Photovoltaic-battery powered bike share stations are not necessarily energy self-sufficient

Yue Li[1,2], Hao Luo[1], Hua Cai[1,3*]

1. Environmental and Ecological Engineering, Purdue University, West Lafayette, IN, USA

2. Libraries and School of Information Studies, Purdue University, West Lafayette, IN, USA

3. Industrial Engineering, Purdue University, West Lafayette, IN, USA

* Corresponding author: Email: huacai@purdue.edu; Address: 315 N. Grant Street, West Lafayette, IN, 47906, USA

This is the author-accepted manuscript version of an article published in *Applied Energy*. The final published version is available online at: https://doi.org/10.1016/j.apenergy.2023.121505.

Abstract

Many cities use solar photovoltaic (PV) panels to power off-grid bike share stations to provide sustainable transportation. When a station's energy demand for operating the station's kiosk and docks exceeds the PV panel's supply, the battery can be depleted, requiring manual battery replacement to avoid service disruption. However, existing research on siting, modeling, or assessing the environmental impacts of bike share stations has not accounted for spatially variable solar PV potential and energy usage. This study addresses this gap to analyze the performances of PV-battery systems for bike share stations and evaluates strategies to improve their energy independence, sustainability, and system reliability. Using Chicago's Divvy bike share system as a case study, we simulated the battery charging, discharging, and replacements, and measured their performances with three metrics: energy self-sufficiency level, energy payback time (EPBT), and station downtime. We found that PV energy alone is insufficient to meet all energy needs of bike share stations, with the average energy self-sufficiency levels being 56%. Additionally, relying solely on battery replacement during rebalancing operations was insufficient to maintain stations' operational status. On average, bike share operators need to manually replace a station's batteries 72 times a year. Furthermore, the current PV panels for most stations are sized too small. Increasing panel sizes could reduce most stations' downtime and increase their self-sufficiency without significantly affecting EPBT. The study highlights the need for bike share system modeling and operation planning to account for battery replacement needs and demonstrates the importance to evaluate smaller yet large-scale street-level PV applications. The modeling framework presented in this study can also be extended to examine other smaller PV-battery systems similar to bike stations.

Keywords: Bike share, PV panel, Battery replacement, Downtime, Self-sufficiency, Energy Payback Time

1. Introduction

To reduce transportation energy consumption, many cities are launching bike share systems, which enable customers to use bikes for a brief period (normally less than a day) [1]. The transportation sector contributes to the second largest share of overall U.S. energy consumption, accounting for 28% (27.25 quadrillion Btu) of total energy usage [2]. Bike share has the potential to reduce transportation energy and emissions as an alternative mode to replace short car trips [3,4].

To make bike share systems more sustainable and easier to deploy, solar photovoltaic (PV) panels are installed on many bike share stations to power the station kiosk and bike docking systems (Figure 1). These modular stations are popular in North American cities because they do not require connection to the electrical grid, which enables more rapid and cost-effective installation and the flexibility to adjust station size and locations after deployment [5]. Due to the intermittent nature of solar energy generation and seasonal variations [6], these off-grid stations are also equipped with batteries to store excess energy and to power the stations as needed.

Figure 1. Divvy Bike Station in Chicago equipped with solar PV panels. Left: the Streeter Dr & Grand Ave station; right: the Fairbanks Ct & Grand Ave station. Photographed by the authors (Y.L.) in August 2021.

When insufficient solar energy is generated and stored to meet a station's demand (e.g., on extended cloudy days with little sunlight or when sunlight is blocked by nearby obstacles), these off-grid PV-battery bike stations could experience system downtime (i.e. the system is forced to shut down due to power loss), requiring bike share system operators to replace the batteries with fully charged ones to regain usability. For example, many CitiBike's solar-powered stations in New York City were reported to be inoperable on rainy or cloudy days, or when the stations were located under tall buildings, preventing consumers from renting or returning bikes [7]. In September 2017, it was reported that half of Boulder, Colorado's solar-powered bike stations were out of service owing to an unusual period of cloudy and cold weather and operational difficulties in charging and swapping the batteries in time [8].

Whether a bike share station can be reliably powered by solar energy depends on both the energy supply and demand. In terms of energy supply, the solar PV electricity generation at the station relies on the amount of solar radiation received and the characteristics of the PV panels. Geographic location, time of day, season, and local weather are key factors that affect solar radiation [9]. Moreover, many features of the environment that prevent solar radiation from reaching the panel surface, such as tall buildings that cast shadows on the surroundings, will decrease solar energy potential [10]. The characteristics of PV panels, such as the size and material, also influence PV electricity generation. In terms of energy demand, higher station use and parking more bikes at the station would require more energy. Bike share station use varies with the weather, population density, employment, proximity to transit, and whether or not the station is located in a Central Business District (CBD) [11,12]. Therefore, a station's location influences both its energy supply and demand.

