ChargeWise

Be Smart, Charge Wise

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I. ABSTRACT

Electric Vehicles (EVs) are rapidly becoming more popular as consumer demand for environmental sustainability, energy system decarbonization, and social equity increases. Although EVs provide great strides forward in all of these areas, they also pose an existential threat to grid stability. While charging, EVs draw huge amounts of power; with a greater number of electric vehicles on the road, the grid is consequently at risk of overloading. This project, nicknamed ChargeWize, mitigates the adverse grid impacts caused by societal-scale EV charging, while simultaneously saving individual users money. This is accomplished by using EVs as shapeable loads, offsetting their charging times to periods of low grid stress. This consequently helps users save money, approximately $1.25 per charge, as electricity is cheaper when grid stress is lower. ChargeWize is unique from other smart chargers, however, in that it creates a platform for users to donate their savings toward reducing cost barriers to EV adoption in low income communities. Aggregating all 1.3-million EV owners projected in CA by 2025 results in a potential $593 million raised annually; in this way, ChargeWize hopes to enable unbounded EV proliferation while also allowing everyone, regardless of socioeconomic background, to experience the benefits that EVs provide.

II. INTRODUCTION

Electric vehicles are the future of transportation. Though they are slowly permeating the market currently, their proliferation is expected to increase at an exponential rate. The technology surrounding EVs will only improve, appealing evermore to the consumer. Thus, it is only a matter of time before the “EV revolution” occurs and EVs takes over the transportation market. But as of right now, our electric grid is not technologically capable of dealing with this EV revolution and would be at risk of catastrophic failure.

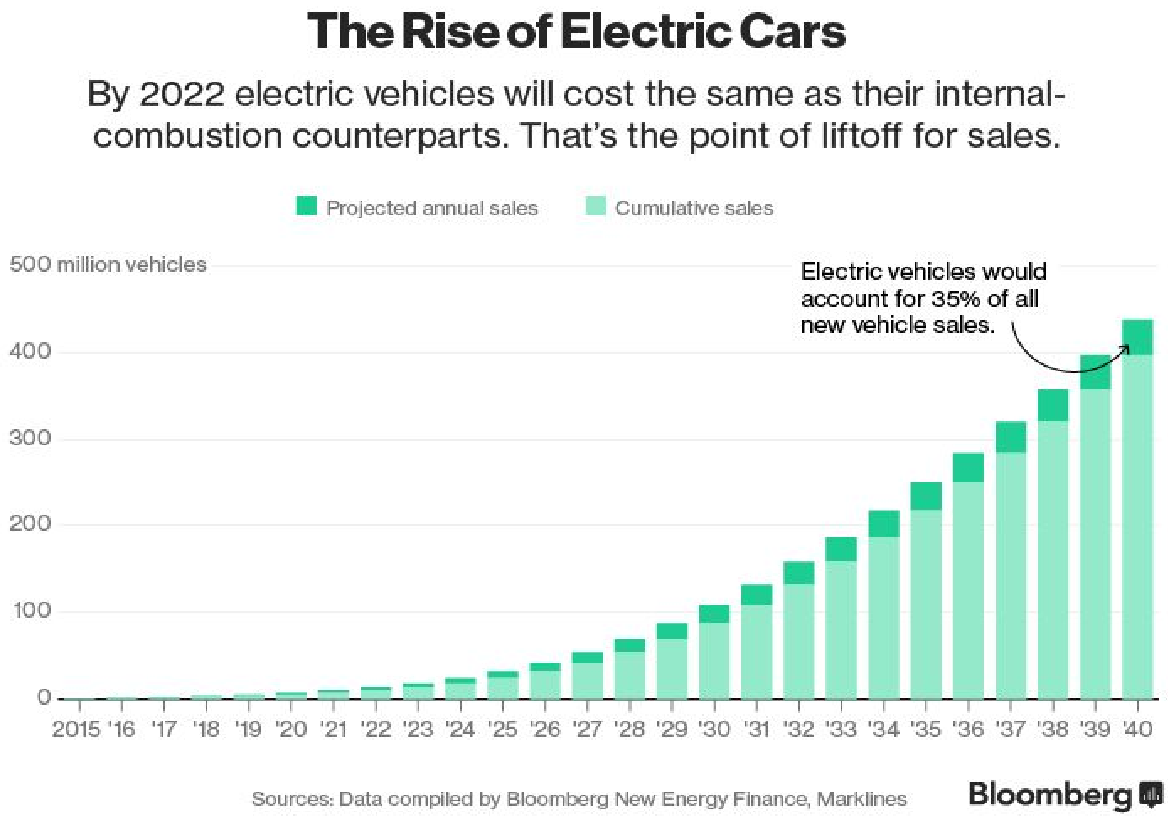

Fig. 1: The rise of electric cars in annual sales.

