car battery from the comfort of the home, V2G and V2H compatibility
4. Smart Devices – Connectivity between phones, tablets, and EVs
5. Commercial Charging – Charging stations distributed throughout the country by EV companies.
6. Data Management and Communications – The collection of data from the grid, charging stations, EVs, homes, etc.
7. Sustainable EV Materials – Lighter materials and sustainable materials are used in the construction of the vehicle and other applicable components (e.g., charging supply equipment)
8. Sustainable Energy Storage – Battery recycling, repurposing, and optimal storage and restoration methods

There is a varying level of connectivity between the eight areas of advancement. The current electric grid is a network of transmission lines, substations, and transformers that deliver electricity from the power plant to homes or businesses unidirectionally (SUNY Buffalo State College, n.d.). The smart grid will enable communications to be exchanged from these networks to its customers to create a more efficient, secure, and green grid (SmartGrid.gov, 2019). The smart grid will implement renewable power sources and energy production methods to meet growing electricity demands. Due to the intermittent nature of RES, BESS can be utilized to store excess energy in times of high production and used during unfavorable weather conditions. In addition, there is a great opportunity for repurposing LIBs, SIBs, and other battery materials that have a reduced capacity and are unsuitable for EVs. BESS can be installed in homes supplemented with solar roofs and used as backup energy sources for emergencies or used by the smart grid. Home charging will utilize electricity from the grid to supply energy to vehicles, or this energy could be supplied by the power produced from solar roofs. V2G technology will allow energy from the vehicle to go back to the grid during times of high-power demand, and vehicle-to-home (V2H) will enable EVs to be the primary power source for homes during power outages or as a supplement during the night. Smartphone connectivity will allow users to keep track of charging at home or while on the road, available charging stations, optimal charging times, and practices. Commercial charging is key to the success of EVs, and different levels of charging will be available throughout the country. As the ecosystem develops, so will the methods of energy restoration. The primary method in the U.S. is plugin charging, but EV

manufacturers and EVCS manufacturers will delve into battery swapping, mobile charging, and wireless charging. Reducing station congestion, monitoring peak energy demand, and identifying future charging stations will rely on effective data management and communications. Finding sustainable EV materials will help increase the range of vehicles and reduce the need for raw materials for EV components to create a circular economy.

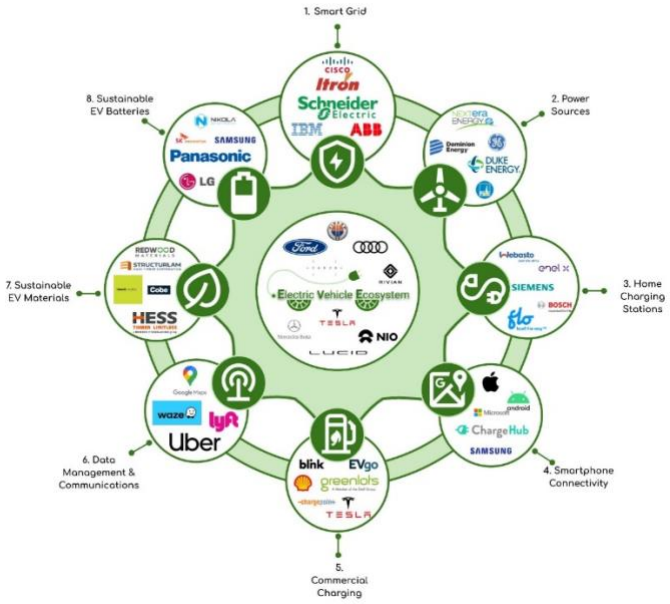

Figure 3: EV Ecosystem Model – areas of advancement in the EV ecosystem and its constituents.

5. Design Aspects of Electric Vehicle Charging Stations (EVCS)

5.1 EVCS Deployment and Potential Issues

One of the main issues associated with EVs is the design and deployment of proper charging stations (Mehrjerdi & Hemmati, 2019). Between 70–90% of the EV charging demand comes from home charging, so it is assumed that most EV owners do not often charge their EVs outside of the home (Fuels Institute, 2021). However, fast charging deployment is essential to reduce range anxiety, and fast chargers are more effective at increasing BEV sales (Levinson & West, 2018). The unavailability of such stations decreases the adoption of electric vehicles, so to improve the public's acceptance of EVs, building adequate EVCS is necessary (Mehrjerdi & Hemmati, 2019). EVCS placement should consider the comfort of the driver. Comfort or wellbeing can be categorized as the location of the charging station, proximity or walking distance to waiting areas or desired destination, and the distance between chargers and the

number of chargers in an area. Personal space, weather conditions, and safety (especially at night) should also be considered as EV owners will be more comfortable when less exposed to the elements and placed in well-lit and populated areas. A case study done on charging behavior found that females and older EV owners felt more comfortable and were more likely to charge vehicles at home (Lee et al., 2020). While other factors such as work schedule, income level, and convenience influence this behavior, the safety issues as mentioned above are prominent in the user's decision-making.

When it comes to charging, EV owners can run into many issues. Bonges & Lusk (2016) detail many of the issues EV owners can encounter when trying to charge a vehicle. One of the issues they highlight is that users might be unable to charge their vehicle because another EV is plugged, or the spot is occupied by a non-charging vehicle. It can be frustrating for users to have to wait in a queue for 30 minutes to an hour for each driver in front of them to finish charging a vehicle. EV owners may also be unaware that parking in charging spaces for long periods is improper. Out of desperation or negligence, EV owners might unplug other EVs to deliver a charge to their vehicle. Conflicts can arise upon finding their EV unplugged, and victims can claim that their vehicle was not charged or there was harm to the vehicle, such as the car being scratched. In such a situation, one can imagine that things could escalate quickly depending on the individuals involved. Therefore, charging an EV should be as convenient as possible and limit the time someone has to wait in a queue to charge and wait for the vehicle to charge. One of the ways to do this is by increasing the number of EVCSs in an area which enables cars to be immediately plugged in and alleviates the issue of station congestion. Current literature on EVCS highlights the importance of increasing the number of EVCSs, parking spots, and available charging ports to reduce range anxiety and promote adoption (Afshar et al., 2021; Mehrjerdi, 2019; Mehrjerdi & Hemmati, 2019). In addition, doing so can help to relieve or eliminate social anxieties associated with a low number of charging locations.

Mobile charging is a novel alternative to stationary charging, both public and private. Mobile charging systems (MCS) offer EV charging services for EV users at convenient times and locations (Afshar et al., 2021). For example, MCSs seem more appropriate for roadside assistance and emergencies when the battery is at a low charge level, similar to services offered

by AAA. As the EV market upsizes, it is plausible that rental and insurance companies will adopt MCS, and companies like Tesla and Nio have experimented with this in the past (Deveza, 2019; Lambert, 2018). Even so, since MCSs are a new charging method, there is a possibility for this to start with a small coverage zone, and service will be limited.

5.2 Sustainable Gas Station Retrofitting

A future exists for current gas stations to be converted to EVCSs. As more vehicles switch to alternatives, current gas stations will begin to experience a demand shortage and could require retrofitting (Shukla et al., 2011). Retrofitting gas stations into EVCS is a highly discussed topic. However, the existing literature that discusses the cost, advantages, and disadvantages or the best approaches for gas to EV station retrofitting is limited. In a 2011 study by Shukla et al. (2011), the authors note that a high capital investment is required to construct a new refueling station. They suggest that replacing one or more existing gasoline dispensers at a station with EV charging equipment could be more cost-effective. Compare this to RS Automotive in Takoma Park, MD, which in 2019 was the first U.S. gas station to be fully converted to an electric vehicle charging center (Hagemann, 2019). Behind this was a grant of $786,000 to help pay for the conversion. The convenience store was turned into a charging lounge with complimentary coffee, water, restrooms, and several couches, televisions, and Wi-Fi at this charging station. People would typically spend 15 – 30 minutes charging vehicles (Hagemann, 2019; Holley, 2019). From a business side, gas station retrofitting could greatly minimize the overall cost associated with establishing new locations. From an environmental and sustainability perspective, this helps reduce the need for the upheaval of trees, dirt, and other processes involved in constructing a new location. This example can be seen in Shell, a multinational oil and gas company committed to becoming one of the largest electric charging solutions providers globally and has set a goal for 2025 to operate over 500,000 charging points worldwide (Shell Global, n.d.). Shell has also started exploring gas to electric station conversion in the UK. The converted gas station in Fulham Road, London, is now exclusive to EV charging and has nine charge points, a supermarket, a coffee shop, and free Wi-Fi (S. Jones, 2022; Ramey, 2022a). The chargers are reported to be able to charge most EVs from 0% to 80% state of charge in 10 minutes, similar to the traditional gas station experience. The gas station was constructed with

tall timber canopies fitted with solar panels. It has signs showing drivers which charging areas are occupied and which are available and signs that show that it is exclusively for EV charging.

6. Future Technological Developments

6.1 Integration of Renewable Energy Sources (RES)

There is a growing effort to incorporate renewable energy sources (RES) into charging stations that can supply energy to EVs for sustainability and environmental friendliness. The EU, for example, has commenced a thorough reform of its energy model. There is an 80-95% greenhouse gas (GHG) reduction goal set for the EU by 2050 (Colmenar-Santos et al., 2019). If derived from RES such as wind, solar, water, biomass, or other low-emission sources, electricity can almost eliminate CO2 emissions. With the implementation of RES, however, there will be challenges for the power grid, and new grid techniques that are optimal for renewable resources need to be discovered.

The biggest drawback of RES-based power plants is that most are supplied by fluctuating energy sources. The amount of solar or wind energy an area receives is dependent on weather conditions, with differing daily patterns that can restrict the consistent operation of RES facilities. Hybrid renewable energy systems can be highly efficient by merging multiple renewable energy sources and implementing battery energy storage systems (BESS) (Dai et al., 2019; X. Li et al., 2013). Combining multiple energy sources is a common strategy that has been suggested and employed in similar studies. For example, Mehrjerdi & Hemmati (2019) created a model where the EVCS was connected to the distribution network and equipped with a battery energy storage system, diesel generator, and solar panels. The diesel generator and solar system were used to supply power to the grid. In this model, the diesel generator's primary purpose was to serve as a supplementary generation system to deal with high-pricing time sections. During discharging time sections, the BESS injects power into the grid and power is consumed from the grid during charging periods. It also includes a multilevel charging facility that can accommodate three different types of charging modes: slow, medium, and fast speed charging and with all being considered, help to reduce investment cost on charging facilities.

Interestingly methods exist for hydrogen and electricity for fuel cells and hydrogen vehicles. An off-grid charging method was developed by Mehrjerdi (2019) for electric and hydrogen vehicles. In off-grid charging stations, the energy supply comes from resources such as wind-solar systems

and is accompanied with energy storage systems. Mehrjerdi's (2019) proposed system uses a solar system to power a water electrolyzer that produces hydrogen. When solar energy is insufficient, a fuel cell and diesel generator supply energy to vehicles. Such methods are not at the forefront, but this capability encourages other electric vehicle types. Due to availability, diesel is a reliable addition to grid systems, but it would be best to seek an alternative to pairing with these systems. Instead, in the future, biomass generators could be used as a supplemental power source. A novel grid-connected solar/wind-powered electric vehicle charging station with vehicle-to-grid technology proposed by Fathabadi (2017) does not rely on BESS or diesel. Instead, it maximizes charging capability using a novel maximum power point tracking technique. This technology could be employed near warm coastal areas with abundant wind and sun energy. Another model proposed by Dai et al. (2019) does not utilize a diesel generator but solely relies on photovoltaic cells (solar panels) and a BESS. In the report, the solar panels and BESS, collectively are referred to as PBES (Photovoltaic/Battery Energy Storage). A PV power generator, a battery bank, EVs, and an energy management system are the major components of this system. The PBES collects, controls, and shares data from generation, energy storage, and load. The system can operate as either standalone or grid interactive.

6.2 EV's Impact on the Grid

Several papers discuss the impact of EV charging on the power grid. The expansion of the electric fleet will result in significant growth of electricity demand (Dkhili et al., 2020; Y. Huang & Kockelman, 2020; Kapustin & Grushevenko, 2020). Large-scale deployment of EVs demands additional power and grid stability. Such a rapid transition to an EV fleet that is dependent on the grid for power supply can cause significant adverse impacts that can occur on this distribution network. The impacts can vary based on EV penetration levels, EV battery characteristics, charging patterns, locations, modes, times, EV driving patterns, driving distances, and many others (Shareef et al., 2016). It is important to consider that the grid not only serves to power the EV fleet in the future but will also need to provide power to meet the demands of society. Progress in the scientific and technological fields has generated significant improvements in the standards of living across the globe. Human activity continues to become more energy-intensive and consequently, energy demand is constantly growing. According to a 2017 report from The Energy Information Administration (EIA), it was estimated that between 2015 and 2040, the

world's energy consumption would increase by 28%, while the net electricity generation will increase by 45% in the same time (Mead, 2017). In every region of the world, energy consumption will continue to grow from almost every energy source. The switch to RES to meet electricity demand is especially important to relieve environmental concerns and replace fossil fuels as the sources deplete.

There are several motivations to incorporate RES into the grid. While the share of fossil fuel-based energy generation is decreasing, many sectors are still dependent on oil-based fuels. The EIA reports that in the U.S. about 60% of electricity generation comes from fossil fuels as seen in Figure 4 (EIA, 2021). Such dependency influences the price of oil which has a drastic impact on the global economy. Therefore, the fossil fuel industry continues to develop more effective methods of oil extraction and drilling techniques. Being that oil fields are becoming more depleted over time; more energy and money is required to extract fossil fuel as the number of fields decrease and become less accessible (Dkhili et al., 2020). Such activities further reiterate the importance and the attractiveness of renewable energy use for electricity production. Investments in renewable energy can have tremendous benefits for U.S. energy security. As of 2021 renewables accounted for 20.1% of the electricity generated in the U.S. (EIA, 2021). Even with the growing attraction for RES because of their intermittent nature, RES connections can impact grid operations. Renewable energy generation resources can exist as a distributed generation, which refers to small renewables on the distribution grid where electricity load is served and centralized. The next is utility-scale generation which refers to the large-scale generation of electricity at centralized facilities (Cleary & Palmer, 2020; Ellabban et al., 2014; US EPA, 2015a). Between 2010 and 2035 globally, electricity generation from renewable energy sources is expected to grow 2.7 times (Ellabban et al., 2014). Ellabban et al.'s (2014) research indicates that by 2035, renewables will account for 31% of electricity generation globally, solar will account for 10%, wind will account for 23%. With increased EV uptake it is likely to see more grid-independent homes as they rely on solar panels for energy production for the home and vehicle and take advantage of the V2G capabilities to supplement the home's energy use during the night hours. Large-scale generation smart grid technologies would enable two-way communications between the grid and consumers allowing renewable energy sources such as solar, wind, and hydrogen to be managed and distributed more effectively (IEEE, 2019; L. Liu et

al., 2015). Balancing the electricity generation from RES on the grid can be achieved by adopting stationary energy storage and can be a promising solution (Cheon, 2019). Stationary energy storage systems are useful as they can store or provide needed electricity during times of excess and low power generation (Mwasilu et al., 2014).

Smart meter devices are used to record and obtain information such as energy consumption, voltage levels, current and power factor and provide feedback of consumption data to the customer (Van Gerwen et al., 2006; Z. Zhang et al., 2020). Smart meters in combination with electricity pricing and tariffs are set to be an integral part of the smart grid as a means of managing the influx of EVs and heightened demand of electricity. As a result, the heightened demand for electricity will likely cause the prices to rise and overload the grid (Soares et al., 2017). How expensive electricity becomes will also be dependent on the electricity mix and the grid's ability to supply the demands. Smart meters and smart charging in combination with dynamic pricing or demand response will enable EVs to be charged during off peak power demand. To help alleviate peak demand and grid overload, demand response or dynamic pricing are used to influence the behavior patterns for charging and electricity use in general. The premise behind dynamic electricity pricing is to encourage EV owners to charge during times where electricity demand is low and discourage charging during peak periods. Scholars have often stated this premise however the effectiveness of this methodology is in question (Ito, 2014; Soares et al., 2017; K. Zhou et al., 2020). Ito (2014) conducted a study to gauge how increases in monthly prices of utility bills were perceived by homeowners. The study concluded homeowners were more responsive to changes in the monthly average price of electricity as opposed to nonlinear electricity prices throughout the day. While home electric utilities differ from charging, EV integration will soon make mobility a significant part of the electric bill in the future (Soares et al., 2017). This result implies that more drastic pricing may be necessary to influence behavior for EV charging. The home energy management systems (HEMS) sector is growing in in the era of the smart grid and smart homes (Zandi et al., 2018). As noted by X. Hou et al. (2019) with the implementation of smart grids, HEMS will be essential to responsibly manage the use of EVs as well as renewable energy systems, energy storage system and appliances throughout the home. The National Renewable Energy Laboratory (NREL) has developed a HEMS that learns the patterns and schedules and home occupants and can there predict the energy consumption in

homes. With a HEMS, results show that there are 5%-12% energy cost savings. Overall the HEMS is used to predict energy consumption, and reduce energy cost and impact (NREL, n.d.).

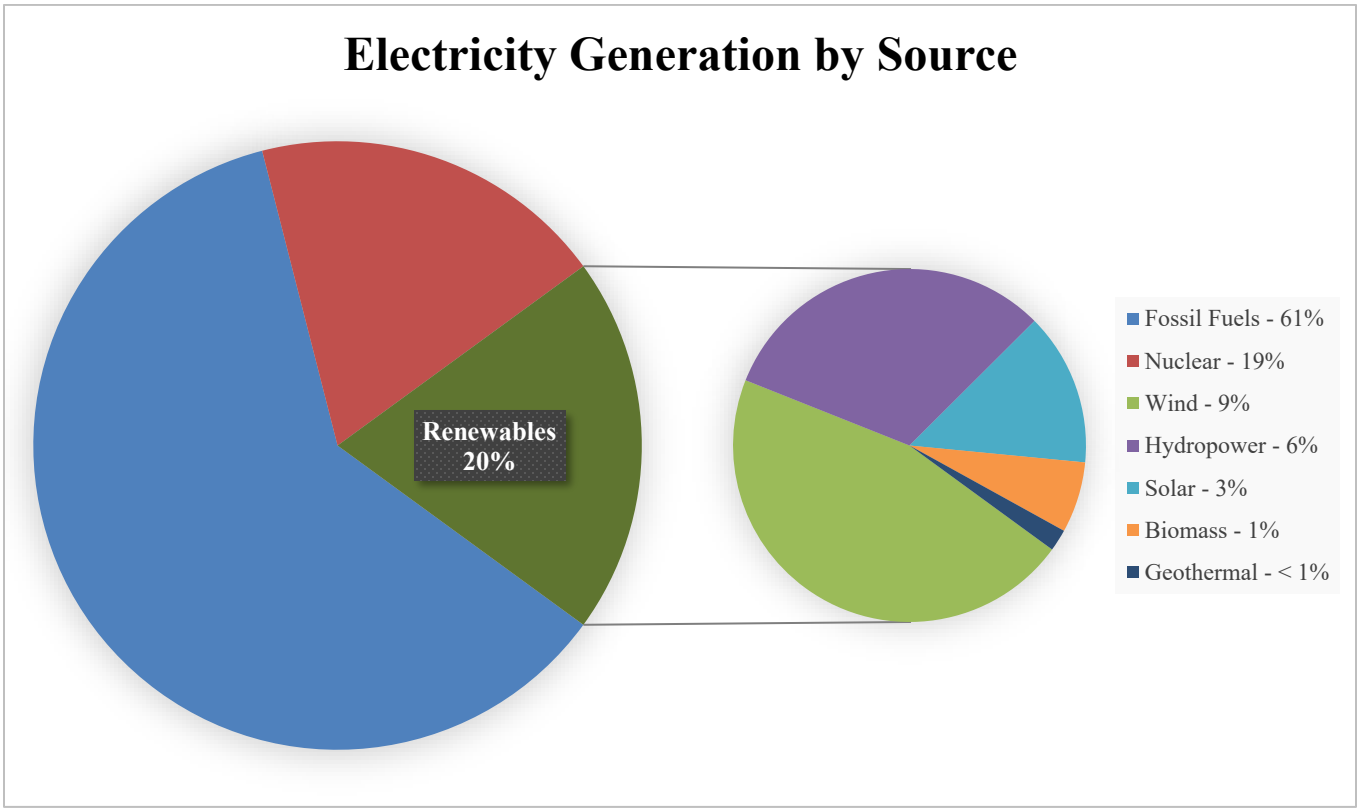

Figure 4: Electricity generation by source in the United States (2021). (EIA, 2021)

6.3 Alternative Charging Methods

Range anxiety is a key concern for EV consumers and is one of the major roadblocks to EV adoption. In conjunction with an optimized charging network, battery swapping stations can offer a solution during long trips when a driver's depleted batteries are exchanged for recharged ones. Depleted batteries can be swapped and recharged, then later swapped for depleted batteries in other arriving EVs. This innovative remedy allows EVs to be effectively "refueled" in only one to two minutes instead of hours (Mak et al., 2013). In such a scenario, in essence batteries are leased to EV owners and not the primary responsibility of the owner (F. Ahmad et al., 2020). This method can also prove to optimize battery performance through optimal charging. However, an appropriate charging strategy prevents damage and performance degradation. Since there are

different charging modes, it seems best to take responsibility of battery management and put it on more sophisticated technology (Klein et al., 2011).

Companies in the past have looked to utilize battery swapping. Better Place (BP), a venture-backed company based in Israel, users were charged based on usage (i.e., miles driven). Unfortunately, due to high capital investment associated with charging development and infrastructure, the company suffered severe financial losses and was eventually liquidated (F. Ahmad et al., 2020; Noel & Sovacool, 2016). Even so, this arrangement poses several potential benefits. Mak et al. (2013) make a significant point that battery swapping dissociates the ownership of the battery and the EV, two items with different life cycles. Future improvements in battery technology can be taken advantage of by regular battery replacements, compared with other solutions that bundle the EV and battery as one single unit. Similar to other charging infrastructures the placement of battery-swapping stations is important and there is existing research that aims to develop models that aid the planning process for deploying battery-swapping infrastructure (Mak et al., 2013). Among the things to consider is the high cost attached to BSS. Service providers must ensure that there are enough spare batteries at a location to meet the demand for full batteries. Even with this research companies and EV manufacturers are hesitant to adopt and rely on this technology. Nio a Chinese-based car company is one of the few EV companies in the entire world that delves into BSS. In fact, Nio in the beginning of 2022 completed over 800 BSS in China and has opened one station in Norway (Ramey, 2022b). NIO Power Swap as it is referred to, takes 3 minutes to swap to a fully charged battery and there are automatic checks performed during each swap to ensure both the battery and the vehicle are maintained (NIO Inc., n.d.).

In the future, wireless charging systems (WCS) can alleviate some of the need for plugin chargers. WCSs have been proposed in EVs and in static applications and have many advantages in simplicity, reliability, and user-friendliness (Barth et al., 2011). There is also the convenience of automatic charging without the user providing a physical contact path between the vehicle and the power source (Lukic & Pantic, 2013). Furthermore, static charging can eliminate wires' shock hazard and be installed in convenient charging locations (A. Ahmad et al., 2018). However, the issue with static WCSs is that the method only applies when the car is parked or in

stationary modes, such as in car parks, garages, or traffic signals (Stegen et al., 2015). Dynamic WCSs allow battery storage devices to charge while the vehicle is in motion. Dynamic WCSs can be installed in roadways and form dedicated charging lanes along the highway and continuously charge the EV en route (A. Ahmad et al., 2018; Lukic & Pantic, 2013). Additionally, charging can be achieved through the quasi-dynamic charging system, which provides power to EVs while stopped for short periods, such as at traffic lights. Since dynamic and quasi-WCSs supply power to EVs en route, both methods increase driving range while potentially decreasing the need for a larger battery. Research suggests dynamic WCSs could alleviate the need for such a heavy battery since energy is constantly being supplied to the vehicle (A. Ahmad et al., 2018; Bosshard & Kolar, 2016; Di Capua et al., 2015). Even so it will be many years before dynamic WCSs are integrated on roadways and would require a lot of investment and resources.

WCSs hold many advantages over the plug-in charging systems. Plug-in connections can be very dangerous, particularly in bad weather conditions. There is a potential for sparking to occur during plugging and un-plugging, which limits the application of EVs near places like gas stations and airports (Machura & Li, 2019). Automatic power transfer is particularly appealing for charging public transportation EVs because the charging process can be integrated with regular vehicle operation instead of the need to move charging components to connect to the vehicle (Bosshard & Kolar, 2016). However, there are still some major potential health and safety issues to consider fire hazards. High current and voltage levels which can cause a higher chance for electrical shock risk can occur due to malfunction or accidental damage to the device. There are also other electrical magnetic and fire hazards as mentioned by Panchal et al. (2018). Even so there is still a great potential for WCS in future applications like vehicle to grid concepts and bus charging applications (Panchal et al., 2018). Different wireless power transfer methods are utilized for WEVCS: traditional inductive power transfer, capacitive wireless power transfer, magnetic gear wireless power transfer, and resonant inductive power transfer. Each method varies in price, performance, size and suitability (Machura & Li, 2019).

6.4 Tribology

Tribology is the science of wear, friction, and lubrication and pertains to how surfaces interact and other tribo-elements act in relative motion in natural and artificial systems (GGB, 2019). In terms of efficiency, ICEVs pale in comparison to EVs. About 21.5% of fuel energy supplied to a combustion vehicle is used to move. Compare this to EVs, which use around 77% of the total supplied electric energy, meaning that EVs can be almost three times more efficient than combustion vehicles (Farfan-Cabrera, 2019). Most of the inefficiencies in ICEVs come from exhaust and cooling losses. According to the DOE electric vehicles can experience a loss of energy at about 16% during charging (Energy.gov, 2018). Even so energy gains from regenerative braking help to recover energy and increase EV efficiency. While EVs are highly efficient in terms of energy consumption, there is a desire to increase efficiency even more and this can be achieved by addressing energy lost during charging and discharging of battery, cabin heating and ventilation, air dragging and friction (Farfan-Cabrera, 2019). Friction, consumes around one-fifth of all energy used worldwide and nearly one-third of all energy used in transportation goes to overcome friction (Holmberg & Erdemir, 2019). New tribological solutions such as new ceramic materials, and innovative lubricants can significantly decrease energy losses and lead to increased range, improved performance, and lower carbon emissions. Furthermore, as Farfan-Cabrera (2019) discussed, the growing interest in electrification is not exclusive to passenger travel but also to heavy-duty vehicles and buses. Looking into other modes has helped proliferate the development and research of topics based on energy storage, autonomous driving, thermal and electric efficiency increase, and more.