To improve the reliability and sustainability of bike share systems, it is important to evaluate the energy generation and use of bike share systems at the station level to identify station-specific improvement strategies. Bike share systems tend to be placed in the downtown region of a city, where the shadow of surrounding buildings can significantly impact solar energy generation. However, prior research on bike share station siting and modeling has not taken into account the variable solar PV potential at different locations. Researchers have proposed various modeling and frameworks to integrate factors such as potential demand and coverage of stations [13], budgetary constraints [14], social equity [15], transport network, and users' urban life [16] into siting the stations. But none of them considered the impact of solar PV potential on the station performance, which is location-dependent (Table S1). Neglecting the station-specific energy supply and demand dynamics may lead to an overestimation of the demands that a station can serve (e.g., due to system downtime) or an underestimation of operation cost (e.g., for the additional trips required to replace depleted batteries).

Additionally, a better understanding of the energy use of bike share stations can help improve assessments of their environmental impacts. Existing research on the energy use and greenhouse gas emissions of bike share systems has mainly focused on the reduction from replacing short car trips, public transit trips, walking, and bicycling [4,17–20], with few considering the impacts from bike rebalancing [21]. These studies estimated the amount of energy and emissions saved from the trips [4,17–20] (Table S1), but did not consider the advantages of powering the stations with solar energy, and thus might underestimate the environmental benefits of bike share systems. On the other hand, prior life cycle assessment (LCA) studies of bike share systems have either assumed all stations being solely powered by PV electricity [22] or excluded the impact of station energy consumption [23,24] (Table S1). Luo et al. assumed that the PV panels could provide sufficient energy for the stations when estimating the environmental impacts of station-based and dockless bike share systems with LCA [22]. However, when the PV-battery system is unable to provide sufficient energy, the system will require supplemental grid power (through replaced batteries charged with grid electricity) and extra trips to conduct battery replacement. Sun and Ertz did not include station energy consumption in the use phase of LCA for bike share systems and only considered the energy used for charging electric bikes and scooters [24]. Nevertheless, bike share systems require energy to operate, resulting in greenhouse gas emissions and other environmental impacts. Therefore, these studies would underestimate the environmental impacts of bike share systems. By analyzing the performance of the PV-battery system to quantify its actual electricity generation, we could better understand the energy source used to power the stations, thereby enhancing the assessment of environmental impacts for bike share systems.

Furthermore, the energy performance of off-grid PV applications, such as those installed on bike share stations, needs to be better understood, as their adoption is rapidly increasing [25]. Many off-grid PV applications are installed on the ground or street level, but existing studies have extensively focused on modeling rooftop PV potential at the city [26], regional [27], and country scale [28] (Table S2). With the development of solar radiation models based on Geographic Information Systems (GIS) and the availability of high-resolution Light Detection and Ranging (LiDAR) data, PV potential on the building rooftop has been well estimated with high accuracy in the urban area [28,29]. Researchers have also evaluated the performance of households rooftop PV-battery systems by analyzing and optimizing PV self-sufficiency (the degree of PV generation sufficient to fill energy needs) and self-consumption (the portion of PV generation that is directly consumed) [30–32]. Yet few studies have quantified the PV potentials for street-level off-grid PV deployment or evaluated their performances, except for roads and traffic lights. Liu et al. modeled the solar radiation and electric energy generated by roads and demonstrated that PV road could supplement city power for charging cars [33]. PV panels have also been used to power traffic light-controlled pedestrian crossings, reducing energy consumption for traffic management [34]. Similar methods and frameworks developed to study rooftop PV potential could also be adapted to study PV panels used in bike share systems and other street-level applications to better support decision-making on when and where to use them.

To address the issues and gaps mentioned above, this study developed an integrated model to evaluate the performances of PV-battery systems for bike share stations by estimating their solar PV production and energy consumption. Using Chicago's Divvy bike share system as a case study, we simulated each station's battery charging and discharging activities, and measured their performances with three metrics -- energy self-sufficiency level, energy payback time, and station downtime. To the best of our knowledge, this is the first study to examine the performance of PV-battery systems for bike share stations. In the context of existing literature, the main contributions of this research are that we: 1) developed a modeling framework to simulate PV battery charging and discharging activities with real-world solar PV energy and station use data; 2) assessed the performance of PV-battery systems for bike share stations from energy self-sufficiency, energy payback time, and station downtime, and 3) proposed potential strategies for improving the performances through more properly sizing the PV-battery system. The findings and insights generated from this work will not only help improve the efficiency and sustainability of bike share systems but also provide an important perspective and useful tools to guide the use of solar PV energy for charging shared electric bikes and electric scooters, which are being increasingly adopted by shared mobility systems and are expected to have higher energy demands than traditional shared bikes [6,35].

2. Data and Method

We selected Chicago's Divvy bike share system as a case study for its wide variety of station locations, capacities, demands, and solar radiation. Launched in 2013, the Divvy bike share system is one of the biggest in the U.S. in terms of the number of stations, bicycles, users, and transactions [36]. Divvy operated over 5,800 bicycles at 608 stations as of July 2019, serving over 1,773,622 trips in 2019 [37]. Bike stations are located throughout Chicago, with the majority concentrated in the CBD (Figure 2). Stations located within the CBD generally have a greater capacity, with the majority having over 20 docks per station. Stations outside the CBD tend to be smaller, with stations in the suburbs only containing 7 to 11 docks. Regardless of the station capacity and location, all stations are off-grid and equipped with identical PV panels and batteries. In this study, we focus on regular pedal bikes that do not have batteries. From the perspective of solar energy, Chicago has an average annual solar radiation of around 4.55 kWh/m^2/day with significant seasonal variations [38]. Additionally, Chicago is well-known for its architecture, with a skyline dominated by skyscrapers, indicating the possible impacts of buildings blocking solar radiation and casting shadows on the PV panels. Due to the large scale of the bike share system and seasonal variation of solar radiation, Chicago is an ideal case for evaluating the performance of solar-powered bike stations in different settings such as downtown versus suburb, with or without the impact of shadows, and at different times of the year with different solar radiation levels. The diverse conditions could also help us better evaluate potential strategies to enhance the systems' sustainability.

