TEAM CHARGEX

Vehicle-to-Vehicle Charging: Prototype Development and Future Potential

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We pledge on our honor that we have not given or received any unauthorized assistance on this proposal.

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Abstract

As widespread electric vehicle (EV) adoption faces hurdles due to limited charging accessibility, this research explores the potential of Vehicle-to-Vehicle (V2V) charging technology, particularly for residents in multi-unit dwellings. To assess the feasibility of this concept, we constructed a functional V2V charger prototype through multiple iterations. Using various Arduino projects focused on PWM and charging circuits, we achieved a successful V2V charger prototype, enabling data collection to inform future advancements in this promising technology.

Introduction

Overview

In the not-too-distant future, we can envision a transportation landscape where electric vehicles (EVs) operate with a newfound confidence. No longer will they be constrained by the limitations of range anxiety, the ever-present concern regarding the availability of the next charging station before their batteries become depleted. Instead, EVs will evolve into mobile power banks, not just capable of receiving energy, but also possessing the remarkable ability to dispense it. This is not the realm of science fiction; it is the intriguing reality on the horizon, fueled by the expanding potential of Vehicle-to-Vehicle (V2V) charging, a technology poised to revolutionize the electric transportation landscape.

V2V charging directly addresses a critical impediment hindering widespread EV adoption: range anxiety. For many potential EV owners, the fear of being stranded on the road with a depleted battery looms large, casting a long shadow over the allure of electric mobility. V2V charging disrupts this narrative, weaving a tapestry of interconnectedness. Imagine a scenario where a depleted EV receives a life-saving energy boost from a fully charged car parked nearby, a benevolent stranger encountered on the open road, or even a designated fleet vehicle. This peer-to-peer energy exchange fosters a sense of community and collaboration, transforming the solitary act of driving into a collaborative endeavor on the electric highway.

The benefits extend far beyond mere convenience. V2V charging unlocks a treasure trove of possibilities, each more intriguing than the last. Envision a world where idle EVs parked during the workday function as mini-power stations, silently feeding excess energy back into the grid. This bidirectional flow could assist in stabilizing power demands, potentially reducing reliance on fossil fuel power plants during peak hours, when the strain on the grid is at its highest. Imagine V2V charging empowering emergency vehicles, such as electric ambulances or fire trucks, to share power with life-saving equipment on the scene. This could extend their operational capacity during critical situations, potentially saving lives in the process.

The possibilities transcend individual vehicles. V2V charging could pave the way for the creation of dynamic charging networks, a groundbreaking concept that redefines the very notion of powering EVs. Fleets of electric delivery vans or ride-sharing cars could be strategically deployed throughout a city, acting as mobile charging stations on wheels. This would ensure a constant flow of readily available power for on-the-go EVs, revolutionizing urban transportation. Imagine a bustling cityscape where not just personal vehicles, but also commercial applications seamlessly integrate into the electric ecosystem, fostering cleaner air and reduced emissions.

However, the path towards a V2V-powered future is not without its challenges. Technical hurdles stand as obstacles that need to be overcome. Standardization of charging protocols and connectors is paramount to ensuring a smooth and seamless energy exchange between disparate EV models. After all, a world where a Tesla cannot share power with a Nissan wouldn't be a true interconnected ecosystem. Safety considerations must be addressed with robust systems in place to prevent over-discharging or power surges that could damage vehicles. Cybersecurity measures need to be developed to safeguard against potential hacking attempts that could disrupt the charging process or even damage vehicles. These challenges are not insurmountable, but they necessitate a concerted effort from researchers, engineers, and policymakers to ensure the safe and efficient implementation of V2V charging.

Despite these hurdles, V2V charging research is progressing rapidly, fueled by a collective sense of purpose. Automobile manufacturers, technology giants, and research institutions are dedicating significant resources to developing efficient, safe, and user-friendly V2V charging solutions. Pilot programs are already underway, testing the feasibility and effectiveness of this transformative technology in real-world scenarios. Each successful test, each hurdle overcome, brings us closer to a world powered by V2V charging. In North America, as of now, there are three main EV charging stations types. These are shown in the figure below.

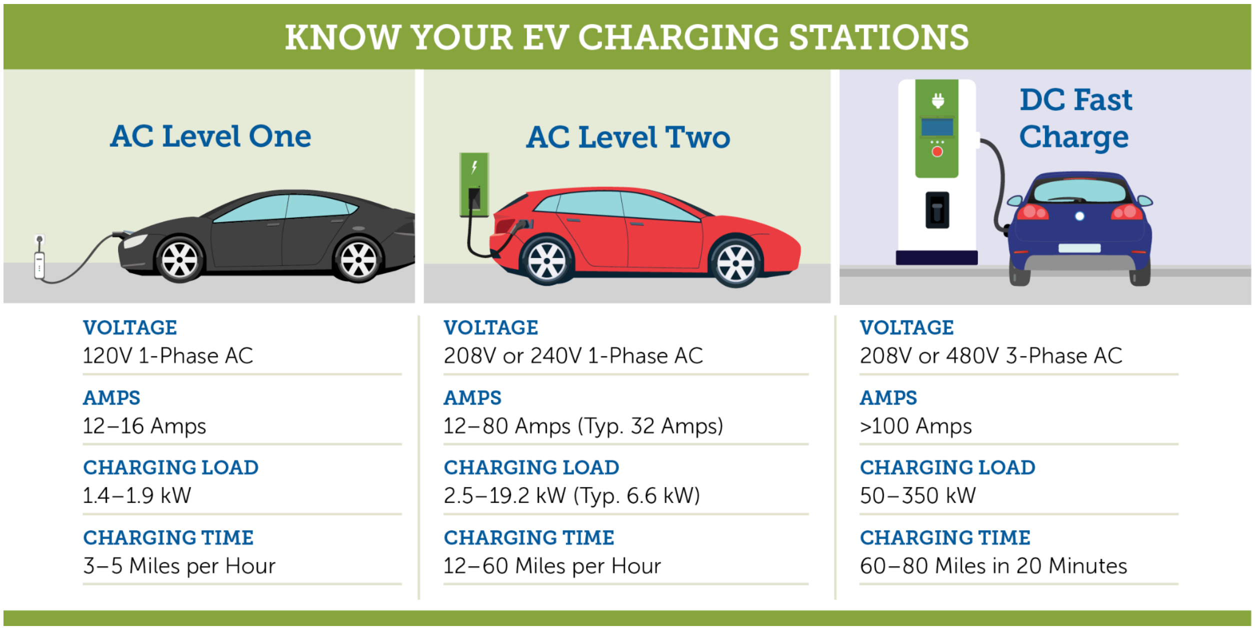

Figure 1: Different Types of EV Charging Stations [68]

This research investigates Vehicle-to-Vehicle (V2V) charging technology for electric vehicles (EVs). V2V charging could address range anxiety, a key barrier to EV adoption. The research will examine technical aspects, potential social collaboration, and the impact on the transportation system. It will also explore how V2V charging might change how we use electricity, vehicles, and travel.

Feasibility

An electric car is a vehicle powered by electricity with the help of a rechargeable battery and a set of motors mated with mechanical components. These energy-efficient vehicles are pivotal in the alleviation of fossil fuel usage and foreign oil dependency of the transportation sector. This is because the Internal combustion engine (ICE) vehicles operate by burning fossil fuel derivatives. Exhaust emissions are their major contribution to environmental pollution. Gas leaks, oil spillage, noise and air pollution are additional shortcomings of an ICE vehicle. Incomplete combustion of hydrocarbons present in fuel also results in carbon monoxide pollution which can be harmful to both the environment and to human population. Additionally, carbon dioxide is released when hydrocarbons present in fuel are burnt which is a leading cause of global climate change and the acidification of oceans. The United States Environmental Protection Agency, states that a typical passenger vehicle emits about 4.9 metric tons of carbon dioxide annually [1].

However, the most common reason that electric vehicle adoption is not as widespread when compared with their internal combustion engine vehicle counterparts is the lack of accommodating charging infrastructure [2]. One of the challenges is that the density of charging stations varies, with some areas being heavily populated with chargers while others have little to no chargers for large stretches of land. The varying density of charging stations is a significant problem, as it may cause range anxiety–the uncertainty of finding a charger that electric car users may face when embarking on longer trips with their electric cars. Range anxiety also leads to reluctance towards purchasing an Electric Vehicle (EV) [3]. Moreover, to secure the consumer base, both car and charging companies are introducing specific adaptors unique to different geographical locations and car models; this lack of uniformity across regions and brands also reduces charger accessibility [4].

To only accentuate the problem of charger inaccessibility, EV chargers are expensive. Reducing the costs of the hardware, installation, and internal circuitry can make them more affordable to a greater population [5]. A journal published by Harvard's Henry Lee and Alex Clark highlights the approximate total cost of installing an EV charger [6]. The charging levels indicate what type of charger is being installed, with Level 1 being the slowest and Level 3 being the fastest. Installing a level 2 charger in a new residence costs approximately $2500 plus the charger, whereas it costs $7000 to install the same charger in a commercial setting. A level 3 charger, which is the fast DC charger, costs around $50,000 to install. The journal breaks down costs based on the location of installation, such as residential and commercial parking spaces. The total costs are dependent not only on the physical charger itself, but also on site preparation, utility services, and type of transformer in order to make high amounts of electricity available for charging an EV.

Several solutions in the past have been implemented to overcome the challenges of inadequate charging infrastructure. Recently, Germany constructed an overhead charging highway lane for trucks, employing the same concepts as electric trains and trolleys, by using overhead cables to charge while in motion.