7. Societal Impacts of Electric Vehicles

7.1 Environmental Impacts of CO_2 Emissions and Tailpipe Emissions

Often the social aspects of using EVs are ignored or neglected. Issues such as human health, air quality, the environment, economic growth, and grid resilience are impacted by the adoption of EVs (Malmgren, 2016). Airborne fine particulate matter is a contributor to mortality and disease. According to the EPA and other research, fine particle pollution that can be found in vehicle tailpipe emissions can cause premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, increased respiratory symptoms, such as coughing or difficulty breathing (Steiner et al., 2016; Sydbom et al., 2001;

US EPA, 2016b). In 2019, transportation accounted for about 29% of carbon emissions in the U.S. In addition, the transportation sector was responsible for over 55% of nitrogen oxides, less than 10% of particulate matter and volatile organic compounds (US EPA, 2015b). In 2012 it was calculated that 10.2 million global excess deaths occurred due to PM2.5 from fossil fuel combustion (Vohra et al., 2021). The widespread adoption of EVs will help decrease particulate matter that comes from tailpipe emissions, especially if adoption occurs in highly populated high-traffic cities that suffer from air pollution. The Social Cost of Carbon (SCC) is used by federal agencies to estimate the climate benefits of CO_2 emissions reductions (Malmgren, 2016). The purpose of the SCC is to identify the social cost of carbon by estimating the economic costs, or damages, of emitting one additional ton of carbon dioxide into the atmosphere, and the benefits of reducing emissions. The estimate helps to inform policy and investment decisions in the United States and abroad (Nordhaus, 2017; Rennert et al., 2021; University, 2021). The EPA further describes the SCC as an estimation of changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced heating costs and increased air conditioning costs (US EPA, n.d., 2016a). However, since some of the damages are difficult to quantify, it does not capture all the economic, ecological, health, and physical damages linked to climate change (Chaudhry et al., 2020; Malmgren, 2016). Increased carbon emissions are a driving factor for global warming, which has made natural disasters and extreme weather like hurricanes, droughts, floods and storms more severe and frequent and can result in unpredictable consequences (Balaguru et al., 2018; Bhatia et al., 2019; Holland & Bruyère, 2014). Atlantic hurricanes have been extremely costly, with the costliest storms exceeding 100 billion dollar's worth of damages (Blake et al., 2011). Such catastrophic events lead to loss of life, displacement from homes and businesses and damage to crops and public infrastructure. Increasing the EV market share can be key to reducing carbon emissions, but the actual environmental benefits from EV usage is dependent on several factors. One being the energy sources used for vehicle production and manufacturing, raw material extraction and electricity production. As discussed earlier it is critical that there is a transition from fossil fuels to RES to realize the benefits of EV usage.

7.2 Environmental Impacts of Battery Materials

Lithium batteries at the moment are the most reliable energy storage method for EVs and until there is a more suitable method the demand for lithium for EVs will continuously increase. Lithium is quite abundant on Earth being the 25th most terrestrial abundant element, and is found in more than 150 minerals, in clays, in many continental brines, geothermal waters, and in seawater (Flexer et al., 2018; S. R. Taylor & McLennan, 1985). Currently it is a relatively inexpensive metal (about 15,000 US$ for a ton of battery-grade Li_2CO_3), but its price is likely to increase with demand (The Economist, 2016). Nations globally have lofty goals of EV adoption, and this could put a strain on lithium resources. According to a 2022 report from USGS the continuous exploration of lithium resources has increased substantially worldwide and lithium resources total to about 89 million tons (USGS, 2022). However, some research suggests the resources required to make LIB will be depleted in the next ten years or so because the demand for batteries in smart devices and laptops will need to be met in addition to vehicles (Wanger, 2011). Lithium materials will be a key component in the expansion of EVs however there are many environmental impacts associated with lithium extraction. Lithium is primarily extracted from hard rock and brine solutions and both extraction processes require large quantities of energy and water (Nature, 2021). In brine solution process approximately 500,000 gallons of water are required per metric ton of lithium (Institute for Energy Research, 2020). To extract lithium, holes are drilled by miners into salt flats and salty mineral rich water is pumped to the surface. Once the water is evaporated a mixture of minerals and salts including lithium is left after many months and lithium carbonate can be extracted (Flexer et al., 2018). Large operations and practices leave these areas susceptible to pollution of local water supply due to infiltration of chemicals into groundwater and reduces available water for farmers and the general population. Water and chemical pollution also have adverse impacts on native wild and aquatic life (Wanger, 2011). Social issues particularly in South American countries, such as Chile and Argentina where mining takes place are associated with the violation of human rights, discrimination, and restriction of access to communal land and water (Agusdinata et al., 2018).

7.3 Employment Opportunities

Nevertheless, EV uptake will have economic benefits. In addition to the health benefits, the EV market also helps create jobs and provide other economic benefits. The economic benefits

include reducing fuel costs and transitioning from imported oil to locally produced electricity sources (Salisbury, 2014). In Salisbury's (2014) report about economic benefits of EVs in the state of Nevada the author discusses the consequences of being a state that does not produce much of its own oil. States that don't produce any oil rely on vehicle fuel imports from outside the state, meaning that nearly all the money spent on fuel leaves the state's economy. With widespread EV adoption, the money saved from reduced fuel costs could help people spend less money on energy for vehicles and more on services and goods in the local community. Job creation is another key benefit that occurs from the shift to all electric vehicles. According to the EPI a 50% rise in domestic BEV auto sales by 2030, could result in 150,000 jobs in the auto industry being created (Economic Policy Institute, 2021). However, if there is political inaction nearly half those jobs could be lost as the components that power the BEVs continue to be produced abroad. The transition from ICEVs to EVs may lead to job losses in the oil industry, but it also depends on political factors. However, new job opportunities will exist in manufacturing components like batteries, electric motors, power electronics, and charging infrastructure. The transition could also potentially impact how gas stations, auto maintenance and mechanic industry operate. The automobile industry contributes significantly to the U.S. labor force, with nearly 3 million Americans in auto dealerships and manufacturing, with many more working in key steel and aluminum suppliers (Walter et al., 2020).

7.4 Possible Concerns

Automation in EVs, the automotive industry, and many businesses in general, is a growing trend. Currently, there are concerns about the risk associated with having driverless cars. Vehicle error, over-reliance on vehicles, and overall distrust of driverless vehicles keep these technologies from being as popular. In the next few decades, however, it is projected that fully automated vehicles will become a normal part of society as consumer fear dies down and people become more accustomed to them. However, there are some unintended consequences, the biggest one being unemployment. With artificial intelligence (AI), the demand for human drivers might dwindle. In the U.S. alone there are nearly 180,000 bus drivers (Career Explorer, n.d.), 3.5 million truck drivers (Stasha, n.d.), 1.49 million delivery drivers (U.S. Bureau of Labor Statistics, 2022), and 1.5 to 2 million rideshare drivers (Berry, 2022). Politicians like Andrew Yang have voiced concerns about automation and the loss of jobs that could occur in the truck driving industry

(PowerfulJRE, 2019). Even so, it will be a long time before such things can happen since truck drivers execute many other processes that cannot be automated. Rideshare apps like Uber have invested more than $1 billion into autonomous vehicles and postponed some efforts (Marshall, n.d.). More immediately are examples of self-driving delivery vehicles. Companies like FedEx have experimented with this but it is mostly done on a small scale with small vehicles or robots that deliver goods from stores to shoppers and are often used for same day deliveries (Fedex, n.d.).

8. Sustainable Materials & Alternatives

During operation, PEVs have zero CO2 emissions; in this sense, these vehicles are very eco-friendly. However, the energy required to produce an EV is higher than other vehicle types (Podder & Grover, 2019). A crucial LCA study by Pipitone et al. (2021) compared the environmental impacts between ICEVs, HEVs, and BEVs. As shown in Figure 5, the energy consumption used to produce the BEV was 127,893.40 MJ compared to 68,705.20 MJ for the ICEV and 83,576.50 for the HEV. The energy required to produce an EV, including raw materials extraction, assembly, and transportation of the product, and the CO_2 emissions are higher than that of an ICEV. According to Faias et al. (2011), battery production and the production of other EV components contribute to the majority of the energy emissions from EVs. The materials required to make the EVs are quite heavy, making the acquisition, processing, and transportation of these materials very carbon-intensive (Podder & Grover, 2019). In the automotive industry, lightweight design has become an important strategy to reduce fuel demand. Implementing lightweight design into EVs could reduce environmental impacts even further (Delogu et al., 2017). EVs benefit from lightweighting as it reduces the rolling resistance of tires, which is proportional to the weight of the vehicle (Brooker et al., 2013). Secondly, the energy needed to accelerate a vehicle lowers, reducing the energy lost to friction brakes. Probably the biggest benefit of lightweighting EVs is that it reduces the amount of battery energy needed to achieve the same range, reducing cost for consumers and increasing the attractiveness of such vehicles, thus improving sales (Brooker et al., 2013). It is said that a 10% weight reduction for electric vehicles could equal a 13.7% increase in the range (Czerwinski, 2021). Some materials considered for lightweighting include high-strength steel, aluminum, magnesium, and polymer composites. Other options include bioplastics and biopolymers, which

have yet to become a highly prioritized option in EV design. Each option has different mass reductions, cost impacts, and GHG emissions. The production of lightweight materials is generally more energy-intensive than conventional materials, and this needs to be considered when assessing the net benefits of lightweighting (H. C. Kim & Wallington, 2016). The automotive industry as a whole is making lightweighting a part of the circular economy (Circular Cars Initiative, 2022). Transitioning towards a circular economy will help to delay the depletion of scarce natural resources, reduce environmental damage from raw material extraction, and reduce pollution caused by their processing, use, and end-of-life recycling of materials (Ekins et al., 2020).

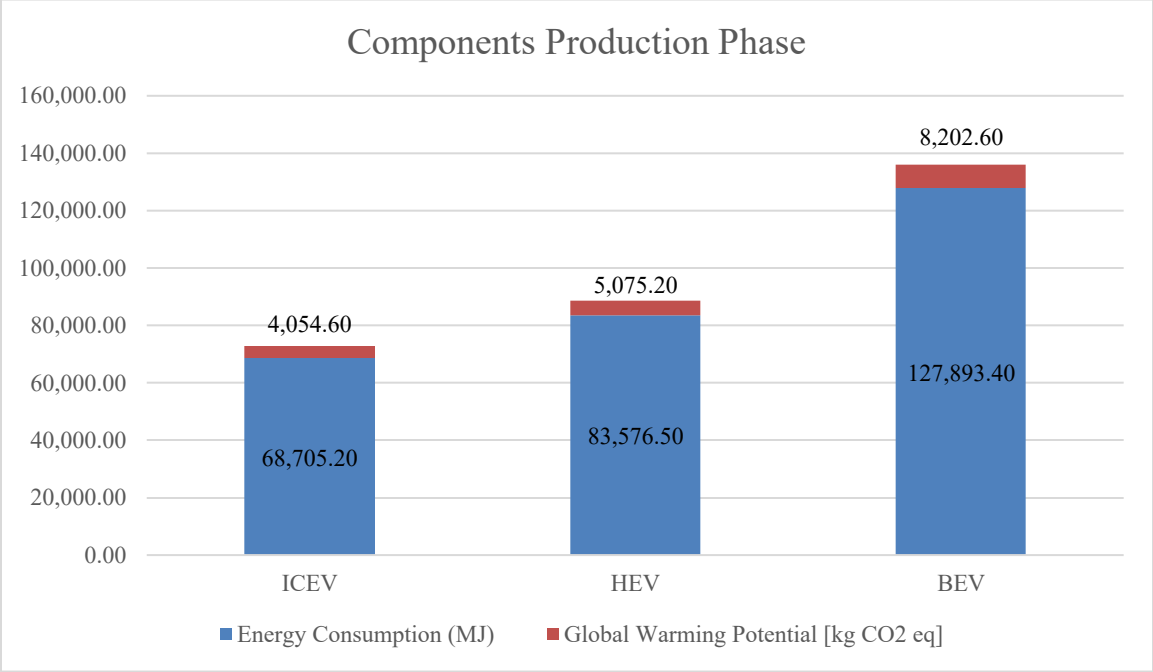

Figure 5: Energy consumption and GWP of different vehicle types. Data retrieved from Pipitone et al. (2021)

8.1 Sustainable Wood Materials and Natural Resources

Incorporating wood-based products, biomass-derived products, and other sustainable materials in the design of EVs and EVCS is relatively novel. Wood is a natural, renewable, and sustainable material (Falk, 2009; Jiang et al., 2018; Think Wood, 2022; Woodard & Milner, 2016). It is abundant, biodegradable, lightweight, and durable, making wood suitable for a wide range of applications (Falk, 2009; Jiang et al., 2018). Wood has been used in the construction of homes and other low-rise structures for a significant period of human history; however, wood is

perceived as an inferior material to concrete and steel for high-rise structures. Upgrades in engineering and wood technology have helped to improve the qualities of wood, and are now stronger, fire-resistant, and possess better thermal properties. Among these developments include cross-laminated timber (CLT). CLT is a large-scale, prefabricated, solid-engineered wood panel (Mahdavifar, 2017). It is a lightweight but strong material that offers design flexibility and low environmental impacts. CLT panels are made of layered lumber boards stacked crosswise at 90-degree angles and glued into place, resulting in alternating grains that improve CLT panels' dimensional stability and strength (Think Wood, 2022). Such qualities make it an alternative with many advantages over conventional materials like concrete, masonry, or steel, and can even be used in hybrid applications with such materials (The Engineered Wood Association, n.d.; Think Wood, 2022). Common applications for CLT include use in floors, walls, and roofing and now make the construction of large wooden skyscrapers possible (Chamernik, 2016; Malone, 2016). Traditionally electric vehicle supply equipment (EVSE) is constructed from different metals & alloys (stainless steel, carbon steel, aluminum) and polymers (PC resins, PC blends, polyurethanes) (Meticulous Market Research, 2021). Other materials include plastics that are made from fossil-based materials; however, these are unsustainable, and alternatives should be explored. EV Box is a leader in charging solutions, and Covestro, a leader in the polymer industry, aims to construct charging stations from sustainable plastics and lightweight materials (Covestro Solutions, 2022; EVBox, 2021). Covestro has made breakthroughs in the polymer industry, having developed low-carbon footprint materials. Such materials can be used in the base of EVSE. Recently the utility of CLT in charging hubs and charging stations has been explored, but there are only a few reported instances. Additionally, these designs primarily occur within European nations. In those cases, the wood and timber materials are constructed in such a way to make a canopy that is overhead with charging ports underneath. Cobe, a Danish-based architectural firm, designed a timber structure that was used to create a "restful and Zen-like feel," one that differs from the experience of a traditional gas or petrol station. In this model, designers can incorporate other natural materials and sunlight and add greenery such as grass and other plants to the roof (Ravenscroft, 2020). Hewitt Studios, a UK-based company specializing in sustainable urban design, architecture, and energy, developed the K: Port® mobility Hub (Hewitt Studios, 2021). Its purpose is to offer attractive, safe, and sustainable neighborhood EV and e-bike charging with amenities like a café and demonstration space. It consists of rapid

chargers, PV power generation and battery storage, integrated low-power services and lighting, elements of landscape and planting, and a future-proof laminated timber structure (Hewitt Studios, 2019).

8.3 Lithium Reuse Recycling & Recovery

Lithium is a highly desirable and utilized material in EV car batteries due its high energy density, high energy efficiency, low self-discharge, and overall longevity. However, lithium production has a slew of environmental issues associated with its extraction processes and mineral processing activities (Agusdinata et al., 2018). Over the last ten years, the demand for LIBs has grown significantly, driven by the demand for consumer electronics. This demand will continue to remain high and increase due to the shift from fossil fuel-based mobility towards EVs (Costa et al., 2021; Ellis & Nazar, 2012). The growing demand and production of lithium will not only lead to a reduction of available natural resources but will continue to proliferate environmental issues that are associated with lithium (Costa et al., 2021). Appropriate LIB re-use and recovery strategies should be implemented in an effort to prevent such problems. The disposal of LIB is also highly pollutant (Oliveira et al., 2015), and economically wasteful as the materials in the disposed product can be recovered and reused (Heelan et al., 2016). Recycling and reusing lithium is useful, as it can save resources and reduce waste, but doing so effectively is a very challenging approach. For LIB recycling to be a reality, it needs to be economically viable; however, it is difficult because of the recovery cost and the disassembly process (Costa et al., 2021; Heelan et al., 2016). Optimally LIBs should be used so that they take advantage of its full capacity and then be recycled afterward. LIBs used in EVs are expected to last at least 8–10 years (Chen et al., 2019) and are typically replaced after reaching less than 80% of its capacity rate (Wood et al., 2011). Retired batteries with at least 70–80% of the initial capacity can be used in less-stressful demanding applications (Hua et al., 2020). For example, the batteries are used as an energy storage system in hybrid energy systems that rely on intermittent RES like solar and wind (Z. Huang et al., 2019).

8.4 Suitable Alternatives for Battery Components

Lithium-ion-based batteries (LIB) are comprised of four components cathode, anode, electrolyte, and separator (L. Liu, 2020). Several different LIB technologies exist today, and battery

characteristics depend on the materials used in the four active components. As described by Tran et al. (2021) the name of the LIB is often denoted after the cathode materials, such as the lithium nickel manganese cobalt oxide (NMC) battery or lithium manganese oxide (LMO) battery. Researchers continuously pursue alternatives to replace the cathode and anode material for battery components.

The cathode, the negatively charged component, is key in determining the energy and power density of the battery and constitutes more than 20% of LIB's overall cost. The presence of cobalt (Co) is a driving factor for the high cost of cathode materials and, in the past, considered necessary to deliver high energy densities in LIBs (Murdock et al., 2021). While other alternative monovalent battery technologies exist, lithium is still the most reliable and preferred option but has a high price attached to it. LIBs will continue to be the preferred energy storage option without a suitable alternative, so it is vital to lower the cost of other battery materials. Political instability in cobalt-rich countries, and social impacts within the mining sector, have further driven the desire to decrease the cobalt content in cathodes (Murdock et al., 2021). Maximizing the cathode's performance and minimizing its cost can help to make EVs more accessible to society. Current literature often highlights the drawbacks of widely utilized cathode materials, including limited capacity, high energy consumption in production, safety hazards, and high-cost raw materials (Lyu et al., 2021). The development of green and sustainable organic cathode materials shows promise and exhibits better attributes than inorganic ones, with a higher specific capacity, better safety properties, and more abundant natural resources. Organic cathode materials also have no heavy metal toxicity, fast reaction kinetics, and outstanding structural controllability (Lyu et al., 2021). However, poor electronic conductivity requires the addition of highly conductive agents, which lowers the battery's energy density. Cheap transition metals such as Ni, Mn, and Fe can be used as complete or partial substitutes for Co but have shown significant performance issues like limited lifetimes and slower charge rates. Despite this, there should be a focus on producing cathode materials without a heavy reliance on Co (L. Li et al., 2017).

The aim of future LIB cathodes is to reduce the cobalt and lithium required for batteries to operate while maintaining or improving electrochemical performance (Nelson et al., 2012).

Options exist for recycling cathode materials from spent lithium-ion batteries. However, recycling methods (pyrometallurgy, hydrometallurgy) are often associated with hazardous gas emissions or long treatment periods (Ordoñez et al., 2016). Of the existing methods, acid leaching is the most cost-effective and environmentally friendly hydrometallurgical method. It can be performed with inorganic acids like HCl, HNO_3, H_2SO_4, etc. Nevertheless, the environmental and human health risk from releasing Cl_2, SO_3, and NO_x gases during leaching can be an issue (L. Li et al., 2017). In comparison, organic acids like citric and malic acid are natural and easily degradable. In L. Li et al.'s (2017) experiment, lactic acid is used as the leaching agent and results in the recovery of 98% of the Ni, Co, Mn, and Li from spent LIBs. The resulting regenerated cathode material in the experiment possessed all the qualities of freshly synthesized $LiNi_1/3Co_1/3Mn_1/3O_2$ (L. Li et al., 2017). Different cathode regeneration methods exist and seem to be favorable for cobalt recovery and can reduce the need for mining and extraction (Gao et al., 2022; Z. Zhang et al., 2020). To conclude, current research does not point to any mal effects from regeneration and is a way of alleviating environmental pollution and promoting solving energy problems.

Anode material alternatives also have promise, including carbon-based materials, graphene, titanium-based oxides, etc. (H.-J. Kim et al., 2020). Graphite is the preferred choice for anode materials in LIBs due to its long life cycle, abundant material supply, and relatively low cost (W.-J. Zhang, 2011). Flake graphite, a naturally occurring graphite material, has been recognized as one of the critical materials for lithium-ion batteries for vehicular applications (Moradi & Botte, 2016). While relatively abundant, countries like the U.S. have no graphite production. The recycling of graphite from different waste sources could potentially be a solution to meet future demand for anodes (Moradi & Botte, 2016). However, similar recycling recovery techniques used for cathode material recovery are insufficient and fail to recover graphite with a retained structural and chemical integrity suitable for reuse. Furthermore, as previously mentioned, they are associated with environmental and health problems. Physical recycling methods can rid the need for chemical processes for extraction; however, the aging mechanisms of graphite make it susceptible to capacity degradation and structural changes. Therefore, instead of recycling, anodes can be made from biomass. Due to their suitable structures and high abundance, several biomass-derived carbons have been used as high-performance anode replacements for LIBs

(Luna-Lama et al., 2019). The molecular structure of biomass-derived carbons can offer a higher capacity than graphite and are favorable for charge, storage, and transport (Gaddam et al., 2016). In addition, it is an extremely abundant and cheap precursor for the production of carbon anodes. Carbon anodes for LIBs/SIBs have been produced from orange peels (Xiang et al., 2017), snake fruit (Arie et al., 2018), corn straw (K. Yu et al., 2020), palm kernel shells (Zhao et al., 2017), and sisal fiber (X. Yu et al., 2015). However, derived from biomass still are plagued with various challenges such as lower capacities and poor rate capability (Luna-Lama et al., 2019; X. Zhang et al., 2020).

8.5 Alternatives to Lithium Metal

Alternatives to LIBs include but are not limited to lead-acid batteries, sodium-sulfur (NaS) batteries, flow batteries, supercapacitors, and flywheel energy storage. Each energy storage method has its own drawbacks, advantages and characteristic differences in capacity, energy density, life cycles, and environmental impacts (Mehrjerdi 2019). The research and exploration of alternative battery technologies like sodium-ion, magnesium, and calcium batteries to overcome the main challenges of current LIBs is underway. However, LIB technology will be the preferred method and energy storage leader for the future until such alternatives can become more reliable in performance (Murdock et al., 2021).

Sodium-ion batteries (SIB) perhaps have the greatest potential as an alternative to LIBs. Like LIBs, SIBs have a high energy density and long cycle life and with the correct intervention possess superior operability in a wide range of temperatures (T. Liu et al., 2016). Importantly SIBs appear to have lower environmental impacts than LIBs based on a recent life cycle assessment (Peters et al., 2016). Both metals are found in the alkali group on the periodic table and share similar chemical properties, indicating that sodium chemistry can be applied to the battery system (S.-W. Kim et al., 2012). However, lithium differs from sodium, as sodium is a more abundant element within the Earth's crust (Lutgens and Tarbuck, 2011). The abundance of sodium helps to make it an economically promising alternative to lithium. From a performance standpoint though, lithium batteries have higher energy density than sodium ions. High energy density is not as important in stationary applications like renewable energy storage for homes and the grid or electric buses. Instead, the cost would become the primary concern (S.-W. Kim et

al., 2012; Patel, 2021). Despite this, the energy density of materials remains paramount when calculating costs. Peters et al. (2016) report on the economic benefits of sodium ion technology showed that NMC-type LIB cells are the most competitive in terms of cost, as they require less battery cells to provide a certain amount of storage capacity. Even with high raw material prices, considering the storage capacity of the NMC-type LIBs the price is far below those of other LIB types and SIBs (Peters et al., 2019).

9. Governance of the EV Ecosystem and Existing Bottlenecks

In an environment where multiple autonomous actors contribute to advancing an innovative technology, organizing and strategizing complementarities and services is necessary to strengthen the product further. Technology platform strategies help orchestrate these factors and have been used successfully in the smartphone, commercial software, and industrial sectors (Wareham et al., 2014). The same methodology can be used in the EV ecosystem to optimize the ecosystem; however, sustainably managing the ecosystems is a complex challenge. In these systems, the purpose is to optimize the contributions of independent actors to cultivate generativity. Even so, when left to their own devices, independent actors' creative output is risky and can lead to the ecosystem's depreciation (Hagiu and Halaburda, 2009). A prominent example of this can be seen in the failures of the now-defunct company Better Place, which invested in battery-swapping technology and had beneficial and ambitious EV battery-swapping goals but were executed and managed poorly. Better Place’s example became a waste of financial and material resources, creating mistrust and hesitation in battery swapping technology as many EV companies delay pursuing the technology. Ecosystem stakeholders will have independent goals and targets yet, will still rely on the external actors that assist in the development of technology and to help fuel innovative competition. Single actors can succeed and grow when focused on their own self-interest, however as noted by Wareham et al. (2014), generativity potential increases substantially in an ecosystem. Take for example, General Motors (GM) Ultium Platform proposed battery system, which possesses a flexible architecture and will be used across many of the vehicle models under the GM brand (General Motors, 2022). Here one can observe that the ultimate purpose of the advancement and development of the battery platform is to create a vehicle that excels and in turn, will beat out its competitors. Still, GM relies on car-rental companies like Hertz to aid in the distribution and future use of GM vehicles; companies like

LG, Wolfspeed, and MP materials to improve battery technology; and General Electric to create opportunities to sustainably gather raw materials needed for EVs. Additionally, successful collaborations between firms are mutually beneficial for the individual firms and the ecosystem. Collaborative efforts will be essential for actors in the EV industry as, yet again, this was another factor that was instrumental to the failure of Better Place. The company opted to license its technology instead of manufacturing its own vehicles and therefore was dependent on manufacturers adopting it. Unfortunately, the system was not standardized across car manufacturers (Noel and Sovacool, 2016; Strickland, 2019). In addition to the poor decision-making, it seems that the battery-swapping technology far outpaced the EV ecosystem at that point. Faraj et al. (2011) emphasize the importance of limiting the sudden growth and mass implementation of new technology to ensure there are appropriate complementary options, all the while continuing innovative measures to help the market evolve, meet client requirements, and produce high quality products that encourage adoption (Wareham et al., 2014). Synergies must also be made to connect diverse knowledge systems and develop these ideas (Tengö et al., 2014).

As discussed, ecosystem governance will be necessary for the EV ecosystem and help alleviate some of the problems that firms have encountered. However, several issues or bottlenecks are still present in EV ecosystem. Bottlenecks are constraints in the overall progress of the ecosystem due to poor quality, weak performance, or scarcity (Adner, 2012; Baldwin, 2014), but identifying bottlenecks can help to improve product quality (Ju et al., 2014). The EV battery system presents challenges in regard to cost and technical issues. The EV battery system is critical to its function and is a major contributing factor towards the total vehicle cost varying between 30% and 57% (P. Jones, 2022). The development of batteries is a key factor in commercializing and marketing EVs. Range anxiety is one of the inhibitors of EV adoption, so EVs must have high energy density and a long life span to compete with combustion vehicles (Bin and Fushan, 2011). The overall cost of EVs can be discouraging to consumers. As a result, auto manufacturers and battery manufacturers may opt for batteries that omit controversial metals like cobalt or possess lower energy densities than lithium. In addition to EV battery material demand, raw material suppliers and battery manufacturers are facing fast-growing demand from the expanding renewable energy sector and smartphone producers. The

popularization of EVs will cause many ethical, social, and pollution issues to promulgate and may result in controversy and opposition to the EV industry. EV deployment must not exacerbate inequalities and neglect marginalized groups and such opposition encourages lawmakers and governments to advocate for better methods and to seek resources domestically. EV penetration can also put tremendous stress on the current power grid. California recently faced a major heat wave that strained the power grid (State of California, 2022). As a result, Governor Newsom asked residents to reduce power consumption. California currently has the highest number of EVs in the U.S. This is a severe issue as many EV owners and skeptics found this would be problematic in the future with larger penetration. Valero and Valero (2019) state that green technologies often require large amounts of raw materials that differ from those required for established technologies. The demand for metals required in building the body of vehicles will slowly shift from utilization in combustion vehicles and switch towards EVs. With that being said the vehicle body frames differ in both types of vehicles. There is a possibility of metal reuse for electric vehicles from old, scrapped vehicles as a solid method of recycling and could be a feedstock for a circular economy. McKinsey further emphasizes that regulations, resources, cost could turn charging into a bottleneck (Heldmann et al., 2021). As discussed earlier in Chapter 3 the possibility of charging station congestion is present. Areas where EV charging is available but limited, could experience long queues where EV drivers are looking to charge a vehicle. Especially in times of high demand during commuting to work or returning home and need a charge.