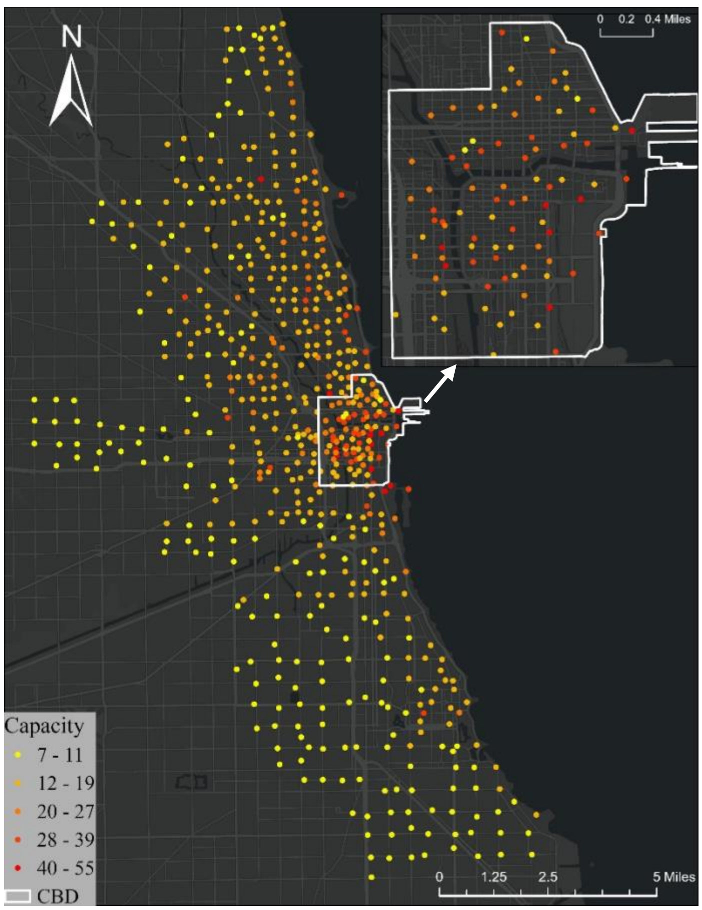


Figure 2. Map of Divvy stations in Chicago with color representing capacity (the total number of docks at each station). The insert zoomed in on the Central Business District (CBD) of Chicago (1 mile = 1.6 kilometers).

The proposed modeling framework includes four key components (Figure 3). First, we quantified the hourly PV electricity production based on each station's solar radiation (Section 2.1.1) and estimated the energy demand required by each station based on its use and bike docking status (Section 2.1.2). Second, using this energy supply and demand information, we simulated energy flow between PV panels, bike docks/kiosks, and batteries (i.e. battery charging and discharging), and analyzed the need to replace depleted batteries (Section 2.1.3). We considered two scenarios for battery replacement: 1) an extreme "zero downtime" scenario, in which a battery would be replaced by a fully-charged one as soon as it reached a low charge level, and 2) a more realistic "no extra effort" scenario, in which low charge level batteries were only replaced as part of the bike rebalancing operation without making dedicated trips for battery replacement. The results of these two scenarios could provide insights into the system's performance as well as the amount of effort and resources necessary to maintain system reliability. Third, we assessed the performance of the bike share PV-battery system with three metrics: energy self-sufficiency level, energy payback time (EPBT), and station downtime due to insufficient energy (Section 2.2). Energy self-sufficiency level measures how much of the station's energy demand is met by solar energy; EPBT evaluates how long it takes for the station to recover its energy investment; and station downtime quantifies the impact of insufficient energy on system operation. Finally, we proposed four strategies based on the "no extra effort" scenario and evaluated their performances to provide insights on improving the system performance (Section 2.3).