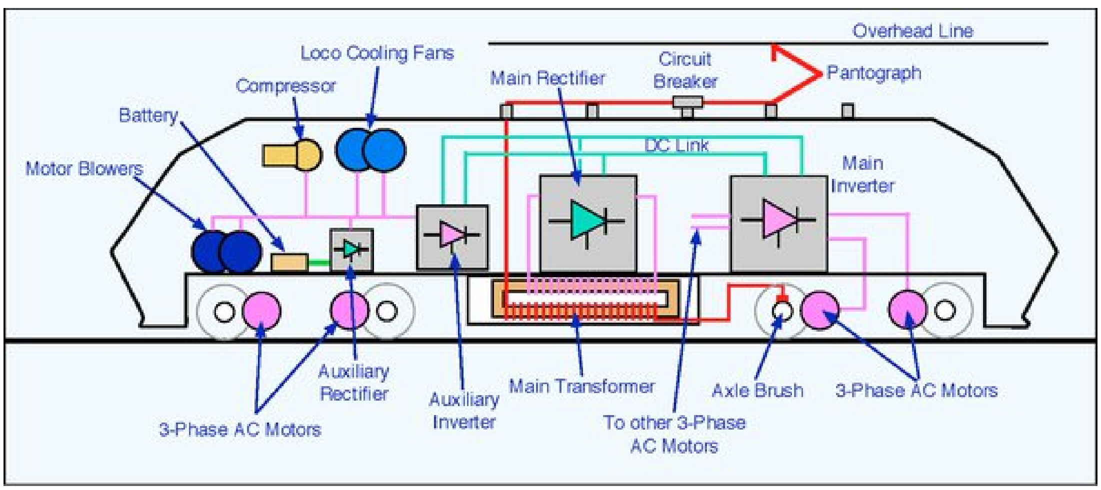

Figure 2: Overhead Electric Train Diagram [60]

Figure 1 depicts how current overhead electric wires work to power electric buses or trains. There is a possibility to use this technology to advance on-the-road charging for electric vehicles.

However, this can be expensive to implement and the charging times are relatively slow [7]. There have also been attempts to use current infrastructure to bolster charging availability.

Siemens, a German multinational conglomerate and the largest industrial manufacturing company in Europe, has developed smart compact chargers and controllers with the Radio Frequency Identification (RFID) tag payment system and installed it in the street lamps of Central London in the United Kingdom. The controllers are capable of Over The Air (OTA) updates for softwares in chargers. This is helpful as all of the charging software can be updated simultaneously and engineers are not required to physically go to the location of the chargers to install updates manually. Siemens' controller also allows owners of different types of electric vehicles to charge at their charging point as the adaptors are compatible with CCS (Combined Charging System) and CHAdeMO charging systems [8]. Other attempted solutions include Audi's experimentation with installing a solar panel on the roof of their hybrid vehicles.

Beyond technical improvements in the charging infrastructure itself, policy measures have been taken to expand charging networks. For example, President Biden's infrastructure plan puts special focus on encouraging sustainability within the transportation sector [9]. Part of the plan aims to make residential spaces more EV compatible so that EVs can be charged in the future without additional charger installation costs or expensive garage renovations. As previously alluded to, the variation in adaptor types and voltage values over different geographical locations is a major weakness in current charging infrastructure. Team CHARGEX's solution to expand the scope of electric vehicles would involve researching the internal components of the charging circuit, such as transformers and rectifiers and the various other circuit components, in order to be able to alter the voltages internally. This will be accomplished through simulations and experiments of the various circuit configurations using softwares like 'PSpice' to evaluate the circuit models in order to reduce the SWaP-C (Size, Weight, Power and Cost) of the charging station. This way, we hope to make chargers capable of operating at both Level 1 and Level 2 as a result of varying voltages accessible in households across the United States.

Beyond the lack of compatibility between charger types, the number of charging stations is extremely limited in comparison to the number of EVs that are present, and this is a problem that will continue to persist at the rate of rollout of charging stations in comparison to EV production. One of the most effective solutions to the lack of charging stations would be developing charging stations that utilize pre-existing infrastructure (e.g. turning lamp posts into charging stations) [10].

In order to facilitate the transition to widespread EV adoption despite the relatively limited charging infrastructure, we note that aiming to make compact chargers or small battery banks, which provide a temporary range boost, could be beneficial.

The feasibility of this project entirely depends on the scale. We will focus on small scale, smart, fast chargers to prove the solution methodology. This research will then be beneficial for those with the ability to mass produce large-scale chargers for the purpose of electric vehicles.
After doing some general research stated above, we came up with a few leading questions for our project:

- Can V2V charging overcome range anxiety and become a key factor in widespread EV adoption?
- How can technical advancements, user behavior changes, and economic incentives work together to optimize V2V charging?

Literature Review

Existing Technology

Studies have been conducted in regards to creating charging infrastructure that would manage the power flow from the grid while aiming to reduce the cost of charging [11]. There are existing Federal efforts to expand the EV charging network (such as the expansion of electric vehicle charging proposed by the Trillion dollar Biden infrastructure plan). $5 Billion has been allocated to all 50 states in total to develop their own electric vehicle charging network along the interstate highways. The Biden administration outlined a relatively speedy timetable for deploying an initial installment of $615 million. All 50 states, as well as Washington, D.C. and Puerto Rico, would be required to submit plans by the beginning of August 2022 explaining how they would install high-voltage chargers along or very close to major highways. The plan also outlines that the chargers must be no more than 50 miles apart, and states are encouraged to place them at rest areas or other places with food and other services [12]. Existing plug types vary by region as shown in the figure below. The issue being the plug ports are not universal for all electric vehicles which makes implementation of EV infrastructure difficult and expensive.

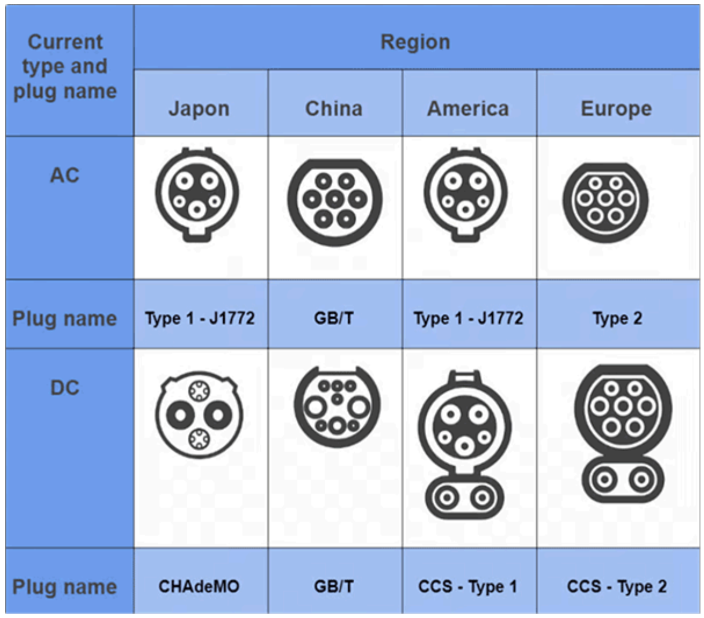

Figure 3: EV Plug Types [65]

In addition, research has been done in the area of universal inductive charging, which can both increase efficiency and provide a universal charging standard, increasing accessibility. Inductive charging is a technology in which magnetic fields generated between the primary and secondary coils are coupled with current, without the need for either wires or direct electrical contact with metal conductive plates. The concept is similar to that of power transformers. The main advantage of inductive wireless power transfer (WPT) is that the currently available technology can transfer electrical power at greater than 98% efficiency. However, inductive WPT is only effective at a short distance between the primary coils and secondary coils, one of which is present inside the electric vehicle and the other is present in the road. Inductive WPT can work when the electric vehicle is parked and also while it is in motion. However, the misalignment between the two coils can reduce efficiency. A perfect concentric overlap of both the coils is necessary for maximum charging speed and efficiency which is not perfectly ideal in real world scenarios [13].

One of the previous Gemstone teams, Team FORMULA, has looked into the possible application of wireless charging for EVs using DWPT (Dynamic Wireless Power Transfer) technology – this approach addresses many of the common problems of existing plug-in systems, such as the lack of compatibility between charger types. This is because there are four types of electric car charging plugs (CCS, ChaDeMo, Tesla, and J1172) in North America, (as shown in the figure above). Each plug is compatible with different electric vehicles as well as capable of providing a certain amount of power. Just like how the iPhone has one plug and Android phones have another, the same goes for electric vehicle brands [14]. DWPT in urban areas also ensures an uninterrupted power supply for EVs, extending or even providing an infinite driving range with significantly reduced battery capacity. The underground power supply network also saves more space and hence is important in urban areas.

Another area of existing technology is in the realm of smart, fast chargers for smartphones. Qualcomm Quick Charge is the main choice for fast charging. Quick Charge 5 is the world's Fastest Commercial Charging Solution delivering astonishing charging speeds of up to 0-50% in five minutes with 100W+ charging power. It charges smartphones up to 10 ^{o}C cooler, up to four times faster, and up to 70% more efficiently than existing chargers on the market [61]. However, in order for Qualcomm Quick Charge to work, a Qualcomm Snapdragon processor must be installed in the device. The technology boots the voltage, thus allowing for faster charging without increasing the current significantly, minimizing heat generation. The charger uses dynamic voltage adjustment which allows for automatic voltage adjustment in real-time for optimal voltage levels to ensure the utmost safety and efficiency. As a smart charger, Qualcomm Quick Charge technology incorporates intelligent charging algorithms to monitor factors such as temperature, voltage, and current during the charging process. Team

ChargeX will try and replicate this technology on a small scale in order to understand and provide research for those with the ability to duplicate it on a mass scale for the electric vehicle industry.

