Greening Electric Bike Sharing Using Solar Charging Stations

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ABSTRACT

Electric bikes have emerged as a popular form of transportation for short trips in dense urban areas and are being increasingly adopted by bike share programs for easy accessibility to riders. Motivated by the rising popularity of electric bikes, a form of an electric vehicle, we study the research question of how to design a zero-carbon electric bike share system. Specifically we study the challenges in designing solar charging stations for electric bike systems that enable either net-zero or a fully zero-carbon operation. We design a prototype two bike solar charging station to demonstrate the feasibility of our approach. Using insights and data from our prototype solar charging station, we then conduct a data driven analysis of the costs and benefits of converting an entire bike system into one powered using solar charging stations. Using empirical analysis, we determine the panel and battery capacity for each station, and perform a feasibility evaluation of the system using 8 months of ridership data. Our results show that equipping each bike station with a single grid-tied solar panel is adequate to meet the annual charging demand from electric bikes and achieve net-zero operation using net-metering. For an off-grid setup, our analysis shows that a bike station needs twice as many solar panels, on average, along with a 1.8kWh battery, with the busiest bike station needing 6× more solar capacity than in the net-metering case. Our analysis also reveals a tradeoff between the array size and the battery size needed to achieve true-zero carbon operation for the electric bike share system.

CCS CONCEPTS

• **Applied computing** → **Transportation**.

KEYWORDS

Solar Energy, Electric Bikes, Bike Sharing

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1 INTRODUCTION

Bicycling has enjoyed a renaissance as a form of urban transportation that is well suited for shorter rides. The emergence of bike share systems in cities around the world has further increased the popularity of bicycling as a "fun" form of transport. By deploying thousands or tens of thousands of bicycles in a city, bike share systems have made it very convenient for riders to pick up and drop off a bike from practically any location within a city and at any time e.g. [1–3, 5] and many more. Bicycling provides many benefits, both to riders and to cities. From a rider's standpoint, bicycling is seen as a form of transportation that is well suited for quick getaways and one that promotes an active lifestyle that provides health benefits. From the standpoint of cities, bicycling and bike share systems provide greening benefits. Bike rides can reduce reliance on cars, especially for very short rides (e.g. a few city blocks to a few kilometers), which reduces congestion on city roads. Bicycling is also a zero carbon form of transportation which reduces pollution and carbon emissions.

More recently, electric bikes have begun to surge in popularity as a new form of transportation [19, 21, 27]. An electric bike (See Figure 1) is a type of an electric vehicle (EV) where the bike is equipped with a motor and battery to provide pedal assist to riders, making biking effortless. Electric bikes make it feasible to support longer rides than traditional bikes and make it easy to navigate roads with hills or steep slopes. Due to their many benefits, they have become quite popular in China, Europe and North America [6].

As a result, bike share systems have begun to adopt electric bikes as a means of making bicycling more convenient on urban roads. Several bike share systems in many cities such as Raleigh [4] and Riverside in the USA, Borken, Germany and Guildford [10], UK already offer all electric bikes. Bike share systems in larger cities such as New York's CitiBike have announced plans to electrify their bikes [7]. Like any EV, electric bike share systems require a charging infrastructure to be installed in bike stations to charge the bikes between rides. While traditional bikes are zero-carbon vehicles, the carbon footprint of electric bikes depends on the carbon mix of the electricity used to charge them. Thus, their carbon footprint is no longer zero.

Motivated by these observations, in this paper we examine the feasibility of using solar charging stations to make electric bike share systems zero carbon like their manual counterparts. Specifically, we consider two different designs: grid-tied solar-powered stations that

Figure 1: An electric bike is powered using an electric motor and a battery [27].

use net-metering to achieve net-zero operation and off-the-grid solar-powered stations that yield a true zero carbon design without relying on the grid. In addressing these research questions, this paper makes the following contributions:

(1) We prototype a two bike solar powered bike charging station and conduct an experimental study to demonstrate the feasibility for using solar EV charging for bikes.
(2) Using data from our prototype and solar data from a local array, we examine the feasibility of converting an actual all-electric bike share system into a solar powered one. We use 8 months of ridership data from our electric bike share system to analyze the solar and battery capacity needed at each bike station to meet its charging energy demands. We analyze and compare two designs: net-zero grid-tied solar charging stations and true-zero carbon off-grid solar charging stations.
(3) Our results shows that equipping each bike station with a single grid-tied solar panel is adequate to meet the annual charging demand from electric bikes and achieve net-zero operation using net-metering. For an off-grid setup, our analysis shows that a bike station needs two solar panels, on average, along with a 1.8KWh battery, with the busiest bike stations needing 6× more solar capacity than in the net-metering case. Our analysis also reveals a tradeoff between the array size and the battery size needed to achieve true-zero carbon operation for the electric bike share system—since energy storage is still expensive to deploy, the cost of installing batteries can be reduced by increasing the size of the solar array at each bike station. We also show that significant carbon savings can be achieved, with a total of 0.2MT and 1.1MT of CO_2 emission reduced in the off-grid and grid-tied cases respectively.

2 BACKGROUND

In this section, we present background for our work and the problem statement.

2.1 Electric Bikes and Bike Sharing

Electric bicycles (e-bikes) have steadily grown in popularity in recent years. An e-bike is a bicycle with an electric motor and a battery (often lithium-ion) that has the ability to provide pedal assist when bicycling (See Figure 1). The level of pedal-assist, which can be adjusted, reduces the manual pedaling effort expended by the rider. E-bikes are particularly well suited for roads with upslopes, and also make longer rides effortless. Electric bikes as a mode of urban transport has been studied by researchers [18, 20, 26, 27], who have argued for their sustainability and wellness benefits.

Bike sharing systems, which allow short-term bike rentals, have recently begun to adopt electric bikes. Many small cities in the United States and Europe have adopted an all electric bike system [1–5, 10]. Our local bike share system ValleyBike Share [12] also uses electric bikes.