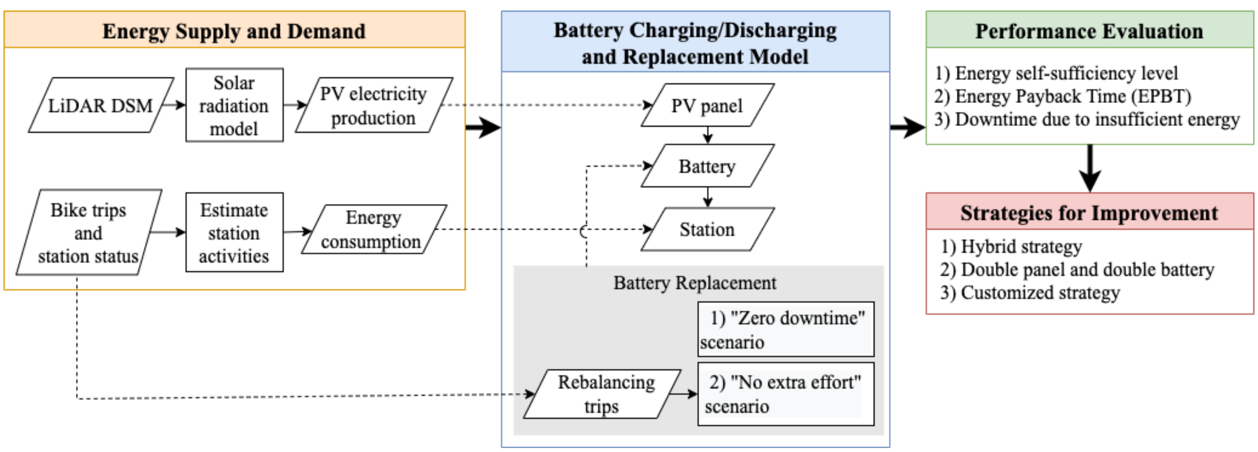


Figure 3. Overview of the modeling framework

2.1 PV-battery system modeling for bike share stations

2.1.1 Estimation of PV electricity production

To estimate the energy generated by PV panels, we first computed the solar radiation received at each bike share station using the Digital Surface Model (DSM) derived from LiDAR data and the solar radiation tool in ArcGIS Pro [39], and then estimated the amount of electricity generated using the PV panel characteristics.

DSM depicts the surface with topographic details including all above-ground features, such as buildings and plant canopies, that surround each bike share station [28]. By inputting this information into a solar model, solar irradiance (Wh/m^2) received at a given surface during a certain period can be estimated [10]. The LiDAR data (collected at a derived nominal pulse spacing of one point every 0.35 meters) and the derived DSM were provided by Illinois Geospatial Data Clearinghouse [40]. We resampled the DSM to a 1x1 m^2 raster to reduce computation time while maintaining the required precision. DSM's high resolution allows for the accounting of complex urban environments by considering the effects of shadows of neighboring man-made structures and tree canopies.

We used the solar radiation tool in ArcGIS Pro to determine the solar radiation received by PV panels at the bike share stations. This tool accounts for the atmospheric effects, site latitude, elevation, slope and aspect, shifts of the sun angle, and effects of shadows from nearby buildings and topography, and outputs a continuous surface of solar irradiance (Wh/m^2). Solar irradiance at each bike share station was extracted from this output raster. Details of the solar radiation model can be found in [41] and the model parameter setting is discussed in Section S2.1 of the Supplementary Information (SI). Following the approach in [42], we computed solar radiation for the 15th day of each month when the sun is in the average position of each month as representative solar radiation of that month at an hourly interval. The solar radiation tool was implemented with a Python package, arcpy, and a multiprocessing Python module to take advantage of 10 CPU cores and available system memory of 64 GB to reduce computation time.

The conversion of solar radiation to electricity depends on technical components and characteristics of PV panels. Each Divvy bike station is equipped with polycrystalline silicon PV panels with a total power of 114 W (data collected by authors from field investigation). The PV electricity generation is determined by three key factors, solar irradiance, PV panel efficiency, and performance ratio. The electricity generated at station i in hour j, E_i (in kWh), is computed with Equation (1):

$$E_{ij} = I_{ij} r \mu a \quad (1)$$

Where,

I_{ij} is the solar irradiation received by the PV panels at station i in hour j (kWh/m^2);

r is the solar panel efficiency (%), which is the percentage of solar energy converted to electricity. It is set at 15% based on the typical range (14-17%) for a polycrystalline silicon module [43];

μ is the performance ratio of the solar panel, which is the percentage of actual energy output over the theoretical output and is set at 86% [43];

a is the area of PV panels, which is 0.84 m^2 (data collected by authors from field investigation).

2.1.2 Estimation of bike share station energy demand

The power consumption of a bike station stems from the kiosk and bike docks. To estimate the kiosk's usage and associated energy consumption, we used Divvy trip data, which contains each trip's start and end time, start and end stations, as well as the rider type (subscriber or customer) (Table S4). We assume that non-subscriber users (i.e. those with the "customer" rider type) who have not purchased annual membership would need to use the kiosk to buy passes, which would consume station energy. However, the "subscribers" would use the Divvy key or smartphone app to unlock bikes which does not consume kiosk energy.

When bikes are docked, electromagnets at the docks are activated to lock the bikes [44]. Therefore, the power consumption of docks depends on the number of bikes docked in the station. Additionally, different amounts of energy are needed when the kiosk is idle or activated. To estimate the use and activities at the docks and kiosks, we used the Divvy station status and trip records [45–47] (Table S4 and S5) from 2019 to better reflect the normal operation before the COVID-19 pandemic. The station status data includes information about the availability of bikes and docks at each station at an hourly interval (Table S5). The number of docked bikes was used to estimate the energy consumption of docks. Due to a system upgrade that interrupted the real-time data feed [48], some data in 2019, including most days from July to September, were missing and we used corresponding records in 2018 to represent these days. As we were not able to find specifications for the docks for Divvy stations, we conducted an extensive literature and patents search and set the energy consumption as below in equation (2).