Charging one electric vehicle, in some cases, is the equivalent to adding 3 additional houses to the grid. Multiply this by 1.3 million electric vehicles, the number forecasted to be on the road in California in 2025, and utilities would suddenly have to deal with an additional 3.9 million house-sized loads [1]. Our current grid infrastructure could simply not handle this kind of stress, and it seems implausible that infrastructure could advance as rapidly as the projected adoption rates of EVs. This could result in power outages and decreasing grid reliability. Even now, while electric vehicles are only 2% of the market, they can exacerbate peak demands and stress the grid [2]. This is because many electric vehicle owners charge their cars once they return home from work between 5-7PM, a time period that corresponds directly with peak demands in residential electricity usage. Thus, if all electric vehicles were charged at the same time, not only would they pay a costly premium for electricity, but we would also suffer from a less reliable grid, as power outages would become far more frequent. As a result, it is imperative to be able to shift and stagger the EV load to avoid these grid stresses and price hikes [3]. However, the odds are low that EV owners will, without incentive, come together as a community to ensure that the charging times of their vehicles will be ideally staggered to avoid creating synthetic demand peaks at otherwise off-peak hours.

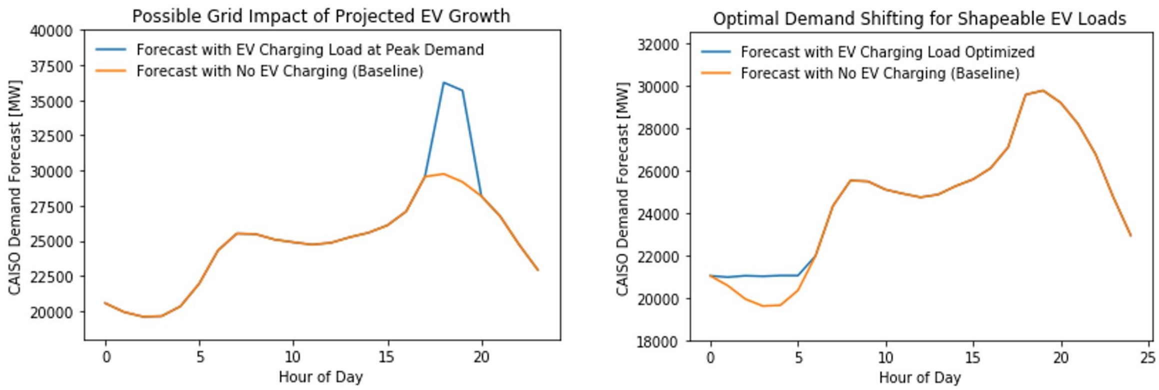

Fig. 2: Displacement of EV charging impact on grid from peak to trough through smart charger.

Furthermore, EVs in their current perception do not coincide with an equitable distribution of green technology. However, the transition to a future fueled by renewable energy requires everyone's participation, regardless of socioeconomic background. Leading a sustainable life should be accessible to all, not just an option for those who can afford it. EVs for those living below the poverty line can assist in saving money on transportation and electricity because low-income households spend higher proportions of their income on energy and transportation. Underserved populations also have more to benefit from Electric Vehicles because areas with higher rates of vehicle emission related diseases are located in the most vulnerable and susceptible neighborhoods [4]. Finally, gasoline consumption and production disproportionately affects communities of color, exposing these often susceptible, intersectional communities to toxic chemicals [5,6]. Fortunately, California policies and organizations recognize the need to address equal access to Electric Vehicles and an inclusive framework for "environmentalists". These include the Clean Vehicle Assistance Program, Clean Vehicle Rebate Project, Clean Cars 4 All Program, and support from Grid Alternatives & One-Stop-Shop Pilot [7]. These programs help people become agents of sustainable change, find green jobs, and build healthier communities in neighborhoods most affected by gasoline pollution.

Focus Statement:

With the exponential proliferation of electric vehicles in the market, there is an urgent need to understand and mitigate the technological stresses EVs put on the grid as well as ensure that everyone benefits from the EV revolution, not just the wealthy.

III. TECHNICAL DESCRIPTION

In light of all the issues described above, ChargeWize seeks to both provide relief to the grid during peak hours and incentivize low income communities to participate in the coming EV revolution. The product consists of 5 main components: a user interface, a grid interface, an optimization algorithm, charging hardware, and charge tracking visualizations. Each of these will be discussed in detail in the following sections. A flow diagram for how all of these parts interface is shown below.