Since an e-bike is a form of an EV, it requires a charging infrastructure like any electric vehicle. In this case, each bike station needs bike stands with charging capabilities. Since electric bike batteries are much smaller in size and capacity than electric cars (e.g., Tesla, Nissan Leaf) batteries, the use of solar powered bike stations to charge such e-bikes becomes an interesting possibility.

There are two key advantages of employing solar bike stations. First, the use of solar charging stations potentially makes the bike share system zero-carbon—since e-bikes can be charged using green electricity from renewables. Second, bike stations with full off-grid solar charging capabilities can be deployed as standalone stations without any grid connections and can be deployed "anywhere" without incurring wiring costs.

There are several design challenges however. First, sizing of the solar panels needed for autonomous operation of a solar bike station is important. The number of panels required should roughly equal the physical footprint of the station (e.g., to serve as the solar roof of the station). Second, since renewable solar generation is intermittent, off-grid operation will require battery storage to support evening or night charging as well as for charging on cloudy days. The size of the battery can have an impact on cost.

In this paper, we analyze the feasibility of a net-metered net-zero bike station design as well as a fully off-grid true-zero one.

2.2 Renewable Solar and Energy Storage

Renewable solar has become increasingly popular in recent years. Like any renewable energy source, solar generation is intermittent and exhibits seasonal variations (see Figure 4a). Day-to-day variations depend on the amount of cloud cover, and hence, the amount of solar irradiance seen by solar panels. The generation can also vary significantly between summer and winter months due to the length of the day and position of the sun in the sky – in many parts of North America and Europe, the summer output can be 2-3x greater than winter output [14]. These factors have a key implication on sizing of solar arrays to meet a specific need. A common approach for sizing solar arrays is to achieve *net-zero* carbon operation, which means that the total energy produced over a period such as a year should equal or exceed the total energy consumed over the same period.

Typically, solar installations on residential or business buildings can achieve net-zero operation through net-metering to the grid. Net-metering allows the solar array to feed excess power generation to the grid whenever the instantaneous generation exceeds demand, and draw power from the grid when demand exceeds generation. Since there is no solar generation during night hours, a net-metered system can achieve net-zero operation by overproducing during the day and drawing power back from the grid during evening and night hours. Similarly, the system overproduces during summer months to compensate for the underproduction during winter months.

In contrast, a full off-grid operation can offer *true-zero* carbon operation but requires different sizing considerations. Such a system should not only have a zero carbon footprint, but the total cumulative production at all times needs to exceed the total consumption since the grid is no longer available to "borrow" power during a deficit. Energy storage in the form of batteries is necessary in such a system to store excess energy for later use. The energy storage can handle intermittency by providing power during deficits – during nights, during cloudy days or during winter months. However, since the energy storage is finite, the system should be sized appropriately to balance the tradeoff between system cost and perpetual operation.

Our work considers two design alternatives – a grid-tied solar charging station with net-metering, as well a fully off-grid station with energy storage. We analyze the feasibility of each design and compare their costs and benefits.

2.3 Problem Statement

Given the above background, this paper examines the feasibility, cost, and benefits of using solar powered charging to design a sustainable electric bike share system. To do so, our first goal is to design a prototype solar charging bike station to demonstrate the feasibility of using solar energy to charge electric bikes and to understand the solar array and energy storage capacity needed to handle bike charging demand. Our second goal is to use a data-driven analysis to scale this design to an actual electric bike share system. Our analysis needs to determine the solar and battery sizes needed to handle charging demand from real ridership data so as to ensure perpetual operation for both grid-tied and off-grid designs.

3 SOLAR POWERED BIKE STATION PROTOTYPE

In this section, we describe our design of a two-bike prototype solar-powered bike charging station.

3.1 Hardware Design

Our prototype solar powered bike charging station has four key hardware components. The architecture of our prototype is shown in Figure 2a, while Figure 2b depicts an annotated photo of our prototype.

Solar array. Our prototype uses two 120W solar panels (model AIMS PV120POLY) connected in series to generate electricity. Each panel has a compact footprint of 113cm by 67cm. Our measurements, shown in Section 3.2, show that on a typical sunny day, each panel generates 0.54kWh of energy, which is enough to charge 1.7 electric bikes. We have also gathered measurement data from larger 320W solar panels (model LG NeOn 320), each of which generates 1.9kWh on a sunny day, which is capable of charging 6 bikes per panel. The footprint of these panels is 164cm by 100cm. From a sizing perspective, a small array of either type of solar panel, mounted on the roof of a bike station, can generate adequate energy to meet charging demand. In Section 5, we analyze the solar array size needed based on actual ridership data and charging demand.

Energy storage. Off-grid operation of the solar charging station requires the ability to store excess energy generation so that the stored energy can be used during evening hours or on cloudy days. Consequently, our prototype includes a MPPT charge controller (model TRIRON2210N 20A MPPT Solar Controller), and two Lithium Iron Phosphate (LiFePO4) batteries that are specifically designed for use with solar arrays.

The MPPT charge controller uses maximum power point tracking (MPPT) to continuously adjust the output voltage of the arrays to maximize power generation and feeds this electricity to the battery array. Each LiFePO4 battery has a capacity of 1.2kWh, which is sufficient to charge 3 bikes in the absence of solar generation.

Our data driven analysis, shown in Figure 7b, shows the battery capacity needed in an actual bike station. For our prototype, however, which is designed to support two bikes at a time, a two battery array is adequate to fully charge 6 electric bikes.

Bike charging. Our hardware prototype uses a combination of an AC converter and a configurable bike charger to charge each electric bike. Since the LiFePO4 outputs DC, while the bike charger expects AC power, we use an inverter to output AC power from the battery. The bike charger uses the AC power from the inverter and charges an electric bike when plugged into the charger.

We note that this is not an optimal design due to the DC to AC to DC conversion, which incurs around 20% loss. An optimal design would include a custom-designed bike charger that directly takes DC input from the battery and provides DC output to a bike battery. However, since we use off-the-shelf electric bikes, such DC bike chargers are not presently available commercially for these e-bikes.

Our bike charger (model: Cycle Satiator) is a programmable bike charger that can supply up to 8A to a bike battery and can be programmed with different charging profiles depending on the model of the battery being charged; using a programmable charger allows us to support a wide range of e-bikes with our setup.