10. Conclusion

This paper analyzed several key components of EV technology and the ecosystem. We reviewed the current status and loosely discussed some of the developments and strategies of international auto brands, sustainable materials, alternative storage methods, current issues and potential solutions. The U.S. EV ecosystem has a promising outlook. By the year 2030, it is expected that there will be over 18 million EVs on the road, and policies are in place to help support the expansion of charging infrastructure (Edison Electric Institute, 2018; Harvey, 2020). EV uptake is increasing and is a key approach to reducing the global carbon footprint and harmful emissions. However, current challenges and barriers for the ecosystem are vehicle cost, limited driving range, and charging availability and times. EV penetration has the potential to change

society, and several global supply chains will shift. Global supply chains in the energy sector will switch from fossil fuels to renewables; power grid operations will change and demand upgrades to energy security, data management, and the ability to handle increased electricity demands. Manufacturing will increase to accommodate renewable energy demand, extracting raw materials to build PV cells and wind turbines. The focus on sustainability will push companies and researchers to discover recycling and repurposing methods for batteries and vehicles in the end-of-life stages. The evolution and construction of the ecosystem will be a slow but progressive process that involves many sectors in business, transportation, government, and more. Learning from the international business models, we have found that much of the success is due to a solid foundation of knowledge and policies envisioning EV uptake and building on top of it. Government plays a significant role and can ultimately be the precursor to companies, researchers, and universities formulating ways to succeed in the EV market and expanding it. Ultimately the local, state and national policies, incentives, and funding will dictate how quickly an optimal EV ecosystem can be established. Innovation in the four following areas: business models, manufacturing, and delivery, charging infrastructure, and sustainability, will determine the outcome of the U.S. ecosystem. The future of charging is a very fluid situation. While plug-in charging is the most popular energy restoration method, different methods like battery swapping and wireless charging are suitable for different situations and applications. The overall outcomes of the ecosystem should include sustainability, increased wellness, and affordability. Alternative materials for battery components, alternative monovalent metals, and other energy storage methods were extensively reviewed. Present energy storage methods (LIBs, supercapacitors, and fuel cells) show promise, and while LIBs are the most utilized, cheaper and more environmentally friendly alternatives are sought after. EVs can be a vital tool and a steppingstone toward a sustainable future, but the ecosystem's success depends on the development of each ecosystem area. Its success will also rely on the development and advancement of charging infrastructure. The demand for lithium and other energy storage materials can be leveraged as energy storage and grid support in the future to support energy independence and localized renewable energy systems. Reducing CO_2 and other harmful emissions is a goal for passenger transportation, and an optimized business EV ecosystem can serve as a precursor for decarbonizing other popular transportation methods. In summary, this

review helps to provide additional frameworks that can be used to optimize the advancement of the EV ecosystem.

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3

Creating an Optimal Electric Vehicle Ecosystem

An Investigation of Electric Vehicle Stakeholders and Ecosystem Trends in the US

ABSTRACT

Electric vehicles (EVs) are a key transportation alternative that can help reduce tailpipe emissions associated with internal combustion engine vehicles (ICEV). The overall emphasis on sustainability, energy independence, and rapid technological advancement has influenced the US to set targets to increase EV adoption. This study investigates emerging technologies within the EV ecosystem, including those likely to take precedence, phase out, or require strengthening. In pursuit of comprehensive insights, we gathered stakeholders' perspectives on current and future EV ecosystem trends targeting different facets of the ecosystem. Existing EV surveys often center on specific issues like charging infrastructure, purchasing intentions, or battery swapping. However, no literature has comprehensively examined stakeholders' perspectives on various dimensions of the EV ecosystem. To address this gap, we conducted a survey using SurveyMonkey, an online survey tool employing a purposive sampling technique to target stakeholders within the EV ecosystem. The results of this survey highlight several key findings. Stakeholders express a strong preference for alternatives to traditional plugin charging methods. Additionally, cybersecurity emerges as a paramount concern, underscoring the critical need to address potential vulnerabilities in EV systems. This study highlights obstacles and possible pathways for developing the EV ecosystem. Moreover, these insights can guide policymakers, industry leaders, and researchers to shape effective strategies and regulations. By incorporating stakeholder perspectives and leveraging emerging technologies, the EV ecosystem can be fortified to accelerate widespread EV adoption and meet sustainability goals. Finally, this study paves the way for more comprehensive research, including in-person interviews.

1. Introduction

Electric vehicles (EV) are viewed as a promising alternative to internal combustion engine vehicles (ICEV) that emit harmful gases (Ehsani et al., 2021; Un-Noor et al., 2017b). Due to policies supporting EV adoption, rapid development is expected in the next 10-30 years, influencing transportation's future (IEA, 2023). Government support and technological progress have propelled the EV industry, with the number of EVs in the United States steadily increasing since 2010. As of 2021, over 1.8 million EVs are registered in the country (IEA, 2021a). The US is committed to electrifying transportation, with the Biden-Harris Administration aiming for EVs to make up 50% of new vehicle sales by 2030 under the Bipartisan Infrastructure Law. Furthermore, $7.5 billion will be allocated for EV charging infrastructure and over $7 billion for supply chain materials used in battery and vehicle component production (whitehouse.gov, 2021b). EVs are transformative and impacting transportation, the energy sector, and society.

An immediate example is the emphasis on transitioning the current electricity mix from fossil fuels to renewable energy sources (RES). This transition aims to reduce carbon emissions from electricity production and meet the increased demand for vehicle charging (Colmenar-Santos et al., 2019; C. Jin et al., 2014). In addition, due to the increased electricity demand, smart grid integration will become essential for grid stability and security.

However, recent global events in the past few years have impacted EV growth. The COVID-19 pandemic severely disrupted the EV and automobile industries. Lockdowns and travel restrictions hindered the workforce, compelling many to work from home. Global affairs include the Russo-Ukrainian War, which has caused a sharp increase in gas prices worldwide (Mbah & Wasum, 2022). Such events have disrupted the supply chain and led to price hikes for vital EV materials like nickel and lithium (Hockenos, 2022; Lavelle, 2022). Furthermore, several European nations are advocating for restrictions on petroleum imports from Russia (Patt & Steffen, 2022). This disruption in global supply chains has heightened the discussion on energy security, renewable energy, and vehicle electrification. Beyond electrifying smaller passenger vehicles, prominent transportation and freight vehicles, including buses, delivery vans, and heavy-duty trucks, are adopting various energy methods. Many passenger buses worldwide utilize alternative fuels, such as propane, hydrogen, biodiesel, ethanol, and electricity, yielding success (Alternative Fuels Data Center, 2021b). Transport giants like Amazon, FedEx, and UPS have also electrified some of their smaller vehicles. Nevertheless, vehicle electrification poses

challenges for heavier vehicles as the battery requires longer fueling times. Additionally, from a logistical standpoint, thorough planning and infrastructure are necessary for this method to be reliable. In exploring these options, it is conceivable that electrification may not be suitable for certain vehicle types, prompting the exploration of alternative fuel methods.

A robust EV ecosystem is crucial to support EVs in society, and each part must be optimized for success and stability (Agbesi et al., 2023). In a vast country like the United States, distinct needs and requirements for EVs are likely across different regions. The EV ecosystem also drives societal and environmental changes viewed as solutions for a sustainable future.

As previously noted, EVs are a transformative technology, warranting an assessment of current and future prospects, developmental trends, and overall perceptions of the EV ecosystem. Surveys are valuable for efficiently gathering substantial data to measure preferences, intentions, attitudes, and opinions. Research surveys gauging views on various aspects of EVs have gained prominence. For instance, some surveys look into participants willingness and intent to purchase an EV (Carley et al., 2013), their perception of EVs and views on battery swapping (Bobanac et al., 2018), or their perception of EV charging services (Dorcec et al., 2019). This study aims to survey stakeholders in the EV ecosystem to gauge current attitudes toward the diverse elements involved, building upon previous work related to establishing a sustainable EV ecosystem (Agbesi et al., 2023). This work differs from the previous work in that we now highlight some of the major implications and possibilities that may unfold in the near future due to the presence of EVs, taking into account stakeholder perspectives. Comparatively, we also heavily emphasize exploring the financial aspects of EVs and the retrofitting market, which is unique. Additionally, this study adds to the literature by offering an evaluation of the future of the EV ecosystem in the United States, a comprehensive perspective not previously undertaken. Moreover, it will furnish many considerations for sustainable EV ecosystem development and provide a framework for future work in academia and practice.

2. Ecosystem Theory

The research literature shows a wide variety of ecosystem types, as explained by Cobben et al. (2022) and Thomas & Autio (2019). However, the innovation ecosystem most aptly characterizes the EV ecosystem framework. The ‘innovation ecosystem’ consists of different actors, activities, institutions, and relations used to develop the innovative performance of the

actors and focal firms (Granstrand & Holgersson, 2020). In Kapoor's (2018) work, the author emphasizes that the innovation, or the focal offering, can be broadly or narrowly defined. For this research, we use a broad innovation: the electric car or EV. In the EV ecosystem, there are multiple developmental areas, and we want to observe the technological trajectory within each domain. Innovation ecosystems exhibit interdependencies and complementarities and advancements in one sector of the ecosystem often influence or necessitate improvement in others. This concept is akin to the backward linkage effect that Hirschman (1958) developed and permeates throughout the discussion. The following research focuses on the power grid, electricity, incentives, the future of charging and battery technology, automation, software, and sustainable materials.

3. The Importance of Stakeholders and Stakeholder Opinions

3.1 Stakeholder/ Actor Importance

Stakeholders play a crucial role in any business market. Freeman (2010) defines stakeholders as “any group or individual influenced by or that can affect the achievement of an organization’s objectives” (pg. 46). In the EV ecosystem, key stakeholders, including governments, suppliers, and the public, significantly impact the success of the EV industry/ecosystem is dependent on their involvement and efforts (Bakker et al., 2014; C. Lu et al., 2014b). In Bakker et al.'s (2014) paper, the authors elaborate that in the future, the success of the EV industry’s sustainable development will be dependent on whether key stakeholders remain committed to their involvement and efforts. In some cases, the advancement of the EV industry poses a threat to their vested interest, which could cause them to withhold effort into the EV ecosystem. For example, the sale of EVs will eventually lessen the sale and demand for gasoline and diesel. Therefore, stakeholders participate in the development of the emerging EV ecosystem to be informed of the potential positive and negative impacts of the EV ecosystem on their interests and, ultimately, to be able to make use of the opportunities and lessen the threats (Bakker et al., 2014). In Cao et al.'s (2021) work, the authors propose a stakeholder engagement system to analyze the driving forces behind EV industry development and the necessary stakeholder commitments. Key driving factors include addressing environmental concerns, energy security, decarbonization, and technological innovation (Coffman et al., 2017).

Stakeholders in the EV ecosystem must be committed to implementing policy changes, incentivizing EV adoption, and expanding charging infrastructure to drive broader societal acceptance (Wolbertus et al., 2020). Prominent stakeholders in this context are EV companies (e.g., Tesla and Rivian) and EV charging suppliers (e.g., ChargePoint and Blink Charging). Additionally, national and local governments play a vital role in facilitating and incentivizing EV ownership and constructing charging infrastructure. Federal agencies like the Department of Transportation and the Department of Energy collaborate with universities nationwide to conduct research and assess trends in the EV. Power utility companies (e.g., Duke Energy, Dominion Energy) are responsible for generating the electricity necessary to power EVs. Furthermore, advocacy groups focused on EVs, and green energy exert significant influence, advocating for the adoption of EVs and bringing forward issues and ideas that can shape the development of the EV ecosystem.

3.2 Opinions on Charging

Plug-in charging is the most widely favored method for EVs. However, this dynamic landscape is witnessing the emergence of diverse charging approaches like battery swapping, wireless charging, and inductive power transfer. The development and implementation of charging infrastructure have become a subject of debate among stakeholders (Wolbertus et al., 2020). The availability of charging infrastructure, specifically fast-level chargers, is pivotal in alleviating range anxiety. Nevertheless, plug-in charging is inconvenient even at its fastest levels compared to gas refueling, which typically takes less than 5 minutes, while fast-level charging demands up to 30 minutes to reach an 80% charge. Some facilities, however, offer a sufficient charge in just 10-15 minutes (Ramey, 2022a). Battery swapping is a viable alternative ensuring a full charge in just minutes, ideally suited for highway refueling where charging speed is of the essence (Wu et al., 2015). However, this method is not without its drawbacks. Charging post-swap takes time, necessitating a substantial stock of batteries at larger swapping stations, which comes with a high initial cost (Chau, 2014). Comparatively, wireless charging is more convenient than plug-in charging as drivers only need to position the vehicle over the charging element. The wire-free setup minimizes vandalism risk and accidental damage and reduces electrical hazards (K. Song et al., 2023).

3.3 Incentive Measures

Government incentives play a crucial role in encouraging EV adoption. These incentives can come from both federal and state levels and other entities, like utility companies, aimed at supporting EV owners. European countries display this, especially Norway, which has the highest percentage of EV penetration of any nation. Many of the incentives in Norway include the no purchase/import tax on EVs, exemption from 25% VAT on the purchase, no annual road tax, and no annual road tax, amongst others (Aasness & Odeck, 2015; Figenbaum & Kolbenstvedt, 2013). With the largest EV market, China has also effectively employed incentives to drive adoption. Reports indicate that individuals in China choose to purchase EVs due to their direct benefits, even without factoring in available incentives (Wakabayashi & Fu, 2022). This stands true as these incentives may be subject to reductions or discontinuation in the future. However, until the pricing and production of EVs are comparable to ICEVs, incentives will be necessary to help combat the purchase price (Assum et al., 2014). In Santos & Davies's (2020) research, the authors conducted a questionnaire to gauge the impact incentives had on EV uptake in Germany, Austria, Spain, the Netherlands, and the UK. The study showed that nearly ¾ of the respondents to the survey felt that purchase subsidies and tax incentives positively impacted EV adoption.

3.4 Grid Stability

The penetration of EVs will inevitably impact the grid as the demand for electricity increases. Additionally, the amount of pressure the grid will face depends on how soon the power grid can be upscaled. The current power grid cannot fulfill the current and future needs of the 21st century, and upgrading to a smart grid will be very challenging (Gungor et al., 2010). Aging grid infrastructure is a primary motivator for implementing smart grid technology. Many of the shortcomings of conventional grid systems include unreliability, major blackouts, high transmission losses, poor power quality, inadequate electricity production and supply, and discouraging the integration of distributed energy sources (Parvin et al., 2022; Saidani Neffati et al., 2021). The upcoming smart grid is agreed upon to help reinforce and stabilize the grid (Bakker et al., 2014). Smart grid technology has undergone several recent technological developments, as described by Butt et al. (2021). The authors lay out some of the frameworks required for a smart grid to succeed and describe a successful smart grid as reliable, secure, has significant management and metering systems, and can self-heal. Communication is also a key

component, as large amounts of data will be generated, and cybersecurity will be an integral part of the smart grid and the entire ecosystem. The self-healing aspect of the smart grid seems to be a vital part of the advancement. This ability allows the grid network to sense, control, and communicate to help troubleshoot unforeseen events (Ambort, 2020). Severe weather and other natural disasters present the opportunity for possible infrastructure damage, but with this ability to respond and anticipate natural disasters, the impact of such events can be mitigated. Fast charging capabilities are among the most important factors in the smart grid, as this will put the most strain on the grid.

3.5 Battery Materials

The battery is arguably the most critical element of an EV, and the success and perception of EVs fall on the battery performance. Battery technology is also the leading solution for supporting renewable energy sources and grid decarbonization for energy storage (Bonsu, 2020). Lithium is the most popular EV battery material due to its lightweight and high energy density properties. However, there are concerns mainly stemming from pollution during the extraction process and the high cost of the material. Other critical metals in EV batteries, such as cobalt, manganese, and nickel, share the same sentiment (Cano et al., 2018). These characteristics make lithium batteries desirable for other applications, as billions of mobile phones, laptops, and tablets worldwide rely on lithium batteries (Costa et al., 2021). However, lithium reserves are limited, and the growth and demand of lithium production could potentially reduce natural resources. Reusing and recycling batteries present some of the largest sustainability benefits as lithium battery recycling can help to preserve resources and reduce waste volume, and in certain scenarios, it is possible to experience a 51% decrease in natural resource savings (Makuza et al., 2021; Neumann et al., 2022). Outside of use in EVs, spent EV batteries can be utilized in second-life applications such as energy storage for renewable and stationary energy systems. An alternative to lithium is sodium, a premier candidate material for energy storage in EVs and stationary storage systems due to its high abundance and low cost (Hernández et al., 2022; Z. Lu et al., 2022). However, the tradeoffs must be assessed and weighed thoroughly since sodium batteries are less energy-dense and will take a few years of development before commercialization.

3.6 Retrofitting & ICEV Recycling

ICEV transportation contributes significantly to greenhouse gas emissions, accounting for 27% of the U.S. greenhouse gas emissions in 2020, with over 80% of which came from road transport (U.S. EPA, 2022). In the next two decades, the diffusion of EVs can help to reduce the greenhouse gases emitted by the transportation sector. Even with the diffusion of EVs and reduced ICEV sales, the transition from combustion vehicles raises questions about the fate of millions of existing vehicles. Many vehicle owners will continue driving combustion vehicles as long as no ban exists. Additionally, concerns arise about the eventual accumulation of vehicle waste and how to manage the materials from these older vehicles. A possible solution to reduce car waste could be vehicle retrofitting. Current research on EV retrofitting is sparse, but this area is growing. Many of the documented cases of retrofits are done by freelancers, hobbyists, and small local shops specializing in combustion vehicles to EV conversion. In the US, there does not appear to be any regulatory standards on the federal level for conversion, but most likely, there are standards that shops adhere to during the conversion process. Watts et al. (2021) propose that a regulatory framework should be established to ensure high levels of safety and good practice. In addition, this has several impacts for users who choose this conversion, as full EV retrofits are no longer subject to certain taxes and fees applied to combustion vehicles. A study by Santis & Regis (2021) compared the economic and environmental impact of combustion and retrofitted vehicles and found that the carbon emissions of combustion vehicles were significantly higher than those of retrofitted vehicles. Additionally, there is a significant potential for savings in fuel costs; however, the conversion cost, while cheaper than an EV purchase, may not be appealing enough. Recycling is a solution, as car metal extraction is an established process for extracting metals from end-of-life vehicles. The Automobile Recycling Association reports that each year in the US, 12 million end-of-life vehicles are recycled, and 80% of the material can be recycled and reused. In addition to that, more than 18 million tons of steel is melted down and reused in the automotive industry (Sinai, 2018). With an influx of used cars and car parts, the possibility of reusing car parts in future vehicles has become favorable. This could introduce a circular economy to the automobile industry that can help extend a product's life and enhance sustainability (Wurster, 2021).

3.7 Automation/Technology/Safety

Automation, specifically vehicle autonomy, is a highly discussed topic and is expected to be a revolutionary technology in the next few decades (Kang et al., 2016). Many EV brands already have some level of autonomous capabilities, and brands like Tesla have fully autonomous cars. Rideshare companies like Uber and Lyft and startups like Halo are also experimenting with autonomous vehicles that passengers can request. Introducing such an idea offers a solution to several of the issues that large cities endure when reducing emissions, congestion, parking demand, and rider cost (Millard-Ball, 2005). However, the potential social advantages make autonomous vehicles (AV) appealing, and technical, social, and regulatory issues must be changed. Pettigrew & Cronin (2019) conducted a qualitative analysis of stakeholders' opinions regarding the perceived benefits of AV technology. The analysis found that the most commonly mentioned issues were accident reduction, increased mobility for the elderly and disabled, and reduced congestion. Martinho et al. (2021) found a positive outlook on AV technology through a thorough literature search that investigated the opinions of AV in technical and business reports. Even so, there are many controversies and issues associated with such vehicles. Among them are safety, cybersecurity, common good, sustainability, hidden costs, fairness, and non-discrimination (Martinho et al., 2021).

4. Methodology

A survey was developed through SurveyMonkey, an online survey tool, to research and collect data from individuals and stakeholders within the EV ecosystem. The study aimed to gain insight into how stakeholders within the EV ecosystem feel about future technologies, gauge the stakeholders' knowledge, and figure out possible trends for the EV ecosystem. The questionnaire consisted of 24 questions, 22 of which were five-point Likert scale (“strongly agree to strongly disagree”) and two ranking questions. To ensure we received quality data for the questionnaire, we targeted the survey toward stakeholders within the ecosystem at the middle, upper, and senior management levels and operations. We were also curious about the level of influence each person had, as this would tell us what type of decision-making each individual had in the EV ecosystem. People who did not meet the work level criteria and had no influence in the EV ecosystem were eliminated. Within the survey, there was a key focus on power grid capabilities

and electricity, incentives, the current and future state of EV charging, battery technology, and more.

The questionnaire was distributed from October 5, 2022, to October 6, 2022, to 103 participants. We employed purposive sampling, which is advantageous for this study as it can help researchers gain insight from individuals who fit a specific set of criteria (Mikecz, 2012). Sixty-seven user surveys were deemed usable for this research, a 75.1% success rate. The goal was to seek influential stakeholders in the ecosystem. The validity of survey results can be increased by including stakeholders involved in the processes under review in the survey. These individuals will be most knowledgeable concerning the services and products offered to consumers, especially for those in senior or middle-level management. For this reason, we considered individuals who fit these distinctions to be influential stakeholders. To determine which survey participants match these criteria, we asked the following questions, as shown in Figure 6. Additionally, entry-level employees with significant decision-making roles in EV adaptation were included in this category.

	CHOICE			
Q1: "What best describes your job level within your company?"	Senior Management	Middle Management	Operations	Entry Level
	Qualified	Qualified	Qualified	Go to Question 2

Q2: Rate your influence over operational decision-making with the adaptation of electric vehicles.	Strong Influence	Influence	Little Influence	No Influence
	Qualified	Qualified	Qualified	Disqualified

Figure 6: Criteria used to determine the influential stakeholders

It should also be noted that surveys are valuable and efficient for obtaining relevant data and opinions; it is important to acknowledge the limitations of Likert scale surveys. Specifically, online surveys are prone to nondifferentiation or straightlining, which occurs when respondents rush through the survey by selecting the same answer or nearly identical responses throughout

the survey (Qualtrics, 2018; Yan, 2008). This behavior may stem from a desire to obtain the offered incentive or promptly fulfill the survey requirement. Considering these factors, we still have confidence that the collected data is substantial and offers valuable qualitative insights for analysis.

5. Results & Discussion

5.1 Reliability analysis and Statistical Analysis

The Cronbach's α coefficient checks the internal consistency among items. The acceptable value for Cronbach's α is above 0.70 (Bonett & Wright, 2015), and the results of the Cronbach test are shown in Table 6. The alpha score of each factor is within 0.760–0.928 except for Charging Tech which only had three items, otherwise the scores for each item suggests strong consistency.

Table 6: Results of the reliability analysis.

Element	Cronbach's α	Item
Grid Capabilities (GC)	0.761	**6**
Incentives and Pricing (IP)	0.596	3
Charging Tech (CT)	0.776	6
Sustainable Materials (SM)	0.818	7
Entire Sample	0.927	22

A bivariate analysis was used to examine the relationships between variables. Table 7 contains the correlation matrix of the measures. The bivariate correlation matrix in Table 7, showed all of the independent variable construct had a positive and significant correlation at $p < .01$.

Table 7: Bivariate correlations of constructs.

		GC	IP	CT	SM	EV Diffusion
GC		1				
IP		.755**	1			
CT		.828**	.681**	1		
SM		.806**	.702**	.734**	1	
EV Diffusion		0.092	.241*	0.103	0.087	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

To test the relationship between the dependent variable (EV Diffusion) and the independent variables we employed a multiple regression analysis was used to see there is any correlation

between the item constructs and EV Diffusion based on the 4 item constructs. Table 8 shows that R is 0.167, R square is 0.028 and adjusted R square is -0.014. This model is considered as a poor fit since it fails to explain the variance in dependent variable. The results of the multiple regression are found in Table 8. Nevertheless, there is meaningful discussions surrounding the item constructs that are found in Section 5.2.

Table 8: Model of Best Fit

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.167[a]	.028	-.035	.82243

Table 9: Multiple regression Analysis of EV diffusion.

		B	Std. Error	Beta		
1	(Constant)	4.100	.603		6.795	<.001
	GC	-.159	.295	-.149	-.539	.592
	IP	.280	.223	.249	1.257	.214
	CT	-.051	.260	-.045	-.195	.846
	SM	-.081	.250	-.071	-.323	.748

a. Dependent Variable: EV Diffusion

5.2 Government Incentives and Finances

We asked participants to rank the given criteria in the ranking section. A rating of 5 indicates the highest level of influence or preference, while a score of 1 indicates the lowest. We computed the average score to assess the favorability or relevance of each item. A higher score signifies that the factor holds a more significant sway over the participant's decision-making process.

In our questionnaire survey, participants responded to five questions concerning the influence of government incentives and financial aspects. Two of these questions involved ranking, as shown in Figure 7 and Figure 9. In Figure 7, respondents identified the federal tax credit for EVs as the most impactful government incentive. Given that vehicle costs are a significant barrier to EV adoption, this incentive aims to alleviate some financial burdens (Larson et al., 2014). To help combat high vehicle prices, President Biden signed the Inflation Reduction Act (IRA) into law in August 2022, allocating $370 billion towards climate and clean energy provisions. This funding will expand tax credits and incentives, supporting the EV supply chain and charging infrastructure (Slowik et al., 2023). Consumers who want to purchase EVs

are eligible for up to $7500 worth of tax credits for new EVs and up to $4000 for a used EV. In 2024, the discount will be applied at the time of purchase for the vehicle (Barry, 2022). However, it's worth noting that several stipulations are associated with claiming this credit, which may lead to debates over its long-term importance and effectiveness.

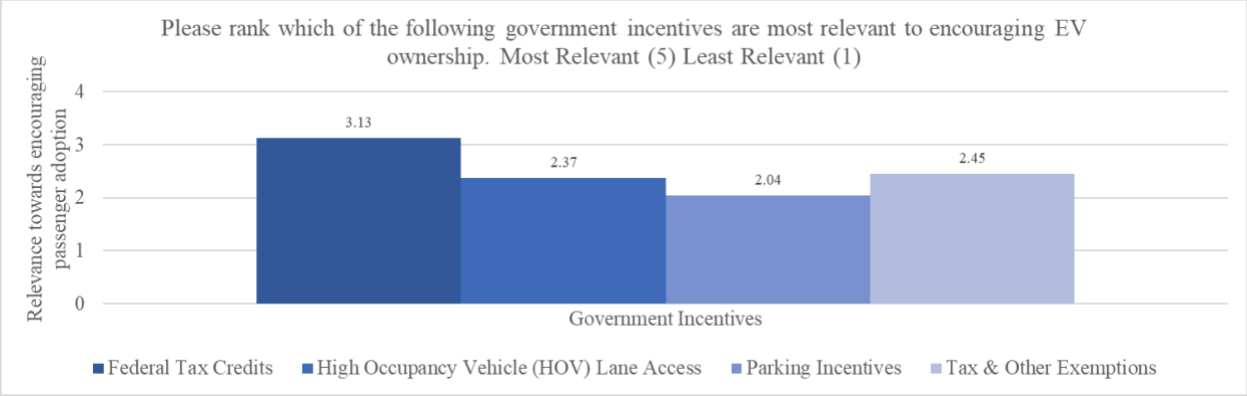

Figure 7: Average ranking of the most impactful incentives to encourage EV ownership.