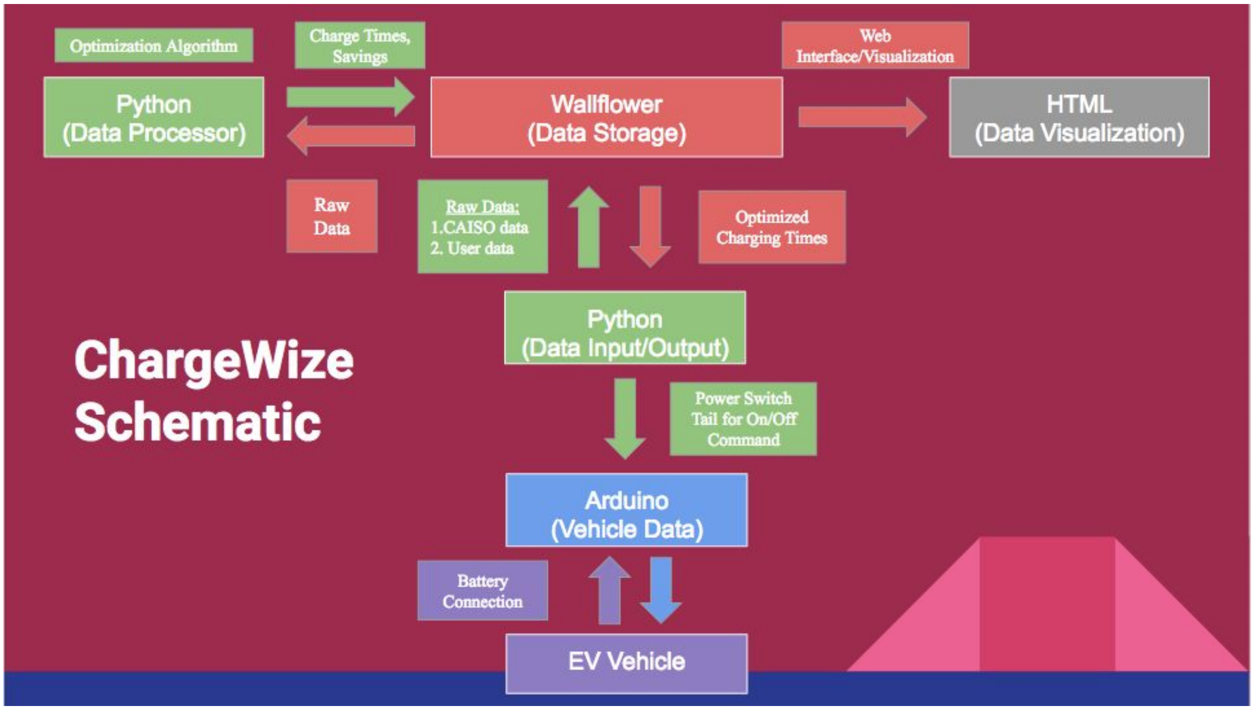

Figure 3: ChargeWize smart charger schematic

The ChargeWize charger has two main goals: relieve grid stress and improve EV equity. To relieve grid stress, ChargeWize takes in user inputs and combines them with CAISO load forecasts to determine the optimal window of charge for every EV using ChargeWize. By staggering our users' charges within their desired charge window, ChargeWize ensures that everyone on the network receives the highest quality charge while minimizing the load seen by the grid. This also saves customers money because the highest electricity prices typically occur at the times of highest grid stress. To improve EV equity, ChargeWize asks users to donate a percentage of the cost saving we provide from our optimization algorithm toward subsidizing EV purchases and building out charging infrastructure in qualifying low income communities. With this feature, ChargeWize hopes to increase low income communities' participation in the EV revolution so that they too can have better air quality in their neighborhoods and reduce impact on the environment. To further incentivize people to increase their donations, ChargeWize promises priority charging slots to users who donate more.

Utilized Materials

The ChargeWize project utilizes the following pieces of hardware:

- An Arduino to serve as an actuator based on signals sent from Python

- A Power Switch Tail relay, which opens and closes a circuit at an on/off signal from the Arduino
- A cell phone and cell phone charger; for the purposes of our interactive demo, this item symbolizes an electric vehicle. The Power Switch Tail starts and stops charging the cellphone on signal, which is based upon real-time user inputs into our user interface.
- Plywood and acrylic, using which several small wooden cars and plastic bicycles were constructed. In our interactive demo, these items came together in a mocked-up neighborhood of diverse electric transportation loads, each belonging to ChargeWize users with different charging preferences and different optimized charging windows.
- Wires and LEDs in red, yellow, blue, and green. These LEDs were tied to the various cars and bicycles in our interactive demo, and were toggled on and off by the Arduino to represent the active charging of the transportation devices to which they were tied.