Established Theories and Methods

Some theories and methods were fundamental to the success of this project:

1. **Grid Load Analysis:** We investigated the overall load demand on the electrical grid during normal use and peak times. This included analyzing both theoretical and practical capacity of the power grids based on existing research [15, 16].

2. **Charging Pattern Analysis:** We analyzed charging patterns and usage trends at different times of day and locations [17]. This analysis aimed to determine whether fast chargers were necessary everywhere or only in specific areas.

3. **Cost and Efficiency Optimization:** We planned to estimate the cost of electricity based on time and location. Additionally, we experimented with different charging methods and adapters for various electric vehicle categories to optimize efficiency and cost [18].

4. **Underground Infrastructure Exploration:** We explored the possibilities of expanding charging infrastructure in areas with underground electrical lines.

5. **EV Market Forecasting:** We utilized market trends to forecast electric vehicle ownership and demand. This data would help us identify gaps in the EV accessory industry and inform future product development [19, 20].

Past measures, concepts, tools, and materials

This research delved into the feasibility and potential benefits of Vehicle-to-Vehicle (V2V) charging technology, particularly for residents of multi-unit dwellings with limited access to private charging infrastructure. To assess this concept, a functional V2V charger prototype was constructed. The initial design, utilizing an Arduino project with Pulse Width Modulation (PWM) and a charging circuit, encountered limitations. However, by persistently exploring various Arduino projects focused on PWM and charging circuits, a successful V2V charger prototype was ultimately achieved. This functional prototype enabled data collection to inform future advancements in V2V technology.

Several tools played a crucial role in supporting this research. MATLAB, NumPy, and PSpice software provided platforms for mathematical and electrical circuit simulations, respectively. TinkerCAD and Circuit Lab offered virtual environments for testing various circuit combinations, eliminating the need for constant physical lab setups. This streamlined approach facilitated rapid experimentation during the design phase of the V2V charger prototype.

The research also examined existing approaches to EV charging and identified their strengths and limitations. A study by scientists at the University of California at Irvine explored a microgrid system that maximized charging efficiency through photovoltaic arrays and battery management systems. While highly efficient, this approach was deemed impractical for large-scale EV implementation. Additionally, Constant Current, Constant Voltage (CCCV) charging, a common method for lithium-ion batteries, was reviewed. This approach involves applying a constant current until the battery reaches a specific voltage, followed by a constant voltage stage. CCCV is applicable to various battery sizes but has limitations in dynamic cost optimization based on factors like time of day. Economic models have been developed to optimize charging costs for EVs, but none have yet achieved the speed and efficiency of refueling gasoline-powered vehicles.

Insights gleaned from existing research informed the development of a future-proof and consumer-friendly V2V charging solution. Simulations and hardware tests from prior studies provided valuable data on grid integration and load balancing strategies. Studies on LED lighting's lower energy consumption compared to sodium vapor lamps also offered valuable data points. Research on modifying load balancing to accommodate increased EV charging demand has shown promise in improving overall charging efficiency and user experience without overloading the grid. Finally, implementing smart charging systems can address issues like "ICEing" and optimize disordered charging for greater cost-effectiveness and efficiency. By leveraging knowledge from prior research on cost reduction strategies, this V2V charging solution has the potential to accelerate EV adoption in the US market, particularly for residents in multi-unit dwellings.

Cell Chemistry

There are many types of batteries that have been used in recent decades, from alkaline to lithium ion batteries. Each of these batteries have their own characteristics, such as whether they are rechargeable or not. In this project, rechargeable batteries will be the focus, but it is important to note what other kinds of batteries there are and the cell chemistry within each to put them into perspective.

What is a battery?

A battery is a gadget used to store electrical energy in the form of chemical energy, which is then used to create electricity to power other devices [32]. It is necessary to understand what makes up a battery and how they work.

Electrodes. An electrode is a conductor often made of metal that is in contact with a typically non-metallic portion of the circuit. This is where the oxidation-reduction equilibria occur [33] One type of electrode is the anode (the positive electrode): electrodes which are oxidized (loses electrons) in the electromagnetic chemical reaction (discharging), and may contain zinc metal, especially in Alkaline batteries. Another electrode is the cathode (the negative electrode): electrodes that are reduced (gains electrons), the opposite of the anode, in the chemical reaction. The cathode is usually the most expensive part of the battery. Nickel manganese cobalt (NMC) is the most common cathode used in today's EVs, although lithium iron phosphate (LFP) is also sometimes used in lithium-ion batteries [34].

Electrolyte. Electrolytes are the medium in which ions move, between the anode and cathode. This is where the current takes place [35].

How batteries work. According to Energizer, one of the largest manufacturers of batteries, once a battery is connected to a device, the chemical reaction occurs where the metal from the anode is oxidized by the electrolyte and reacts with the substance in the cathode to make electrons (anode to cathode), which power electronics as electricity. This occurs in all batteries. However, rechargeable batteries can reverse the reaction to get the reactants back which can be used again to create more electricity. According to the Department of Energy, this is by the electrons moving from the cathode to anode, which increases the chemical potential energy, which charges the battery [36].

Types of Batteries

Lithium ion. Lithium ion batteries are the most common rechargeable batteries used in electric vehicles, such as Tesla (which mostly used Lithium-iron-phosphate batteries). Lithium ion batteries are very expensive, making each electric vehicle that much more expensive as well, however, the lithium ion battery cost has been decreasing since about 2010 [37]. It is also important to note that lithium is another hazardous waste, so proper disposal of semi-charged lithium-ion batteries is needed. However, lithium is the lightest metal on the periodic table, having the smallest atomic weight of 6.94 g/mol, making the battery lighter and more applicable for vehicles.

Alkaline. Alkaline batteries are one of the oldest batteries on the market. A Zinc anode and manganese dioxide cathode react and are used up as the battery discharges. These batteries cannot be recharged, as recharging them would be dangerous; even so, they are difficult to recycle [38]. However, they are relatively cheap and have consistent performance as it discharges.

Lead acid. Lead acid batteries are high power, safe, reliable, and cheap. Like the other batteries, though, they have their downfalls: bad performance at low temperatures, short lifecycle, and low specific energy [39]. Sealed lead-acid batteries are also rechargeable, but are relatively heavy compared to other batteries [40].

Nickel Cadmium. Nickel-cadmium (Ni-Cd) is the most common rechargeable battery [41]. This type of battery is where nickel is the positive electrode, and cadmium is the negative electrode. However, like many batteries, cadmium batteries especially need to be disposed of properly, as cadmium in incinerators can release cadmium gas, a cancer-causing agent, into the breathable air [42].

Nickel-metal hydride. Nickel-metal hydride batteries (NiMH) are often used today in medical equipment and computers. However, compared to Lithium ion batteries, for example, they have a high self-discharge rate, high cost, heat generation and high temperatures, and need to be controlled for their hydrogen loss [39]. On the plus side, they have a low-drain and high energy capacity [41]. Additionally, they can be charged hundreds of times, although only for 2-5 years, and have a higher capacity than its predecessor, the NiCd battery (see Evolution of Batteries). NiMH batteries also have a wide temperature range for its charging and discharging: ~0℃ to 50℃ [43].

Sodium-ion. Another battery that is gaining attention is the sodium-ion battery. They are similar to lithium-ion in that they also use a liquid electrolyte, however they use sodium instead of lithium. The largest EV battery manufacturer, CATL, a chinese company, has stated that it would begin mass producing these batteries in 2023 [34]. Sodium-ion performance isn't necessarily better than lithium-ion, but they are definitely cheaper and sodium is more widely available. However, it is not clear if these batteries can withstand the range and power needed for electric cars, so many electric motor companies have started using these batteries for smaller vehicles, like e-scooters.

Evolution of batteries

Knowing the evolution of rechargeable batteries will help understand where issues with certain materials and cell chemistries stand, as well as where we are today, including the progress that needs to be made.

The experiments leading to the creation of the first electric battery were inspired by the idea of "animal electricity" discovered by Luigi Galvani in 1791. Galvani found that an animal's muscle would contract when in contact with different metal objects [44]. The first electric battery was revealed by Italian physicist Alessandro Volta on March 20, 1800, who experimented with various metallic objects. It included alternating silver and zinc wafers - which are very thin, round (usually silicon) pieces, a material commonly used in semiconductors – with a salt-water soaked cloth between them [45]. Volta then placed a wire connecting the two, creating a current.

Jumping forward 50 years, the first rechargeable battery was created: the lead-acid battery, discovered in 1859, by French physicist Gastone Planté [44, 46].

Then in 1899, the nickel-cadmium battery was invented by Waldmar Jungner. However, cadmium was quite expensive, so it did not receive as much attention until 1932 when Shlecht and Ackermann invented the "sintered pole plate," which improved current and longevity of the battery. In 1947, Neumann was able to completely seal the NiCd battery, which prevents the loss of electrolyte and the release of toxic gases.

As these batteries were becoming more and more popular into the 80s, many European nations were concerned about the environmentally hazardous effect of improper NiCd disposal. Therefore, NiCd production was restricted and nickel-metal hydride (NiMH) batteries came to light [44]. The NiMH battery, patented by Stanford Ovshinsky in 1986, was about 1.5-2 times higher in energy density, compared to the NiCd battery, meaning it could store more energy in less space. When the lithium ion battery came around, the NiMH battery's use declined; however, NiMH batteries continued to be used in hybrid electric vehicles as they were tolerant to being overcharged, and were generally safe [47].