Incentives are also available on the state and local levels, and private companies operating in the EV sector offer their own incentives. Considering that the survey respondents came from various regions across the US, certain incentives may hold varying levels of appeal depending on each location. For example, access to the high occupancy vehicle (HOV) lane is a notable incentive, but it is only available in 20 states. Furthermore, of the 20 states, only nine permit alternative vehicles to use these lanes. Highlighting the necessity of incentives, a study by Sierzchula et al. (2014) analyzed the EV markets of 30 countries. It concluded that the number of charging stations and the availability of financial incentives were the most effective and predictive factors for EV adoption. A 2016 report by the Argonne National Laboratory reviewed 18 studies examining the impacts of incentives and policies on EV adoption in the US. Among the most impactful incentives were the purchase rebate, tax credit, sales tax waiver charging availability, and HOV exemption (Y. Zhou et al., 2016). Norway and China stand out as successful nations boasting some of the highest percentages of EV adoption and the total number of EVs. These nations have a longstanding history of initiatives aimed at increasing adoption. Norway, for instance, has a well-established incentive system for EV owners, including exemptions from specific vehicle-related taxes and tolls and access to free parking spaces (Mersky et al., 2016). In 2009, China launched several projects and policies to promote New Electric Vehicles (NEV) throughout several pilot cities. Coupled with these initiatives were subsidies that helped lower

the purchase price of vehicles, resulting in substantial growth across the demonstration cities (Yuan et al., 2015).

Q1. Do you think government subsidies for EV purchases in the US (vehicle purchases, home charging, commercial charging) will be critical for advancing the EV ecosystem?

In Figure 8, three Likert scale questions were used to gauge stakeholder perspectives on government incentives and financing. As we discussed earlier, incentives are pivotal in driving EV adoption. They also extend support to commercial and residential properties in EV integration. Over 70% (n=47) of the respondents believed that government intervention is essential for forwarding the EV ecosystem. Without such financial backing, progress in the EV ecosystem might be hindered. This assistance comes mainly through grants and funds for increasing charging along major highway networks and key locations. In European nations, local governments provide incentives for charging infrastructure when the private market is less likely to invest (Hall & Lutsey, 2020). They assist with the installation and labor costs in apartment buildings and offer subsidies for home charging for taxi drivers. In the past, the US federal government provided a 30% reduction on home EV charging stations and associated installation expenses. Numerous state-level incentives and rebates further support individuals in purchasing and installing EV charging stations. Government aid will also be crucial in building the necessary EV infrastructure to instill confidence in current and potential EV owners. While firms generally acknowledge the importance of subsidies, Costello (2023) notes the potential downside for government-subsidized electrification, which could negatively impact society. Some argue that current taxpayer-funded subsidies may disproportionately benefit higher-income households. Additionally, though past green energy subsidy programs have shown success, they have also faced criticism due to prominent failures and bankruptcies in the industry. Due to these failures, evaluating the advantages of these subsidies and ensuring better business decisions is crucial (Jung & Feng, 2020).

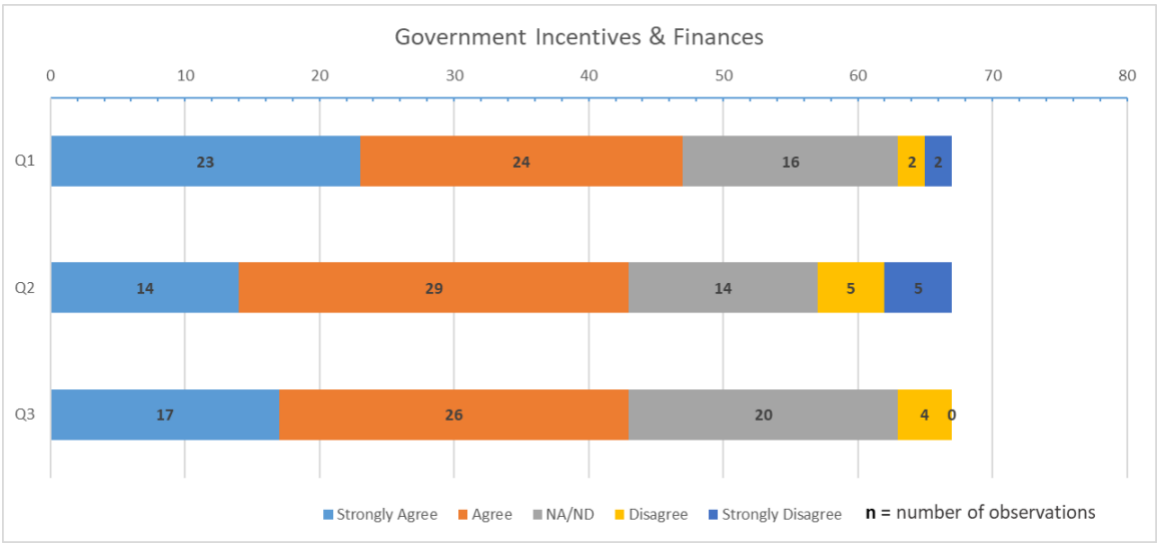

Figure 8: Stakeholder opinions toward governmental and financial institutions influence.

Q2. In the next ten years, do you believe there will be deterrents set by the government, banks, and other financial institutions to people looking to purchase combustion vehicles? (Ex. Cease to give auto loans for CVs, heavily taxing the sale of a CV)

To further investigate changes in EV financing, we asked participants whether they foresee financial institutions offering loans for ICEVs in the next decade. An overwhelming 64% (n=43) agreed that financial institutions would likely impose restrictions on ICEV purchases. Many global governments have committed to phasing out the sale and registration of ICEVs, prompting financial institutions to potentially adjust their eligibility criteria for vehicle financing (Wappelhorst, 2021). Table 9 provides an overview of planned international bans on specific vehicle types. Internationally, certain banks have begun discontinuing loans for ICEVs. Bank Australia intends to cease loans for new ICEVs to encourage greater EV uptake as early as 2025, although they will still be available for used models (Frangoul, 2022). Phasing out ICEVs has gained traction in the US, but the timeline for implementation will vary by state. In California, the goal is for all new passenger vehicles to be zero by 2035 (Wappelhorst, 2021). Prominent financial institutions like Bank of America and Wells Fargo expressed commitments to environmental sustainability. However, it remains uncertain when they will extend this commitment to discontinuing loans for ICEVs. Nonetheless, as per President Biden's executive order, a shift is expected to occur within the next 10-15 years, ending combustion vehicle purchases by 2035. Another tactic is a substantial increase in the sales price of ICEVs. Denmark,

for instance, imposes a 180% tax on ICEVs (Towoju & Ishola, 2020). This shift will likely drive greater EV adoption, coupled with the potential tax reduction for EV owners and continuing long-term tax benefits. Plötz et al. (2019) argue that in their present form, ICEVs might be ineffective as their usage will still be permitted, and there appears to be no clear enforcement or implementation mechanism in place. Furthermore, the strong ideological differences between the two major parties complicate the implementation of bans. Instituting these bans will hinge on the current administration's stance in office determining whether to hasten or delay ICEV phase-outs. Some politicians and citizens oppose EVs due to economic implications. In early 2023, Wyoming introduced legislation to initiate an approach that will eliminate new electric vehicle sales by 2035, citing the state's robust oil and gas industry as a primary source of employment. The bill also emphasizes the vast stretches of highways and limited charging infrastructure, deeming statewide EV use impractical.

Table 10: ICEV bans announced worldwide.

Coverage	**Start Year**	**Ban of Diesel vehicles**	**Ban of Gasoline Vehicles**	**Ban of Hybrid Vehicles**	**Limit**	**Status**
Norway	2025	Yes	Yes	Yes	New Sales	Target
Israel	2030	Yes	Yes	-	Car Import	Planned
Ireland	2030	Yes	Yes	-	New Sales	Planned
India	2030	Yes	Yes	-	New Sales	Target
Denmark	2030	Yes	Yes	-	New Sales	-
California	2035	Yes	Yes	-	-	-
Los Angeles	2030	Yes	Yes	Yes	Driving	Target
New Jersey	2035	Yes	Yes	Yes	?	-

Adapted from "Designing car bans for sustainable transportation." by Plötz, P., Axsen, J., Funke, S. A., & Gnann, T. (2019) *Nature Sustainability, 2(7)*, p. 535, Springer Nature, reproduced with permission from SNCSC.

Q3. GREEN AUTO LOANS are similar to traditional car loans but typically offer lower interest rates and longer repayment terms. Do you foresee financial institutions offering other innovative EV financing plans to encourage EV adoption?

As the availability of auto loans for ICEVs diminishes, an increase in diverse financing options for EVs is anticipated, alongside innovative measures to boost adoption. Of the participants, 64% (n=43) foresaw financial institutions broadening their opportunities for EV financing. However, nearly 30% (n=20) of participants expressed uncertainty. Green auto loans, primarily provided by credit unions and online lenders, cater to eco-friendly vehicles like hybrids, hydrogen fuel, and battery electric vehicles. Some startups and small companies offer innovative financing plans. Notably, EV companies collaborate with banks to extend financial services to customers. Lucid Group Inc., a luxury EV brand, unveiled a servicing program with Bank of America, which includes leasing and loan options and additional user benefits. Bank of America's loan options for EVs mirror those of traditional vehicles. Car subscription services are gaining traction, and the business model is relatively new. Table 10 highlights some of the available offerings. Autonomy, for instance, offers a subscription-based leasing program for Tesla vehicles. Instead of loans, users commit to a minimum 3-month term and subsequently pay a monthly fee for as long as they wish to drive the vehicle. The subscription covers maintenance, roadside assistance, and tire replacements. It offers flexibility without the entanglements of a long-term commitment, often resulting in lower short-term expenses than an outright purchase. However, some may find the initial start fee and ongoing monthly payment unappealing. Several automotive giants such as Porshe, Cadillac, Lexus, and many more offer subscription-based vehicle plans but are limited to specific locations. Fisker, an upcoming California-based EV, also offers a subscription-based service for its vehicles.

Table 11: Available EV and car subscription services.

Subscription Service	**Start Fee***	**Monthly Payment***	**Term**	**Availability**	
Autonomy	$1000- $5,900	$490-$1000	3 Month Min.	CA, WA, FL	
Steer EV	No fee	$999	Not specified, but no long-term commitments	Ontario, British Columbia	TX, Fl MD, VA, D.C.
T4L	Requires inquiry	Requires inquiry	24 Month Min	FL	
Fisker – Flexee Lease	$2,999	Starts at $379	No set term	-	
Borrow		$199-$1099	9 Month Min.	Los Angeles	

*Prices may vary based on the vehicle model. Data from the graph was obtained from the company websites. (Autonomy, 2022; Barry, 2022; Fisker, 2023; T4L, 2022)

Participants identified the primary obstacles to EV adoption as the lack of charging infrastructure and range anxiety illustrated in Figure 9. The participant response underscores the crucial role of available charging infrastructure in driving EV adoption.

Vehicle pricing emerged as the third most significant barrier to widespread EV adoption. Admittedly, EVs are costly in the US. Given the preference for larger vehicles in America, the added expense for large EVs can dissuade potential buyers. Potential solutions may involve shifting towards smaller vehicle models, manufacturers, and researchers exploring cost-effective materials and streamlined features. Additionally, the expense of EVs is attributed to the high cost of the battery component, which is projected to decrease across various vehicle models over the next decade (Mauler et al., 2021; Zheng et al., 2022). This trend is anticipated to drive down overall vehicle prices. Many EVs are equipped with an array of in-built features that enhance safety and comfort. However, to make vehicles more accessible, manufacturers of the driver and passengers. However, EV manufacturers may consider streamlining these features to make vehicles more affordable for consumers. This approach mirrors the distinction between iPhone Pro models, which offer larger sizes, increased storage, and advanced features compared to base models.

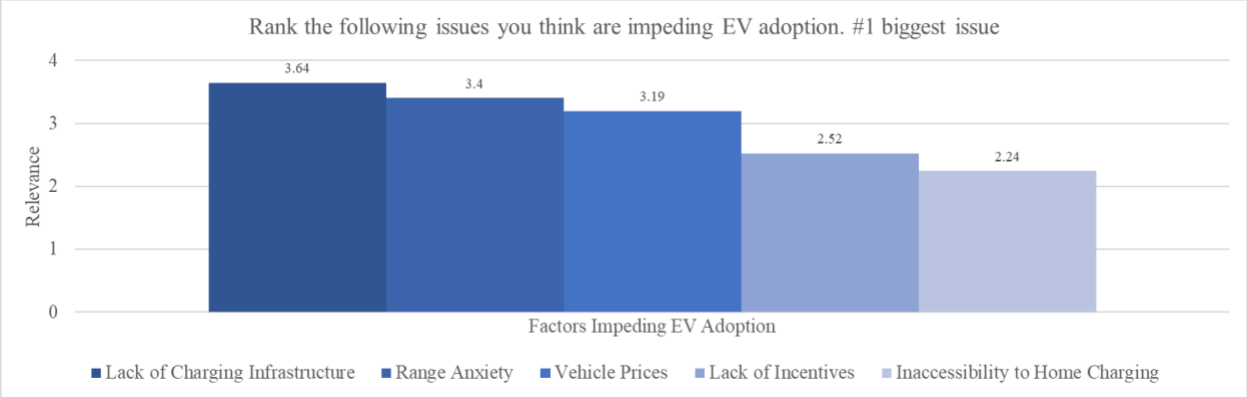

Figure 9: Average ranking of the biggest impediments to EV adoption.

5.3 Grid Capabilities and Electricity

Q1. Recently, California faced a massive heat wave that put a strain on the state's power grid, so citizens were asked to lower their electricity consumption. Do you foresee the power grid having issues supplying and sustaining energy output with the increased electricity demand?

Q3. Do you think electric utility companies in their current state can adequately provide electricity to meet the new demand for electricity from EVs in addition to the societal demand for electricity?

Stakeholder opinions on the current grid, electricity capabilities, and pricing are shown in Figure 10. Q1 and Q3, though distinct, share a similar discussion, prompting a combined discussion. Q1 focuses on the present state, while Q3 addresses the outlook. A striking 82% (n=55) of participants agreed that the power grid may struggle to sustain the heightened energy demand brought on by the increasing prevalence of EVs. The electric grid, a complex network that supplies power to various essential sectors, faces the challenge of meeting the demands for charging and daily societal needs. In California, for example, due to a massive heat wave, citizens were asked to conserve electricity to alleviate the strain on the grid (State of California, 2022). This event is troubling and indicative of potential challenges, especially considering California has the highest EV penetration in the US. Therefore, the power grid needs a massive upgrade and improvement to accommodate the influx of EV owners seeking to charge their vehicles and prevent grid instability. EVs can exert several adverse effects on the grid, as Das et

al. (2020) outlined. Additionally, potential power loss and stability issues underscore the importance of proper EV integration. However, the gradual adoption of EVs offers a crucial advantage—the opportunity to implement essential grid upgrades, including introducing smart grids and renewable energy sources. This integration also holds potential cost benefits, as renewable energy sources can offer electricity at a lower cost amid rising fuel prices. Improved power management, quality, and reduced carbon emissions are among the additional advantages.

Opinions on the capability of electric utility companies to meet electricity demand were divided. While 46% (n=31) believed the current providers were sufficient, 54% (n=46) expressed uncertainty or lacked confidence in meeting societal needs. The surge in global electricity demand in 2021 strained power systems worldwide (IEA, 2022a). Much of the electricity in the US is generated from fossil fuels, constituting over 60% of total production (EIA, 2021). To maximize the benefits of EVs, it is crucial to derive electricity from sustainable sources. However, this transition is a formidable task given the stability and consistency of fossil fuels, which currently dominate the US energy landscape. The existing infrastructure is optimized for fossil fuels, necessitating significant investments for a shift. Despite uncertainties, electric utility companies are gearing up for electrification. The National Electric Highway Coalition (NEHC), comprising over 60 electric companies and cooperatives, is dedicated to establishing fast-charging stations along major US travel routes. Integrating renewable energy sources (RES) into the electric grid holds the potential for heightened electricity production but presents challenges. This shift would demand substantial infrastructure for power generation and an upgrade of the current grid. Additionally, intermittent energy sources like solar and wind energy pose unique issues.

Q2. During high electricity demand, Vehicle to Grid (V2G) technology enables fully charged vehicles to feed stored energy back into the grid, lowering the cost of electricity at peak times and compensating EV owners. Do you think that V2G can supply power back to the grid to alleviate peak demand?

Vehicle to Grid (V2G) technology is a relatively new technology that enables EVs to return stored energy to the electrical grid. Its primary purpose is to help relieve peak demand and

enhance grid management during EV charging. The survey revealed that 63% (n=42) of respondents have confidence in V2G as a viable solution for peak demand. The surge in EV adoption and the need for fast charging will present challenges to existing grid infrastructure. Peak demand times strain the grid due to heightened electricity consumption. However, V2G-enabled vehicles can discharge power, relieving this strain and stabilizing the grid (T. Li et al., 2021)—the success of V2G hinges on its widespread implementation. Interestingly, 37% (n=25) of participants remained uncertain about V2G's effectiveness in reducing peak demand. To achieve this goal, broad participation from EV owners would be crucial. Experts anticipate that V2G and V2H (vehicle-to-home) technologies will be more impactful locally and serve as valuable energy storage for solar roofs and backup power.

Q4. Electricity derived from renewable energy sources (RES) (i.e., solar, wind, geothermal, etc.) in combination with EVs can help to reduce carbon emissions even further. However, due to their intermittent nature, the power produced from these sources can be deficient. Therefore, do you think that RES can be used to supplement the electricity needs for EVs?

RES will be crucial for future energy production, benefiting not only EVs but society. Notably, 61% (n=41) of participants expressed confidence in RES as a supplementary source for powering EVs, with 19% (n=13) uncertain and the remainder in disagreement. The integration of RES into the grid could be complex due to their intermittent nature and energy usage fluctuations. However, EVs can support renewable energy generation, acting as a means of energy storage, thereby improving energy efficiency and reducing costs (C. Jin et al., 2014). While sources like solar and wind offer seemingly boundless energy potential, there are limits to harnessing and storing this power and considerations for energy losses. As of 2022, RES accounted for 19.8% of US electricity production, while fossil fuels represented 61%. RES-derived electricity has the potential to reduce CO2 emissions drastically (Colmenar-Santos et al., 2019). On a local level, homeowners can tap into these resources. Investing in solar roofs can supplement home and charging station power needs, significantly reducing carbon emissions and fostering energy independence.

Q5. The heightened demand for electricity will make electricity prices more volatile daily. Will the fluctuations in electricity pricing negatively impact the EV market?

Rising electricity demand is set to drive up electricity prices, dependent on several factors like region, time of day, electricity production methods, and charging demand. Additionally, average monthly electricity rates are expected to fluctuate from year to year, as outlined in Table 11. Over 70% (n=47) of the respondents believed these fluctuations in pricing could negatively impact the EV market. Prices can surge drastically depending on the time of day, known as dynamic pricing. It involves aligning the price of electricity with the current market conditions, commonly used to encourage scheduled EV charging (K. Zhou et al., 2020). Doing so can incentivize behavior changes among EV owners. Many may avoid high-priced charging periods, emphasizing night charging and overall conservation. However, Ito (2014) challenges this notion in his study, where he found that non-linear pricing was ineffective in achieving any energy conservation or changing consumer behavior. The author elaborates that consumers are more likely to react to the average monthly electricity price rather than understand the intricate price schedule. In the future, to offset these costs, homeowners and EV owners may look to pursue off-grid renewables or standalone systems. These systems operate independently of the electricity grid and can be a useful method that can reduce electricity prices.

Table 12: Average price of electricity by end-use sector (Cents per kWh).

	Residential		Commercial		Industrial		Transportation		All Sectors	
	Apr-23	Apr-22	Apr-23	Apr-22	Apr-23	Apr-22	Apr-23	Apr-22	Apr-23	2-Apr
U.S. Total	16.11	14.71	12.22	11.93	7.62	7.84	12.31	11.26	12.27	11.72

The average price of electricity from year to year by end-use sector in the United States. Data from this table is adapted from Source: U.S. Energy Information Administration (May 2023)

Q6. In the event of a significant natural disaster (hurricane, flash flooding, blizzards), would an all-electric vehicle be a reliable mode of transportation or means of escape?

The reliability of EVs during a significant natural disaster is heavily debated. Only 46% (n=31) of participants agreed that EVs would be reliable in such a scenario. The remaining 54% (n=46) were divided between uncertainty and disagreement. The prominent discussions primarily focus on EV battery performance during major weather events like hurricanes, flooding, and blizzards,

which pose challenges for EV operation, especially as a reliable means of escape. ICEVs hold an advantage due to quick refueling, the widespread availability of gas stations, and their abundance along evacuation routes. Hurricane-induced flooding presents a serious hazard to EVs, which can potentially short-circuit or even catch fire once saltwater infiltrates the vehicle. Florida officials reported numerous EV fires following Hurricane Ida. These fires prove exceptionally challenging to extinguish, requiring 10-12 times more water, and reignition remains a risk (Łebkowski, 2017). To address this, EV manufacturers may design vehicles less susceptible to water intrusion into the battery unit or implement self-extinguishing capabilities. Unpreparedness and negligence can also significantly impact EV owners who fail to charge their vehicles before a storm, potentially forcing them to abandon them. Hurricanes are a primary concern in the southeastern United States, but natural disasters and their challenges will vary by region. Therefore, proper preparation and planning are essential to mitigate losses and malfunctions in the future. EV weather-related issues vary by region across the country. The northeastern and midwestern US experience extremely cold weather, snow, and icy conditions, which can lead to vehicle inoperability and temporary battery life degradation. Encouraging clean hybrids, which can rely on biofuels or gasoline as alternatives, offers a safeguard in the case of battery failure.

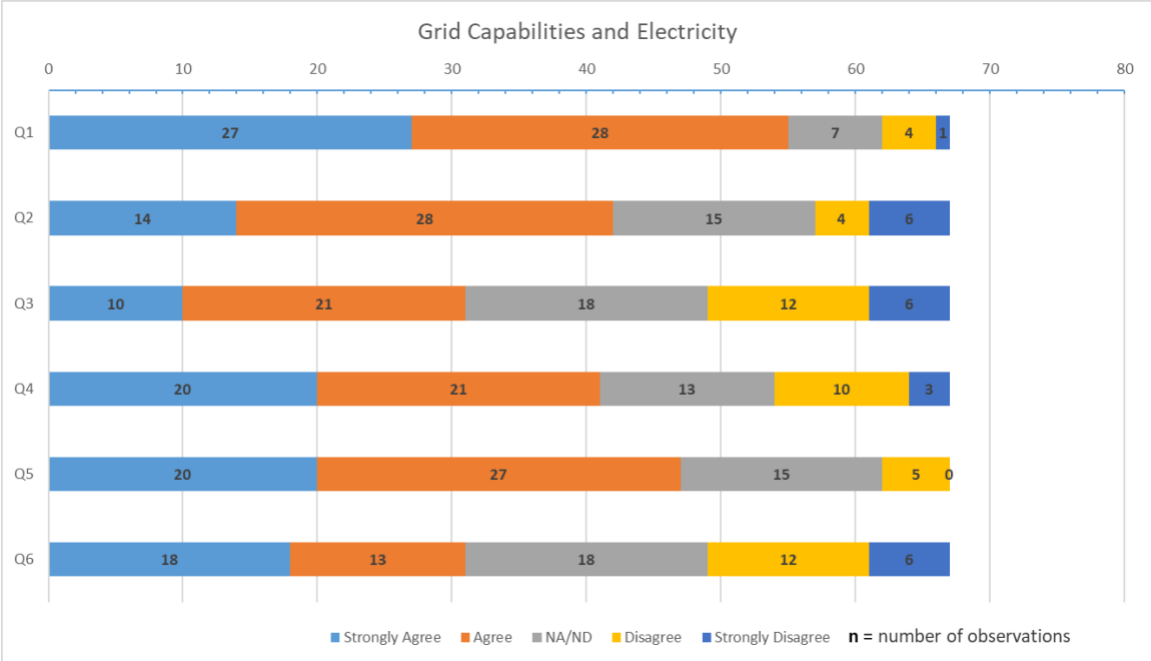

Figure 10:Stakeholder opinions on grid capabilities and electricity.

5.4 Charging & Technology

Q1. The most popular and reliable method of EV charging is plugin charging. Do you foresee significant developments in the current charging technologies and becoming a competitive alternative to plugin charging? (i.e., battery swapping and wireless power transfer)

Plugin charging is the predominant method for EVs, but promising alternatives include battery swapping and wireless charging. Although not as well established, they come with their pros and cons. Survey results for the Charging and Technology section are shown in Figure 11. Around 73% (n=49) of participants anticipate significant developments in EV charging and competitive alternatives to plugin charging. Only about 4.5% (n=3) of respondents doubted the emergence of a solid alternative. Interestingly, 22% (n=15) expressed uncertainty about new charging technologies. This hesitancy is understandable, given that plugin charging is the most established method, having undergone extensive development and production. Comparatively, battery swapping offers faster charging times, taking around 3 minutes for a swap versus the 15-30 needed for plugin charging. Additionally, it shifts the responsibility of charging and maintenance from the vehicle owner to the swapping station. These stations are equipped with software that optimizes charging and prolongs battery life. However, the investment cost for battery swapping stations (BSS) is high, with NIO reporting a price of around $500,000. The newest NIO swapping stations have 14 battery slots and can conduct 312 battery swaps daily, but their numbers must be sufficient to create a reliable network (Ramey, 2022b). It is worth noting that EVs must first be constructed specifically to have this functionality, which essentially renders all current models' ineligible for battery swapping. Considering the diverse battery models, builds, and sizes across manufacturers, the feasibility of a one-size-fits-all battery for swapping stations is uncertain. Furthermore, EV manufacturers produce vehicles with proprietary batteries, limiting swapping to specific car models. NIO is the sole car manufacturer with a functional BSS network with over 700 stations across major highways in China as of 2021. This underscores the challenges in implementing a widespread battery-swapping infrastructure.

Q2. In the case where gas stations begin to adopt EV chargers, do you foresee gas stations switching from a vehicle-centric model to a more customer-centric business model?

Continuing to examine upcoming changes in charging, we inquired participants on the outlook of gas stations and the integration of EV chargers. A notable 63% (n=42) anticipated transitioning from a vehicle-centric to a customer-centric approach. This shift will be intriguing for gas stations entering the realm of electric vehicle charging. Currently, the bulk of gas stations' revenue is not from fuel sales but from the associated convenience store purchases. The current vehicle-centric model drivers refuel their vehicles, occasionally stepping in for refreshments or essentials before continuing their journey. With fast charging requiring a minimum of 15-30 minutes, gas station business models must adapt to cater to EV owners' needs. Although relatively uncommon, a few retrofitted gas stations in the US embraced a customer-centric model. Those incorporating EV charging may soon partner with well-known brands like McDonald's and Starbucks, creating hubs for refueling and rest stops. This concept is not completely foreign in the US either and aligns with truck stops and travel centers like Love's and Pilot across the US. These destinations could serve as ideal pilot programs to assess feasibility.

Q3. Without help from the government, will gas stations and EV charging companies risk investing in charging equipment in rural areas?

Retrofitting gas stations into EV charging hubs involves substantial costs, a risky proposition for many small, independent gas station owners, particularly those in rural areas. About 57% (n=38) of participants believed these rural gas stations and EV charging companies would require government assistance to consider EV infrastructure investment. This perspective holds significance when considering the intricacies of the matter. Notably, over 60% of the retail stations in the US are independently owned, often single-store operations, and are located in rural areas (American Petroleum Institute, 2021). For these owners, revenue from the gas station may be the only income source. Additionally, the shift to EV charging may entail business losses, given the concentration of EV owners in urban areas. Presently, there is no incentive for rural areas to embark on such investments independently. In 2019, a gas station in Takoma Park, Maryland, was the first to be converted into an EV charging station facility. The conversion cost was over $700,000, financed with aid from the local government and the Electric Vehicle Institute (EVI), an EV company based in Baltimore, Maryland (Hagemann, 2019). Without this support, such a transformation would not have been possible for the facility owner. Beyond

financial challenges, some gas stations are in areas where an EV charging retrofit may not be suitable, either because of the lack of EV owners or land area restrictions. In response, smaller chains could abandon fuel sales altogether and pivot to convenience stores to cater to patrons' product needs. Unlike traditional fuel dispensers, EV chargers are versatile and can be located in various high-traffic areas, including malls, workplaces, schools, and businesses, not restricted solely to gas stations. Repurposing gas stations may also entail removing old fuel tanks and addressing potential petroleum leaks, primarily affecting older stations, as newer facilities adhere to better regulations.