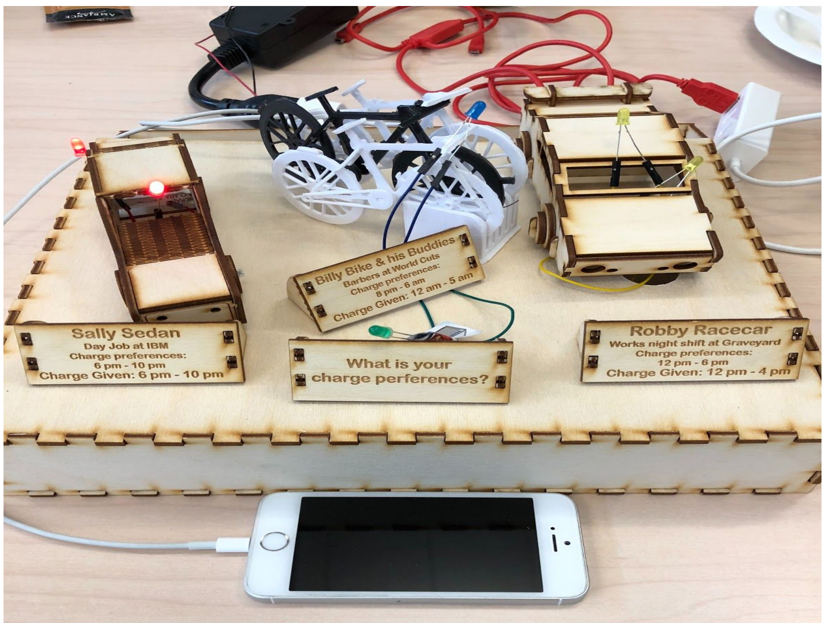

Figure 4: ChargeWize Physical Demo

Additionally, this project originally sought to use a current sensor to run a small amount of test current through the power relay into a pack of rechargeable batteries. Based upon the batteries' data sheet, they should display charging behavior which falls upon some state-of-charge vs. current curve, thus allowing us to monitor the state of charge of the user's vehicle. However, this curve proved to be extremely steep, and although we were able to take in and analyze current measurements from the current sensor, it was impossible to accurately match those measurements to a state of charge. Because state of charge is a necessary parameter to calculate how much energy an EV needs to achieve a full charge, and thus how long it needs to charge at some power output to achieve a full charge, we resorted to asking users to input their state of charge in our user interface to estimate how much power they would require.

User Interface

Built in a Jupyter Notebook, the ChargeWize user interface allows users to easily input their charging preferences so that ChargeWize can be sure to give them the right amount of charge when they need it. To provide an optimal charge, ChargeWize asks users to input the time window over which they would like to charge their vehicle and the state of charge of their vehicle at the time of plugging into ChargeWize. These inputs determine when and how much ChargeWize needs to charge their vehicle. Additionally, ChargeWize asks for the percentage of savings a user wants to donate to our low income EV incentive program. As a behavioral nudge, an interactive bar graph appears below the charge preferences to show the estimated yearly donations based on the user's inputs. Eventually, the user interface will include social networking features such as a leaderboard which shows the leading donors in a user's neighborhood.