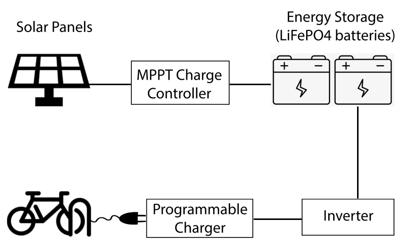
Electric bikes. Our prototype includes two electric bikes (model Merax 26" Aluminum Electric Mountain Bike), each with a 317Wh Li-Ion battery. While our configurable charger is capable of charging many types of bike batteries (and bike models), we have currently configured it with a charging profile of this bike battery. Our measurements show that the setup can fully charge a bike with a depleted battery in approximately 190 minutes (3 hours).

Each of our electric bikes is instrumented with a custom-designed sensor package (see Figure 3) comprising a CycleAnalyst controller [11], which can measure and log various parameters of the bike motor and battery (such as voltage, current, power, speed and distance), and a ConnectCycle cellular tracker [9] that can track the GPS coordinates of the bike at a minute granularity. We use a custom programmed Arduino board with WiFi to log data from the CycleAnalyst at a programmable frequency and periodically upload it to a server whenever the Arduino board is connected to a WiFi network. The ConnectedCycle GPS logs are periodically downloaded using a cloud API.

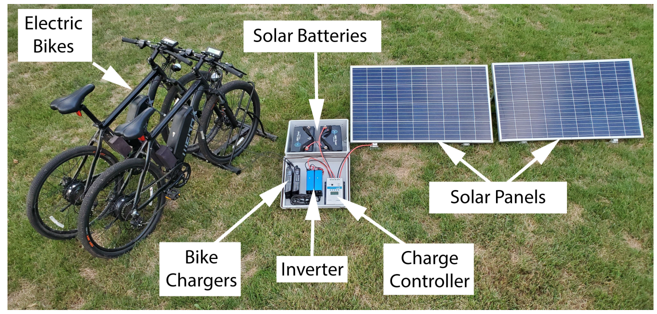
3.2 Prototype Measurements

We conducted a set of experimental measurements of our hardware prototype to evaluate the feasibility of our design. Figure 5a depicts the charging profile of the bike battery from a depleted state. As can be seen, the battery charger uses a fast charge rate until the charge reaches 75% (238Wh), and then uses a slower rate of charge until full. Such trickle charging extends the life of the battery.

Figure 4a depicts the solar power generated by our setup, with each panel generating approximately 0.54kWh on a sunny day, which can charge approximately two bikes per panel per day. Fig 4b and 4c depicts the power generated by the larger 290W panels over the



(a) System block diagram.



(b) Solar powered charging prototype with two electric bikes.

Figure 2: (2a) Block diagram of our solar charging station prototype, and (2b) a photo of our setup with two electric bikes.

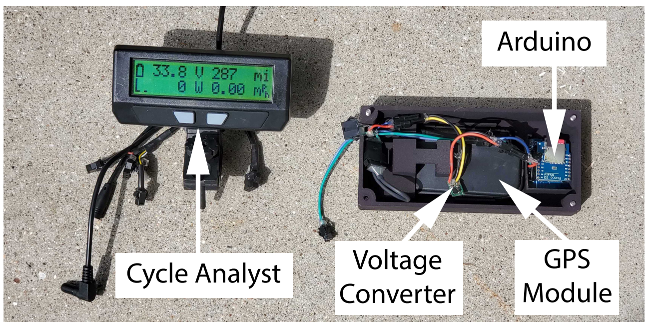


Figure 3: Sensor kit installed on each bike.

course of a week and across season, respectively. As shown, the panels generate 1.9KWh of energy in the summer, enough to charge 6 bikes per panel per day. However, as can be seen, winter generation is approximately 80% lower than summer due to shorter days and lower solar elevation and the winter output can charge only a single bike per day. As we will see in Section 5, this has implications on panel sizing for net-metered versus full off-grid operation.

Finally, Figure 5b depicts the charging of the LiFePO4 battery. As can be seen, the battery voltage increases rapidly in the initial hours (between 2 and 5 hours), followed by intermittent fluctuation between the 5^{th} and 10^{th} hour of charging. This is then followed by a near constant voltage curve, during which full charge in the battery is maintained.

Overall, our measurements show that a modest size array comprising a few 120W panels should be capable of charging several bikes concurrently over the course of a day, thereby demonstrating the feasibility of using solar energy to charge bikes at a bike station. The array size will be even smaller for the 320W panels.

Having established the basic feasibility of our design, in the next section, we analyze the size of the solar array and batteries needed to handle the actual charging demand seen by a bike share system.

4 DESIGNING A SOLAR POWERED E-BIKE SHARING SYSTEM

In this section, we use the measurements from our hardware prototype and conduct a data driven analysis of how to scale the design to an entire electric bike sharing system. We first describe the datasets and methodology used for our data driven analysis followed by our results.

Table 1: Summary of Bike Sharing Dataset

Bike type	Electric
Number of bikes	490
Number of stations	59
Number of trips	70,076
Duration	April 1st, 2019 - November 30th, 2019

4.1 ValleyBike Electric Bike Sharing

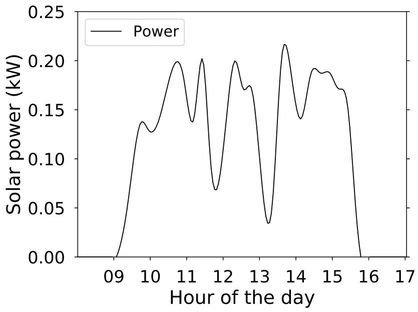
Our analysis targets the ValleyBike bike share system in the United States that employs an all electric fleet of bicycles (see Figure 5c).