The total energy consumption of bike station *i* in hour *j*, D_{ij} (unit: Wh), is calculated using equation (2):

$$D_{ij} = E_m + MIN\left(0.067U_{ij}, 1\right)E_k + B_{ij}E_d \tag{2}$$

Where,

E_m is the hourly energy consumption of the main controller in the station, which is estimated as 10 Wh [49].

U_{ij} is the number of non-subscriber users at station i in hour j. To find out the average use time of the kiosk, we tested on the Divvy kiosk at several stations and found that the average time to purchase a pass from the kiosk is 4 minutes (0.067 hours). If the total time of uses exceeds one hour, we assume the kiosk is active for the full hour.

E_k is the hourly energy consumption of the kiosk when active, which is estimated as 30 Wh [50]. When it is idle, the energy consumption (less than 2 W) is negligible [51].

B_{ij} is the number of bikes docked at station i in hour j.

E_d is the hourly energy consumption of locking one bike, which is estimated at 1 Wh [49].

Based on equation (2), the average daily energy consumption of a station is 414 Wh/day, which matches the value (450 Wh/day) provided by the Boulder B-cycle bike share operator through email communications.

2.1.3 Battery Charging/Discharging and Replacement Model

We simulated the operation of the off-grid PV-battery system with Python using the estimated PV electricity generation from Section 2.1.1 and the demand profiles from Section 2.1.2 as inputs, using a battery charging/discharging and replacement model. The PV-battery system powers the kiosk and docks while storing excess electricity in the battery (Figure S1). Each station is equipped with a 1200 Wh battery [52]. The battery charging and discharging model was based on the PV and battery dispatch model in [53] but removed the grid connection. When the PV power is higher than the load (energy demand), the battery is charged until full; when it is lower than the load, the battery is discharged until a cut-off point of 20% [54]. When the battery state-of-charge (SOC) is below 20%, the station shuts down due to insufficient energy supply.

In addition to using PV generated electricity as power source, bike share operators may replace low-charge batteries with fully charged ones to maintain station operation. These batteries are normally charged at the depot using grid electricity (stations cannot charge spare batteries). We evaluated two scenarios to model the battery replacement activities: 1) "zero downtime" scenario and 2) "no extra effort" scenario (Figure 4). In the "zero downtime" scenario, a battery would be replaced with a fully charged one as soon as it reached the 20% SOC threshold (Figure 4). Thus, no station would shut down due to insufficient energy. This is an ideal scenario to identify the battery replacement needs to keep the stations fully operational. In the real world, it is unlikely that the system operators would visit stations only for battery replacement and replace them at the exact moment of reaching 20% SOC. Routine bike rebalancing provides convenient opportunities for staffs to also replace low-charge batteries while rebalancing the bikes. Therefore, we assessed the "no extra effort" scenario to examine whether relying on rebalancing trips to replace batteries was sufficient to meet station energy needs. In this scenario, batteries with low SOC (SOC < 40%) would be replaced when bike operators visit the stations for bike rebalancing. We assumed that the operators would not visit a station only for battery replacement. As a result, stations that have depleted their batteries (SOC < 20%) would shut down due to insufficient energy and remain so until the SOC increased to at least 20% with PV electricity or a fully charged battery was installed during the next rebalancing visit (Figure 4).