Q4. The way EVs are serviced in the event they run out of power will differ from CVs. Do you foresee any upcoming emergency charging services (i.e., mobile and portable charging stations) coming to the forefront?

A significant portion, 70% (n=47) of the participants, acknowledge the importance of emergency services in the context of evolving vehicle technologies. Vehicle emergencies and breakdowns are everyday occurrences affecting all vehicle types. In combustion vehicles, fuel depletion issues are relatively straightforward to resolve with options like walking to a nearby gas station, calling emergency services like AAA or a friend for assistance, or jump-starting the battery. However, EVs present a different problem, as energy depletion is not as readily fixable. Due to this, long road trips require sufficient planning on how often charging is needed and where charging locations are for the vehicle. EV battery depletion requires the owner to call roadside assistance to provide a portable charger or tow the vehicle to the nearest charging station, which can be time-consuming. Portable charging systems offer a potential solution, allowing vehicle owners to recharge their EVs during emergencies. Moreover, there are new options for emergency charging in the form of mobile charging systems (MCS). These systems encompass truck mobile charging stations, portable charging units, and vehicle-to-vehicle power transfer, offering convenient and on-the-go charging services, potentially accelerating EV adoption.

Addressing vehicle emergencies entails recognizing the unique challenges EVs pose compared to ICEVs. One often overlooked aspect is the increased weight of EVs, which can lead to more severe auto accidents. Unfortunately, auto accidents cannot be entirely eliminated, but with the

help of responsible driving, automated collision detection, and avoidance systems. Nevertheless, rapid emergency response remains crucial. Emergency services must also be prepared to handle specific EV-related challenges, including vehicle fires and submerged vehicles. In 2012, following Hurricane Sandy, there were 16 reported cases of Fisker EVs igniting and burning down due to flooding (Herron, 2012). EV fires typically take longer to develop, which allows passengers time to escape the vehicle in such an event. However, they often go unnoticed until reaching an advanced stage, complicating firefighting efforts. Integrating self-extinguishing systems into future vehicles could prevent fire escalation and protect the vehicle and its surroundings.

Q5. EV companies are constructing fully automated vehicles. Moreover, rideshare companies are looking to incorporate driverless EVs into their fleet. Do you expect a decline in vehicle ownership and an increase in passengers opting for autonomous rideshare vehicles?

Vehicle automation is an upcoming technology that could change the landscape of vehicle ownership. Brands like Tesla already offer full automation, enabling seamless point-to-point travel. However, concerns persist due to accidents often attributed to vehicle miscalculations or driver fatigue. Attitudes towards automation varied; only 43% (n=29) believed ownership would decline in favor of autonomous vehicles. The appeal of this technology lies in its potential to reduce accidents and congestion. Enhanced vehicle communication can improve road safety, significantly decreasing accidents and creating a safer environment for pedestrians and cyclists. There is also an opportunity to decrease the number of cars on the road and reduce the space needed for parking. The rise of rideshare apps like Uber and Lyft has led some to forego personal vehicle ownership, benefiting from the absence of associated ownership costs, expenses, fuel, maintenance, or insurance. However, these platforms have also faced backlash from drivers demanding higher wages. Adopting an autonomous fleet could be a way for these companies to relieve themselves from this pressure. Understanding the demographics of vehicle ownership and rideshare services can provide insights into AV adoption. Nevertheless, public trust in fully autonomous vehicles will take time as patrons acclimate to the concept. Regarding automated driving systems, high-profile crashes are impactful and can negatively influence public opinion; thus, it is important to understand whether and to what extent they do.

Q6. How important is cybersecurity/ data security to the ecosystem?

Cybersecurity will be critical in the EV ecosystem as modern vehicles become more software-driven, connected, and complex (Wolf et al., 2017). The entire ecosystem must be secure as the software present throughout EVs, the smart grid, power sources, charging stations, and other entities make it susceptible to cyber threats, malware, hacking, and more. Nearly 80% (n=53) of participants agreed that cybersecurity would be critical in the EV ecosystem, while less than 8% (n=5) felt it was unimportant. Arguably, the most susceptible ecosystem component is the charging infrastructure due to the built-in connectivity, link to the power grid, and relative novelty in society. Hacking these systems can expose a plethora of data, including names, addresses, and charging histories, enabling cybercriminals to pinpoint EV owners. Such security breaches have significant consequences in the EV ecosystem beyond compromised data, encompassing exposure of financial information, malware, and other malicious activities such as vehicle tampering.

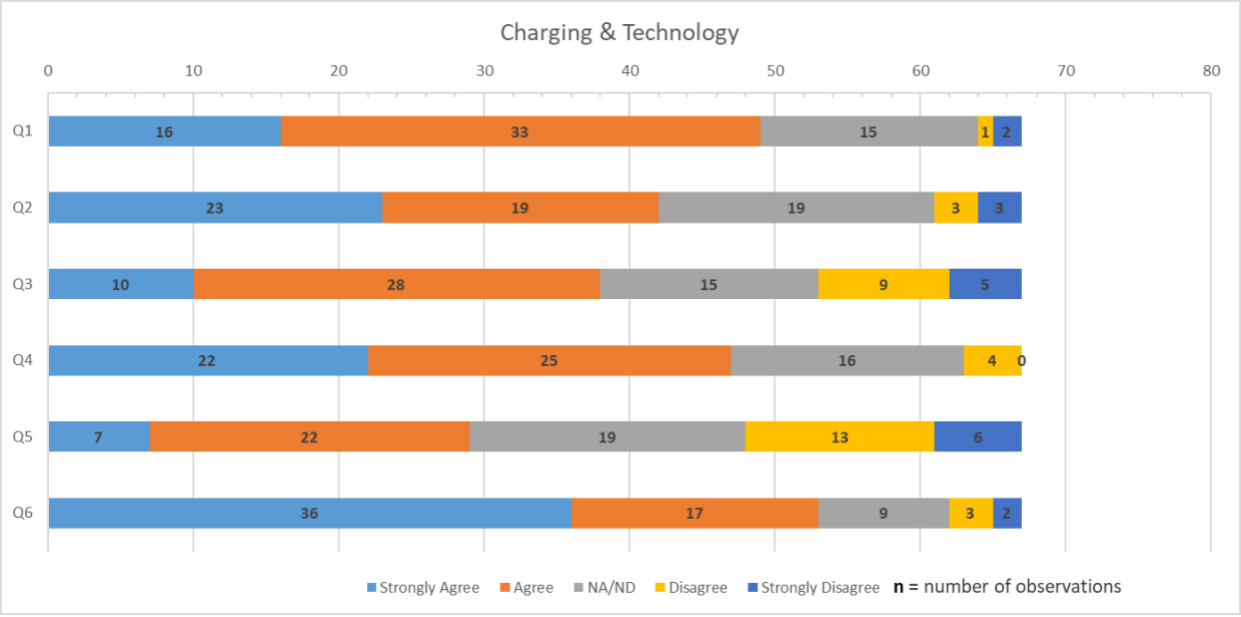

Figure 11: Stakeholder opinions on charging and technology.

5.5 Sustainable Materials and Batteries

Q1. Do you think that combustion vehicle recycling/retrofitting will be a significant factor in the development of EV commercialization?

One issue that remains unexamined is the use of ICEVs once EVs become the mainstream option for transportation. For the foreseeable future, ICEVs will still outnumber EVs on the road. However, a point will come when many of these vehicles become inoperable or subject to bans. Vehicle retrofitting could be an opportunity to introduce EVs to consumers. The average cost of an originally manufactured EV is upwards of $35,000, compared to the cost of retrofitting an original EV, which can range from $5,000 – $10,000. The cost disparity addresses one of the major barriers to widespread EV adoption, and embedded EV features contribute to vehicle prices. Opinions on the impact of EV retrofitting on EV commercialization varied. Nearly 57% (n=38) of participants felt it would significantly develop the EV industry, as shown in Figure 12, while 43% (n=29) were uncertain or undecided. EV retrofitting is the process of transforming an ICEV into an EV, which is relatively cheap compared to buying a new or even used EV. It also serves as an introductory method to EVs and showcases their benefits. Furthermore, it provides an eco-friendly option for repurposing vehicles that would otherwise rely on fossil fuels.

Currently, there are a limited number of EV conversion shops across the US, primarily small mechanic shops specializing in retrofitting vintage and modern vehicles. While car manufacturers offer new electric options for standard vehicles, a niche market exists for vintage cars. This caters to owners of classic, sentimental, or collectible vehicles, allowing them to keep their cherished vehicles on the road without significant financial burdens. Additionally, retrofitting is quicker than producing a new EV, expediting the transition to zero-emission vehicles and reducing the number of vehicles requiring disposal (Watts et al., 2021).

Q2. Do you foresee retrofitted vehicles threatening the sales market for new EVs from automotive companies (Tesla, Toyota, GM)?

Participant response was also mixed regarding whether the EV retrofitting would threaten original EV manufacturers like Tesla and Ford. Close to 55% (n=37) believed it could be a threat, compared to 45% (n=30) who disagreed or were unsure. Retrofitted vehicles do have the potential to challenge major OEMs like Tesla, GM, and Toyota, who capitalize off of new vehicle sales. However, the market for retrofitted EVs is small and limited, with only a few

companies offering retrofitting services. In the case of a retrofitted EV, the range is often 50% - 75% less than a manufactured EV. Nonetheless, some owners may find this sufficient for short drives like daily commutes or store trips. Due to the smaller battery size, retrofit vehicles will also charge faster, although it will require more frequent charging. From a sustainability perspective, some argue that retrofitting is a suitable approach since it reduces the need for raw materials, requiring only a battery pack and a few minor modifications. Car purchase motivations vary; some buy for leisure, while others replace troublesome vehicles. Government intervention that accelerates and mandates EV adoption could make EV retrofitting more widespread. For instance, the government could ban passenger combustion vehicles within a specific timeframe, compelling vehicle owners to switch to an EV or convert their current vehicle. Given EV prices, it is plausible that many people will seek conversions rather than spend much more on purchasing a new car.

Q3. Do you think there is a market/future for recycling or reusing materials from combustion vehicles in EVs?

The possibility of reusing car parts from combustion vehicles in EVs While 67% (n=45) of participants agreed that there would be a future for using recycled materials in EVs, the existing research on how to incorporate these car materials is limited. In addition, there are not many documented instances of repurposing materials from existing ICEVs for use in EVs. Current vehicle recycling consists of dismantling vehicles for spare parts, which can then be used for replacement or modification in other vehicles. Vehicles can also be shredded and sorted to take out and reuse desirable metals and other materials such as glass and plastic. According to the EPA (2016), recycled metal uses nearly 74% less energy than making new steel. However, recycled metal does not present the same attributes as fresh steel used for vehicle frames. Recycled metals from ICEVs may not be suitable for EVs, raising the question of what to do with the millions of ICEVs soon. Often, recycled steel is used as rebar but can also be used in major appliances, machinery, etc. Other than the perceived benefits for consumers that are considered, the environmental impact of retrofitting should be considered.

Q4. Eventually, will EV manufacturers sacrifice driving range by opting for cheaper battery materials?

Lithium is the most popular energy storage material used in EVs today, but it is expensive. Alternatives like sodium and aluminum air are cheaper and less pollutant but offer lower driving ranges. Lithium batteries are currently the most popular energy storage method in EVs due to their high energy density and long-life cycle. Yet, it is an expensive material, contributing to EVs' high price tag. A majority, 61% (n=41) of respondents, anticipate that EV manufacturers may seek more affordable battery materials. While alternatives like sodium, aluminum air, nickel metal hydride, and supercapacitors exist, they offer less driving range than lithium. However, ongoing research aims to conquer this problem. Due to range anxiety, many drivers want vehicles that have large vehicle ranges surpassing 400 and 500 miles for comfort and reliability. Achieving such ranges demands large, optimally designed batteries, driving up costs. A potential future approach may involve constructing EVs with smaller, lighter batteries that necessitate more frequent charging. However, this shift would hinge on establishing a robust charging network. Lightweighting is a strategy used to reduce the vehicle's overall weight and enhance the driving range of EVs. Lithium resources are finite, and current reserves are dwindling due to the increased demand for EV batteries and other applications. In light of the previous discussion regarding the retrofitting market, the state of the lithium market will also be influential. Maisel et al.'s (2023) study underscores that meeting future demand for raw materials, particularly lithium, could necessitate a sixfold production increase, presenting substantial challenges. However, many current EV conversion kits and supplies come from the aftermarket. Typically, the battery modules used in the conversions are sourced from reclaimed Tesla modules, although some companies offer unused battery packs. It is unclear whether the lithium market will have some effect on aftermarket pricing or availability, but there are many other factors to consider.

Q5. EV battery recycling is an excellent opportunity to give used EV lithium batteries a second life in applications such as battery energy storage systems and possible reuse in EVs. However, considering the metal extraction process, use of harsh chemicals, and transportation of materials, is battery recycling worth the investment?

As EV batteries typically last from 5 to 8 years, the growing EV population will lead to an influx of retired batteries (Sun et al., 2022). Recycling these battery packs presents a grand opportunity to reclaim valuable metals and components. Improper disposal of these components in their end-of-life cycle can lead to soil, underground water, and air pollution during incineration (Al-Thyabat et al., 2013). Battery recycling reduces waste sent to landfills and conserves natural resources, reducing the need for virgin materials. Therefore, effective lithium-ion batteries (LIB) recycling is crucial (Yang et al., 2023). However, the battery recycling process can be very chemical and energy-intensive. Survey results indicate that 55% (n=37) of respondents consider battery recycling a worthwhile investment, while 45% (n=30) were unsure or disagreed. Established extraction includes hydrometallurgy, pyrometallurgy, and direct recycling. In many cases, a combination of pyrometallurgical and hydrometallurgical processes is utilized (Velázquez-Martínez et al., 2019). Hydrometallurgical techniques employ aqueous chemical solutions to extract metals, including acid and base leaching, solvent extraction, and chemical precipitation. On the other hand, pyrometallurgy employs high temperatures to convert metal oxides into metal or metal compounds for recovery (M. Zhou et al., 2021). Hydrometallurgy is a better option of the two processes due to lower energy consumption and easier waste control (Tunsu & Retegan, 2016, p. 6). Nonetheless, these methods must continuously be explored, and we must also assess the proper disposal of the materials. Additionally, when it is time to dispose of battery materials, strict protocols must be enforced to prevent further environmental damage. If recycling is going to be an approach then it is essential to increase the recovery rate of the metal because current recovery rates are low (Mrozik et al., 2021). Additionally, it's essential to consider the environmental impacts and pollution associated with the metallurgical process, as the byproducts can be harmful.

Q6. Acquiring lithium and other precious metals for EV batteries is energy and water-intensive and pollutant. Considering that other environmentally friendly modes of transportation exist (biomethane, hydrogen vehicles, biofuels), do you believe that the benefits of EVs outweigh the negative aspects of metal extraction?

Prominent social issues surround EVs. Only about 51% (n=34) of participants believe that the benefits of EVs outweigh the negative aspects linked to metal extraction, while 16% (n=11)

oppose this notion. Approximately 33% (n=22) remained uncertain on this matter. The global expansion of vehicle electrification is evident, with the lithium market projected to grow from USD 3.83 billion in 2021 to USD 6.62 billion in 2028 (Fortune Business Insights, 2022b). Yet, there exists a notable cognitive dissonance. On the one hand, EVs are lauded as environmentally superior, promising employment opportunities, improved air quality, economic growth, and the integration of cleaner systems as incentives for adoption. Conversely, some extraction processes required for EV metals are highly polluting and energy-intensive. A prime example is lithium, arguably the most pivotal and contentious material for EVs. The 'lithium triangle' region in Bolivia, Chile, and Argentina hosts substantial concentrations of high-quality lithium, with salt lakes holding approximately 75% of global lithium resources (USGS, 2022). However, mining activities heavily rely on groundwater extraction in one of the driest regions globally. This has resulted in ecosystem degradation, forced native populations to migrate due to water scarcity, and occurred within conservation areas, leading to soil degradation, biodiversity loss, and impaired ecosystem functions (Agusdinata et al., 2018). Addressing the impact on humans is imperative and an integral aspect of the EV market. Cobalt, utilized in cell phones and EVs, sees nearly half of the world's supply concentrated in the Democratic Republic of the Congo (DRC), the largest producer and exporter of cobalt in 2021 (Brown et al., 2022). Cobalt mining is also highly pollutant, with workers enduring suboptimal conditions and lacking proper safety gear and regulations. This exposes them to respiratory and skin issues, heavy metal poisoning, and cancers. Tragic mining accidents, including collapses, explosions, and suffocation, result in severe injuries or fatalities (Bamana et al., 2021; Brown et al., 2022). The prevalence of child labor, sexual abuse, and prostitution further compound these challenges (Calvão et al., 2021). Car and battery manufacturers are confronted with these ethical dilemmas and acknowledge the repercussions. Academics and researchers are also keenly aware of the implications and are exploring sustainable management approaches for these metals. Lithium recycling offers a potential avenue to lessen demand, and implementing regulations governing the production, disposal, and recycling of lithium-containing products can help mitigate pollution.

Q7. Due to heavy batteries and limited driving range, the feasibility of electrifying heavy-duty vehicles (semi-trucks, refrigerator vans, garbage trucks, etc.) is a topic of debate. Do you still

foresee a switch to electricity for these heavy commercial vehicles compared to other methods (hybrids, hydrogen, methane, biofuels, etc.)?

As society shifts towards EVs for passenger vehicles, alternative energy vehicles are also gaining ground in heavy-duty models. However, the feasibility of electrification for larger and heavier trucks is under scrutiny. Approximately 58% (n=39) of participants believe heavy-duty trucks will continue with electrification, while 31% (n=31) are unsure, and 10% (n=7) disagree. According to the Federal Highway Administration (FDWA), vehicles weighing over 26,000 lbs. are classified as heavy-duty. This category encompasses city transit buses, truck tractors, dump trucks, and sleeper trucks. With various successful experimental cases, city transit buses have shown promise as candidates for alternative fuel sources. However, batteries pose challenges for semi-trucks and other freight vehicles primarily due to the substantial weight of the required battery pack. A typical unladen semi-truck weighs between 10,000 and 25,000 pounds, whereas a Tesla semi-truck can range from 25,000 to 30,000 pounds (J.D. Power, 2021). Charging time is another significant concern due to the battery's size. Fast charging could reduce range requirements, making heavy-duty truck electrification more viable. Additionally, Forrest et al. (2020) suggest that level 3 charging and higher battery capacities increase the feasibility of heavy-duty battery vehicles. Yet, from a logistical standpoint, even with a 30-minute charge, this remains less efficient than the typical 10-minute refueling time for semi-trucks. Until better battery and charging technology emerges, relying solely on battery electric trucks may not be practical. For heavy-duty vehicles to operate successfully and efficiently, the fuel source must have high energy density and quick refueling. Batteries may fall short in this context, but alternatives like biofuels, fuel cells, and electrofuels have been explored. Biofuels offer the advantage of utilizing existing infrastructure with minimal adjustments required for existing combustion engines. In a study by Wang et al. (2000), emissions from unmodified heavy-duty trucks fueled with a blend of diesel and biodiesel were tracked. Carbon monoxide and hydrocarbon emissions decreased compared to trucks running on 100% diesel fuel. However, studies indicate that NOx emissions increased, presenting a barrier to widespread use, necessitating quantifying biodiesel's impact on emissions (Fazal et al., 2011; Yanowitz & McCormick, 2009). Electrofuels, synthetic fuels created from carbon dioxide and water using renewable energy, hold promise as an alternative to batteries and biofuels in heavy-duty trucks.

These fuels can be used in existing ICEVs without modification (Gray et al., 2022). The challenge lies in establishing carbon capture technology. Without a consistent and affordable source of clean energy, fully implementing this synthetic fuel and its carbon capture process remains theoretical.

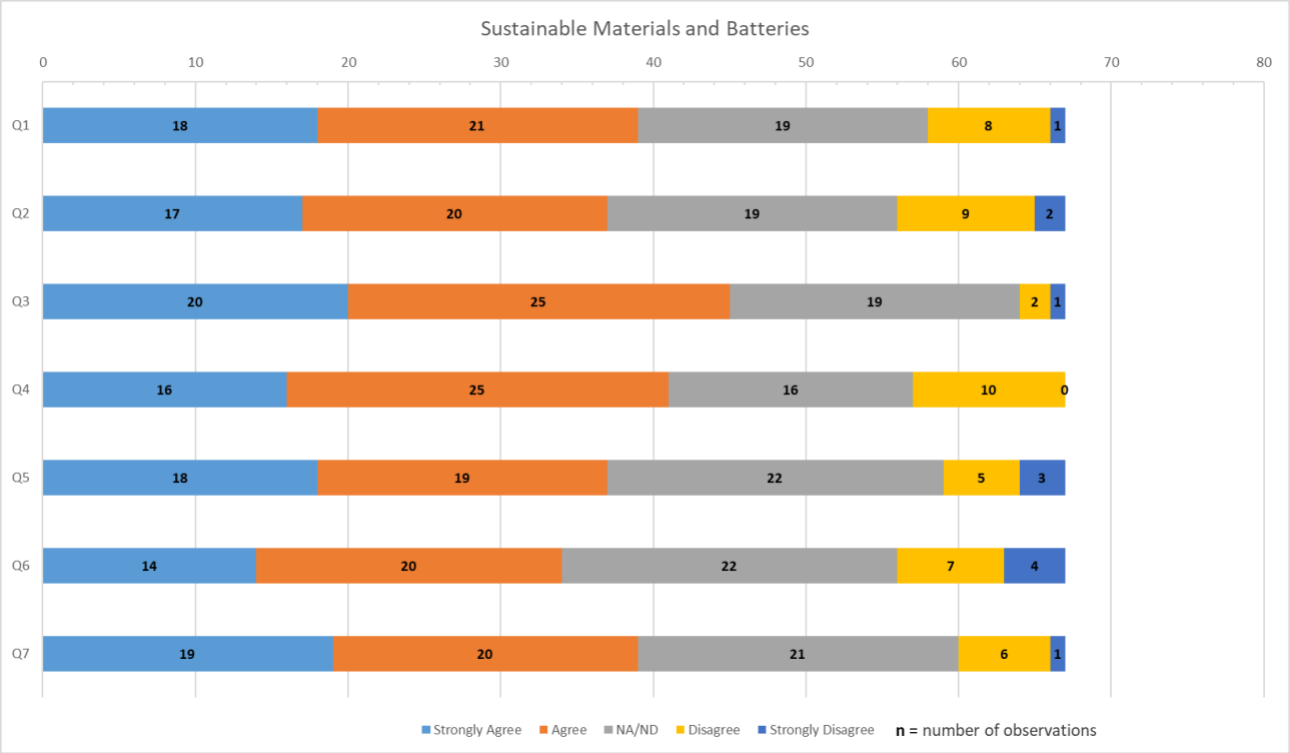

Figure 12: Stakeholder opinions on sustainable materials and batteries Source: Own survey results

6. Conclusion

While ICEVs still dominate the US passenger vehicle market, legislative efforts are underway to help support the shift towards vehicle electrification. This study provides a detailed discussion and overview of stakeholders' perspectives on the future of the EV ecosystem. We conducted a questionnaire surveying various stakeholders to gauge their opinions on crucial aspects of the EV ecosystem. As EVs become more prevalent, significant societal changes will ripple through renewable energy, the automotive industry, gas stations, vehicle financing, and the power grid.

It is important to acknowledge the limitations of this study, which relies on online purposive sampling. This method sought responses from individuals deemed to possess the most reliable expertise. However, as mentioned, online surveys have shortcomings. While online surveys have

shortcomings, they do not necessarily compromise the validity of our findings. Many studies testing theories or models employ non-representative samples and are nevertheless considered valuable (Basil et al., 2002).

The development of the EV ecosystem will be a gradual but transformative process that will have many implications for policymakers and stakeholders. These include changes in charging infrastructure, incentives, and grid capacity. Other implications include factoring in transition costs for business, supply chain management, analytics, and exploring resilient grids and contingency planning. Proper implementation promises nationwide benefits, including enhanced energy security, reduced air pollution, and a transition to renewable energy. Government investment and financing will be crucial in the early stages of establishing a robust EV ecosystem. The government's role in building extensive charging infrastructure will alleviate the concerns about charging accessibility and range anxiety, which are significant barriers to EV adoption. Furthermore, pricing concerns for EVs are expected to diminish as more models enter the market and battery costs decrease. Alongside government incentives, EV charging alternatives and cybersecurity will be pivotal aspects of the ecosystem. Opposition from state governments may also shape the trajectory of the EV ecosystem across the nation. Some states may opt not to invest in EVs and instead implement EV bans. Alternative solutions to fossil fuels should be considered in these cases.

For EVs to gain widespread acceptance, there must be clear benefits for all parties involved. It is evident that certain industries, particularly the oil and gas sector, may face challenges due to reduced demand for crude oil. This research highlights the significant technological advancements in batteries, vehicle manufacturing, cybersecurity, and charging infrastructure. Additionally, optimizing resources and investments in the EV ecosystem is crucial. Stakeholders in the ecosystem play a vital role in introducing necessary components. Future research could delve deeper through in-depth interviews to uncover stakeholders' direct sentiments about EV ecosystem changes. Additionally, similar research on consumers could provide insights into their preferences and concerns. Ultimately, while stakeholders shape the technology and options available, consumers determine the success of these components, influencing which ones gain popularity and require further improvements in the future.

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4

Investigating The Importance of Consumer Preferences in the EV Ecosystem

ABSTRACT

The popularity of electric vehicles has steadily grown over the past several years. This growth can be attributed to the increasing emphasis on environmental sustainability, heightened awareness of climate change, and the detrimental impact of air pollution. To accelerate electric vehicle adoption, establishing a robust electric vehicle ecosystem is vital to facilitate the transition to electrification. Several elements must be developed meticulously within this ecosystem to ensure its optimization. Consumers play a pivotal role in this development. While stakeholders are responsible for introducing and implementing these factors, the consumers ultimately determine the success or failure of each element within the ecosystem. This is a result of the diverse preferences and perceptions held by consumers, which can be effectively gauged through well-designed surveys. This study aimed to understand the perceptions and attitudes of consumers and potential consumers toward pricing, incentives, safety concerns, maintenance, and various technologies within the electric vehicle ecosystem. We collected this information through surveys from 150 respondents. Our findings revealed crucial insights, including that environmental friendliness is a key consideration for consumers when purchasing an electric vehicle. Furthermore, our research highlights significant ethical and safety issues that must be considered as electric vehicles are implemented in society.