Around 1913, Gilbert N. Lewis realized that lithium had potential to be used for battery anode, given its low density, high specific capacity, and low redox potential. In the late 1950s, William Sydney Harris was studying properties of Lithium in different electrolytes. His main finding was that lithium protected itself from directly reacting with the electrolytes, yet still allowing for ion transfer. His work led to more studies on how lithium could be used in batteries, which started in the market in the late 1960s [48].

Additional research on lithium intercalation led to lithium ion use in rechargeable batteries. In the 1970s, Stanley Whittingham thought of a battery that could recharge itself to decrease the usage of fossil fuels, to be more environmental. He tried using titanium disulfide as the cathode and lithium metal as the anode, but it was very dangerous and caught fire, so the project was shut down. Another scientist, John B. Goodenough, in the 1980s experimented with lithium cobalt oxide as the cathode and lithium metal as the anode, leading to double the energy potential of Whittingham's battery. Akira Yoshino then took Goodenough's battery and switched the anode out with petroleum coke, which made the battery safer, more stable, and the first lithium ion battery prototype [49, 50]. The first commercialized lithium ion battery was released in 1991 by Sony and Asahi Kasei [51].

Today, scientists are trying to find even better battery replacements with quicker charge times, more energy density, and cheaper costs [34].

One hot topic is that of solid-electrolytes, such as lithium metal, which in theory would allow for greater energy density and faster charge times. QuantumScape is a company currently trying to find a good liquid lithium-ion battery replacement using lithium metal and a ceramic, non-reactive material with lithium. They state that they created the first anode-less battery concept.

Sodium-ion batteries are another new battery concept. The main difference is that sodium, rather than lithium, is used as the charge carrier, making it even cheaper than batteries today.

Charge and Discharge Curves

Charge curves show the variation in speed when charging a rechargeable battery. They can show the peak charging performance [52]. For example, the Tesla Model 3 Long Range & Performance has a peak charging power of 250 kW. Meanwhile, the Nissan Leaf has a peak charging power of 45 kW. As depicted, the charge curves are different for most vehicles, and are also based on outside factors such as temperature and even weather conditions. Discharge curves show the rate at which a battery discharges (loses charge). They usually show the relationship between the cell voltage (in Volts) and the percent of cell capacity discharged. It is important that the x-axis is the *percentage* of capacity discharged because not all cells have the same capacity or discharge times.

Some batteries show more flat discharge curves, such as the lithium ion battery, and others show curves that are more sloped, such as the lead acid battery. This means that the power given by the cell throughout the discharge cycle decreases, which causes issues for high-power charging later in the cycle [32]. For the flatter discharge curves, the voltage supplied by the battery is relatively constant and more reliable. An example of these curves is shown in the figure below.

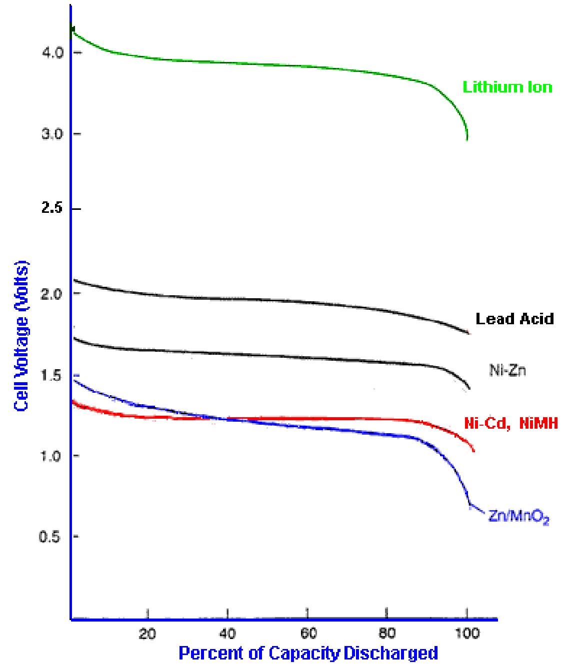

Figure 4: Discharge Curves for different Battery types [69]

Conditions impacting battery performance and self-discharge rate

A self-discharge rate is the rate at which a battery loses its energy when not in use (i.e., simply sitting on the shelf). Some factors can impact the rate of self-discharge as well as battery performance, which will be described in the following paragraphs.

Temperature.

Because cells contain chemicals and chemical reactions are usually catalyzed by heat, the chemical reactions within the cells are sped up with temperature. At very high temperatures, the chemicals inside the cell can break down, which can actually destroy the battery; meanwhile at very low temperatures, the electrolytes can freeze which will lower the temperature at which the cell can operate [32]. This concept is shown in the graph below.

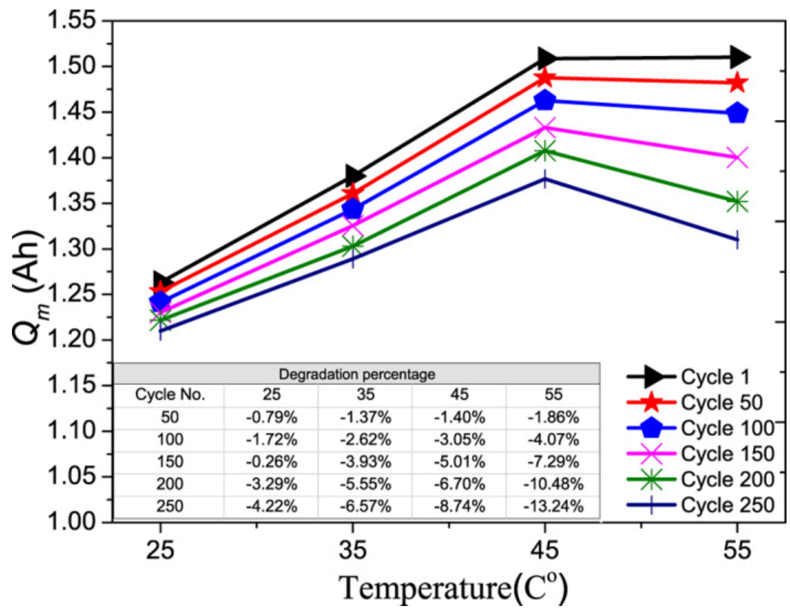

Figure 5: Charge Capacity vs. Temperature Graph [67]

To be more specific, at around 0°C, the battery capacity (of a lead-acid battery) drops by 20%, and at -30°C, the amount of amp-hours the battery can hold drops to 50% [53]. Additionally, Intercel says, despite the negative effects of hotter temperatures on a battery, the battery capacity actually increases by 12% at 50°C. One of the negative effects of high temperature they name is the reduction of battery life. They say for every 9.4°C over 25°C, the battery life is halved. However, at cold temperatures, like -30°C mentioned before, battery life can increase by up to 60%. In a study by Ma et al. (2018), they determined that the ideal temperature range for lithium-ion batteries is about -20°C to about 60°C, and anything outside of this range can lead to irreversible damages to the battery [54].

There are some solutions to the problem with high temperatures, such as temperature sensors and insulators, and in some places, varying electrolyte acid strength. Intercel states that the internal temperature of a large battery with insulation can change as little as 10°F over a day, despite the temperature outside ranging from 20°F to 70°F. A solution they propose is addition of temperature sensors and insulation to the positive plate terminal of the capacitor to more accurately read the internal temperature of the battery. In a study by Novais et al. (2016), fiber Bragg grating (FBG) sensors were used to measure the internal temperature of lithium-ion batteries at C-rates ranging from 1C to 8C. They found that the internal temperature varied by < 5°C [55]. Another solution in very hot or cold climates is having a battery that has non-standard electrolyte acid strength. In hot climates, weaker electrolytes may be sold, and in colder climates, stronger electrolytes are sold [53].

Changes in temperature are also related to changes in internal impedance for the lithium-ion battery.

Internal impedance. Internal impedance is the internal resistance – or opposition – to current flow for the AC current [56]. It is affected by the size of the electrolyte's material: the smaller the size, the less impedance [32]. The size of the electrolyte's material is determined by the manufacturer's milling process – a machining process using rotary cutters to get a desired final shape. A specific process called spiral construction is often used to maximize surface area, reduce heat, and increase charging rate [32].

Internal impedance can be used to give insight into the state of health (SOH) and state of charge (SOC) of a battery. The internal impedance of a lithium-ion battery can be determined using electrochemical impedance spectroscopy, pseudo-random binary sequences, or discrete-interval binary sequence [57, 58].

Discharge rate. Capacity offset is when batteries are less effective when they are discharged at very high or very low rates [32]. This is common for many cells, including lithium ion batteries.

Electric Boats

Traditional gasoline-powered boats pose significant environmental challenges, with their emissions harming ecosystems and contributing to broader environmental issues. Electric boats offer a cleaner alternative for enjoying our waterways. The idea of silently cruising through clean waters without emitting harmful gasses motivates me. Beyond environmental benefits, electric boats offer a quieter experience, reducing disturbances to marine life and creating a more serene connection with the water. This tranquility would benefit both boaters and marine ecosystems.

Moreover, electric boats could lower operating costs due to reduced maintenance and fuel consumption. However, challenges like range limitations and the need for charging infrastructure must be addressed through research and development efforts. Despite these challenges, progress is being made in electric boat technology, driven by various stakeholders. Pilot programs are already testing the feasibility of electric boats in real-world settings. The transition to electric boats presents an opportunity for a cleaner, quieter future. As research advances, electric boats have the potential to transform our relationship with water.