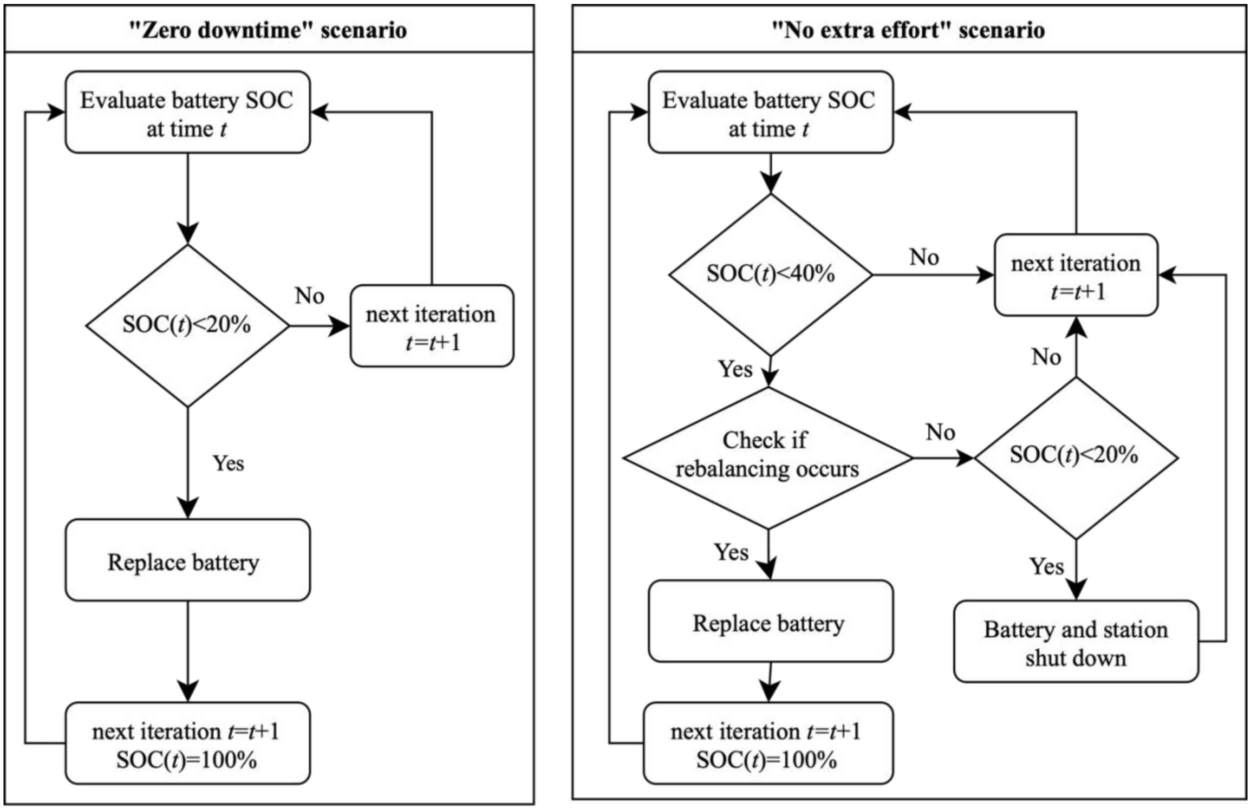


Figure 4. Process flow diagram of the "Zero downtime" (left) and "no extra effort" scenarios (right)

To model battery replacements for the "no extra effort" scenario, we first used the rebalancing activity identification model proposed in [55] to identify the station-level rebalancing visits. Rebalancing activities were determined from the discrepancies between bike trips and station status data. When the net bike flow from trips that started and ended at a station was different from the change in the number of bikes docked at this station, a rebalancing activity would have occurred at the station during this time [55]. Using this rebalancing identification model, we calculated the number of rebalancing activities for each station (Figure S2). By examining the battery SOCs of the stations at the time of the estimated rebalancing visits, we could estimate the number of batteries being replaced during rebalancing.

2.2 Performance metrics

Using the PV electricity generation, station energy demand profiles, and battery replacement activities in different scenarios, we simulated the hourly operation of the PV battery system for

2019 and evaluated the performances through several metrics from different perspectives. First, the energy self-sufficiency level (Section 2.2.1) was computed to measure the stations' independence from grid electricity using PV panels. Second, energy payback time (EPBT, Section 2.2.2) was calculated to measure when each system can provide a net energy return using the LCA framework. Finally, to quantify the impact of insufficient energy supply on the system operations, we calculated station downtime (Section 2.2.3).

2.2.1 Energy Self-Sufficiency Level

The energy self-sufficiency level quantifies the degree to which the PV electricity generation can satisfy the energy needs of the stations. Because the stations use energy from both PV panels and replaced batteries charged by grid electricity, this metric shows a station's independence from grid electricity. The self-sufficiency level is typically defined as the ratio of the locally consumed PV power to the load for grid-connected residential systems [30], in which the grid is used as the backup power source when needed. This definition needs to be modified for the PV-battery system for bike share stations to account for the impact of station downtime due to insufficient energy. Therefore, we define the self-sufficiency level of station *i* as the ratio of the station's annual PV energy consumed to annual energy demand (as reflected from the historical station use data), as presented in equation (3). The standard integration time to calculate the self-sufficiency level is one year, which is long enough to account for seasonal changes and limit the impact of random fluctuations in short-term energy generation and demand [47].

$$Self-sufficiency\ (i) = \frac{\sum_{j=1}^{T} M_{ij}}{\sum_{j=1}^{T} D_{ij}} \tag{3}$$

Where,

M_{ij} is the PV energy consumption of bike station *i* in hour *j* (Wh). The energy wasted is not included in M_{ij}, such as those wasted as heat while charging and discharging or the produced solar electricity that could not be used because the battery is full.

T is the total number of hours in a year.

D_{ij} is the total energy demand of bike station *i* in hour *j* (Wh).

2.2.2 Energy Payback Time

LCA quantifies the potential environmental and energy impacts of a system, service, or product through its entire life cycle, including extraction of raw materials, manufacturing, transport, distribution, operation, maintenance, reuse, and recycling [56]. In the context of LCA, we computed the Energy Payback Time (EPBT), which measures the number of years for the PV panels to generate equivalent amount of electricity to the primary energy being invested. The life-cycle cumulative energy demand (CED) is the total primary energy harvested from the geo-biosphere to provide the direct energy and material inputs for all life-cycle stages [57]. EPBT for PV-battery systems of bike share stations can be calculated from CED using equation (4) [57]. Similar to previous LCA research on PV systems [62], this study excluded maintenance during the utilization phase;

$$EPBT = \frac{CED_p \times a + CED_b \times n}{\left(\frac{M}{\eta_G}\right)} \tag{4}$$

Where,

CED_p is CED for muti-crystalline silicon PV panels (MJ/m^2) and is set at 3258 MJ/m^2 [58,59].

a is the area of PV panels.