1. Introduction

The popularity of electric vehicles (EV) has grown steadily over the last several years due to the emphasis on sustainability, awareness of climate change and air pollution. As a result, EVs are

viewed as a tool that can help mitigate the negative impacts of fossil fuel transportation. In addition to the perceived environmental benefits, EVs offer unique technology and software that enhance the functionality and safety of the vehicle. The growing attention has led to the success of many prominent EV and traditional car companies. Recently, Tesla announced that it delivered 1.31 million vehicles in 2022 (Business Wire 2023). GM has also introduced the innovative Ultium platform, a flexible battery architecture that can be used across different vehicle types (General Motors 2022). The US government is also promoting vehicle electrification through goals for charging infrastructure, changes in sale requirements, and incentives to encourage EV technology growth (DOE 2023). State and local governments are encouraging this transition, and consumers recognize the practicality and benefits of EVs. However, the general public may still be unaware of EVs' full potential and societal impact. EV technology, along with related advancements in renewable energy, home charging stations, changes to gas stations, and commercial charging, will continue to develop, leading to changes in consumer preferences. The electrification process also presents temporary and permanent challenges that consumers must be aware of. Understanding the opinions of potential EV consumers is crucial, as stakeholders—such as EV manufacturers, charging companies, and gas station owners are responsible for putting out the products and services that are consumed. However, the consumer determines the success of the product and identifies areas for improvement. Surveys are a valuable tool that can be used to gather opinions on EVs and EV technology. In recent years previous consumer studies have explored consumer attitudes toward EVs (Lebeau et al. 2013); the usefulness of plug-in hybrid electric vehicles (PHEV) (Krupa et al. 2014); identifying characteristics of early buyers and reasons for buying (Mandys 2021), and attitudes towards autonomous and connected vehicles (Wu, Liao, and Wang 2020). Conducting these surveys helps researchers and stakeholders understand consumer perceptions of EVs and guide further actions and research to promote EV adoption. However existing studies have not considered consumer perspectives on the EV ecosystem holistically. To address this gap, this study first utilizes a questionnaire to identify current consumer perceptions related to the EV ecosystem. Based on the survey results we then utilize a discussion-based approach to expound upon what these results mean and possible avenues for advancement in the ecosystem. This study employs the use of the diffusion of innovation theory (DoI) frameworks to identify how consumers views adapt the ecosystem. The purpose of this study is to take an approach to

holistically understand consumer perceptions of the current EV ecosystem and feelings toward upcoming changes in transportation. This paper will also add to the existing knowledge of consumer behavioral theories and their application to electric vehicles.

2. Understanding Consumer Intentions

2.1 The Importance of Consumer Preferences Towards Sustainability

Heightened living standards and technological advancements have allowed many individuals to live with abundant resources without regard for the environmental impact. This concept relates to the tragedy of the commons, where individuals prioritize self-interest over the common good of all users (Hardin 1968). However, globally, people seem to be increasingly more concerned about pollution, air quality, environmental impact, carbon footprint, and their consequences. As a result, consumer knowledge of sustainability has grown in many sectors, including food production, packaging, vehicle choices, energy production, transportation, and others. In turn, it has influenced consumer decisions, as many choose to purchase items with a "green" aspect, whether recyclability, carbon neutrality, or reducing the use of unsustainable materials. Several studies show that consumers are willing to adopt more sustainable practices and are even willing to do so at higher costs (Business Wire 2021; McKinsey & Company 2023; SustainableBrands 2022).

As a result, understanding these trends becomes important. As consumers adopt sustainable practices, their views can shape the development of a product, firm, or particular sector. In turn, stakeholders will strive to meet the demands of consumers and will deploy different mechanisms to build a relationship with consumers. As illustrated, the influence between firms/stakeholders and consumers is mutual. We see this through varying marketing strategies, studying business transactions and buying patterns to understand current trends, and provisions such as recycling infrastructure, incentives, subsidies, and other offerings that influence consumer behavior. Nevertheless, consumer willingness and readiness will be crucial for firms/stakeholders to be agents of change (Heikkurinen, Young, and Morgan 2019).

Sustainable development integrates economic, social, and environmental considerations to accommodate the needs of future and current generations (Meadowcroft 2023). In the EV ecosystem, consumer preferences for vehicle purchasing, charging times, availability, and

driving range play a vital role. There is abundant research regarding consumer perceptions of EVs and the previously mentioned topics. Understanding these perceptions and decision-making processes provides a better view of increasing adoption and optimizing the ecosystem. Brase (Brase 2019) argues that current research rarely examines the psychological aspects that deter people from EVs and asserts that much more goes into these decisions than just the economic factors, as commonly referenced. Technology compatibility with the user's lifestyle and behaviors should also be considered. Familiarity is another important factor since consumers' perceptions are more positive among informed people and those with stronger opinions on environmental friendliness (Gallagher and Muehlegger 2007; Zhang et al. 2022). However, (Zhang et al. 2022) also notes that the quality of the information dictates the overall value and trust. Early entrants and those with a pioneering advantage can also largely shape consumers' viewpoints. For instance, Carpenter & Nakamoto (Carpenter and Nakamoto 1989) give a prime example, stating that 100 years ago, it was unlikely that many people had strong opinions on how sweet or carbonated sodas should be. As an early entrant, Coca-Cola significantly influenced the perception of soda, shifting individuals' preferences. The same can be said about the varying ecosystem elements, as the early entrants within their respective spaces will help mold consumer preferences. In addition to understanding consumer preferences, the same literature often analyzes many barriers to EV adoption. Amongst the most common barriers to EV diffusion are high use and purchase costs, insufficient charging facilities, long charging times, limited driving ranges, technological concerns related to batteries, safety issues, and uncertain performance (Liao, Molin, and van Wee 2017; Zhang et al. 2022). Barrier perception can either come from first or second-hand experiences, which can also negatively influence consumer choices. As noted, the quality of information can dictate the views of consumers so it is essential that current views are understood, and this data can be used to dispel and alleviate potential consumers' discomfort. Throughout the ecosystems are interdependencies and complementarities, and the development of one area often influences or requires the development of the others. Companies are now considering the social and environmental impacts production and economic activities have and are taking several approaches to reduce these impacts (Liu and Stephens 2019). There is a need for development in each segment of the ecosystem, and we are curious to see how consumer insight can shape the EV ecosystem. Freeman et al. (Freeman, Martin, and Parmar 2007) state that studies mainly focus on firms within the ecosystem, and these studies have also

overlooked how customers may influence business strategies. The input of consumers is vital to the successful development of products. Moskowitz & Saguy (Moskowitz and Saguy 2013) thoroughly discuss the role of consumers in research and how different tests can be used to gauge reactions. Notably, consumer participation in business processes is usually for the benefit of the business, as it helps to reduce development time and improves the effectiveness of products (Fragidis, Koumpis, and Tarabanis 2007). Additionally, the consumer's role in these processes is not to solve the consumers' problems but to help businesses receive feedback on fixing any issues that may arise.

2.2 Diffusion of Innovation Theory: EV Ecosystem Perspectives

The Diffusion of Innovation (DoI) theory was developed by E.M. Rogers in 1962 to explain how an innovation, idea, technology diffuse through society over time (Rogers, Singhal, and Quinlan 2008). The EV ecosystem as described earlier consists of several entities and is an innovative field. Globally, research scientists, academia, governmental and nongovernmental agencies work to create new ways to optimize EVs and transportation. With this in mind we can expect to see new innovations introduced. One of the models in the DoI theory is the S-curve model which identifies five types of adopters. It shows that in the initial stages there are 1.) Innovators or risk takers that first embrace the new product. 2.) Next are the Early adopters who embrace the new product before most others. 3.) The early majority are usually more cautious and choose to adopt only after it being validated by early adopters. 4.) Once the Late Majority see its utility and it becomes a norm the remaining population begins to use the technology, and it reaches the more hesitant population or 5.) Laggards and diffusion slows due to saturation (Bokolo 2023; Cain and Mittman 2002). Compared to other behavioral theory frameworks, Xia et al. (Xia, Wu, and Zhang 2022) note that the DoI theory is most effective since it successfully captures the interactions between products and individuals and highlights the differences between new and traditional products. This methodology is highly appropriate when applied to an ecosystem environment. One could argue since there is a plethora of innovations within the EV ecosystem the adoption of ideas and technology are constantly dealing with the stages of adoption. The most immediate example obviously would be the EV vs the conventional vehicle or gas station vs electric vehicle charging. Within the DOI consumers are described as the key figures that drive the consumption or adoption of a product. If we view the EV ecosystem as an innovation or

focal point, there are distinct segments, and each segment has its own respective technological advancements. As a result, marketers and stakeholders want to understand the opinions to enhance their products or services and increase adoption.

The adopter categories within the DoI help to illustrate typically how an innovation diffuses. However, the dynamics of innovation diffusion perhaps are more important. Rogers et al. (2008) set the foundation for these dynamics while Cain and Mittman (2002) explicitly name them. The 10 critical diffusion drivers are shown in Table 12. In essence while many of them can be looked at as similar each one of the attributes are distinct. Hence, understanding these attributes can be used to predict how impactful one is to the future rate of adoption of a product (Rogers et al. 2008).

Table 13: Critical drivers of diffusion.

Variable	**Definition**	**Example**
Relative Advantage	The value or benefit of adopting an innovation relative to the current practice.	Adopting a green technology increases the likelihood of adopting another. (Installing solar panels to supplement charging and home electricity production)
Trialability	The ability to try an innovation without a total commitment and minimal investment.	Test driving EVs at conferences or showcases.
Observability	The extent to which potential adopters can witness the adoption of an innovation by others.	Witnessing neighbors and associates with the EVs and conversing about the benefits of the product.
Communication Channels	How opinion leaders and other influencers communicate about an innovation.	Often people are exposed to EV news from TV, social media, online platforms, and advertisements.
Homophilous Groups	Innovations spread among groups with similar characteristics faster than groups that differ (Heterophilous).	A group of friends or associates in the same economic bracket influence on another to consider an EV.
Pace of innovation/reinvention	The speed at which an innovation evolves. Some are more stable than others and can be altered by its users.	Over the past two decades EV capabilities have advanced quickly and permeated throughout society.
Norms, roles, and social networks	Innovations are shaped by the rules, social norms, hierarchies, and mechanisms of the social systems in which they diffuse.	Increasing sustainability outlook encourages people to generally adopt more sustainable practices.

Table 13 continued.

Opinion leaders	Opinions of individuals that are highly respected or listened to by others can affect the pace of diffusion.	Key figures and influencers within society that speak on the power and benefits of EVs.
Compatibility	The ability for the innovation to coexist with technologies and social patterns in place improves the prospects for adoption/diffusion.	Synergy between mobile devices, renewable energy storage, and vehicle to home capabilities.
Infrastructure	The adoption of many innovations is dependent on the presence of infrastructure or other technologies that support the innovation.	Availability of charging infrastructure and hub is highly influential towards adoption.

3 Ecosystem Theory and Consumer Role Within Innovation Ecosystems

The term 'business ecosystem' defines the ecosystem as being made up of customers, market intermediaries, suppliers, and also includes value creation for customers through the supplication of information, goods, and services and the use of the Internet and other enabling technologies (Kandiah and Gossain 1998; Moore 2006). When referencing a business ecosystem, several delineations can be used, as described by (Jacobides, Cennamo, and Gawer 2018; Miguel and Casado 2016). Jacobides et al. (2018) outline three distinct ecosystem streams: business, innovation, and platform. An 'innovation ecosystem' stream is centered around an innovation and the supporting actors and is most applicable to the EV ecosystem described in this paper. It is important to mention that using one term does not necessarily rule out some of the concepts that are applied in the others, which has been highlighted in previous work. The questions formulated for this questionnaire are based on our findings from literature and developing news in the EV sector. We categorized our questions to encompass five areas as shown in Table 13. Many researchers have delved into how to advance these specific sectors or certain aspects that contribute to the growth of EVs. In this work we explore some of the characteristics that influence the ecosystem structure. The novelty of this research evolves around the discussion of pertinent topics that have not been previously discussed or brought to the attention of the general public. Additionally, we provide current consumer insights and discuss how their insights towards the ecosystem and opportunities create opportunities for development. The drivers of sustainable development in the EV industry are centered around technological innovation, market demand, and government policy (Wu et al. 2018). Generally, consumer demand is the initial driving factor in an innovation ecosystem. Meaning that the more desired a product is the more stakeholders and other players will work to fulfill these needs.

1. Pricing and Incentives – Discusses the pricing of vehicles and incentives offered by the government and how they may influence consumer decisions.
2. Embedded Technology – Discusses technology that is embedded in EVs as well as future components that are being introduced to EVs.
3. Issues of Safety – A brief section that gauges how consumers feel about some of the safety issues associated with EVs.
4. Matters of Charging and Energy – Charging and refueling needs are still a work in progress and many generally the longer it takes to charge the more negative the view or EVs is. Here we discussed some of the implications of EV charging and expansion. We also discussed some of the energy storage technology that may soon become more mainstream as EV adoption continues.
5. Maintenance and Purchasing – We discuss new concepts of leasing and EV ownership as well as how EV maintenance is perceived.

Table 14: Areas under scrutiny.

Pricing and Incentives	Maintenance and Purchasing	Embedded Technology	Issues of Safety	Charging and Energy
•Vehicle Prices(Lutsey and Nicholas 2019) •Feature Availability •Government Incentives(Wee, Coffman, and La Croix 2018) •Vehicle Requirements(Slowik et al. 2023) •Retrofit Market(Santis and Regis 2021)	•New Leasing and Rental Options(Zhu et al. 2024) •Battery Leasing(Gonzalez-Salazar, Kormazos, and Jienwatcharamongkhol 2023) •Vehicle Maintenance •Loans and Financing for EVs (Bena, Bian, and Tang 2023; Kennedy et al. 2020)	•AI and Autonomous Driving(Damaj et al. 2021) •Connectivity •Privacy and Piracy •Cybersecurity(Johnson et al. 2022)	•Legal and Ethical Matters(Henderson 2020) •Natural Disaster Response(Adderly et al. 2018) •Vehicle Reliability(Talukdar and Deka 2021)	•Energy Storage Options(D. Li et al. 2020) •Charging Availability(LaMonaca and Ryan 2022) •Workplace Charging(S. Li et al. 2020) •Electricity Production(Barman et al. 2023) •Lithium and Critical Metal Extraction(Zhang, Yan, and You 2023)

4 Methodology

For the purpose of this study, we developed a web-based questionnaire using the SurveyMonkey platform. The data were collected in March 2023. A link to the survey was distributed to 224 participants, using a simple random sampling method targeting the general population since all demographics can be represented as current and future EV owners, although there is research that indicates certain demographics are more likely to own EVs (Jacobides, Cennamo, and Gawer 2018; Kandiah and Gossain 1998; Moore 2006). However, to ensure the quality of the

data, we used filter questions to disqualify certain respondents. Our first objective was to ensure that the survey participants either owned an EV or intended to own one within the next 5 years, as they would be more knowledgeable. Participants without any intentions were disqualified. Next, we wanted to see the reasoning behind a person's decision to own an EV. The participants were given the following choices: "Sustainability / Carbon Footprint," "Lower Vehicle Maintenance," "Lower cost to Refuel," or "Prestige." Any participant who chose "Prestige" was disqualified from the survey. In addition, surveys that were not fully completed were omitted from the final results. In total we collected 150 valid completed surveys, resulting in a 67% response rate. The demographic profile of the respondents and the question results are presented in Table 14. The questionnaire consisted of 25 questions, 22 of which were five-point Likert scale "strongly agree to strongly disagree" and 3 ranking questions. As part of the ranking questions, participants were asked to rank factors they thought were most favorable. A score of 5 was "most favorable," and 1 was "least favorable." The arithmetic means of the scores were then used to rank which factors the participants found most relevant.

5 Results & Discussion

5.1 Descriptive Statistics

To examine the reliability and consistency of this study we used the Cronbach's alpha. Cronbach's alpha is used to measure the internal consistency of a test or scale (Tavakol and Dennick 2011). Usually a score of 0.7 or more signifies adequacy, however some researchers suggest that anything in the range of 0.60 to 0.70 will also suffice (Hasan 2021; Nunnally 1994). In this study all the Cronbach's alpha for all variables were above 0.65 except Embedded Technology/Safety Issues (ETSI).

Table 15: Demographics of participants.

Variable	N	%
Gender		
Male	76	53.1
Female	67	46.9
Age		
18-29	17	11.9
30-44	55	38.5
45-60	55	38.5
>60	16	11.2
Reason for owning an EV?		

Table 15 continued.

Sustainability / Carbon Footprint	58	38.2
Lower Maintenance	23	15.1
Lower cost to refuel	69	45.4
Prestige	2	1.3
Household Income		
$10,000-$24,999	0	0
$25,000-$49,999	30	21.0
$50,000-$74,999	47	32.9
$75,000-$99,999	25	17.5
$100,000-$124,999	16	11.2
$125,000-$149,999	14	9.8
$150,000-$174,999	7	4.9
$175,000-$199,999	4	2.8
Region		
East North Central	16	11.3
East South Central	7	5.0
Middle Atlantic	25	17.7
Mountain	8	5.7
New England	6	4.3
Pacific	26	18.4
South Atlantic	29	20.6
West North Central	9	6.4
West South Central	15	10.6

Table 16: Construct items and statistics.

Constructs	Construct Items	Cronbach Alpha with Item Deleted	Mean	Standard Deviation	Cronbach Alpha of the Construct
Pricing and Incentives (PI)	I am open to vehicle retrofitting.	.671	3.34	1.054	.673
	I would change my EV preference to qualify for the tax credit.	.575	3.57	1.078	
	Even without tax credit I would purchase a vehicle.	.610	3.56	1.017	
	Incentives are important to my purchase decision.	.641	3.90	.856	
	I would consider a smaller vehicle to save money.	.614	3.63	1.052	
	Qualifying for a vehicle credit would be a deterrent.	.664	3.57	1.023	
Charging and Energy Storage (CES)	EV's benefits outweigh their negatives.	.553	3.46	.989	.617
	I prefer cheaper vehicles with less capabilities.	.555	3.48	1.004	
	I trust I can charge my vehicle solely with public charging.	.539	2.99	1.290	
	I find the implications of EVs to be concerning.	.610	3.71	.953	

Table 16 continued.

	I am confident in EVs during emergencies.	.536	3.07	1.538	
	With an EV I would consider incorporating renewable energy into my home.	.566	3.74	1.058	
Maintenance and Purchasing (MP)	I can find a place to service my vehicle adequately.	.455	3.55	1.024	.555 Score after item removal (.684)
	I would participate in a subscription plan.	.394	2.91	1.378	
	I would consider leasing my battery.	.240	3.21	1.133	
	Timely vehicle servicing is important.	.684	4.06	.826	
Embedded Technology/Safety Issues (ETSI)	I am comfortable with autonomous vehicles.	.514	3.16	1.332	.595
	Long charging times would deter me from purchasing an EV.	.510	3.69	1.008	
	Advanced Vehicle features are important.	.388	3.96	.948	
	I am comfortable with increased EV connectivity.	.525	2.91	1.381	
	EV charging price stability is important.	.473	4.12	.960	
	Workplace charging availability is important.	.461	3.91	.982	

Regression analysis was used to predict customer intention based on 7 independent factors which include the following Pricing and Incentives (PI), Charging Energy and Storage (CES), Maintenance and Purchasing (MP), Embedded Technology and Safety Issues (ETSI), Gender, Age and Income. The Table 17 shows that R is 0.250, R square is 0.063 and adjusted R square is 0.014. This indicates that 1.4% of the variance in customer satisfaction can be explained by the changes in independent variables of Consumer Satisfaction. Therefore, this model is considered as a poor fit since it fails to explain 60% of variance in dependent variable. The results of the multiple regression are found in Table 18.

Table 17: Model summary in predicting customer intention.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.250[a]	.063	.014	.68034

Table 18: Multiple regression of consumer constructs.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.194	.457		9.171	<.001
	PI	.096	.098	.109	.981	.328
	CES	-.071	.131	-.074	-.544	.587
	MP	-.093	.091	-.126	-1.024	.308
	ETSI	-.112	.114	-.105	-.981	.328
	Gender	.134	.117	.098	1.147	.254
	Age	.034	.070	.041	.476	.634
	Income	.042	.036	.098	1.161	.248

Dependent Variable: Consumer Satisfaction

Upon conducting the multiple linear regression, we were unable to reject the null hypothesis and found there were no significant correlations between the construct items and EV consumer intention. Nevertheless, previous research does discuss and conclude there are differences among groups when it comes to preference and intention especially from a demographic sense. In this case this may be due to poor reliability that was shown in the Cronbach Alpha score of the item constructs. The demographic items: gender, age, and income in previous research have shown to be key indicators and correlated to consumer intentions.

Age is known to be a key factor in adopting green technology and consumer preference (Sovacool et al., 2018). Sovacool (2018) highlights that men around the age of 30-45 are more likely to adopt EVs. Although there is interest for car ownership amongst younger individuals, income and credit history are among some of the barriers for entry for higher priced and newer EV models. A consideration for some young adults is that they are able to receive monetary assistance from a parent or guardian which can effectively lower the personal burden. Older individuals are more likely to have higher expendable income but also are more likely to prefer older technology they are accustomed to which can be a driver of lower adoption rates among older populations.

Among males and females previous surveys also show significant differences in EV preferences. Females typically believe in higher safety and lower environmental impacts for EVs (Vrkljan & Anaby, 2011). In this society often women are viewed as responsible caregiving

meaning they are more likely to want a vehicle that can cater to the needs of their children. Men tend to be more brand loyal which could be associated with having more general knowledge and experience with vehicles (Moutinho et al., 1996).

Those in higher income brackets are more likely to adopt new technologies simply due to higher expendable income. They can also take more risks when it comes to purchases.

To further investigate possible significance of demographics factors an independent T-Test for Gender, Age, and Income. The results of the independent sample t-test, as illustrated in Table 19 females exhibited a higher mean score for the ETSI3 *(4.12)* and CES4 *(3.87)* constructs. Table 20 shows the two-sided p-value *(<0.05)* for each construct ETSI3 *(0.033)* and CES4 *(0.021)* which signifies the higher mean score was significant regarding concern for the implications of EVs and preferring vehicles with advanced features. Males scored a higher mean score for ETS1 (3.36) were more comfortable with autonomous vehicles, and desired faster vehicle servicing more so than females. There were no significant findings for Age.

Table 19: Descriptive data of significant item constructs found for Gender.

ITEMS		Gender	N	Mean	SD	Std. Error Mean
ETSI1	I am comfortable with autonomous vehicles.	M	76	3.36	1.272	0.146
		F	67	2.96	1.364	0.167
ETSI3	Advanced vehicle features are important.	M	76	3.83	0.971	0.111
		F	67	4.12	0.896	0.110
CES4	I find the implications of EVs to be concerning.	M	76	3.54	0.999	0.115
		F	67	3.87	0.886	0.108
MP4	Timely vehicle servicing is important	M	75	4.19	0.817	0.094
		F	66	3.91	0.818	0.101

Table 20: Independent T-Test results of items.

	F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					One-Sided p	Two-Sided p			Lower	Upper
ETSI1	0.281	0.597	1.814	141	0.036*	0.072	0.400	0.221	-0.036	0.836
ETSI3	2.197	0.140	-1.850	141	0.033*	0.066	-0.290	0.157	-0.601	0.020
CES4	2.707	0.102	-2.054	141	0.021*	0.042*	-0.326	0.159	-0.640	-0.012
MP4	0.483	0.488	2.012	139	0.023*	0.046*	0.278	0.138	0.005	0.550

Significant p-value <0.05 level.

Results for Income are found in Table 21 and Table 22. The mean score for the following constructs ETSI3 *(4.17)* AND CES4 *(4.22)* were higher for individuals with an income over $100,000 signifying that individuals with higher incomes found timely vehicle service to be more important and desired advanced vehicle features. In the automotive world cars with more features and functions tend to have a higher price point. Car manufacturers also offer different versions of the same model vehicle to serve different needs for customers (Volvo, 2025). These higher vehicle functions and amenities are catered to people with more expendable income and can also be desired simply for leisure. Those with lower incomes most likely desire vehicles for utility primarily to take them to the desired destination consistently (Blumenberg, 2016).

Table 21: Descriptive data of significant item constructs found for income.

	ITEMS	Income	N	Mean	SD	Std. Error Mean
ETSI3	Advanced vehicle features are important.	>$100,000	66	4.17	0.815	0.100
		< $100,000	77	3.79	1.017	0.116
CES4	Timely vehicle servicing is important.	>$100,000	64	4.22	0.701	0.088
		< $100,000	77	3.92	0.900	0.103

Table 22: Independent T-Test results of items.

	F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
					One-Sided p	Two-Sided p			Lower	Upper
Equal variances assumed	2.992	0.086	2.401	141	0.009	0.018	0.374	0.156	0.066	0.683
Equal variances not assumed			2.442	140.387	0.008	0.016	0.374	0.153	0.071	0.678
Equal variances assumed	2.123	0.147	2.150	139	0.017	0.033	0.297	0.138	0.024	0.569
Equal variances not assumed			2.200	138.451	0.015	0.029	0.297	0.135	0.030	0.563

5.2 Survey Discussion

Perceptions of EVs differ among the general population and have several disadvantages compared to traditional combustion vehicles. This hesitancy among consumers to switch to EV technology can be attributed to some common and recognized issues, including range anxiety and a lack of charging infrastructure. However, efforts from the government and private companies have facilitated the expansion of charging infrastructure to decrease barriers to adoption. Beginning in late 2019 the number of public electric vehicle supply equipment (EVSE) ports grew from nearly 80,000 to nearly 140,000 ports by late 2022 (Brown et al. 2023). It is often cited that increasing the availability of charging stations is essential to combat both of these matters. Albeit, even with this expansion, the participants still identified the following as the top three barriers or concerns: lack of charging infrastructure, vehicle prices, and range anxiety. Lack of charging and range anxiety ranked as the 1st and 3rd biggest concerns for EV ownership, as seen in Figure 13. Public charging availability is vital for EVs to function, and fast-charging or DC infrastructure is key in reducing range anxiety. However, it should be noted that most charging, upwards of 80%, takes place at home, usually during off-peak periods at night and times of low-price charging. Given this fact, it shows that there is also an overall importance to increase access to home charging. Home charging typically relies on Level 1 or Level 2 chargers. These charging methods are lower power options and charge the battery slower and are key to

battery health since over time fast charging can degrade the battery. Lack of charging infrastructure can also be concerning for individuals that do not have access to home charging, namely those that live in multi-family homes, apartments, and other areas where the ability to install charging is limited. Vehicle owners driving to areas where charging availability is limited also share these concerns and have apprehensions about finding a charging station quickly. This refers more to range anxiety which is understandable; however, Rauh, Franke, and Krems (2015) found that range anxiety is more an issue that inexperienced drivers have. Their work showed that EV owners with experience have less range anxiety and thus, we can conclude that gaining experience with EVs can help to alleviate some of this fear. Increasing the battery size and decreasing the minimum state of charge are also approaches that manufacturers can take to combat range anxiety (Knutsen and Willén 2013). Yet there are other implications to these methods such as increased charging times for bigger batteries and other that still need to be explored.

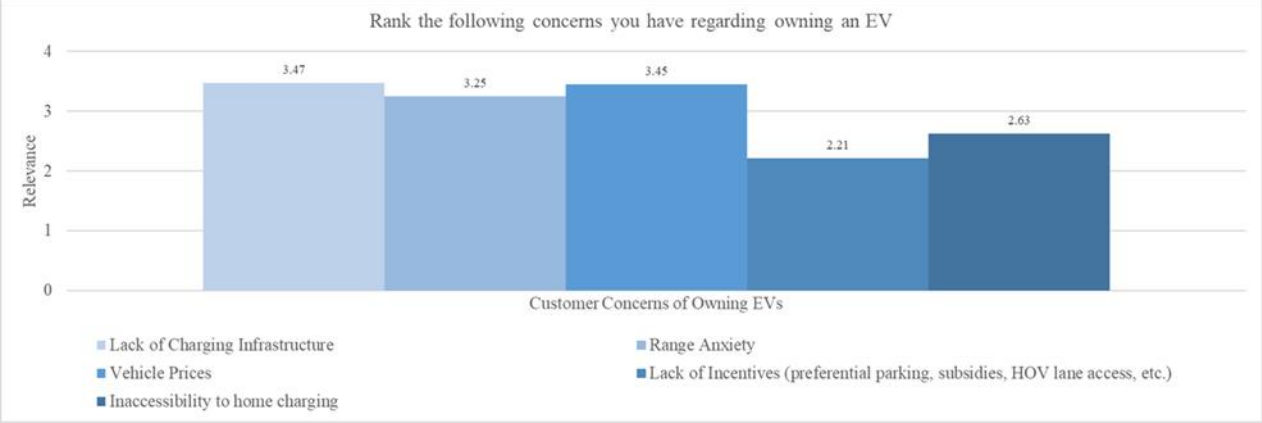

Figure 13: Average ranking of the concerns regarding EV ownership.