As shown in Table 1, the ValleyBike system uses a fleet of 490 bikes deployed at 59 bike stations in its service region. Our dataset spans the 2019 year, its first full year of operation (due to snow in the winter, operation began on April 1^{st} rather than January 1^{st}). The dataset (which we have released publicly along with this publication at http://traces.cs.umass.edu), includes 70,076 trips over an 8 month period. We use this 8 month dataset as the default for most experiments. In some experiments, that require 12 months of analysis, we use data from November and replicate it for the December to March period. Since our goal is to understand solar and battery sizing, we believe that November data is a good "upper bound" for the December to March period, where ridership will be lower due to cold and snow.

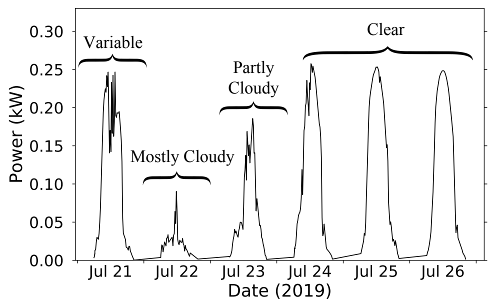
Each bike ride in our dataset comprises of a trip's start and stop timestamp, the start and end station, distance, duration, the bike ID, cost of the trip and anonymized user information.

Finally, each of the 59 bike stations currently use grid power to charge docked bikes. Our analysis examines the feasibility of using on-site solar arrays at each bike station to charge docked bikes.

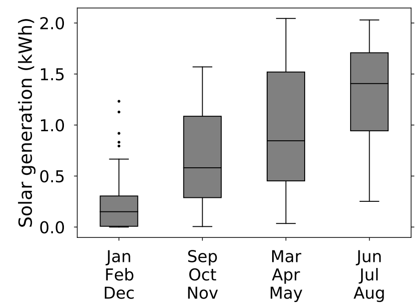
4.1.1 Trip Analysis. Figure 6a depicts the distribution of distance covered by each trip. Trips are usually short, with the median trip covering a distance of 2.9km. The distribution shows a long tail, with the longest trip going as far as 20km. Figure 6b shows the distribution of trip duration. The figure also depicts a long tail with the median duration being 17.1 minutes, which is somewhat long for the expected distance, indicating that some riders may stop enroute during a ride. Looking at the trip demand, Figure 6c shows a unimodal daytime peak usage, occurring between 3-5PM. On a normal clear day, this peak usage, which consequently leads to higher energy



(a) Prototype solar generation trace.

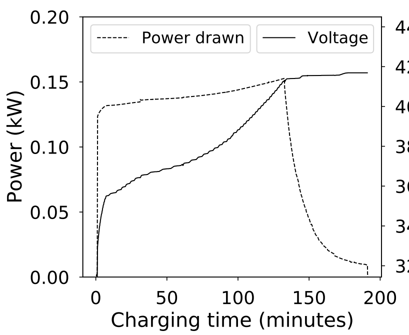


(b) Solar generation trace for a week.

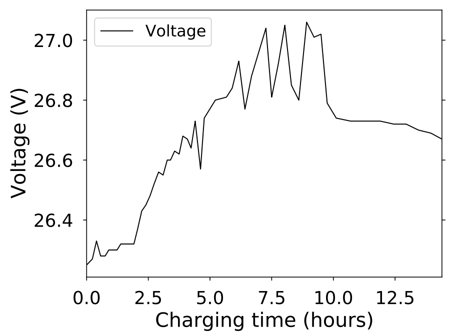


(c) Solar generation by season.

Figure 4: (4a) Solar generation trace by panels in our prototype setup for a single day, (4b) solar generation trace for a sample week by the larger 320W panel, and (4c) solar generation by season of the year (winter, fall, spring and summer).



(a) E-bike battery curve



(b) Solar batteries curve

(c) Bike station

Figure 5: (5a) E-bike battery charging profile, (5b), charging profile of solar batteries, and (5c) a station with docked electric bikes in the TownBike bike sharing system.

demand (see Figure 8b), coincides with higher solar generation at this time of day, making solar an ideal source of energy for such a system.

Figure 6d shows the distribution of durations between trips. During this time, bikes are returned and docked in the station, and are able to draw power and recharge their batteries before the start of the next trip. We eliminate night hours in this distribution because bikes left at a station overnight are most likely to draw enough power to recharge to full capacity. From Figure 6d, we find that the median duration at a station is approximately 50 minutes. During this period, according to our solar charging prototype, a bike can replenish up to 29% of depleted energy between trips.

Key takeaways: The median trip is short (2.9km). Trip durations are long (with a median of 17.1 minutes), suggesting possible stops during a trip. Demand of trips per day is unimodal with a single peak occurring between 3-5PM.

4.2 Solar Dataset

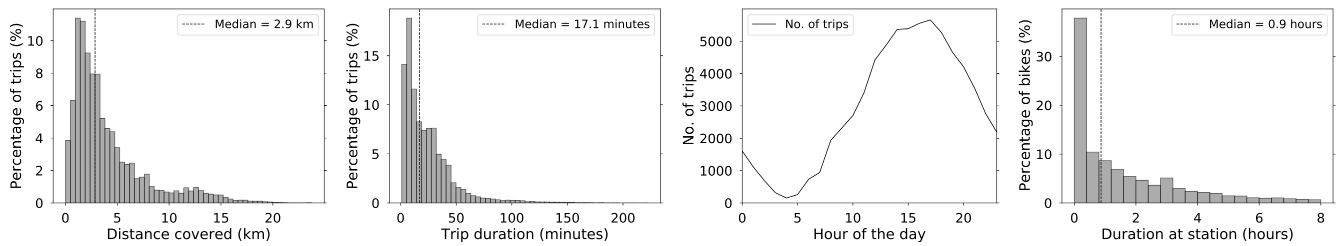
As part of our hardware prototype experiments, we have gathered several days of solar generation data from our two-bike solar station. However, since solar generation varies substantially by season, we use a second year long solar dataset from a residential solar array deployed on a home in the same location as the bike share dataset. We use data from 9 panels mounted on one plane of the house. Each panel is a 320W panel with a micro-inverter that can report panel-level generation data. We have been collecting per-panel solar generation data from this installation for the past three years at one minute granularity.