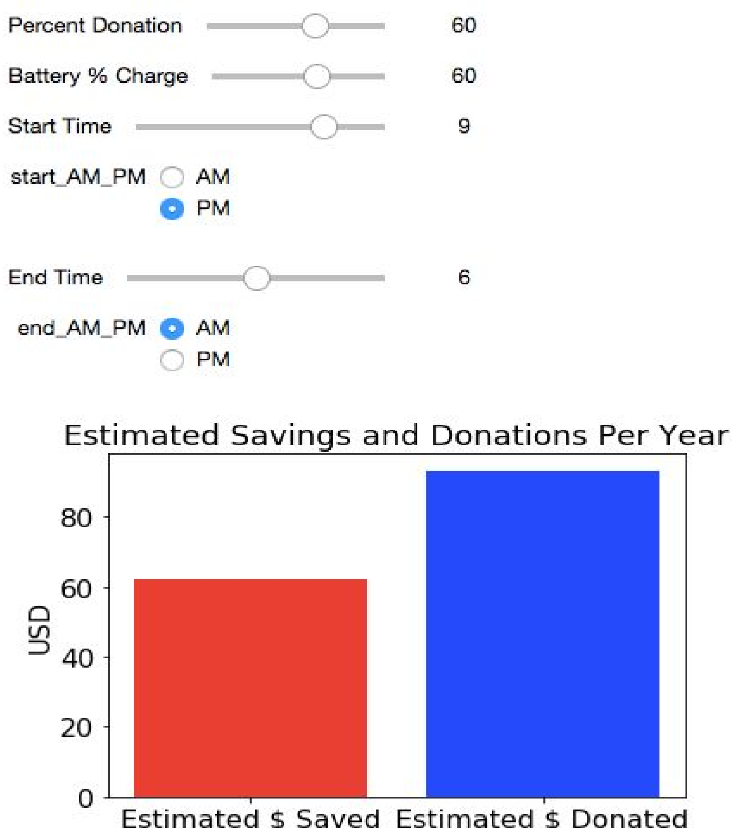

Figure 5: ChargeWize User Interface

Once users are satisfied with their charging preferences, they click a button to "submit their preferences." These preferences are condensed into a string which is sent to Wallflower.

Grid Interface

To determine the level of stress on the grid, ChargeWize utilizes a python package called PyISO which can retrieve data from CAISO, the California electricity balancing authority. Originally developed by WattTime, which uses grid level data for environmental timing purposes, the PyISO package can retrieve all sorts of generation and load data from CAISO. For ChargeWize, the most important of these data is the load forecast which provides an hourly load profile for all of CAISO up to 24 hours into the future. Using these data, ChargeWize can plan optimal charge windows for its users in advance such that grid stress is minimized. Chargewize continuously runs an instance of Python which, every hour, downloads the CAISO load forecast via PyISO, and pushes the forecast to Wallflower for later access by the optimization algorithm. Altogether, the instance of Python which continuously interfaces with CAISO, and the instance of Python which pushes user preferences to the grid, are represented by the green “Python (Data Input/Output” box in the schematic diagram.

Optimization Algorithm

ChargeWize’s optimization algorithm utilizes the user inputs and CAISO load forecast to optimize a user’s charge. The algorithm runs continuously in the background in its own instance of Python, and every five seconds accesses the Wallflower stream which aggregates user inputs. The algorithm cross references the user preferences present in Wallflower with a list of user preferences for which optimized charges have already been served; the timestamp at which the user preferences were submitted is used as a unique identifier to achieve this goal. If the optimization algorithm notes that new user preferences are present within wallflower, it also collects the 24-hour CAISO load forecast, and separately for each set of user preferences (in the order that they were submitted) conducts the optimization.

Behind the scenes, the optimization algorithm runs through several steps. First, the algorithm notes the state of charge of the user. Assuming that the average fully electric vehicle has an average battery size of about 50 kWh, and that the level 2 charger being utilized is rated for approximately 5 kW of power, it follows that it should take roughly one hour to deliver 10% charge. In mathematics:

$$Charge\ Time = \ \Delta t = \ \frac{100 - SOC}{100} \times 50\ kWh \div 5\ kW$$

This meshes well with our user inputs page which allows users to input their state of charge at a resolution of 10%, and with the CAISO load forecast which provides an hourly resolution for electricity demand. Then, for every 10% of charge below 100% charge, the algorithm estimates that one hour must be added to the time window necessary to serve a full charge. With this timespan determined, the optimization algorithm calculates and stores the values for all possible integrals on the CAISO load vs. time curve from time "t" to time "t + Δt", where "t" and "t + Δt" are constrained to be times which fall within the user's input time preferences, and "Δt" is equal to the calculated timespan which is necessary to achieve a full charge. In mathematics:

$$Charge\ Value\ =\ \int_{t}^{t+\Delta t} L(t)dt;\ t_{start} \le t \le t+\Delta t \le t_{end};\ \Delta t\ =\ Charge\ Time$$

Where t_{start} is the user's start time preference, and t_{end} is the user's end time preference, and L(t) is the piecewise CAISO load forecast. Because the CAISO load forecast is an amalgamation of 24 piecewise constant load values with steps in value occuring every one hour, this integral is simply the rectangular sum of the load forecast bound by the times t and t+Δt. In mathematics:

$$\int_{t}^{t+\Delta t} L(t)dt = L(t) + L(t+1) + ... + L(t+\Delta t - 1) + L(t+\Delta t)$$

After calculating all possible integrals, where t and t+Δt span all possible values that the constraints indicated above permit, the algorithm selects the integral which results in the minimum integral evaluation, and serves the corresponding start time "t" and end time "t + Δt" back to the user as the optimized charge period which both meets user specifications and occurs when the fewest units of energy are otherwise being consumed on the grid.