Vehicle pricing ranked as the 2nd highest barrier. EVs are notoriously more expensive than combustion vehicles. The US government has made some incentives available for customers looking to purchase EVs and is discussed more thoroughly in Q2. However, the purchase price can still be unattractive to some, even for a used EV model. One of the ways that consumers may combat the high purchase price is by purchasing smaller vehicle models. Smaller vehicle models tend to be cheaper, and certain EV models like the Chevrolet Bolt is notorious for its affordability. Culturally in the US, larger vehicle models are popular, and consumers tend to prefer larger vehicles either because of family size, comfort, convenience, pure desire, and

relative inexpensiveness. However, the Russo-Ukraine war has had some impact on critical supply chains globally and has also caused the price of key minerals to become more expensive which has affected the global automotive industry, yet EV prices as a whole are continuing to decrease. Near the beginning of the second quarter, Tesla decreased the price of its most affordable model, Model 3, by $2000, bringing the price to $39,990 (USA Today 2023). The company has also cut the prices of many of its other models. The full scope as to why Tesla continues to do this is unclear, as analysts believe it could hurt profitability; still, doing so could be an attempt to boost sales and be more competitive against rival car makers (Sharma and Roy 2023; Weatherbed 2023). Due to these price changes, more Tesla models are eligible for the tax credit.

Lack of incentive measures and inaccessibility to home charging ranked 4th and 5th in the survey. The most powerful and effective incentives are monetary, ones that help to lower the cost of vehicles. Aside from pricing, other incentives include free parking, HOV lane access, and charging station incentives. As of now these seem to not be as concerning for consumers, yet it is still important to inform consumers about the benefits available. Views on home charging can also vary based on the type of city a person lives in, current housing situation, or knowledge of current charging station availability.

In addition to finding the barrier perceptions, we also wanted to see what consumers felt were the most beneficial aspects of EV ownership and the results of this are seen in Figure 14. Our study found that consumers felt most strongly about the environmental friendliness of EVs. Engagement in environmentally friendly behavior can feel good, and Venhoeven, Bolderdijk, and Steg (2016) found that people that exhibited environmentally friendly behavior had a more positive view of their self-image. For some, the decision to adopt EVs is a moral issue, and for those individuals doing so helps to mitigate climate change and air pollution. Others also recognize how beneficial EVs can be in society. Many people also feel a connection to nature and agree that there is an intrinsic value to nature, and it is their responsibility to engage in activities that can preserve it (Leiserowitz, Kates, and Parris 2005) — especially considering the increased media coverage of environmental and social problems has also increased public

interest (Roberts 1996). Americans are also willing to pay at least 5-10% more for products they deem ecologically compatible (Coddington 1990).

The second highest-ranked benefit was the cheaper cost of refueling. Global crises have influenced the price of crude oil and therefore have caused the price of gas to increase. Fluctuations in gas prices can be a factor in a consumer's decision to make the switch to EVs since the current perception is that charging is cheaper than current gas refueling. Although this is valid, charging can vary based on demand, time of day, season, and other intermittent factors. Nevertheless, there is some form of consistency when it comes to vehicle charging. Charging opportunities are also very diverse, meaning that different charging levels are available. Some can be very cheap and done at home or the workplace (L1 and L2), and others can be done very quickly (DC fast charging or battery swapping). The electricity source, whether from the grid or from solar or wind energy, can also dictate the charging costs.

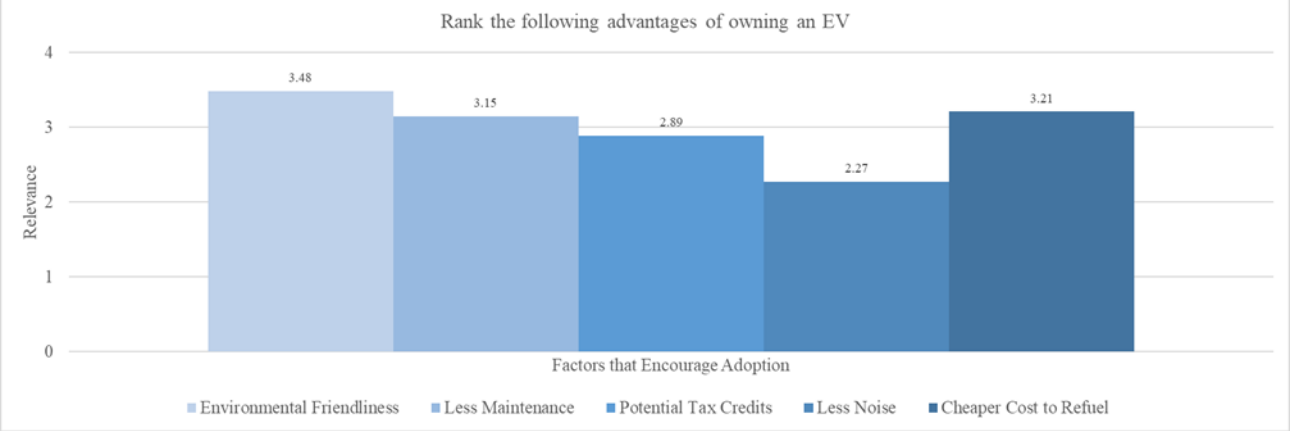

Figure 14: Average ranking of the EV ownership benefits.

Q1. The driving range of a retrofitted EV (<150 mi) is less than an original EV (200–500 mi). The conversion cost ($5,000-20,000) is lower than a new or used EV purchase ($25,000-100,000). Would you prefer to retrofit a combustion vehicle over purchasing a new or used EV?

While EVs in general tend to have higher price points than traditional cars, EV prices have reduced significantly and are becoming increasingly more affordable. Innovation in the EV industry, falling price points of EV components, and overall market competition are a few primary reasons for this decrease (Lutsey and Nicholas 2019). EV manufacturers are inclined to

gain a competitive advantage by producing more affordable vehicles. Additionally, the US government has incentives in place that help to reduce the cost of EVs and encourage the sale of EVs nationally. Even with these measures, EVs still have high purchase prices and is one of the top barriers in EV adoption (Diamond 2009; Egbue and Long 2012; Krishna 2021). During April of 2022, the average price for an EV was above $65,000. By comparison, mid-sized cars were about $32,000, and full-sized cars were around $44,000. The EV price point fell between full-size pick-up trucks ($60,082) and luxury mid-size SUVs ($69,608) (Kelley Blue Book 2022). With these factors considered, vehicle retrofitting could be a potential pathway for introducing EVs into the market and increasing adoption. Vehicle retrofitting is the process of taking a conventional engine-powered vehicle and converting it into a hybrid or all-electric vehicle (Karthik and Giriyapur 2019). From a consumer perspective, it is an approach with several advantages; however, it is not a concept that many are familiar with, and there is some uncertainty. We wanted to see how consumers felt about the possibility of retrofitting their vehicles versus buying a new one. According to the survey, 47% of the participants preferred a retrofitted vehicle versus purchasing a new or used EV. Nearly 32% were undecided on the matter. The primary benefit of this technique is the cost-effectiveness. The exact price of a conversion varies, with some starting at $2000 and some going to $20,000. User familiarity is also a factor, and according to Hoeft (2021), most people have confidence in their used vehicle's reliability and safety. Many car owners prefer to keep the same vehicle but lower the costs of ownership and environmental impact. This can be especially true for older and vintage model (Watts, Ghosh, and Hinshelwood 2021). With the goals set by the US government to increase adoption, EV retrofitting could be a pathway to accelerate the process. With the available benefits, nearly 21% of the participants preferred purchasing a new or used EV. Retrofitted vehicles have several limitations, including the range. The range of these vehicles is often much less than that of an original equipment manufacturer (OEM) vehicle. The driving range of retrofit EVs is limited by the size of the car and other shape modifications. For drivers that need a vehicle with a longer range this approach might not be appropriate. The range for some of these vehicles is also less than 150 miles, compared to an original EV, which is 200-500 miles. Not to mention maintenance for these vehicles is still required, and the lifespan of the batteries is limited as well. The availability of these conversion shops is also limited and only a few offer

these services. Some car enthusiasts may opt to do the conversions themselves but for most people, they would prefer work done by a professional.

Q2. Ineligibility for the tax credit includes income level (ex. $150,000 or less filing single is eligible) or manufacturing and resource restrictions. Regardless of whether there was an EV credit to be applied to my EV purchase, I would still purchase an EV.

The US government has instituted several subsidies and benefits for EV owners to encourage EV adoption. Perhaps the most notable is the available EV tax credit given to those looking to purchase an EV. The credit has been available for years, but several stipulations have recently been added to the eligibility standards and include the requirement for final assembly in North America and specific vehicle types to fall below $80,000 for SUVs and $55,000 for regular vehicles (IRS 2023). In addition to some of the vehicle requirements, individuals and families must also meet the income qualifications. To qualify, individuals must meet the following income qualifications as listed in Table 23. According to the survey 60% of the participants agreed that they would still be willing to purchase an EV without incentives. Potential savings for refueling, which can be seen in Table 25 and other perceived benefits, such as environmental friendliness and reduced maintenance, are key in the decision-making process for consumers. Degirmenci and Breitner (2017) note that EV environmental performance can be a stronger determinant of purchase intention and attitude than the price and range of a vehicle. It seems that even without subsidies, consumers are willing to purchase an EV to reap the benefits of EVs. This occurrence is encouraging for manufacturers and the government alike since the incentives will only be in place for a limited time, like the EV Tax Credit, which expires December 2032.

Q3. Some people decide to purchase EVs regardless of the incentive measures available, instead looking to benefit from the advantages of EV ownership. Is having more incentives the way to encourage EV adoption?

Most participants (70%) still believe that incentives are the best way to encourage EV adoption. Only 6% believed that incentives do not encourage adoption. This continues to affirm that although there are some barriers when it comes to pricing, other benefits still make EVs a

worthwhile investment. Studies have shown that incentives positively correlate with EV sales (Beresteanu and Li 2011; Gallagher and Muehlegger 2011). However, Sierzchula et al. (2014) experiment found that sometimes this is not uniform across different nations. Higher incentives led to increased EV adoption in nations like Norway and Estonia. On the other hand, countries like Denmark and Belgium also have high incentive offerings but an overall low market EV share, meaning in some nations, there are other drivers and barriers to adoption. Comparatively, we can look at incentives offered on a state level. Several states offer rebates for EV charging station purchases. Utility companies also offer additional rebates for those purchasing or leasing new vehicles. California, for example, has an extensive list of incentive offerings and has led to it being the state with the highest market share of EVs (Wakefield 2023). In contrast, despite not having as many incentive offerings, Maine still had a significant share of the total US EV market in 2019 (EVAdoption 2020).

Table 23: Income requirement for EV tax credit qualification.

Filing Status	**Gross Income (less than)**
Married filing jointly or filing as a qualifying surviving spouse or a qualifying widow(er)	$300,000
Head of household	$225,000
All other taxpayers	$150,000

Source: IRS.GOV (IRS 2023)

Q4. Only vehicles assembled in North America that use critical materials from nations with a free trade agreement with the US are eligible for the $7500 tax credit. How likely would this deter you from buying a car that is not qualified for the tax credit?

Eligibility for the $7500 tax credit is dependent on the origin of vehicle assembly and the source of critical materials (nations with a free trade agreement with the US). The qualifications could impact the purchase decisions of some individuals. Current vehicles that meet the qualifications can be seen in Table 24. These requirements, as proposed in the Inflation Reduction Act, ensure that American workers, companies, and consumers continue to benefit from private-sector

investment (US Department of Treasury 2023). For those eligible for the tax credit, the incentive may help offset the initial cost of purchasing an electric vehicle (EV) and make it a more attractive option. Nearly 51% of the respondents agreed that ineligibility for the credit would deter them from buying vehicles that did not qualify for the credit. The tax credit can significantly reduce the price of the vehicle and make it more competitive with traditional gasoline-powered vehicles. However, for those who are not eligible for the tax credit, the higher upfront cost of purchasing an EV can be discouraging. The cost difference between an EV and a gasoline-powered vehicle can be significant, and the lack of tax credits may make it more difficult to justify the purchase of an EV. Considering other factors beyond the tax credit when purchasing, including the long-term savings on fuel and maintenance costs, the environmental benefits of driving an EV, and the driving experience may still make an EV an attractive option. A relatively low percentage, 15%, said they would not be deterred from purchasing vehicles that did not meet the vehicle qualifications. Due to the stipulations mentioned, several EV models will not qualify. However, it is plausible that consumers will prefer to stick to their preferred models due to brand loyalty and familiarity.

Table 24: Vehicles eligible for the tax credit as of 2023.

ELIGIBLE FOR BOTH CREDITS $7,500	ELIGIBLE FOR SINGLE CREDIT $3,750
CADILLAC LYRIQ	Ford E-Transit
CHEVY BOLT	Ford Escape Plug-In Hybrid
CHEVY BOLT EUV	Jeep Wrangler 4xe
CHEVY SILVERADO EV	Jeep Grand Cherokee 4xe
CHRYSLER PACIFICA PHEV	Lincoln Corsair Grand Touring PHEV
FORD F-150 LIGHTNING	Mustang Mach-E
LINCOLN AVIATOR GRAND TOURII	Tesla Model 3 (Standard Range Rwd)
TESLA MODEL Y	
TESLA MODEL 3	
VOLKSWAGEN ID.4 (STANDARD, S, PRO, PRO S, PRO S PLUS, AWD PRO, AWD PRO S AND AWD PRO S PLUS)	

Q5. AI and autonomous driving are advancing, and the number of automated vehicles on the road is expected to increase. In addition, ride-sharing companies like Uber and Lyft are

experimenting with a driverless fleet. How comfortable would you be driving alongside or being a passenger in one of these vehicles?

The number of vehicles with autonomous driving capabilities is growing, and this technology is expected to have a profound impact on future transportation systems and as a result, has gained widespread attention (Wu et al. 2020). Autonomous vehicles (AV) is a term often used interchangeably with self–driving vehicles or cars, and driverless cars but there are varying levels of automation as described by The Society of Automotive Engineers (SAE). AV integration aims to assist/replace human drivers in maneuvering the vehicle to help reduce accidents caused by human error (Cui et al. 2019). AVs also create an opportunity to reduce fuel consumption and emissions and reduce parking-related problems as the number of parking problems decreases. On the one hand, this can be very beneficial, but there is a varying level of comfort between drivers and passengers. Reviews were relatively mixed with nearly 45% of participants having a positive outlook on AVs, around 25% were uncertain, and the reaming 30% had a negative outlook. Uncertainty in this technology is expected as people are generally hesitant to use technology that takes control away from the user. Tragedies and accidents that occur due to AVs also have the tendency to impact customer views of such technology negatively. A 2022 study by JD Power also showed that overall there is still some hesitancy to embrace AVs (Choksey 2022). Among some of the findings were that people in general are becoming more curious about AV technology, but the comfort level is not growing among consumers. People feel that such vehicles can be better suited for transporting goods rather than the transportation of people. Consumers' overall concerns seem to be the safety of themselves and the people around them and is one of the biggest obstacles to overcome for acceptance (Jing et al. 2020). A 2017 Deloitte study found that 74% of US consumers felt fully autonomous vehicles were unsafe (Vitale Jr and Giffi 2017). For AVs to progress, addressing many potential failures and safety issues is essential.

Q6. Social media apps (e.g., Instagram, Facebook, TikTok) track location information and consumer habits that help them to suggest ads and other posts. EVs may soon also recognize patterns and keep track of information that would otherwise be private. What is your level of comfort with this when connected with your EV?

There is some hesitancy from technology users regarding social media and mobile devices' ability to predict consumers' behavior, wants, and needs. For the purposes of advertising or predicting driver behavior, EVs may also start to have these capabilities. We wanted to see how comfortable EV owners would be with this technology, and over 40% of the respondents found these capabilities concerning. Many people report that after conversing about a certain product, food, or brand name, an advertisement related to that item appears on their mobile device (Hunter 2021; Khan 2021; Komando 2019). Smart speakers, TVs, and other home devices also have access to the microphone and can perform specific tasks based on the speaker's request. Some suspect these devices also eavesdrop on conversations and track people's activities. While this is often brushed off as conspiracy or a minuscule issue, it is a growing concern in cybersecurity. Most recently, TikTok, a Chinese-based social media application, made news regarding the privacy policy. Agreeing with the terms and conditions of the app gives it access to many things on a mobile device, including purchase information, IP address, app, and file names, among many others. Even after deletion, it is reported that the app can still access this data. In February 2023, federal agencies had to remove the app from all government devices because of the potential for spyware (CNN 2023). EVs typically do not possess the capabilities smartphones have, however, many people still connect their phones to vehicles via Bluetooth, where it can access contacts, streaming, and GPS history. In addition, there are models that are being developed that contain sophisticated displays and have connectivity to social media apps. The extent to which the privacy and security risks present themselves is limited at the moment, but the potential is unknown when it comes to matters of spyware. Even more so are the threats of potential hackers of EVs and charging infrastructure which is a serious and present issue.

Q7. EVs are seen as better options for transportation since they eliminate tailpipe emissions. Unfortunately, acquiring lithium for batteries is very energy, water-intensive, and pollutant. Do you believe that the benefits of EVs outweigh the negative aspects of lithium mining?

With many popular consumer products, associated ethical, legal, and safety issues can deter many individuals. These concerns escalate particularly when consumers become more informed about the product’s origin, production methods, and potential exploitation, including low wages

and poor working conditions. However, despite exposure to this information, many people are indifferent to these facts, which does not affect their decision-making. Carrigan and Attalla (2001) highlights that companies like Nike might have cases of unethical conduct; nevertheless, people's purchase intentions are not impacted. The authors also note that although some consumers act with ethical intentions, they are likely to remain in the minority. Burke and Milberg (1993) also found that even if certain company practices are viewed as distasteful or offensive by consumers, the familiarity and overall satisfaction with the product overrules their opposition. This means that although consumers may feel a certain way, their actions may show otherwise. (Coffin and Egan–Wyer 2022) alludes to this in their work, citing a European survey that revealed that 68% of Europeans felt that being environmentally friendly was more important to them now than five years ago. Yet the choices in consumerism were not changing as quickly as attitudes.

We wanted to see whether customers believed that the EV ecosystem's positive aspects outshined lithium mining's negative impacts. Only about 47% of consumers felt that EV benefits outweigh the negative aspects of lithium mining. EVs have a key benefit, the reduction of tailpipe emissions which helps to reduce overall carbon emissions as well as reduce the harmful effects of such as smog, PM release and the release of chemicals. Most EVs are powered by a lithium battery. Lithium is a very energy-dense material and is the most consistent and sought-after material used in EVs today. However, the lithium extraction process is very chemical and water intensive. This process is known to pollute local ecosystems and have an effect on the surrounding people. Other critical mineral mining processes, such as the ones for cobalt, are infamous for placing marginalized people in hazardous conditions. These issues are cause of action for ethical consumerism and with enough opposition could be detrimental to EV adoption. As a result, the extraction processes and sourcing of these materials must be reconsidered.

Q8. While weather patterns and natural disasters are predictable, there are times when such events happen unexpectedly. Such events can cause power outages, road closures, and more. What is your confidence or trust in an EV to help you evacuate during an emergency?

One of the most important things that private transportation can provide is the ability to flee or escape during emergency situations. Confidence in an EV's ability to do this was mixed. 51% of participants trusted EVs, 26% were unsure, and 23% did not trust EVs in the event of an emergency. One of the reasons combustion vehicles are considered more reliable is that refueling is a relatively quick and simple process. Additionally, gas stations are essentially ubiquitous. According to the American Petroleum Institute (API) there are more than 145,000 in the US (American Petroleum Institute 2021). They are located along major highways and often are in close proximity to stores that allow people to buy products quickly and then get back on the road. During an emergency, it is essential to operate promptly to get out of harm's way. People tend to gauge their decision-making based on the experience of others, whether negative or positive. National and local media have reported cases of EV inoperability due to inclement weather, such as extreme cold or during power outages caused by storms and even fires (Osaka 2023; Valdes-Dapena 2020; WXYZ Detroit 2023). Extreme temperatures, such as high heat or cold, can also impact the battery's performance. Another important factor to consider is the range of EVs on a single charge, which varies by vehicle model. Owners must ensure that the EV range is sufficient to reach the desired evacuation location as a means of escape. EVs' effectiveness can be increased with the right arrangements, and owners should make an effort to be more aware of possible emergencies that arise. Awareness of available charging stations along the evacuation route in case of the need for additional charge is also important as well as road and traffic conditions. Road congestion or detours could also impact the driving range, and the time required to reach the destination. With proper planning, however, many of these risks can be mitigated.

Q9. Up to 80% of EV charging occurs at home due to convenience and lower cost. However, some EV owners don't have access to charging at home. Would you be willing to own an EV if you had to rely solely on public chargers to charge your vehicle?

EV charging accessibility has expanded over the last several years. EV stakeholders, the government, and businesses have helped to expand this network by constructing fully dedicated charging areas and integrating EV charging into parking garages and parking spaces. Many researchers affirm that access to public charging stations is key to eliminating range anxiety.

Increasing accessibility also enables EV owners who do not have access to home charging the ability to charge. Consumer opinions regarding owning an EV without access to home charging availability were divided nearly evenly. Among the respondents 42% expressed willingness to own an EV with access to home charging, while 41% of preferred not to own an EV without such. The responses here are significant, and there are some plausible reasons as to why respondents felt this way. Access to charging can vary, whereas in major metropolitans and regions with high population density, EV ownership is higher, and therefore, there is better access to charging. Funke et al.'s (Funke et al. 2019) research also supports this, emphasizing the importance of public charging infrastructure in densely populated areas. In less densely populated areas, public charging availability is likely to be lower, which could explain why residents in these areas are not as persuaded to own an EV. Additionally, the cost of charging outside of a residence is often higher, which also contributes to the lower preferences for EV ownership. According to the DOE, up to 80% of charging occurs at home due to convenience and lower cost (Blonsky, Munankarmi, and Balamurugan 2021). Typically, homeowners opt for Level 1 charging as it is the most cost-effective to install and has fewer hazards when compared with Level 2 and Level 3 charging. However, many do choose Level 2 charging. It becomes more difficult for residents of apartments, condominiums, and multi-family housing units to have unlimited access to home charging due to space constraints and the possible presence of other EV charging users as well.

Q10. To encourage EV adoption, meet sustainability goals and attract/retain employees, many workplaces are beginning to install charging infrastructure for employees. What is the importance you place on workplace charging accessibility?

As discussed earlier, public charging will be of greater necessity in densely populated areas and areas with a high density of attached homes. Outside of home charging, access to workplace charging seems to be the next viable option as both are important to the success of EVs (Hardman et al. 2018). Nearly 73% of the respondents agreed that workplace charging accessibility is important and could be key to increasing EV adoption. Charging companies recognize the importance of EV charging integration as many employees want to adopt sustainable practices, which can be supported at the workplace (Blink Charging Co. 2023).

Providing charging infrastructure presents opportunities to be used as an incentive to attract talent, increase sustainability and enhance affordability and convenience for EV owners. Workplace charging can also be a viable alternative for individuals lacking access to home charging. Similar to home charging, once the vehicle is parked at the workplace, it remains stationary and unused for a significant time so utilizing this time for charging purposes can be beneficial to EV owners.

In addition to finding consumer opinions on the importance of workplace charging, we wanted to see which incentives consumers and employees found most attractive for workplace charging. As seen in Figure 15 respondents found free workplace charging the best incentive. Many existing programs are free or discounted for employees, but the Alternative Fuels Data Center (AFDC) suggests that time limits, reservation systems, and assignments are given to ensure that charging spaces are shared adequately. Consumers also felt that workplaces offering other incentives would be desirable. The incentives offered would vary from place to place, whether monetary, gifts or recognition from the employer. Workplace charging is also often private and is advantageous to employees since it eliminates queues and the need to compete for charging time. EV charging can also be strategically placed and be offered as "premium parking," likely in a spot that is closer to the desired destination.

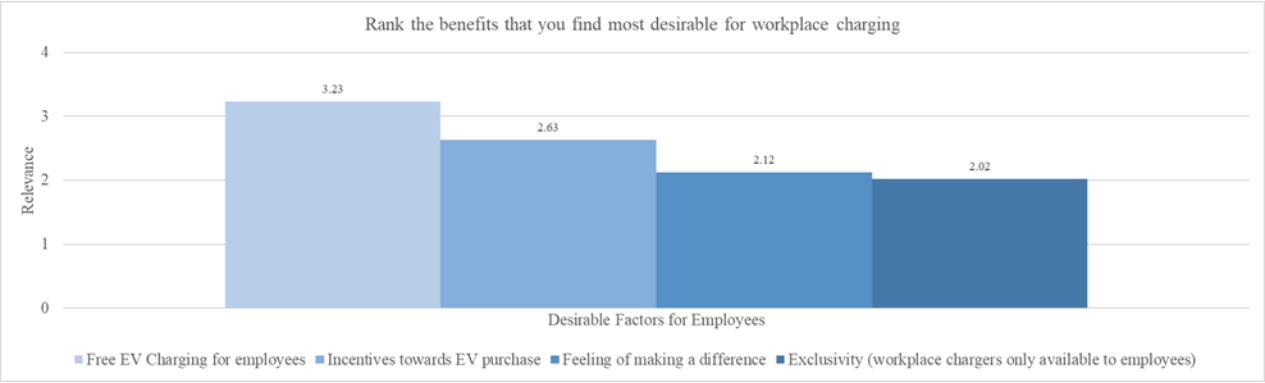

Figure 15: The average ranking of the most desirable incentives for workplace charging.

Q11. Fast plug-in EV charging at most, typically lasts anywhere from 30-45 minutes. Depending on the location and EV charging demand, EV owners would need to wait in a queue for 10 - 30 minutes to charge an EV. Would the potential wait time associated with charging deter you from purchasing an EV?

Ideally, fast-charging infrastructure should be installed on highways and areas with high traffic. Recognizing this need, efforts are underway by the US government to expand this network. EV owners desire the ability to charge vehicles as quickly as possible. Current Level 3 charging technology can recharge an EV from 0% to 80% in 30-45 minutes. Compared to gas refueling, it is considerably longer and can be an inconvenience. EV owners generally are aware of longer charging times and therefore plan accordingly. However, there are instances when queues form at charging stations, especially where space is limited. Many opposed this, as 63% of participants agreed that waiting time would deter them from purchasing an EV. For individuals who regularly drive long distances, waiting times can be problematic however, for shorter commutes and trips frequent charging needs are less concerning. Additionally, when charging stations become more widely available at malls and restaurants people should feel more comfortable with increased availability.

Q12. EVs typically require less maintenance than combustion vehicles. How confident are you that you can find a place to adequately service your vehicle for maintenance?

EVs and gas vehicles have distinct servicing frequencies and specific requirements. A significant portion of the respondents were unsure whether they could locate a place to service an EV, as 31% of the respondents were uncertain. However, 55% did feel they could find a place to service an EV adequately. For the most part, owners will only need to worry about the wiper fluids, brake pads, tire changes, and when possible, avoid extreme temperatures as the battery can be affected. The major issues that can arise will be more complex and require professionals that can deal with these issues. Nevertheless, on a per-mile basis and over an EV's lifetime, owners can expect to save money compared to a combustion vehicle, as seen in Table 25. Since there are less mechanical issues overall, there is expected to be a lower demand for mechanics and technicians in the future (Lopez 2022). Soon many mechanics will need to be retrained as more EVs will penetrate the market because of the different configurations. It has been reported that only around 3% of mechanics are qualified to work on EVs, most likely resulting in EV owners relying more on the dealerships instead of independent. More important perhaps is the speed of service. EV may differ from those of a traditional gasoline-powered vehicle, and it's important to find a qualified technician who is familiar with the unique components of an EV.

Many manufacturers have established their own servicing networks but often these networks are more expensive than third-party networks. Initially, EV owners with newer EVs may be covered under the manufacturer's warranty for a certain period. However, as the used EV market expands many will seek out alternatives.