Small scale electric boats have been in use for quite some time, it is only until recently that we have had the engineering capability to be able to power larger vessels solely off of an electric motor power. As the technology continues to improve, electric boats can continue to get scaled up until eventually even larger cargo ships can be fully electrified. A company in Norway called Yara International has already developed a proof of concept ship called the Yara Birkeland which is both a fully electric and fully autonomous cargo ship. While this vessel only operates in domestic waters and is far from making any trans-Atlantic trips, this proof of concept demonstrates that battery technology is improving by the day.

When the public thinks about pollution, rarely do they ever think about the logistics of importing and exporting goods and what harm that might do to the environment. For most people, they simply order a product online and it magically appears at their front door a couple weeks later. Although water transport is the most efficient way to transport goods pound for pound, the vast size of some of these ships mean that they are still a major contributor to the greenhouse effect in our atmosphere. Although this statistic has been debated, it has been said that the world's fifteen largest cargo ships can produce as much sulfur as all of the cars in the world put together. While this is only one form of pollution, it is still a notable statistic as it shows how cargo ship transport is a much larger contributor to global warming than most people think. Therefore, moving to a sustainable form of propulsion is a key step at tackling this issue as a whole.

Other than major cargo ship fleets, smaller yacht-like vessels can also experience the same benefits and are much more applicable to day to day users of boats such as fisherman or leisurely boat owners. While these smaller ships do not account for nearly as much pollution as the larger cargo ships, researching these vessels is actually a good parallel to road cars because the charging and driving characteristics are much more similar. In addition to that, leisurely boat use has seen a massive uptick since the COVID-19 pandemic as more and more people are looking to get away and enjoy time out on the water while being away from other people. In 2020 alone, boat sales saw a 12% increase across the nation which is similar to the increase in people interested in buying EV's [62].

Existing electric boat charging infrastructure is one of the major holdbacks of more people converting to EV's is easy access to charging stations. With the way the United States electrical grid is set up, certain rural areas will have trouble extracting electricity especially at faster rates. With boat charging stations however, shore power is readily available and most docks will have some sort of energy generation system already in place. In addition to that, based on their proximity to the water, renewable energy sources such as hydroelectric and wave power can be used to charge the boats in a way that truly provides zero emissions. A common misconception these days is that anything electric means clean energy. While electric modes of transportation do not immediately expel any harmful pollutants, many fail to recognize that only 21% of America's grid is currently supplied from renewable sources [63], so in reality the electricity used to charge your EV is still "dirty" in a way. Fast "superchargers" in the boating industry are also keeping up with even the fastest car chargers. A company based out of the UK called Aqua Superpower is a manufacturer of fast charging direct current chargers that are capable of up to 150 kW which allows for quick recharge times. There are many similarities between EV and electric boat charging and by examining this in more detail, we can draw conclusions that can aid the development of the United States electrical grid infrastructure as well as charging infrastructure.

If you've ever run out of gas on the road in your car, you can understand how nerve racking that can be when you are on the side of the highway just waiting for help to arrive. Now imagine that same scenario but you are out at sea with no view of the shoreline. This is the situation you would be faced with if you run out of battery charge on your electric boat.

There are a few temporary solutions that can be used to combat this issue. Firstly, there is a sufficient amount of renewable resources when you are out at sea. Solar panels can be installed to the roof, a small wind turbine can be placed near the top of the boat, and tidal power can be channeled all around the boat to help temporarily recharge the battery on your boat. With any renewable energy source, there are limitations to when you can use it due to mother nature. If it is a cloudy day, the solar panels will not charge the battery enough to get you back to shore. Similarly, if there is no wind that day you will also still be stranded. Finally, if you are in extremely calm waters without any current or waves you will not be able to harness the power of the tidal waves. With that being said, a combination of all of these energy generation factors should be considered in order to have a reliable way to recharge your electric boat in the event of an emergency.

Of course, this is hopefully the worst case scenario as there should be other measures in place to prevent your boat from ever reaching zero charge. This can include, but is not limited to, a digital battery percentage gauge, a backup battery, being able to turn off various functions on the boat that draw unnecessary power when you know you are on low charge (low power mode), and a communication system that allows you to alert people on shore that you need help.

In the event of an actual emergency where you simply can not return to shore either because there are no ways to recharge your battery or if the currents are too strong for the power output of your motor, a recovery boat must be sent out to help you. Similar to a fighter jet refueling in midair, the recovery vehicle can be loaded up with battery cells that can be transferred over to the boat in need either via thick gauge wire or simply by handing over small battery cells (similar to a car battery) that can then be plugged into the boat in need to give it enough charge to return to shore.

Methodology

Methods

We started learning about electric circuits and several circuit solving methods from the book “Fundamentals of Electric Circuits” by McGraw Hill so that everyone on the team is on the same page and is aware of basic electrical concepts and circuit components. Topics covered so far include: Circuit Variables, Circuit Elements, Simple Resistive Circuits, and Techniques of Circuit Analysis (Node-Voltage method). This helped us in utilizing the lab for experiments for our research. This research was carried out with mixed methods in order to collect data and design an adapter and/or charger. We started off by exploring an existing adapter and other EV charging accessories in order to understand their design and circuitry as it is proprietary information as mentioned previously.

Building and Testing a Battery Charging Circuit

This section details the experimental setup and observations made during the testing of a basic DC battery charging circuit.

Materials:

- Arduino UNO R3: A microcontroller board used to control and monitor the charging process.
- 18650 Battery Holder: A secure enclosure for a single 18650 lithium-ion battery.
- Lithium 18650 Battery

- 10 Ω Power Resistor: A resistor with a resistance of 10 ohms and appropriate wattage rating to handle the charging current.
- 1 MΩ Resistor: A resistor with a resistance of 1 million ohms. Specify the type (e.g., carbon film, metal film).
- 1 μF Capacitor: A capacitor with a capacitance of 1 microfarad and appropriate voltage rating.
- IRF510 MOSFET: A Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) used to control the charging current. Gate, Drain, and Source positions are shown in the figure below.
- Power Supply: A regulated DC power supply used to provide the charging voltage.
- Prototyping Breadboard: A reusable platform for assembling electronic circuits.
- Jumper Wires: Short wires used for making temporary connections between components on the breadboard.

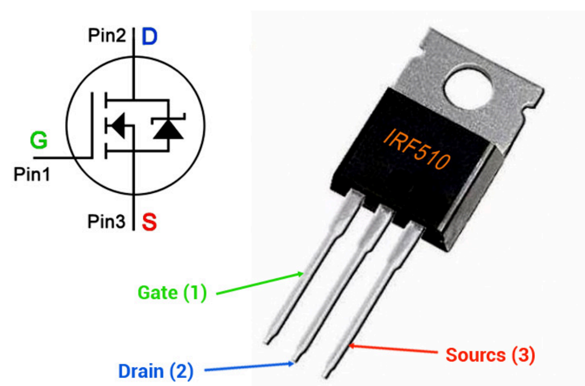

Figure 6: IRF510 MOSFET [66]

Observations

During the experiment, the following observations were made:

1. Constant Current Phase: As predicted, the charger initially delivered a steady current to the battery, causing the voltage across its terminals to gradually rise. This confirms the functionality of the current limiting resistor and the initial charging stage.

2. Voltage Rise: The observed increase in voltage across the battery terminals verifies that the battery is accepting charge.

3. Transition to Constant Voltage: The observation of a constant voltage after reaching the target value indicates successful switching of the circuit mode from constant current to constant voltage.

4. Current Decline: The gradual decrease in charging current as the battery nears full capacity reinforces the concept of diminishing battery acceptance as it approaches saturation.

5. Charging Completion: The termination of the charging process when the current falls below a specific threshold confirms the effectiveness of the program in detecting full charge.

These observations validate the theoretical understanding of the DC battery charging process and demonstrate the functionality of the constructed circuit in replicating the key stages of charging.

The DC battery-charging circuit we built was composed of many electrical components including: Arduino UNO R3, 18650 Battery Holder, Lithium 18650 Battery, 10 ohm Resistor, 1 Mohm Resistor, 1 μF Capacitor, IRF510 MOSFET, Power Supply, Prototyping Breadboard, and Jumper Wires. The circuit below demonstrates how the MOSFET transistor allows for battery charging.

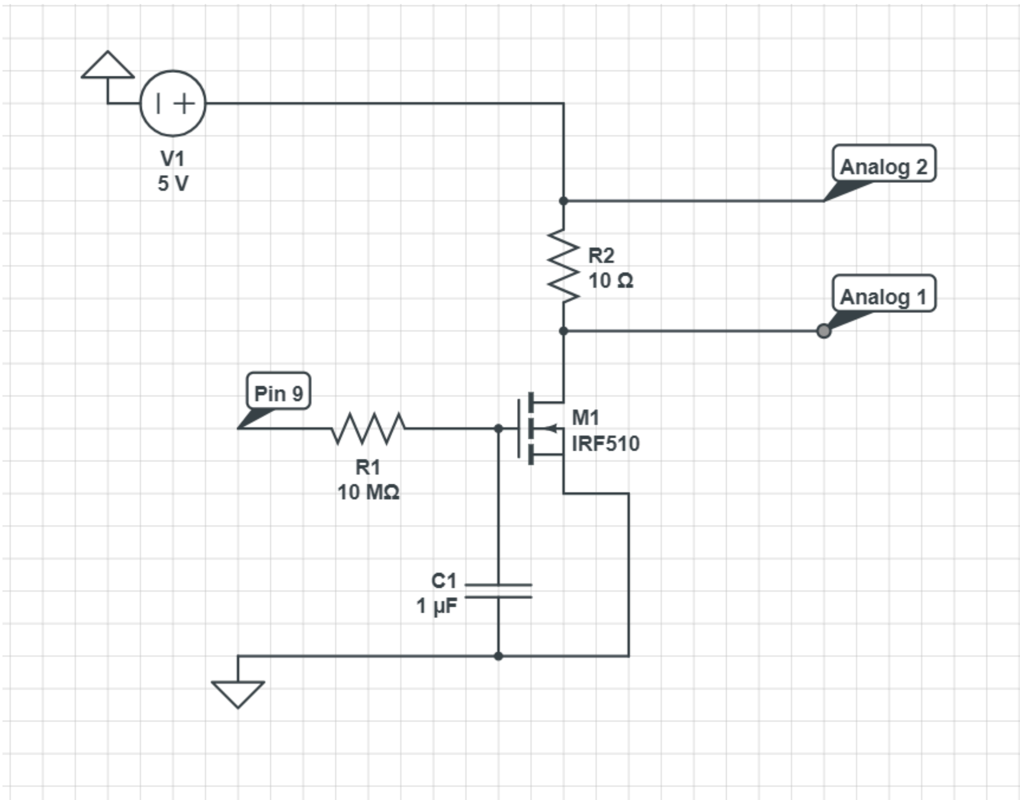

Figure 7. Circuit Design and Functionality (Iteration 2)