For our analysis, we focus on data from Jan-Dec 2019, which overlaps with the period for our ValleyBike dataset. Since this is a 9 panel system, it enables our analysis to customize the number of solar panels deployed at a station from 1 to 9 based on the observed charging demand at each of the 59 stations.

4.3 Trace-driven Replay

We use trace-driven replay to analyze the energy demand at each station as well as to determine the sizing of the solar and battery array needed at each station.

Our trace replay works as follows. We assume a certain number of bikes at each station each morning based on where they were dropped off after the last ride of the previous day. We assume that bikes start the day with fully charged batteries (the only exception to this assumption is a scenario where the station is fully off-grid and has a fully depleted solar battery that can no longer charge the bike). We then replay the ridership trace which involves "simulating" each ride by checking out the designated bike from the pickup station for the ride and then checking it in at the checkin time at the drop-off station. We use the distance reported reported by the bike's odometer as the distance for the trip, which enables us to capture the entire distance covered by the bike including the cases where a bike is picked up and dropped off at the same station. Given the ride distance, we use a linear model to deplete the battery. In other



(a) Trip distance **(b) Trip duration** **(c) Trip demand by time of day** **(d) Bike duration at station**

Figure 6: (6a) Distribution of distance covered by trips, (6b) duration of trips, (6c) demand of trips by time of day, and (6d) distribution of duration between trips during which bikes are docked.

words, if the battery level of the bike at the start of the ride is s and the distance traveled is d, the battery level at check-in time is $\min(0, s - d \times r)$, where r is the rate of battery depletion per km of distance traveled. Based on measurements of our prototype bikes which have a range of 45km, we set $r = 7.9Wh/km$.

Once a bike is checked in, its battery starts charging from the current level. Suppose t denotes the time spent by the bike at the station until its next checkout. We use the battery charging curve from out prototype (Figure 5a) to compute the level of charge that will be attained by the battery from the current level in time period t. The trace replay then proceeds to replay the next ride in the trace and so on, simulating the rides across the entire system. The analysis tracks the battery levels for all bikes before and after each ride as well as charge sessions at each station and the energy consumed by each session.

In addition to replaying each bike ride from the trace, the analysis also replays the solar trace at each station. We assume that station i has s_i solar panels. For off-grid deployment, each station additionally has b_i batteries as energy storage.

The trace replay also replays the solar energy trace for the specific data on all s_i panels. The generated electricity is fed to all bikes that are currently charging (if any). Any excess electricity is fed to the grid for net-metered setup or the batteries for off-grid setup. In cases where solar generation is inadequate to meet charging demand or zero (e.g. during night hours), the station will draw the deficit from the grid (net-metered setup) or batteries (off-grid setup).

4.4 Solar Array and Battery Sizing Methodology

Given the trace-driven replay of bike arrivals and departures at each station and solar generation replay, we use the following methodology to determine the solar and battery array sizes to ensure perpetual net-zero or true-zero operation.

A grid-tied station is defined to be net-zero over a year when the total energy generated by its s_i solar panels is at least equal to the total charging demand from the station over that 12 month period. To determine the minimum size solar array needed for net-zero operation, we perform a trace replay of bike arrivals and departures at each station setting $s_i = b_i = 0$. We compute the total energy consumed by each charging session of a bike and compute the total demand over the 12 month period. Next, we use our solar trace to compute the total energy produced by a single panel over a year. Then, the number of panels s_i needed is **total charge demand (Wh) ÷ energy produced by 1 panel (Wh)**.

For off-grid sizing of the solar and battery array, we use two different methods: search-based and peak-based sizing.

Search-based sizing. The search-based strategy involves using trace-replay to find the smallest number of panels at each station that yields a feasible solution for perpetual operation. To do so, we initialize each station with a single panel ($s_i = 1$) and an infinite battery $b_i = \infty$. We then replay the trace and examine for each bike arrival whether there is enough energy to charge the bike using the current solar generation and the energy stored in the battery. If the battery is depleted and there is not adequate generation, the s_i panels at that station are inadequate. In that case, the replay terminates and we restart it from the beginning by incrementing the number of solar panels s_i at the station by 1. The process continues until the number of panels s_i at each station is adequate for a feasible replay of the trace.

Since the battery is assumed to be of infinite capacity, the trace replay simulator tracks the total energy stored in the battery at each step in each station. The peak amount of energy stored over the 12 month period is the peak battery demand, which yields the number of batteries b_i needed at each station. We also analyze the array-battery tradeoff by increasing s_i further (beyond the minimum size) to determine the reduction in battery size at each station.

Peak-based sizing. For peak-based sizing, we divide the year into 4 seasons: summer, fall, winter and spring. We compute the average daily production of a single panel in each season. We then perform trace replay to compute the peak day with the highest charging demand. The number of panels needed is then computed as **peak demand ÷ average production**. We repeat this for each season and compute the max over all four seasons to compute s_i.

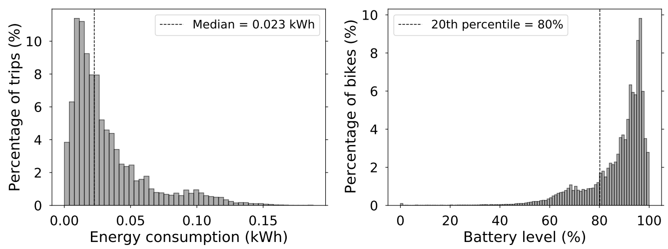
The battery capacity takes the peak demand day and assumes that there is no production on that day and the entire demand must be satisfied by the battery. The size of the battery array is then **peak energy demand ÷ capacity of a single battery**.

5 EXPERIMENTAL RESULTS

In this section, we present the results of our trace-replay based energy analysis and our solar and battery sizing results.

5.1 Energy Analysis of Individual Rides

Figure 7a shows the distribution of energy consumed by each trip. We observe a wide range of energy consumption by each trip, most of which lies between 0 and 0.15kWh. The median energy demand is 0.023kWh, which represents 7.3% of the bike battery capacity.