Furthermore, because ChargeWize is concerned about the impact which its users' cars will have upon the grid, the optimization algorithm modifies the downloaded CAISO load forecast by adding the load of one charging electric vehicle to the hours over which it has decided to charge a user. In mathematics, with a charge served between optimized times "t_0" and "t_1":

$$L_{new}(t_0) = L(t_0) + L_{car},\ L_{new}(t_0+1) = L(t_0+1) + L_{car},\ ...\ L_{new}(t_1) = L(t_1)\ + L_{car}$$

With this new load added, the optimization algorithm overwrites the CAISO load forecast already in wallflower with the new updated load forecast. This new load forecast which reflects the load of an additional EV is then utilized by subsequent optimizations. In this way, when thousands or millions of users are aggregated on a single day, visible alterations on the CAISO load forecast are discernable, and the optimization begins to take the loads of other cars into account when serving optimized charging windows.

Arduino Actuation and Hardware

Once the optimized charging window has been determined, the instance of Python which conducts the optimization sends the charge start and end time back to a stream on Wallflower which aggregates optimized charge windows. This data “push” uses the timestamp of the user’s original request as the timestamp for the new data point which contains the user’s optimized charge window. In this way, charging windows may be matched back to the user who originally issued the charging request. With this data sent to Wallflower, another instance of Python which is constantly monitoring the stream of optimized charge windows notices that there is a new charging window data point, and sends the start and end time of the charge to Arduino via serial communication, in the form of a string with format “STET”, where the first two digits, “ST”, represent the military time of the charge window’s beginning, and the last two digits, “ET”, represent the charge window’s ending. Arduino is not time-aware, however it is running a loop which repeatedly counts up from 0 to 23, corresponding to the hours of the day. The delay between each increase of the count is presently set to one second for the sake of verifying that the Arduino is actuating the charger as desired, however in principle it may be set to count up every one hour so that the Arduino accurately keeps time which is in-step with the day at hand.

Then, the Arduino knows the hour of the present day, and also know the hours over which it needs to be charging. In a simple “for” loop, the Arduino checks whether its current count of the hour is within the time bound by the start and end times of the optimized charge window. If it is, Arduino writes high voltage to the pin which is connected to the Power Strip Tail relay. This turns on the relay, which allows current to flow to the EV, thus charging the car over the hours determined by the optimization algorithm.

Presently, Wallflower and the various consoles of Python which constitute the computational backbone of this project are all hosted locally on a laptop; however, in future iterations of ChargeWize, the database of user preferences and charging windows will be hosted on the web, allowing ChargeWize chargers to wirelessly interface with one another without hard connection to a centered computational resource. In this way, a community of decentralized and mutually communicating smart chargers will be realized.

Web Visualization

After an optimized charge has been served to the user, the various data which are collected in Wallflower are utilized to present the users with a charge “receipt” that informs them of the details of their charge. Utilizing Highcharts, the stored CAISO load forecast and the user’s optimized charge window are used in conjunction to present the user with the demand vs. time curve; within that curve, the points over which their car actually charged are highlighted, allowing users to see how their car’s load was shaped to benefit the grid.

Furthermore, using the user’s input state of charge, the same instance of Python which aggregates and sends user preferences to Wallflower also notes the number of kWh which a user needs to achieve a full charge, utilizing the rough conversion factor of 10% battery capacity to 5 kWh of energy. This instance of Python stores PG&E's time of use rates, and calculates the price difference between fully charging the user with their needed number of kWh, at peak demand pricing and at off-peak pricing. This difference in price is taken to be the user's savings for the charge at hand. Because users also present their desired donation percentage, this percentage is applied to the total charge savings to tease out the fraction of these savings which will be donated, and the fraction which the user will actually see.