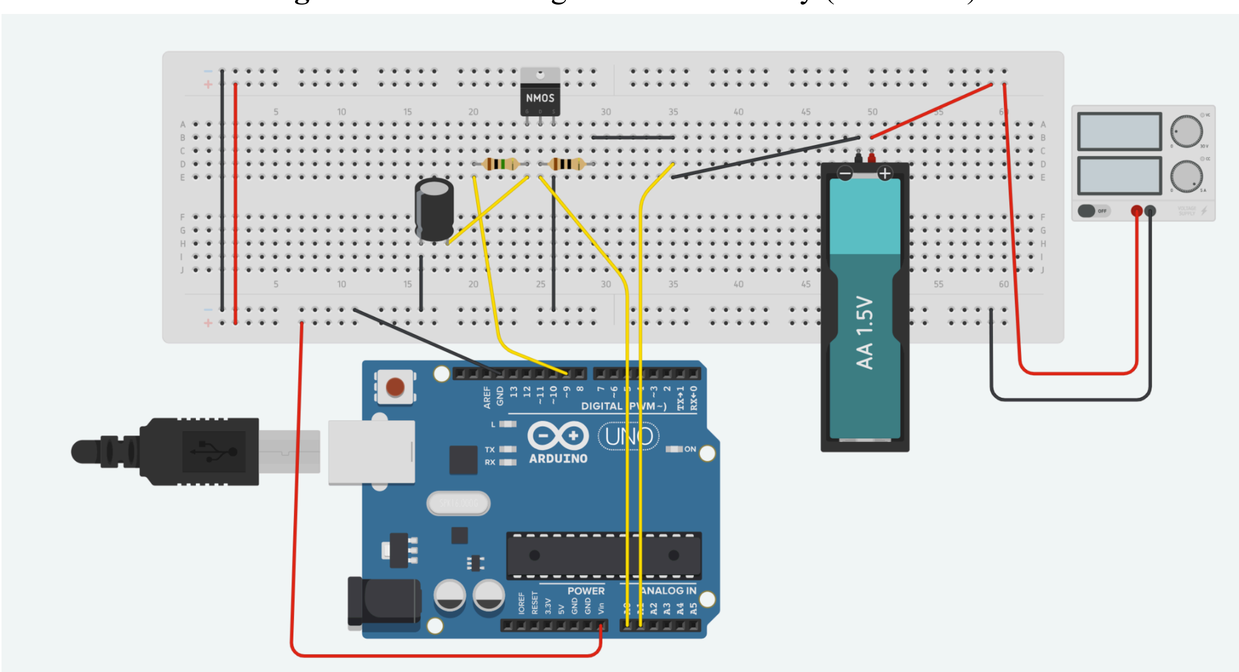

Figure 8. Circuit Design in TinkerCad (Iteration 2)

Figure 2 depicts the schematic diagram of the DC battery charging circuit. The Arduino UNO R3 serves as the central controller, managing the charging process and monitoring key parameters (voltage and current) through appropriate programming.

Figure 3 depicts the circuit design with the components we used. This was done using TinkerCad. This is a simplified version of the circuit, however the charging process is the same. Our circuit also included an LCD to display the real-time voltage of the battery whilst charging.

The IRF510 MOSFET acts as a switch, regulating the current flowing into the battery. The 10 Ω power resistor limits the initial charging current to a safe level. The 1 MΩ resistor and 1 µF capacitor form a voltage divider circuit, providing feedback to the Arduino about the battery voltage. The power supply provides the DC voltage used for charging.

The Arduino program controls the MOSFET based on the measured battery voltage. Initially, the program sets a constant current mode, allowing the battery voltage to rise gradually. Once the battery voltage reaches a predefined target value (programmed into the Arduino), the program switches the circuit to constant voltage mode. In this mode, the voltage remains constant while the charging current gradually decreases as the battery approaches full charge. The program terminates the charging process when the current falls below a predetermined threshold, indicating a fully charged battery.

During the charging process, the charger initially delivers a steady current to the battery, causing the voltage across its terminals to rise gradually as it accepts charge. Once the battery's voltage reaches the desired level, the charger transitions from constant current to constant voltage mode. Throughout this phase, the voltage remains steady, signaling the start of the constant voltage stage. As the battery nears full capacity, its ability to absorb current diminishes, resulting in a natural decline in charging current. Eventually, when the charging current falls below a predetermined threshold, typically indicating full or near-full charge, the charging process is considered complete.

Data Collection

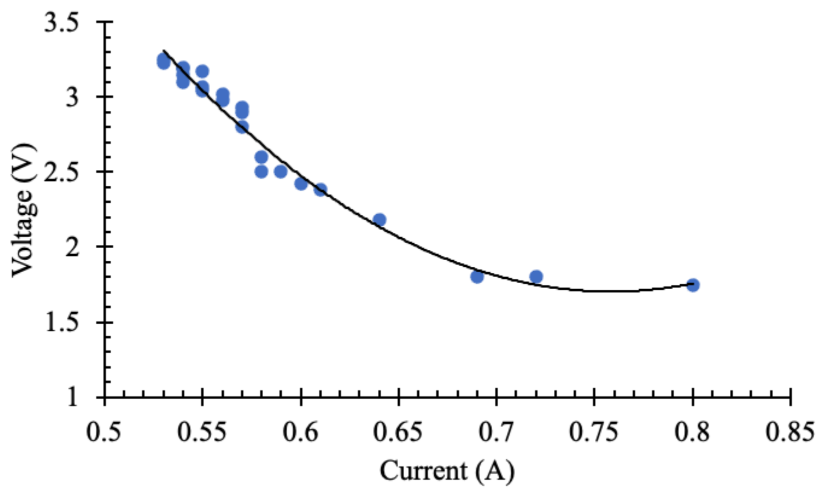

Figure 9. Voltage (V) vs. Current (A). A polynomial best-fit line is shown, with the equation $30.833x^2 - 46.764x + 19.435$, and an R^2 of 0.9743.

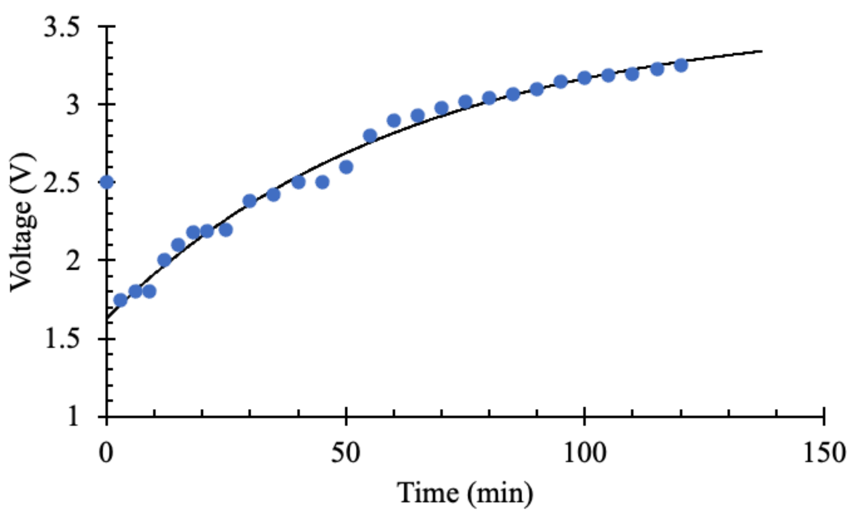

Figure 10. Voltage (V) vs time (min). An exponential best-fit line is shown, with the equation $-1.9316e^{(-0.0159x)}+3.5617$.

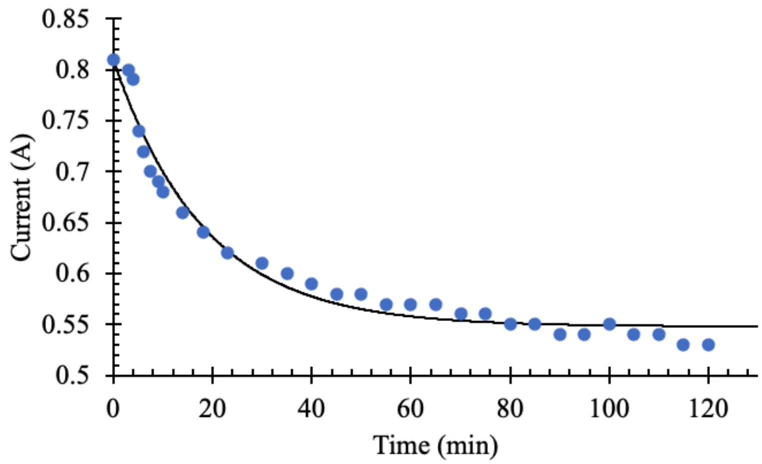

Figure 11. Current (Amps) vs. time (min). An exponential best-fit line is shown, with the equation $0.2613e^{(-0.0546x)}+0.5480$.