(a) Trip energy consumption **(b) Arrival battery level**

Figure 7: (7a) Energy consumed per trip, and (7b) bike battery level on arrival at the station.

The distribution shows a long tail, with the highest energy trip consuming 0.18kWh (57% of battery capacity). The aggregate energy demand across the whole the system varies over time mainly driven by weather and seasonal changes. Figure 8a depicts the energy demand throughout the whole duration (April to November), with energy demand increasing between May and September (summer months). This is brought about by the favorable weather conditions during summer for cycling.

Figure 7b shows the distribution of the level of battery at the end of a trip when they are returned to the station. We observe a broad range of values, most of which lie between 90-100% charge. We find that 80% of all bikes are returned with 20% of their battery energy having been depleted by the trip, while some very long trips completely deplete the battery to 0% charge.

Figure 8b shows the average energy demand and solar generation by time of day. Energy demand shows a unimodal daytime peak usage between 3-5PM. The occurrence of peak usage at this time of day coincides with high solar generation making solar an ideal source of energy for such a bike sharing system.

Result: *The median trip consumes 7.3% of battery capacity, with the highest energy trip consuming up to 57% of battery capacity. Most bikes require less than 10% charge upon arrival at the station, with 80% of all returned bikes requiring up to 20% charge. Daily trip demand exhibits a singular peak which occurs between 3-5PM.*

5.2 Energy Analysis of Bike Stations

Figure 9 depicts the solar energy generation per panel at a bike station over a 12 month period. As can be seen, there are significant seasonal variations and daily variation in the energy generation; the figure shows that a single panel generates 0.8kWh per day and 296kWh per year. There exists high correlation between solar generation and temperature with summer months having the highest solar generation along with the higher temperature compared to other months. Figure 10 depicts a distribution of the total energy consumed per station over the year. As shown, the average station sees an annual demand of 78.3kWh, while the busiest station sees a higher demand of 267kWh.

Result: *There exists strong positive correlation between solar generation, energy demand and temperature (0.6 and 0.7 respectively). Our results also indicate that the total annual solar energy generated by a single panel exceeds a station's demand during the same period.*

5.3 Grid-tied Net Zero Carbon Design

In section 5.2, we analyzed the energy generation from solar and energy consumption from bike charging at bike stations within the bike share system. Our analysis showed that the annual energy consumption of the busiest station in the bike share system is 267kWh, while that of the average station is 78.3kWh.

In comparison, a single 320W LG panel generated 296kWh per year, which sits comfortably above the total demand of the busiest station. This implies that equipping each station with a single solar panel each is adequate for net-zero operation. In fact, a single panel will generate a surplus based on the annual usage, resulting in a small negative carbon footprint. Figure 11 shows the energy fed into the grid. On average, 34.6kWh are fed to the grid every day as surplus energy. Since each station is grid-tied with net-metering, no batteries are necessary.

Result: *A single solar panel per station is capable of meeting the entire annual charge demand of the station, implying that net-zero operation can be achieved in a modest investment cost of a panel per station.*

5.4 Off-grid True Zero Carbon Design

We now analyze the solar and battery capacity needed for full off-grid operation and a true zero carbon design.

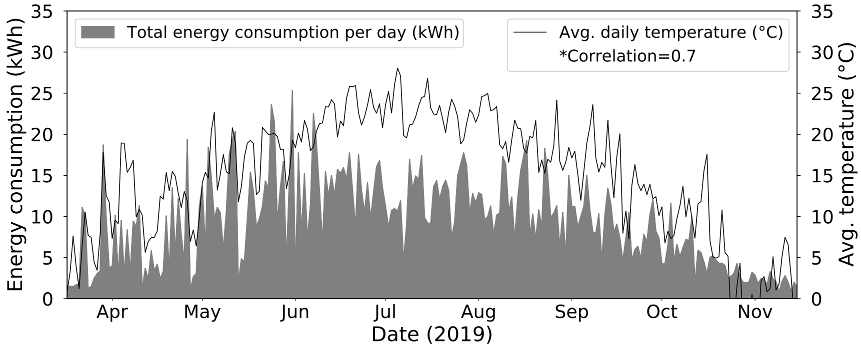
Figure 12a depicts a sample trace replay of energy trace and solar trace at a station during the summer. Since the summer yields the highest solar generation, the figure shows that solar generation even with a single panel comfortably exceeds the total demand (shown in gray). Figure 12b depicts that storing the excess energy in a battery yields battery charge levels that exceed 92% charge more than 80% of the time. However, the situation is different during winter, where production drops by 90% (Figure 4c).

Consequently, we compute the average solar generation for each season and the peak demand day at each station for that season to estimate the solar capacity needed at a station. Figure 13a depicts a distribution of the solar capacity needed across all stations. Note that lower winter production is offset by lower ridership demand in colder seasons. Figure 13b depicts the distribution of maximum number of panels needed at each station across all seasons.

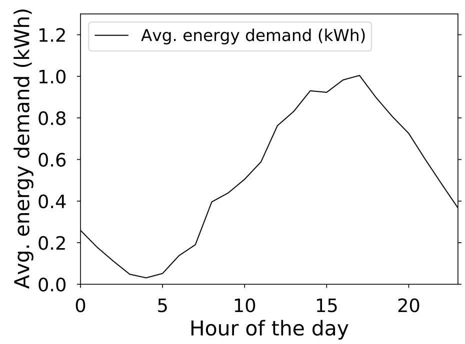
As shown, the number of panels needed varies from 1 to 6 for off-grid operation, with 2.7 being the mean. This implies that each station may need 2× more solar capacity, on average, than a net-metered case, and up to 6× in the worst case. A setup of 2 to 6 panels per station is still a feasible design, but a higher cost investment than net-metering.

Figure 14a depicts the battery capacity needed for the design. The mean is 1.8kWh (1.5 LiFePO4 batteries), and a maximum of 5kWh (4.2 batteries). Figure 14b depicts the tradeoff between the number of panels installed at a station and the required battery size. With a small number of panels, the frequency of instances during which demand exceeds supply increases, and consequently, more energy storage is required to offset the difference. For the sample station shown, a balance in the tradeoff is struck at 4 solar panels along with a battery size of 1.62kWh.