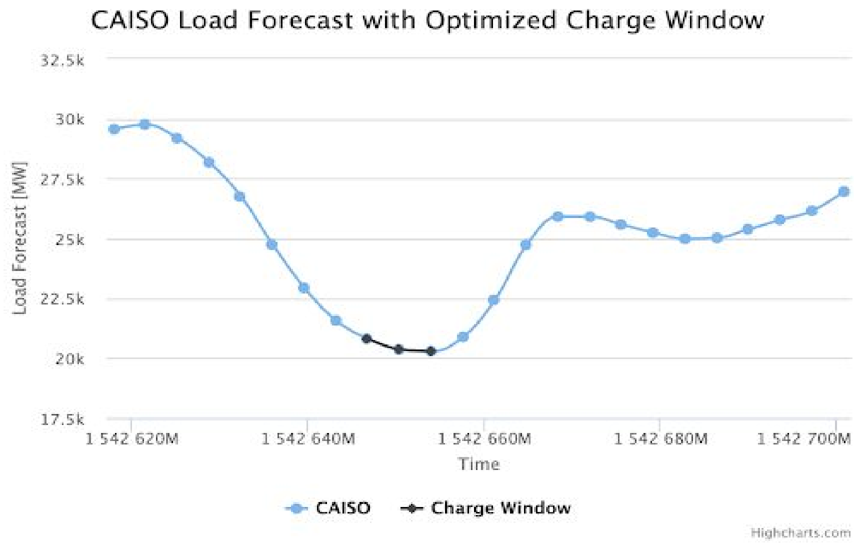

Figure 6: CAISO Load Forecast with highlighted Optimized Charge Window

These donations and savings, in units of dollars, are sent to Wallflower, where they are added to a stream which aggregates the donations and savings history of a single user. The last data point in the stream is used as a reference, and the savings and donations associated with the most recent charge are added on top of the historical saving and donation amounts so that this plot displays cumulative savings and donations amassed over time. In this way, users are motivated to continue using ChargeWize to see their savings grow with time. Furthermore, this visualization subtly nudges them towards donating, as the savings and donations curves are overlaid on top of each other. Users whose personal savings far outweigh their donations might feel pressured to donate their savings in subsequent charges to bring their donations vs. time curve in line with their savings curve. In future iterations of ChargeWize, these visualizations are intended to be served to users via push notification on a mobile app, so that they may be informed of their charges without being hassled to access these visualizations on a website.

Figure 7: Customer Savings and Donations

IV. DISCUSSION

The impact of shifting charge times between EVs with our optimization algorithm greatly reduces grid stress and decreases the chance of power outages. Through the usage of ChargeWize, there would be an estimated average savings of $1.25 everyday per user, using PG&E's residential time of use rates. The calculations for these results are as follows:

In the base-case scenario, assume that EV charging starts when users plug in their cars. Assume 70% of EV users plug in their cars between 4pm and 9pm, when the grid is "on-peak." The "on-peak" price of electricity, according to PG&E is $0.47334/kWh. Assume that 30% of EV users plug their cars in their cars during "off-peak" hours, between 9pm and 4pm (the next day) and between 7pm and 9pm, when the electricity price is $0.25994/kWh, when the electricity price is $0.12753/kWh. Assume that the average driver drives 30 miles per day and that the average EV gets around 30 kWh/100 miles = .3 kWh/mile = 9 kWh/ 30 miles. So, based on these assumptions, the average driver would need 9 kWh per day of charge for their EV. This base-case scenario is modeled below [8,9,10]:

9 kWh/day x [.70 x ($0.47334/kWh) + .30 x ($0.12753/kWh)] = $3.33/day

Using the above assumptions, the average EV user would spend $3.33 per day on electricity to charge their EV. With ChargeWize's optimization algorithm, most EV loads would be shifted to "off-peak" hours. In the ChargeWize scenario, assume that 70% of users charge during “off-peak” hours and 30% of users charge during “on-peak” hours. This ChargeWize optimized scenario is modeled below:

9 kWh/day x [.30 x ($0.47334/kWh) + .70 x ($0.12753/kWh)] = $2.08/day

By shifting charging times, ChargeWize provides users with an average cost savings of $1.25 per day. If every one of the projected 1.3 million EVs in California in 2025 used ChargeWize, the total cost savings would be $593 million per year! If even a fraction of these savings were donated on our social impact platform, they could pay for the cost of thousands of pre-owned electric vehicles for low income families, subsidize the construction of public charging infrastructure, and support environmental equity programs.

For future iterations of this project, mobile app development would be an integral step toward refining the user experience. This would enable users to easily and conveniently interface with ChargeWize and with each other, increasing its appeal and access to consumers. This app would integrate a social network to encourage people to donate through social pressures, incorporating a leaderboard of users who donate the most. With raised donations, ChargeWize could further incentivize donations by periodically giving prizes such as free charges to top donors. Having a sleek and aesthetic hardware casing for the smart charger is also an important aspect to the design of a second iteration of this project. Additionally, the project could be scaled up to commercial applications, whereas it is now only implemented in home charging scenarios. Our optimization algorithm is not inherently limited to residential customers and could easily be applied to charging stations at commercial buildings like malls, businesses, multifamily affordable housing, and parking garages, at any EV charger power level.

The present technical capabilities of this project represent a “Version 1.0” of what this team has planned for ChargeWize. Thus, there are many promising avenues of technological advancement which could magnify the societal impact which ChargeWize is able to make. While ChargeWize presently optimizes charge times in accordance to CAISO load forecasts, it pays no heed to the actual carbon intensity of the grid at various times of the day. Thus, future iterations might allow a user to specify whether or not they would like their charge time to be optimized based on grid load (and thus, by proxy, price of electricity), or by grid carbon intensity. A “green” charge would take into account forecast renewable/zero-carbon electricity generation, subtract these quantities from the CAISO load forecast, and optimize charging times based upon carbon-emitting generation only.