We collected various types of data to answer our research questions. Our focus was on scientific, quantitative data, gathered through laboratory and external experiments. This included data on peak energy costs within a specific electrical grid and times of peak usage for charging units.

To obtain this data, we employed a variety of methods. For laboratory experiments, we set up the required apparatus (printed circuit boards, battery, resistors, and capacitors) and conducted circuit analysis. We initiated data collection by approaching the Department of Transportation Services at the University of Maryland, College Park, as they possess relevant data from existing on-campus EV chargers. Additional quantitative data was obtained through simulations using software like PSpice, TinkerCad, and multiSIM. For prototype design, we utilized general Computer Aided Design software like SolidWorks or Autodesk Fusion 360.

In addition to quantitative data, we also collected mixed data containing both qualitative and quantitative variables. This included information regarding installation criteria for EV chargers on campus, obtained from the University of Maryland's Department of Transportation.

CIRCUIT SCHEMATICS:

The circuit schematic and arduino code below is part of our first iteration of the experiment (Version 1). We had the same goal as our final iteration. However, we found that when we increased the voltage coming from the power supply, the current would be overridden and the display voltage on the LCD would show the voltage of the power supply output and not that of the battery. In addition to this issue, there were many challenges with grounds. The circuit would randomly stop working due to common grounds, which resulted in a dysfunctional charger. We learned from our mistakes and took the entire circuit apart and started fresh, which then led to our final, working design.

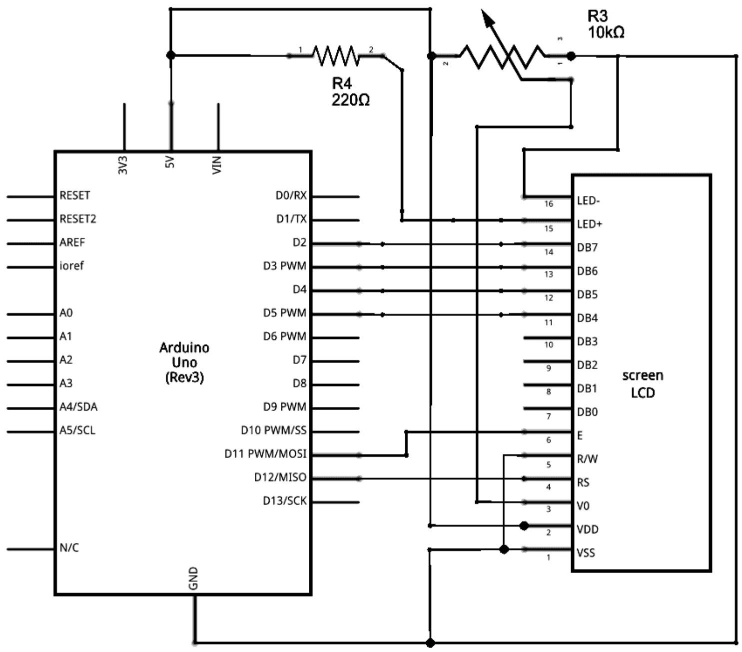

Figure 12. Circuit Iteration 1

Current Research, Impact, and Contribution

We identified a wide range of stakeholders in our project. EV owners were considered as the primary users of the product and accessory (V2V charging technology). Car manufacturers were interested in consumer valuation of car attributes and their supply equipment (chargers). Financial institutions and international organizations played a role in guiding investment decision-making. Finally, governmental and non-governmental organizations at all levels (local, national) were responsible for forecasting transport demand, energy demand, and emissions levels, while also exploring policy solutions to achieve specific environmental targets.

Our research addressed a gap in current research, which, as evidenced by a journal publication from Henry Lee of Harvard Kennedy School, did not prioritize lowering the barrier to entry for low-socioeconomic families seeking to own EVs. The journal cited an average cost of $2,500 for installing a Level 2 AC charger, not including the charger itself. DC fast charging, requiring high-voltage capacity wiring and electrical/construction work, incurred even higher costs [64]. The prevailing research focused on accelerating charging times and integrating EV charging into city networks. Our research, however, specifically targeted households without garages or private driveways. This focus would help the team determine the criteria needed to incorporate V2V charging into all households, with a particular emphasis on increasing accessibility in multi-unit apartment buildings.

Previously installed EV charging stations in multi-unit dwellings offered a unique advantage for attracting and retaining residents while fostering environmentally sustainable communities. However, challenges existed for both building owners and EV drivers when installing new charging stations. These challenges ranged from parking and electrical service access to billing and legal concerns, all of which would be addressed within the scope of our research.

Equity Impact

Vehicle-to-Vehicle (V2V) charging, a technology enabling electric vehicles (EVs) to share energy directly, holds significant promise for the advancement of electric transportation. While the environmental and technical advantages are widely acknowledged, it's vital to assess the potential equity ramifications of V2V charging across various demographic groups.

Accessibility and the Digital Divide

An essential consideration is accessibility. The widespread adoption of V2V charging depends on a critical mass of EVs equipped with the technology. If the initial costs of V2V-enabled EVs are substantially higher than standard EVs, this could worsen existing transportation disparities. Low-income communities and those reliant on older, used EVs might face barriers to accessing the benefits of V2V charging, possibly perpetuating dependence on gasoline-powered vehicles. Moreover, V2V charging systems may rely on digital platforms for user interaction, trip planning, and energy exchange. This raises concerns for individuals with limited smartphone access or internet connectivity. Strategies to address this could include developing user-friendly interfaces accessible through inexpensive devices, providing alternative communication methods for V2V transactions, and ensuring equitable access to digital infrastructure in underserved areas.

Socioeconomic Benefits and Potential Burdens

V2V charging has the potential to reduce reliance on traditional charging stations, potentially saving money for EV owners who frequently use public charging infrastructure. However, the economic benefits may not be equally distributed. Those able to afford newer EVs with V2V capabilities and own multiple vehicles (acting as donor vehicles) may experience the greatest financial gains. Conversely, individuals relying on a single, older EV may find themselves needing to engage in V2V transactions more often, potentially creating a situation where those with fewer resources contribute more to those with more. Incentive strategies, such as reward programs or credits for providing energy, could help mitigate this potential inequality.

Urban vs. Rural Considerations

The advantages of V2V charging may vary geographically. Densely populated urban areas with more EVs are likely to benefit the most from V2V technology. However, rural communities with fewer EVs and longer distances between vehicles may find V2V charging less practical. Investing in rural-specific public charging infrastructure, coupled with government support for V2V technology adoption in these communities, could help bridge this potential gap.

Environmental Justice and Community Benefits

V2V charging offers a pathway to a cleaner transportation sector, potentially reducing tailpipe emissions and improving air quality. However, it's crucial to ensure equitable distribution of environmental benefits. Low-income and minority communities often bear a disproportionate burden of environmental pollution. Prioritizing V2V adoption in these communities could not only enhance air quality but also empower residents to participate in the electric vehicle transition.

The Role of Policy and Public Engagement

Proactive policy measures are essential to ensure equitable access to V2V charging. Government incentives for V2V-enabled EVs, especially targeting low-income individuals and the used car market, could be pivotal. Additionally, promoting public awareness and education about V2V technology, its benefits, and user participation methods can encourage broader adoption across diverse communities. V2V charging presents a transformative opportunity for the future of electric transportation. By carefully addressing potential equity concerns, we can ensure that this technology benefits all segments of society, fostering a cleaner, more sustainable, and fair transportation landscape for everyone.

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Appendix

Raw Data & Code

Table 1. This table shows the voltage (V) and current (A) at times taken (min) for Figure 4 in 3.1

Time (min)	Voltage (V)	Current (A)	Time (min)	Voltage (V)	Current (A)
0	2.5	0.81	40	2.5	0.59
3	1.75	0.8	45	2.5	0.58
4	-	0.79	50	2.6	0.58
5	-	0.74	55	2.8	0.57
6	1.8	0.72	60	2.9	0.57
7.5	-	0.7	65	2.93	0.57
9	1.8	0.69	70	2.98	0.56
10	-	0.68	75	3.02	0.56
12	2	-	80	3.04	0.55
14	-	0.66	85	3.07	0.55
15	2.1	-	90	3.1	0.54
18	2.18	0.64	95	3.15	0.54
21	2.19	-	100	3.17	0.55
23	-	0.62	105	3.19	0.54
25	2.2	-	110	3.2	0.54
30	2.38	0.61	115	3.23	0.53
35	2.42	0.6	120	3.25	0.53

Code (Iteration 1)

```
// include the library code:
#include <LiquidCrystal.h>


// initialize the library by associating any needed LCD interface pin
// with the arduino pin number it is connected to
const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
void setup() {
  // set up the LCD's number of columns and rows:
  lcd.begin(16, 2);
  Serial.begin(9600);
}
// the loop routine runs over and over again forever:
void loop() {
  lcd.setCursor(0, 0);
  // read the input on analog pin 0:
  int sensorValue = analogRead(A0);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage = sensorValue * (5.0 / 1023.0);
  // print out the value you read:
  lcd.print("Cell Voltage:");
  lcd.setCursor(0, 1);
  lcd.print(voltage);
}
```