Table 25: Estimated per-mile repair and maintenance costs by vehicle type.

Powertrain Type	**0-50K Miles**	**50K-100K Miles**	**100K-200K Miles**	**Lifetime Average**	**Lifetime Maintenance and Repair Cost**	**Lifetime Savings vs. ICE**
BEV	$.012	$.028	$.043	$.031	$4,600	$4,600
PHEV	$.021	$.031	$.033	$.030	$4,600	$4,600
ICEV	$.028	$.060	$.079	$.061	$9,200	

Source: Consumer Reports (Harto 2020)

Q13. EV subscription plans allow subscribers to pay a monthly fee to drive a vehicle on a short-term basis. Subscribers benefit as the onus of maintenance and registration is on the company, but the startup and monthly fees are high (Upwards of $1000 a month). What is the likelihood of you participating in an EV subscription plan?

Current customer feelings toward EV subscriptions are not well documented, and it is difficult to gauge what customers may like to see in subscription plans since it is a relatively new offering. In the realm of subscriptions, most literature refers to subscription plans for batteries and not for the vehicle. Private companies and car manufacturers offer some existing plans, but these are limited to a few places across the nation, and current plans are quite expensive and seem to be unrealistic for some. The respondents showed a lot of uncertainty and negativity toward subscription plans. Only 40% of the participants agreed to participate in subscription plans. The subscriptions are meant to serve as short-term commitments for those who might want to try out using an EV. These plans also include insurance and maintenance which is an upside. It also differs from vehicle financing, where the vehicle owner is still accountable for insurance and covering the costs of vehicle breakdowns. Autonomy is an available option that offers these subscriptions for Tesla Model 3s, and the prices start out at $1000 a month with a $1000 down payment. These prices can be adjusted based on preference and there is a monthly 1000-mile limit. Other car rental apps like Turo offer options to rent vehicles but on a day-to-day basis.

Another concept similar to car leasing is battery leasing which consists of customers purchasing the EV like normal and instead renting or leasing the battery. This concept places the ownership of the vehicle into the hands of the owner, and the battery remains the property of the car manufacturer. Consumers benefit from this option since the manufacturer becomes responsible for maintaining the battery. Doing this can also extend the lifetime of batteries overall since the manufacturers will have the technology that can monitor the state and charge of the batteries properly. However, many manufacturers are hesitant to adopt this technology because it would require significant changes to their current fleets and millions of dollars' worth of investments. The only EV company with battery-swapping capabilities is NIO, a Chinese-based company. Most of these facilities are solely in China; however, NIO has expanded its market into Europe.

6. Limitations of this Study and Implications

Likert scale surveys are a valuable tool to quickly gather data; however, they do have limitations. Notably online Likert surveys are prone to straightlining or nondifferentiation. It occurs when respondents rush through surveys selecting the same answer repeatedly or in a quick manner(Qualtrics 2018; Yan 2008). Nevertheless, we are confident the data was sufficient and provides useful quantitative data that can be used for analysis.

7. Conclusion

Our study looks into consumer opinions regarding the EV ecosystem, identifying significant factors for optimization. Charging infrastructure, range anxiety, and vehicle pricing remain major barriers to EV adoption. However, government incentives and infrastructure expansion aim to address these concerns. Additionally, sustainability is becoming more important to consumers, and they want to begin or continue pursuing products that help them to achieve this, but convenience and pricing often outweigh sustainability considerations.

Public education and engagement are crucial as EV technology becomes increasingly integrated into society. Additionally, as EV technology continues to expand, educating people through test driving experiences and initiatives will help to improve the outlook as well.

For future work in-depth interviews with consumers can offer deeper insights into the EV ecosystem. Ultimately, the goal of this study is to understanding consumer needs is essential for sustainable growth and electrification promotion within the EV ecosystem. The collective efforts

of various stakeholders, including governments, automakers, infrastructure providers, and energy companies, will be crucial in developing effective policies and strategies. In conclusion, with collaborative efforts and growing expertise, a greener and more sustainable transportation system can be realized.

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5

Thermal Modification of Steam Bent Wood: Expanding Design Aspects of Thermowood

Abstract

Wood is a material that has been used by humans in a wide range of applications, from simple shelters to the complex extraction of components for paper making. Historically it was one of the main components in housing construction especially where trees where abundant and were deemed to be the best option for building. Today it is still a key structural component for outdoor and interior design applications however due to the wood's susceptibility to insect, microbial and fungal decay wood is often pretreated with chemicals to increase its durability. Unfortunately, often these chemicals also pose environmental and health hazards. Thermally modified wood or Thermowood is a timber product developed in Finland that helps to circumvent these hazards as it is a clean process that only utilizes heat and steam. After treatment the resulting product is one with dimensional stability, low equilibrium moisture content and increased durability, which makes it desirable for outdoor applications like cladding and decking. This increased durability is favorable however due to the chemical changes that occur during the Thermowood process the bendability also decreases, which limits its use in design applications where curves and bends are desired. In this work we propose wood can be first steam bent and then thermally modified to increase durability while enhancing aesthetic appeal. Our results showed that with the correct parameters, wood can be successfully steam bent and thermally modified. Springback of wood after steam bending is inevitable but should be anticipated and with correct modifications springback can be limited.

1. Introduction

Wood is a versatile material that has been utilized by humans for centuries in several applications and is a key material in almost all of human civilization (Wimmers, 2017). Historically, wood has been used to construct shelters, build furniture, and for creating tools. As technology advanced and the properties and composition were better understood, its applications made way into today's paper and composite industries, complex architectural structures and other high-performance applications. As a building material wood has several advantages when compared to steel and concrete. It is a lighter material with desirable strength properties and has a lower carbon footprint (Maier, 2021). Wood has not only made a resurgence as a building material due to these favorable properties, but it has also moved beyond its limitations as can be seen in developments with mass timber. Additionally, due to its lignin content wood is pliable and can be configured to create beautiful shapes and architecture. Wood bending is achieved through heat and chemical treatments and is common in furniture making and building structures. Bending is advantageous since whole pieces of curved wood exhibit better strength properties than pieces that are sawn and also proves to be less wasteful (Cottey, 1975). However, air dried and kiln dried wood require proper preparation and specific processes to assume the desired shapes and remain defect free. From a durability point of view, wood is prone to microbial and fungal decay which can reduce its strength (Marais et al., 2022). Additionally, it is prone to insect infestation which can be problematic especially in the construction sector where problems often go undetected and can be prolonged. To increase the stability and durability of wood, pressure treatments with chemicals can be employed. Common methods include copper, chromium, ammonium-based treatments, however these methods present potential environmental and health hazards (Schiopu & Tiruta-Barna, 2012). In search for an alternative, thermal modification is a promising resolution. More specifically thermally modified wood or so-called Thermowood is a wood product that has been treated with heat and steam to improve its durability. The process, originally developed in Finland, creates an end product that is more dimensionally stable resistant to decay and perfectly suited for exterior applications. Over 40 companies throughout the world, mainly Central and Northern Europe, make Thermowood products used in saunas, decking, cladding and other exterior applications. As noted, the Thermowood process extends the applications of wood, but the end product increases in rigidity and decreases in bending strength. Due to these changes the shape of thermally modified wood

can only be altered through cutting or sawing but not through steam bending. In this research we propose the use of steam bending to create round shapes and subsequent thermal modification to improve the durability.

2. Background

2.1 Wood Bending

Bending wood creates compressive strains on the interior side and tensile strains on the exterior side of the curvature (Kuljich et al., 2015). Although wood is able to handle the compressive strains, wood is more susceptible to damage on the exterior tension side. To alleviate the risk of damage, tension straps or bands are used to help equally distribute pressure along the convex side as shown in Figure 16. The bendability of wood is also dependent on the wood species and type of wood. Typically, hardwoods such as oak, ash, hickory, and maple more suitable for bending compared to softwoods such as cedar, fir, spruce and pine (Benson, 2008). Softwoods can still be bent; however, they require less, a careful selection of wood samples, specific thicknesses and lower bending angles.

Figure 16: Bent wood sample with tension strap on the exterior face.

Steam bending consists of using some combination of heat, steam, or pressure. In steam bending, wood pieces are placed in a steam box at about 100 °C for a specific amount of time. After removal from the steam environment, the specimen is bent and then kept in a bending jig

until cooled. Additional time in the jig is required to equilibrate the sample to the desired moisture content (MC) (Lemoine & Koch, 1971).

While steaming helps to increase the moisture content in wood, it is preferred to condition the wood prior to steaming. This can be achieved by placing the selected wood samples in a climate chamber to reach the desired moisture content. The suggested steaming times may vary depending on the wood species and thicknesses of wood. The most common practice is 1 hour for every inch (25.4 mm) of thickness (Benson, 2008; Veritas, 2011). However Lemoine & Koch, (1971) found that they could steam 12.7 mm and 25.4 mm thick pieces at 17 % MC for only 10 and 20 min, with sufficient results.

2.2 Springback

The term springback is used to describe the ability of a material to revert to its original shape after a force is applied to it. In the realm of woodworking springback of steam bent pieces is always anticipated. The springback that occurs in a piece of wood depends on several factors including the wood species, wood thickness, duration in the jig, moisture content, the angle or radius of the jig, and time out of the jig.

2.3 Thermowood and Thermal Modification of Wood

Heat treatments to enhance wood durability have been used for centuries in Europe and these treatments can be cited all the way back to the Vikings of Scandanvia. Germany, Finland, France and the Netherlands are among the nations that developed these heat treatments. Thermal modification of wood was first studied in the early 20th century but the industrial scale ThermoWood process was developed by VTT Technical Research Centre of Finland (VTT) in 1993 (Thermowood Association, 2023). Shortly after its development, the International Thermowood Association was founded to advocate for its usage and uphold the standard of Thermowood. As of 2023, there are 17 companies from 8 countries that are a part of the association. It serves as an alternative to physical and chemical treatments used to increase the durability of wood. Instead, the process treats timber using heat and steam with phases that include high temperature drying, thermal modification and cooling, and moisture conditioning. The entire thermal treatment process involves three phases as shown in Figure 17. During the first phase, the wood is quickly heated up to 100 °C followed by a slower temperature increase to 130 °C. The second phase consists of a slow heating period to 160–210 °C for 2–3 h. During the

third phase the wood is cooled, and its moisture content is stabilized at 4–7%. The end result is a timber product that is dimensionally stable, has increased durability, and darker color.

As stated, the thermal modification process increases wood durability and stability due to changes in its composition after the process. The main constituents of wood are cellulose, hemicellulose, lignin and other extractives which vary in ratio across softwoods and hardwoods. In untreated wood, it is namely hemicelluloses, that are susceptible to fungus and other microorganisms which lead to decay. During thermal modification, as the wood is heated, acetic acid is formed from acetylated hemicelluloses by hydrolysis. The released acid serves as a catalyst in the hydrolysis of hemicelluloses to soluble sugars. As a result, the product has significantly lower hemicellulose content, which in turn reduces the amount of material that fungi can decay. Additionally, as the hemicelluloses degrade, water-absorbing hydroxyl groups decrease in concentration and the dimensional stability of thermally modified timber improves (Thermowood Association, 2023).

Due to this increase in durability, stability and overall aesthetic, it is well suited for a variety of outdoor applications. Thermowood products come in different dimensions and is used for cladding, battens, decking, and furniture and other interior applications.

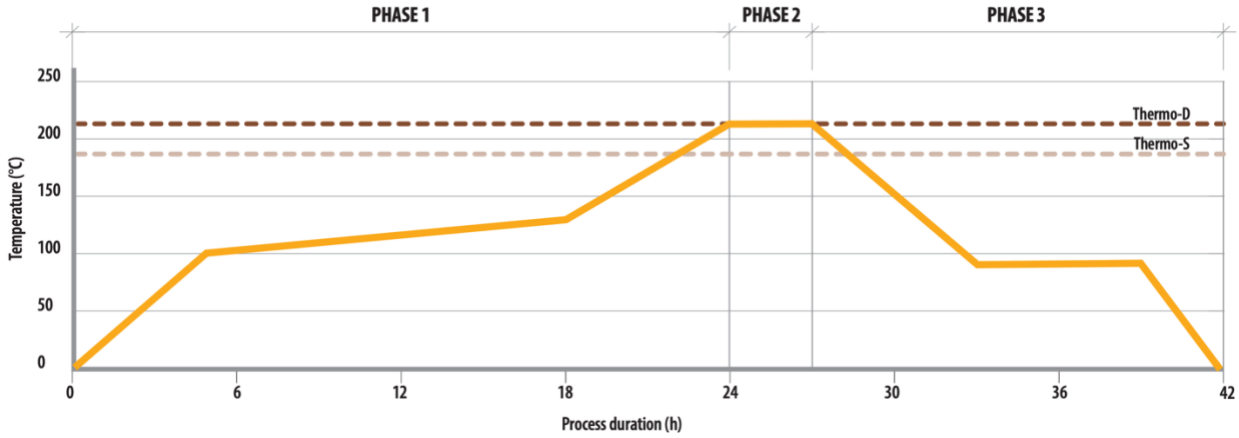

Figure 17: An example of the ThermoWood® process for Nordic softwood (product class Thermo-D).

3. Materials and Methods

3.1 Preliminary Work

To find the optimal parameters for bending wood, we explored research and DIY projects. Additionally, we went through several steam bending trials with a variety of wood species (oak,

poplar, and pine) with varying thickness, and different bending angles or radii as shown in Table 26.

Table 26: Preliminary wood bending parameters.

Bending Radius or Angle	**Wood Type**	**Wood Thickness**
11-Inch (27.9 cm) Radius	Oak	6.35 mm (.25 in)
90-Degree Angle	Poplar	19.05 mm (.75 in)
120-Degree Radius	Pine	
23-Inch (61.0 cm) Radius		

The jigs used for bending were constructed from 2x4 pine lumber. The lumber was sawn along the length of the wood into approximately 3-ft. pieces using a band saw. Then the pieces were glued along the length of the piece to create large makeshift wooden boards to accommodate the angle and radius shapes. After drawing the appropriate shape, the wood board was cut into two pieces, one negative and positive piece as shown in Figure 18.

After steaming, a wood piece is placed inside the jig and two to three wood working clamps are used to slowly press the piece into the desired shape as shown in Figure 19. The target species (the wood samples to be thermally modified) was southern yellow pine.

However, we wanted to observe some of the differences in bendability, steam time, and springback among different species. In the first trials of steaming, all wood species were steamed at their base equilibrium moisture content. Generally, wood should be steamed for an hour for every inch of thickness. Meaning for pieces with .635-centimeter (1/4 inch) thickness, 15-20 minutes of steam should be appropriate. However, during the bending process, we found that for more aggressive curves such as the 11-inch radius and the 90° and the 120° pine and poplar pieces tended to suffer from tension failures, while oak was more resilient to these bends. Initially the idea was to continue steaming the wood for longer time periods upwards of 40 minutes. Following the increase in steaming time we found that the tension failures decreased and nearly subsided. As confirmed in this preliminary work, oven drying tests and through

literature, the initial moisture content for the wood pieces was too low. For the pine pieces the wood moisture content was around 7-9%. To raise the initial moisture content, the wood was conditioned in a climate chamber to at least 12% moisture content. After conditioning the rate of tension failures decreased and the steaming time also reduced to the suggested time of 15-20 minutes.

Figure 18: Negative and positive wood piece.

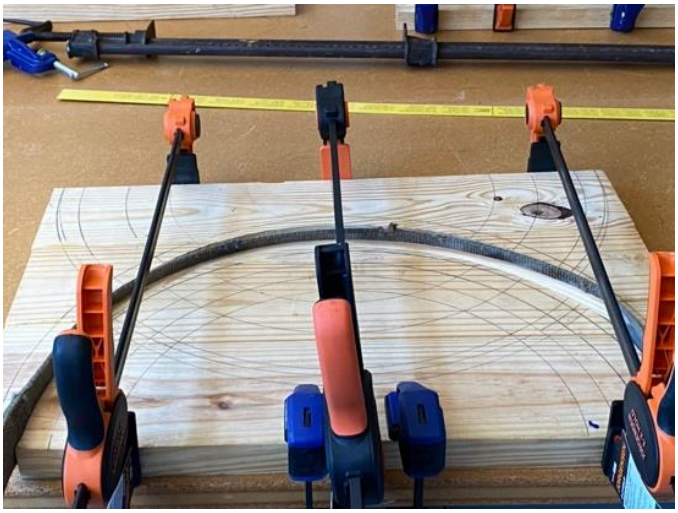

Figure 19: wood jig held together with clamping device

3.2 Selected Factors

Based on a preliminary study and literature resources, we opted to select the following parameters. We used southern yellow pine samples that were approximately .635 centimeters thick. To ensure successful bends with no failures we used a jig with 58.4 centimeters of curvature. Wood samples were free of knots, checks and had straight grain patterns. The original dimensions of the wood were as follows 68.6 – 73.7 cm (L), 8.9 cm (W), .64 cm (H). After splitting the wood, we recorded the weight of each piece and then set the pieces into the climate chamber to be conditioned. Each of the wood samples were conditioned for 10 days at 80% relative humidity and 20° C until they reached an equilibrium between 14-16% MC. For the wood samples to fit inside the steam box, each piece was cut length wise in half. In our experimentation, we also found and concur that a tension strap helps to aid in bending wood while reducing tension breaks. However, due to the relative thinness of the wood samples and the larger radius of the jig it was not necessary.

3.3 Steam Bending

A steam box was constructed from a 1.2-meter-long cylindrical pipe with a 10.2 cm diameter. The back end was sealed with a cap that was secured with a screw. The other end was sealed with a screw cap to allow for entry and removal of the wood samples. We drilled holes into the pipe and placed wooden dowels perpendicularly along the center of the pipe for the wood samples to sit on. At the back of the end pipe, we drilled two holes to connect two steam generators to the steam box. Lastly, we attached a valve to the bottom of the steam box to allow excess steam and water to exit during the steaming process.

Prior to steaming, we recorded the initial weight of the wood samples upon removal from the climate chamber. The steam process was performed in a custom-made steam box for 20 minutes at 100° C at atmospheric pressure. After steaming, the pieces were quickly placed into the bending jig. The clamps were set in place and then used to clamp the jig down until the wood took the desired shape. Bent wood samples are shown in Figure 20.

Figure 20: Bent wood samples produced from 24-inch radius jig.

3.4 Springback

As discussed previously, after steam bending wood will incur springback. We wanted to observe the relation between springback and retention time in the jig. There were three holding times as follows: 2 hours, 12 hours, 24 hours with two wood samples for each time constraint. After the allotted constraint time in the jig, we recorded the weight of each piece and observed each specimen for cracking, noticeable water marks or wetness. The initial radius of curvature for the specimens were recorded. The pieces were placed into a climate chamber ASTM standard conditions (ASTM International, 2004) where the springback and weight of each piece were recorded at the following intervals: 10 mins, 3 hours, 10 hours, 24 hours, and 48 hours.

3.5 Thermal Modification

After recording the final springback and weight of each piece, the wood samples were wrapped firmly in plastic wrap to help retain moisture in preparation for thermal modification. The wood samples for this experiment were modified at the LAB University of Applied Science in Lahti, Finland. The Thermowood kiln was developed by Jartek. The wood pieces were treated with the Thermo-D treatment at 212°C.

4. Results

4.1 Wood Bending

Results from the wood bending phase of our experimentation were satisfactory (100% success rate). All pieces exhibited successful bends due to the preliminary work and selection of a moderate radius of curvature. No sign of tension or convex marks on the wood could be observed.

4.2 Springback Results

The springback value *(sb)* of wood pieces can be measured as a percentage as shown in Equation 1 (Sanne et al., 2020). The formula calculates the ratio between the radius of the jig (r_1) and the radius of the sample (r_2) as seen in Equation 1. More specifically the value is the difference between the radius of the jig and the final radius of the wood sample (Sanne et al., 2020). The initial springback was measured for all six samples as seen in Table 27. The initial springback was more significant in wood samples that were set in place for 2-hours (2A, 2B) as compared to the 12-hours (12A, 12B) and 24-hours (24A, 24B) samples. The results from this work show the wood springback could be related to the wood's moisture content. Additionally, it could be observed that up to 48 hours after extracting the sample from the jig, the 12- and 24-hour samples showed less springback than the 2-hour samples. The tendency for wood to springback is natural therefore it confirms that wood should be given ample time to cool and dry out.

$$sb = r_2/r_1 \cdot 100 - 100$$

Equation 1: Equation to calculate springback.

Table 27: Springback percentages for the designated time interval.

	INITIAL	10mins	3hours	10hours	24hours	48hours
2A*	68.99%	86.46%		112.20%	123.18%	129.17%
2B*	76.74%	103.23%		123.18%	146.14%	151.34%
12A*	34.66%			51.01%	55.78%	57.29%
12B*	33.32%			51.93%	56.58%	59.18%
24A	16.39%	40.70%	43.80%	51.89%	48.49%	51.89%
24B	24.48%	31.94%	40.91%	44.59%	46.69%	49.46%

*Note – the following measurements are missing due to timing

4.3 Thermal Modification Results

Following thermal modification, wood species exhibited favorable properties. There was a noticeable change in color as the wood appeared darker as shown in Figure 21. Each wood piece also maintained its curvature however there was a noticeable increase in the radii of curvature in the pieces. This is most likely due to the high heat the wood is exposed to in the initial stages of the modification process which further encourages the pieces to return back to their original form. After the thermal modification the wood samples were removed from the kiln and weighed and then left to settle at ambient temperature in a woodworking closet. After 5 days the weight of each sample was recorded again. As expected, there was a noticeable decrease in weight of the samples which signifies a decrease in moisture content as shown in Table 28.

Table 28: Weight of wood samples before and after thermal modification.

Pre-Thermal Modification	Five Days Post Thermal Modification
75.9	67.5
68.1	60.3
99.9	89.4
97.0	86.5
79.4	71.2
95.9	85.6

Figure 21: Image A (top-left) is untreated unbent southern yellow pine. Image B (top-right) post thermal modification. Image C (middle bottom) Side view of wood samples

5. Discussion and Conclusion

The bends for the wood species were successful in these trials due to proper selection of bending radius, wood thickness, and moisture conditioning. Although pine is cited as a poor choice for wood bending, it showed evidence of a good choice for steam bending. However, it should be noted that thicker samples of wood and smaller radii or bending angles can lead to less successful bends with tension or compression failures. With that in mind perhaps the most important step is the conditioning of the wood prior to steaming. In our preliminary trials, where we experimented with smaller radii and angle bending, we found that pretreated wood bent far better than unconditioned wood that was air dried and placed straight in the steamer. For thicker

pieces it is even more important as they will need more time in both the steaming chamber and climate chamber to reach an optimal level.

As springback is concerned we have shown that longer holding periods in the jig are essential to decreasing initial springback. Notably the 12-hour and 24-hour holding times had similar springback percentages. Although we have a low sample size, with an industrial framework from a business perspective it may be worth investigating what the minimum holding time for wood pieces should be. With thicker pieces, the stabilization period after steaming and bending will need to be longer.

In future research there are opportunities to explore bending and thermal modification on thicker wood samples. Pine and softwoods such as spruce, generally tend to have a higher rate of failure during steam bending especially with bends that consist of smaller angles and radii. Work to establish the success rate of bending at different thicknesses among different species need to also be established. Hardwoods such as oak have favorable steam bending properties and are better suited for steam bending generally. However, oak performance and durability after thermal modification has not been explored in depth so its feasibility would need to be determined.

As stated, the thermal modification process was a success and to our knowledge this is the first occurrence of thermally modifying steam bent wood. It is a novel approach to creating new timber products to be utilized in the world of design, construction and architecture. With design limitations present with Thermowood due to increase rigidity this research provides a framework to enhance the timber product industry.

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6

CONCLUSION

CONCLUSION

The evolution of electric vehicles has been shaped by cycles of innovation, economic shifts, and technological advancements. Now more than ever the US EV sector can be described as one that is in the middle of uncertainty do to the growing polarization of US political landscape among other challenges. To address these challenges, this dissertation has proposed an innovation ecosystem approach that considers these factors that influence the overall ecosystem and EV adoption. A structured innovation ecosystem should foster collaboration among stakeholders' optimal development. By systematically analyzing this ecosystem, this dissertation provides a holistic view of how EVs can become a reliable and competitive mode of transportation. In Chapter 2 I established the EV innovation ecosystem and provided an overview of historical context, complexities and outlook of EVs and ancillary factors. Nevertheless, it is continuously evolving system that can change drastically due to political shifts, global economics, and overall demand. It can be observed currently in the US where car manufacturers seek to find ways to source materials and manufacturing in North America to reduce tariff burdens enforced by the Trump Administration in March 2025 (House, 2025) .

In Chapter 3 I explored stakeholder perspectives using questionnaire-based analysis. Key stakeholders including automakers, energy providers, and government agencies all have a general outlook of the ecosystem and are responsible for providing services and products for the ecosystem. This work shows how their involvement influences the ecosystem's structure and success. More importantly those who enter this space will need to determine what products and services will be most successful amidst political climates In Chapter 4 this analysis was shifted to consumer behavior. With the aid of behavioral theories, I examined the factors that drive EV

adoption and how different factors are viewed. Among them were consumer perceptions of cost, convenience, and sustainability to help further understand the motivators and barriers that shape purchasing decisions. In Chapter 5 I introduced an innovative approach to implementing wood into the EV ecosystem as a material for EV charging stations and other structural components. By integrating novel design methodologies, this chapter illustrated the potential for alternative materials to enhance EV efficiency and environmental impact.

FUTURE WORK

As the EV industry continues to evolve, each sector of the ecosystem has opportunities for future research and development. Firstly, and arguably most importantly is expanding the nationwide charging network. Charging availability reduces range anxiety and increasing user confidence in EVs. On the other hand, it is necessary that the US can support increased electricity needs so power sources and grid capabilities need to be expanded. Further studies can explore the scalability of EV ecosystems in varying geographic and economic contexts, while assessing how policies and infrastructure investments can be tailored to different regions. Another avenue involves advancements in battery recycling and second-life applications which introduce new streams into the end-of-life cycle for EVs which can help address concerns about resource sustainability and waste management. With continued research, collaboration, and policy support, the future of electric mobility holds promise in shaping a more sustainable transportation system.

A

ACRONYMS

A summary of all acronyms is documented in Table A.1.

Table A.1: A summary of acronyms used in alphabetical order

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicles
Cl_2	Chlorine
CLT	Cross Laminated Timber
Co	Cobalt
CO_2	Carbon Dioxide
Cpt	Capacitive Power Transfer
EU	European Union
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Stations
EVSE	Electric Vehicle Supply Equipment
Fe	Iron
GHG	Greenhouse Gas
G20	Intergovernmental Forum Comprised Of 19 Countries and The EU
H_2SO_4	Sulfuric Acid
HCl	Hydrochloric Acid
HEV	Hybrid Electric Vehicle
HNO_3	Nitric Acid
ICEV	Internal Combustion Vehicle
IPT	Inductive Power Transfer
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium Ion Battery
LIDAR	Light Detection and Ranging

Lini1/3Co1/3Mn1/3O2	Lithium Nickel Cobalt Manganese Oxide
LMO	Lithium Manganese Oxide
MAAS	Mobility As a Service
MCS	Mobile Charging Strategy
Mn	Manganese
NEV	New Energy Vehicle
Ni	Nickel
NMC	Lithium Nickel Manganese Cobalt Oxide
NO_x	Nitrous Oxides
OEM	Original Equipment Manufacturer
PBES	Photovoltaic Battery Energy Storage
PEV	Pure Electric Vehicle
PHEV	Plugin Hybrid Electric Vehicle
PM	Particulate Matter
PV	Photovoltaic
RES	Renewable Energy Sources
SCC	Social Cost of Carbon
SIB	Sodium Ion Battery
So3	Sulfur Trioxide
TEPCO	Tokyo Electric Power Company
V2G	Vehicle To Grid
V2H	Vehicle To Home
WCS	Wireless Charging System