CED_b is CED for the battery (MJ/battery) and is set at 1360 MJ/battery [60].

n is the number of batteries needed for the lifetime of the station. As the lifespan of lead acid batteries is around 3 to 5 years, we assume two batteries are needed (n = 2) for the 10-year station lifetime [61]. A sensitivity analysis was conducted in Section S3.7 in SI to evaluate the impact of needing more batteries.

M is the systems' annual electricity consumption (kWh) previously calculated in Section 2.1.3, which excludes the wasted solar electricity that is not used to power the station from the produced amount;

η_G is grid efficiency -- the electricity to primary energy conversion efficiency at the demand side [56], which was set at 30% for a common grid mix predominantly reliant on thermal technologies [58].

In addition to EPBT, to evaluate the energy payback status as of 2019, we calculated the number of years with energy gain for each station based on their launch time. The launch time of the stations was determined from historical station status data from 2013 to 2019.

2.2.3 Station Downtime due to Insufficient Energy

Station downtime due to insufficient energy (hereinafter referred to as "downtime") is defined as the percentage of a year that the station is shut down because of low battery SOC (equation (5)). As mentioned in Section 2.1.3, in the "no extra effort" scenario, if a battery's SOC drops below the cutoff point of 20%, the battery is considered depleted and the station would shut down, leading to business loss (i.e. users would be unable to check out or return bikes at the station). A higher station downtime indicates a less reliable system with a higher probability of business loss.

$$Station\ downtime\ (i) = \frac{H_i}{T} \quad (5)$$

Where,

H_i is the total number of hours when the SOC for station *i* was lower than the cutoff.

T is the total number of hours in a year.

2.3 Improvement Strategies

To improve the reliability and sustainability of bike share stations with PV-battery systems, we evaluated four improvement strategies (Table 1). These strategies were based on the "no extra effort" scenario because it could serve as a realistic baseline to study how to enhance system performances and what additional costs and efforts are required. We ran yearlong simulations with Python of each strategy, assuming that there would be no operational or use changes from the current system, and evaluated their performances.

Table 1. Summary of the four improvement strategies

Strategy	PV panel size	Battery capacity	Battery replacement
Hybrid	No change	No change	Rebalancing trips + additional battery replacements needed to achieve zero downtime

Double panel	Doubled	No change	Rebalancing trips
Double battery	No change	Doubled	Rebalancing trips
Customized	1) None if EPBT > 10 2) No change if EPBT > 10 with double panel 3) No change if no significant improvement in double panel or double battery 4) Doubled if having better performance with double panel	1) No change if EPBT > 10 with double battery 2) No change if no significant improvement in double panel or double battery 2) Doubled if having better performance with double battery	Rebalancing trips

The first strategy added dedicated trips to replace batteries of low SOC (SOC < 20%) with fully charged ones if there were no rebalancing visits at the stations to avoid downtime (Figure S3). This was a hybrid of “no extra effort” and “zero downtime” scenarios. It can reveal the number of extra battery replacements needed in addition to rebalancing trips.

Another way to improve the system performance is to upgrade the station configuration by increasing the PV panel size or battery capacity to generate or store more solar energy, respectively. To keep the same modularized setting of the stations, we assume that all stations would install the same upgrade. Therefore, the second strategy was to double the PV panel size to increase the PV electricity generation (hereinafter referred to as “double panel”). If the systems are affected by insufficient energy supply, increasing the amount of solar energy fed into the system can increase the system's availability and self-sufficiency. Similarly, the third strategy was to double the energy storage capacity (hereinafter referred to as “double battery”). This could potentially boost the station’s ability to store more power from PV panels and increase the operation time when the stations are powered by batteries.