Result: *An off-grid design requires approximately 2 panels per station in the average case, which is 2× higher than a net-metered design. The busiest station requires 6× more panels. The battery*



(a) Total energy consumption across the whole system.



(b) Demand by time of day

Figure 8: (8a) Total energy consumption during the whole duration, and (8b) average energy demand by time of day.

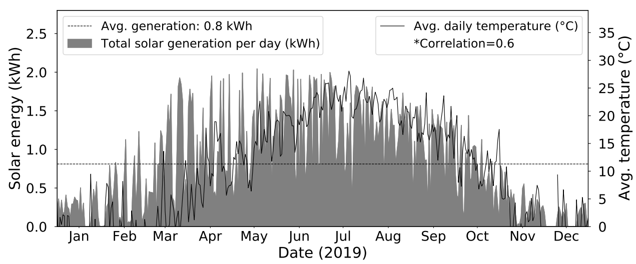


Figure 9: Daily solar generation per panel across the whole period.

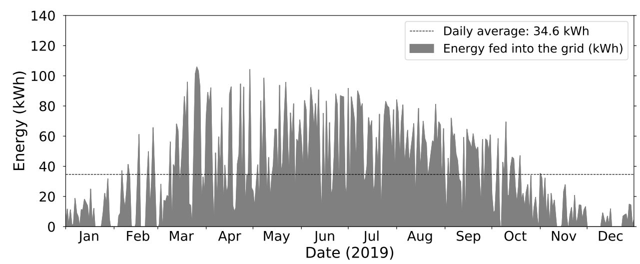


Figure 11: Net energy fed to the grid per day.

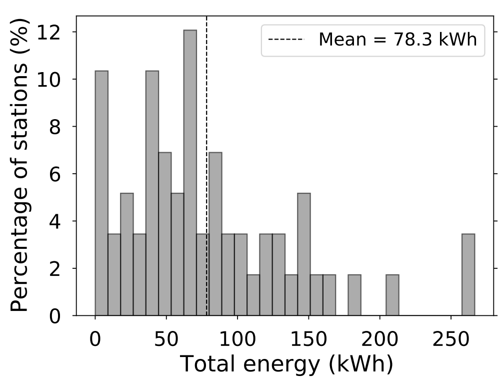


Figure 10: Total energy demand per station for the whole year.

capacity needed varies from 1 to 5 batteries per station of 1.8kWh capacity each.

6 CARBON SAVINGS

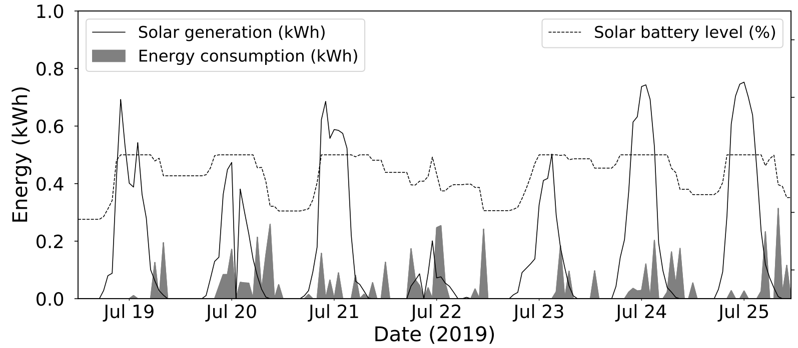
A final goal is to analyze the reduction in carbon emissions brought about by moving from a grid powered electric bike sharing system to a solar powered system. Our methodology for estimating the amount of CO_2 emission per e-bike trip is as follows. First, we use the method described in Section 4.3 to compute the energy consumed by each trip. We then convert the electric energy consumed into the equivalent CO_2 emission using the following equation.

$$CO_2 \text{ em. per trip} = \frac{CO_2 \text{ em. per kWh} \times \text{trip length (km)}}{\text{km per kWh}} \quad (1)$$

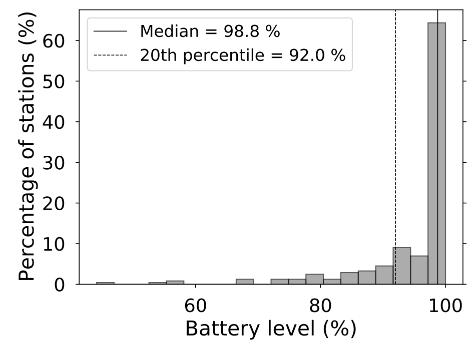
To perform the conversion, we use the CO_2 emission factor of electricity specified in the Greenhouse Gas Equivalencies Calculator of 0.486 MT/MWh [8]. We then analyze the carbon reduction for both grid-connected and off-grid deployment scenarios.

Figure 15 shows the results of our analysis. In the off-grid scenario, since the solar based system is self sufficient i.e. does not draw any power from the grid, carbon reduction comes from the substitution of trip energy demand with renewable solar energy i.e. all trips have zero carbon emissions because they are solar powered. Our calculation shows that 0.2MT and 1.1MT of CO_2 emission in the year of operation is reduced in the off-grid and grid-tied setup respectively.

In the grid-tied setup, reduction in CO_2 emission is made up of two components; (i) reduction from substitution of trip energy demand, and (ii) reduction from renewable energy fed into the grid. As can be seen in Figure 15, CO_2 emission in the grid-tied setup is much higher than the off-grid setup due to the additional benefit of adding renewable energy into the grid. Also, in both cases, we observe higher reduction in CO_2 emission during summer months (Jun-Aug). This is as a result of higher solar generation during summer days.