Code (Iteration 2)

```
#include <LiquidCrystal.h>
int batteryCapacity = 1500;     //capacity rating of battery in mAh
float resistance = 10.0;     //measured resistance of the power resistor
int cutoffVoltage = 4500;     //maximum battery voltage (in mV) that should not be exceeded
//float cutoffTemperatureC = 35;     //maximum battery temperature that should not be exceeded (in degrees
C)
//float cutoffTemperatureF = 95;     //maximum battery temperature that should not be exceeded (in degrees
F)
long cutoffTime = 46800000;     //maximum charge time of 13 hours that should not be exceeded

int outputPin = 9;     // Output signal wire connected to digital pin 9
```

```
int outputValue = 100;     //value of PWM output signal

int analogPinOne = 1;     //first voltage probe connected to analog pin 1
float valueProbeOne = 0;     //variable to store the value of analogPinOne
float voltageProbeOne = 0;     //calculated voltage at analogPinOne

int analogPinTwo = 2;     //second voltage probe connected to analog pin 2
float valueProbeTwo = 0;     //variable to store the value of analogPinTwo
float voltageProbeTwo = 0;     //calculated voltage at analogPinTwo

//int analogPinThree = 2;     //third voltage probe connected to analog pin 2
//float valueProbeThree = 0;     //variable to store the value of analogPinThree
//float tmp36Voltage = 0;     //calculated voltage at analogPinThree
//float temperatureC = 0;     //calculated temperature of probe in degrees C
//float temperatureF = 0;     //calculated temperature of probe in degrees F

float voltageDifference = 0;     //difference in voltage between analogPinOne and analogPinTwo
float batteryVoltage = 0;     //calculated voltage of battery
float current = 0;     //calculated current through the load (in mA)
float targetCurrent = batteryCapacity / 10;     //target output current (in mA) set at C/10 or 1/10 of the battery
capacity per hour
float currentError = 0;     //difference between target current and actual current (in mA)


// initialize the library by associating any needed LCD interface pin
// with the arduino pin number it is connected to
const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);


void setup()
{
  Serial.begin(9600);     //  setup serial
  pinMode(outputPin, OUTPUT);     // sets the pin as output
    // set up the LCD's number of columns and rows:
  lcd.begin(16, 2);
  Serial.begin(9600);
}



void loop()
{

  analogWrite(outputPin, outputValue);  //Write output value to output pin
```

```
 Serial.print("Output: ");     //display output values for monitoring with a computer
 Serial.println(outputValue);

 valueProbeOne = analogRead(analogPinOne);    // read the input value at probe one
 voltageProbeOne = (valueProbeOne*5000)/1023;     //calculate voltage at probe one in milliVolts
 Serial.print("Voltage Probe One (mV): ");     //display voltage at probe one
 Serial.println(voltageProbeOne);

 valueProbeTwo = analogRead(analogPinTwo);    // read the input value at probe two
 voltageProbeTwo = (valueProbeTwo*5000)/1023;     //calculate voltage at probe two in milliVolts
 Serial.print("Voltage Probe Two (mV): ");     //display voltage at probe two
 Serial.println(voltageProbeTwo);

 batteryVoltage = 5000 - voltageProbeTwo;     //calculate battery voltage
 Serial.print("Battery Voltage (mV): ");     //display battery voltage
 Serial.println(batteryVoltage);

 current = (voltageProbeTwo - voltageProbeOne) / resistance;     //calculate charge current
 Serial.print("Target Current (mA): ");     //display target current
 Serial.println(targetCurrent);
 Serial.print("Battery Current (mA): ");     //display actual current
 Serial.println(current);

 currentError = targetCurrent - current;     //difference between target current and measured current
 Serial.print("Current Error  (mA): ");     //display current error
 Serial.println(currentError);

// valueProbeThree = analogRead(analogPinThree);    // read the input value at probe three
 //tmp36Voltage = valueProbeThree * 5.0;     // converting that reading to voltage
 //tmp36Voltage /= 1024.0;

 //temperatureC = (tmp36Voltage - 0.5) * 100 ;     //converting from 10 mv per degree wit 500 mV offset to
degrees ((voltage - 500mV) times 100)
 //Serial.print("Temperature (degrees C) ");     //display the temperature in degrees C
 //Serial.println(temperatureC);

/*
 temperatureF = (temperatureC * 9.0 / 5.0) + 32.0;     //convert to Fahrenheit
 Serial.print("Temperature (degrees F) ");
 Serial.println(temperatureF);
*/

 Serial.println();     //extra spaces to make debugging data easier to read
 Serial.println();
```

```
  if(abs(currentError) > 10)     //if output error is large enough, adjust output
   {
    outputValue = outputValue + currentError / 10;

    if(outputValue < 1)    //output can never go below 0
     {
      outputValue = 0;
     }

    if(outputValue > 254)     //output can never go above 255
     {
      outputValue = 255;
     }

    analogWrite(outputPin, outputValue);     //write the new output value
   }


  //if(temperatureC > cutoffTemperatureC)     //stop charging if the battery temperature exceeds the safety
threshold
   //{
    //outputValue = 0;
    //Serial.print("Max Temperature Exceeded");
   //}

  /*
  if(temperatureF > cutoffTemperatureF)     //stop charging if the battery temperature exceeds the safety
threshold
   {
    outputValue = 0;
   }
   */

   if(batteryVoltage > cutoffVoltage)     //stop charging if the battery voltage exceeds the safety threshold
   {
    outputValue = 0;
    Serial.print("Max Voltage Exceeded");
   }

   if(millis() > cutoffTime)     //stop charging if the charge time threshold
   {
    outputValue = 0;
```

```
    Serial.print("Max Charge Time Exceeded");
   }

  lcd.setCursor(0, 0);
  // read the input on analog pin 0:
  int sensorValue = analogRead(A5);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  float voltage = sensorValue * (5.0 / 1023.0);
  // print out the value you read:
  lcd.print("Cell Voltage:");
  lcd.setCursor(0, 1);
  lcd.print(batteryVoltage/1000);
   delay(10);     //delay 10 seconds before next iteration
}
```

Sub-Teams

The team was split into sub teams to take advantage of everyone's different strengths and weaknesses. These teams included a research and development team, thesis research team, and a team focused on equity impact. These sub teams were delegated a variety of different tasks such as creating various circuit models using several circuit components such as transistors, inductors, diodes, capacitors etc. and building prototype of a charger that will create one cohesive solution and answer the research questions. However, as the project neared its conclusion, the structure of these sub teams dissolved. This dissolution occurred gradually as team members dropped out, leaving the remaining members to collaborate on tasks previously assigned to the sub teams. Thus, during the final stages of the project, there was no distinct division into sub teams, and the remaining members worked collectively to complete the tasks required to fulfill the project objectives.

Timeline

Fall 2020:

- Brainstorm potential project ideas
- Identify research interests

Spring 2021:

- Formation of Team CHARGEX
- Determine broader research questions
- Begin literature review

Fall 2021:

- Continue literature review
- Initial Librarian and Mentor meetings
- Outline more specific research questions and objectives
- Develop methodology
- Begin Project Proposal
- Identify and contact field experts

Spring 2022:

- Defend Project Proposal
- Learn circuit analysis
- Acquire necessary materials and equipment
- Create engaging content for teams' social media and apply for funding

Fall 2022:

- Begin experimental research, continue survey and lab research
- Participate in the Do Good Showcase

- Launch UMD Campaign: Giving Tuesday
- Begin Thesis

Spring 2023:

- Launch UMD Campaign
- Design circuit and charger hardware
- Continue Thesis
- Create Project Poster
- Participate in Undergraduate Research Day

Fall 2023:

- Complete thesis
- Manufacture prototype
- Have a completed prototype of a charger
- Finish data collection (lab, survey, and experimental)
- Complete data analysis
- Draw conclusions based on data and analysis

Spring 2024:

- Thesis Conference

Research Budget

Based on the materials and supplies used for our data collection, a total of **$500** was used to complete this project. An itemized list of needed items and their costs have been provided below:

<u>Materials and Supplies:</u>

Current chargers and adapters (for existing charger's specific circuit components exploration).. $150

3D printing miniature prototype costs………………………………………………. $150

Electrical components and wiring…………………………………………………… $200

Glossary

Adaptor: a device used to connect a power supply to an electric system in order to allow for compatibility

Circuit Modeling: the use of computer software to model and predict electrical flow in a circuit

Disordered charging: Modifying charger for non linear or variable charging speed.

DWPT: Dynamic Wireless Power Transfer, the ability to charge a car while in motion (an idea proposed by Team FORMULA)

Electric vehicle (EV): a vehicle powered by electricity with the help of a battery and a set of motors mated with mechanical components

Fossil fuel: a natural fuel such as coal or gas, emit lots of carbon dioxide when burned

ICE: internal combustion engine

ICE-ing: deliberately parking an ICE vehicle in front of a public electric car charging space, keeping EVs from charging there

Multi-unit dwellings: housing where one building contains several individual units for housing

Power grid: the connected network of electrical lines that provide electricity to a large area

Range anxiety: the uncertainty of finding a charger that electric car users may face when embarking on longer trips with their electric cars

Rectifier: an electrical device used to convert alternating current (AC) into direct current (DC) by allowing a current to flow through the device in one direction only. Diodes work like one-way valves within the rectifier to maintain this flow of current. This process is generally known as "rectification." [59]

Reverse engineering: the process of understanding a device or system through the disassembly of it and analyzing the individual pieces

Step up or step down charger: chargers with the ability to shift charging levels at the discretion of the car owner

SWap-C - Speed, Weight, Power, Costs

Transformers: an electrical component that “steps up” or “steps down” the voltage

Voltage: electric potential, measured in volts (V)