Furthermore, ChargeWize’s optimization algorithm presently makes several sweeping first-order approximations when calculating the window for which a user must be charged to achieve a full charge. Namely, these are that the charger will draw 5 kW, and assumes that all electric vehicles have approximately 50 kWh of battery storage. This corresponds to a near 5 kWh per 10% charge, with 10% of charge taking one hour to complete. This is accurate, but not very precise, depending on the particulars of the charger in question. Some level 2 chargers go up to 6.6 kW, while others can achieve 19.2 kW [11]**.** Furthermore, the battery capacity is highly dependent upon the model of car. For instance, a Prius has a 4.4 kWh battery pack, while a Nissan Leaf has a 30 kWh battery; meanwhile, a Tesla model S has 70 kWh of battery storage [12]. In future iterations of ChargeWize, users will be able to specify their car model and charger size, allowing for more precise estimate for time necessary to achieve a full charge; this in turn feeds our optimization algorithm with better data.

ChargeWize's optimization algorithm also has significant room for improvement. Currently, the algorithm takes advantage of vehicles as a moveable load, and shifts charge windows to points of minimum grid stress. The algorithm does not, however, take advantage of EVs as a shapeable load, because it does not under any circumstance split charges into multiple smaller charge windows, altogether culminating in a full charge. Furthermore, it does not utilize the full range of possible power outputs which the level 2 charger is capable of; for instance, it never decides that a user should be charged at half-power to halve the load which the charging EV presents to the grid. A more sophisticated charging algorithm could, for instance, decide to complete a user's 12AM to 7AM charge request in two stages, charging at full power over two hours from 2AM to 4AM at minimum grid stress, taking a break from charging from 4AM to 5AM when a neighbor needs to charge, finally completing the charge from 5AM to 7AM while charging at half power to accommodate another user who is also charging at the same time. This more advanced optimization might take advantage of methods like mixed-integer linear programming optimization. Should users opt into it, the advanced optimization algorithm might also be able to take advantage of the remainder of a user's battery charge if the user has their vehicle plugged in at peak grid demand, exporting energy to the grid to lower peak demand, while re-consuming that energy at off-peak hours, essentially engaging in energy arbitrage which simultaneously benefits the grid while gathering even more savings for users, culminating in even greater donations.

To magnify the benefit which ChargeWize has upon power quality and grid reliability, particularly at a local level, the future optimization might place greater weight on the grid load of cars belonging to geographically nearby ChargeWize users. This is because power quality issues associated with large or unpredictable loads have the most severe and immediate impact upon customers served on the same distribution feeder as the large load, as these are the lines which must actually rise to the occasion of serving sudden spikes of kW's of load. Thus, cars and their large loads present a particular danger to the distribution feeders of neighborhoods filled with many EV owners. To prevent tripping fuses and breakers, or causing voltage sags due to hyper-local EV load compaction, future iterations of ChargeWize may keep track of the distribution feeders which users are served upon. If multiple users on one feeder are requesting charges at the same time, ChargeWize should offset their load accordingly, even if the overall grid load forecast indicates that it would be favorable to charge them all at the same time.

V. SUMMARY

As the push for a more sustainable future continues, the number of electric vehicles are on the rise. Eventually the increase of electric vehicle will negatively and dramatically impact the grid, causing a large spike in power demand if this problem is not properly addressed. ChargeWize has managed to solve this problem with addressing environmental equity issues.

The ChargeWize platform facilitates communication between EV owners and the grid to achieve lowest cost charges that have minimal stress on the grid. EV owners will input their preferences at the times they are able to charge and the state of charge they are currently at. This along with CAISO's next-day energy forecast demands gives ChargeWize the data they need to allocate specific time slots for each user to charge for optimal periods. The user will also input the amount of money they would like to donate from the money saved from charging. ChargeWize will use all the money saved to support low-income communities through implementing more EV charging infrastructure and incentivizing EV adoption. The ChargeWize charger significantly less expensive than competing technology, making it highly cost effective. ChargeWize has developed a working prototype and the next stages will be to create a functional, user-friendly mobile app with efficiently packaged hardware and improved optimization algorithm.

In closing, ChargeWize aims to be a platform which serves the needs of the individual customer, providing them with charges that meet their expectations and values, while also ensuring that the aggregation of these charges at scale does not contribute to grid distress on a local or system-wide level. In achieving this mission, the value which ChargeWize's optimized charges generate are shared with underserved communities, ensuring that the green transportation revolution serves everybody equally, regardless of socioeconomic background. In short - we hope to convince all EV owners that they should be smart, and Charge Wise!

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