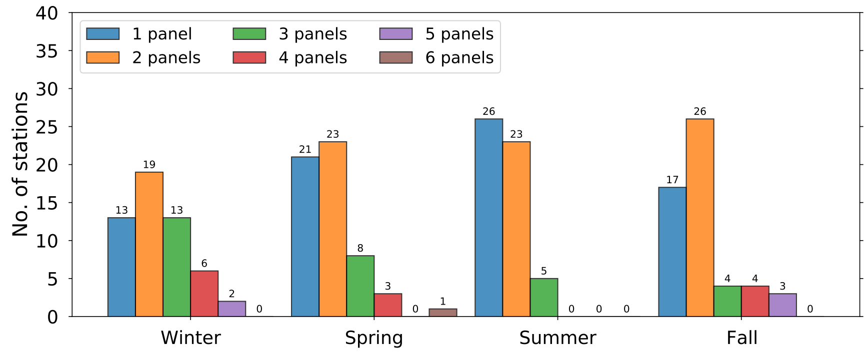


(a) Energy consumption, solar generation and battery status for sample week.

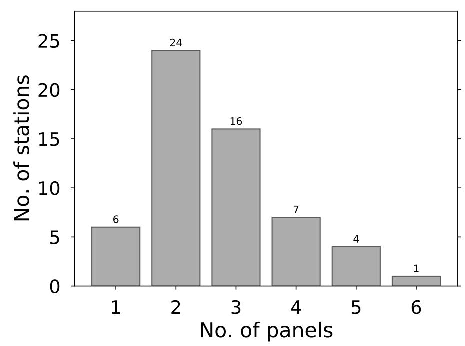


(b) Battery level at start of day (5AM).

Figure 12: (12a) Energy consumption, solar generation and battery level for sample station during a week, and (12b) solar battery level at start of day before solar generation.

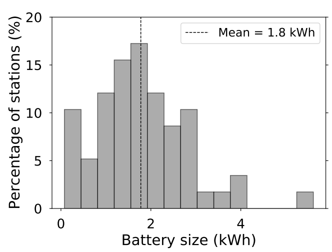


(a) Number of panels required at each station by season.

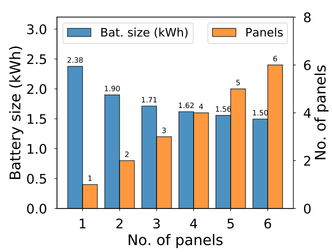


(b) Max no. of panels required at each station.

Figure 13: (13a) Number of panels required at each station by season, and (13b) max number of panels required at each station across all seasons.



(a) Battery size.



(b) Panel-battery tradeoff.

Figure 14: (14a) Battery size by peak energy demand, and (14b) tradeoff between number of panels and required battery size.

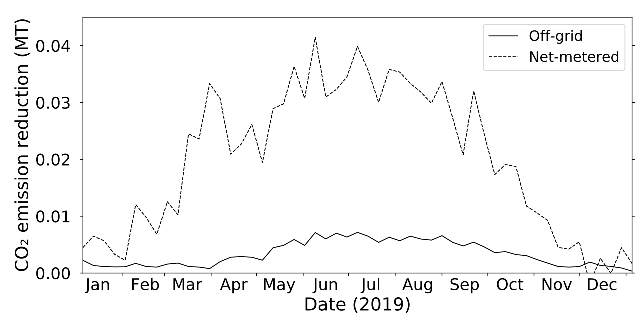


Figure 15: CO_2 emission reduction in grid-connected and off-grid deployment scenarios.

Result: *A solar-powered charging infrastructure can yield a reduction of up to 1.1MT CO_2 emissions annually in our bike share system.*

7 RELATED WORK

In this section, we discuss related work in designing solar powered e-bike charging stations, capacity sizing and carbon reduction brought about by substituting grid energy with solar energy. Previous studies indicate that e-bikes are increasingly becoming popular [6] and bike share systems have begun to adopt them. Other studies have shown that e-bikes are often used for long distance commutes [16, 26, 27].

Prior efforts have built prototype solar e-bike charging stations but have not studied scaling them to a city-wide bike share system like our work. Mouli et al [24] present the design of a solar powered charging system that provides AC, DC and contactless charging while avoiding the conversion between DC to AC and back. Demeter et al [17] present a modular approach to solar powered bike charging in public spaces. Zhang et al [30] subject solar powered e-bike charging stations to experimental power quality tests. Other works have studied the placement of such solar charging stations with the aim of maximizing the amount of solar energy harvested and integrating seamlessly with user behavior. However, our work is complementary as we consider the problem of scaling such designs to entire bike sharing systems by analyzing ridership demand. Further, our work provides key considerations such as the tradeoff between solar arrays and battery sizing, which may significantly influence the cost of such scaling.

Others have studied the use of solar power for charging electric vehicles beyond bikes. Siddique et al [29] detail the implementation of solar powered stations in a system of small electric three-wheeler EVs. Mouli et al [25] explore the feasibility of solar charging infrastructure installed at the workplace, where users are most likely to be during day time hours. Lee et al [23] present an analysis of the feasibility and benefits of using solar in EV charging stations. Ali et al [13] explore the potential of solar and wind energy to substitute grid energy in EV transportation. Other studies have experimented with solar powered stations equipped with storage for EVs [15, 28]. In other work, Ji et al [22] explore the problem of localization and sizing of solar powered EV charging stations. However, our work differs from this prior work by providing insights into panel and battery sizing driven by usage characteristics and ridership demand, both for grid-tied and off-grid designs.

8 CONCLUSIONS

In this paper, we presented the design of a solar powered bike charging prototype. By combining measurements taken from the prototype with real world ridership data, we showed how the design can be scaled to an entire bike sharing program. We performed data-driven analysis to show feasibility of the design in net-zero and fully-zero carbon electric bike share systems. Our results indicated that a single solar panel installed at each station in the bike share system is sufficient to meet the annual demand of energy by the station, and that net-zero operation can be achieved using net-metering. We also showed that for an off-grid setup, a station needs twice the number of solar panels on average, along with a 1.8KWh battery, with the busiest bike station needing 6× more solar capacity than in the net-metering setup. Further, we showed that to achieve true-zero operation, a tradeoff between the size of solar array and battery size exists, with the number of solar panels ranging from 1 to 6, and battery size varying between 2.4kWh and 1.5kWh for a sample station. Finally, we showed that up to 1.1MT of CO_2 emission can be reduced annually by substituting grid energy with solar in a bike sharing system.

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