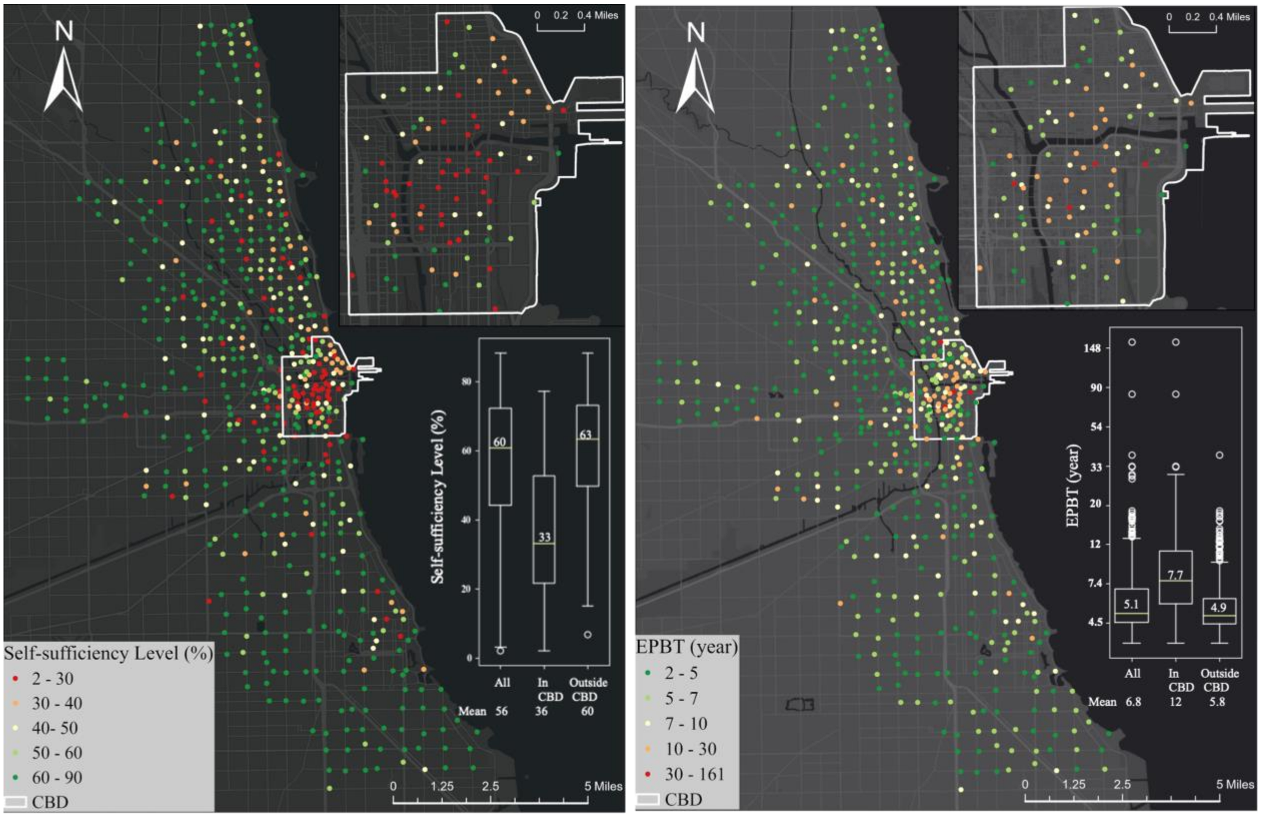
Furthermore, considering that not all stations may benefit from the same setting, we developed a customized strategy to evaluate potential benefit of customized station configurations. For stations that could not pay back their energy investment within the station’s lifetime (EPBT > 10 years) [22], we consider installing PV panels on these stations as unsustainable and would remove them. These stations would solely rely on batteries charged by grid electricity. For stations with a current EPBT under 10 years that would exceed 10 years after doubling the PV panel or battery, we will keep the current setting if both strategies' EPBT exceed 10 years, or select the one with EPBT below 10 years. Additionally, for stations whose performance would improve less than 10% by both double panel and double battery strategies, we would consider the upgrade ineffective and keep the existing configurations. Last, for the remaining stations, we compared the performance of the double panel and double battery strategies and would implement the more effective one.

3. Results and Discussions

This section first reports the performance of PV-battery stations for bike share systems in terms of energy self-sufficiency and EPBT for the "zero downtime" scenario (Section 3.1). It then compares the "no extra effort" scenario to the "zero downtime" scenario, and discusses the station downtime (Section 3.2). Last, using three performance metrics, we compared the effectiveness of four improvement strategies, including hybrid, double panel, double battery, and customized strategy (Section 3.3).

3.1 "Zero Downtime" Scenario

In general, solar PV alone is insufficient to fully meet the station energy demand, but the need for supplementary grid electricity from replaced batteries varies spatially (Figure 5a). From the perspective of the entire system, the energy self-sufficiency level was 54.6%, meaning that the solar panels were able to provide slightly over half of the needed energy for the bike share system. At the station level, the self-sufficiency levels vary significantly, ranging from 2% to 88%, with the average being around 56%. Around 32% of the stations had a self-sufficiency level below 50%, showing that around a third of the stations mostly rely on grid electricity. The energy self-sufficiency level was affected by both PV production and energy demand. On average, the PV battery system produced 106 kWh of solar energy annually, less than the 151 kWh average energy consumption (Figure S4).



(a) Self-sufficiency Level

(b) Energy Payback Time (EPBT)

Figure 5. Map of Divvy stations in the "zero downtime" scenario with color representing (a) energy self-sufficiency level and (b) energy payback time (EPBT). 1 mile = 1.6 kilometers. The boxplots in both figures present the value distributions for all stations, stations in CBD, and stations outside CBD, labeled with median values and having the mean values listed at the bottom.

Generally, the stations in CBD had lower self-sufficiency levels than those outside CBD due to their lower PV production (Figure S4a) and higher energy demand (Figure S4b). The tall buildings surrounding CBD stations created shadows, significantly decreasing the amount of solar radiation received at these stations. For example, stations D and F in Figure 6 received less than 300 kWh/m^2 of solar radiation annually, resulting in their self-sufficiency levels below 20%, while stations located in relatively more open areas, such as C and H, received over 700 kWh/m^2 of solar radiation annually and had self-sufficiency levels over 45%. On the other hand, stations inside CBD had higher energy needs (Figure S4b) due to their greater station capacity (i.e., being able to dock more bikes as shown in Figure 2) and heavier use (i.e., more bike check-out and return). As a result, CBD stations tended to have severe imbalance between PV electricity generation and energy demand (Figure S4), leading to low energy self-sufficiency levels. Conversely, stations outside CBD tended to have higher PV production and lower power consumption (Figure S4), resulting in an overall higher self-sufficiency level and greater independence from grid electricity (Figure 5a).

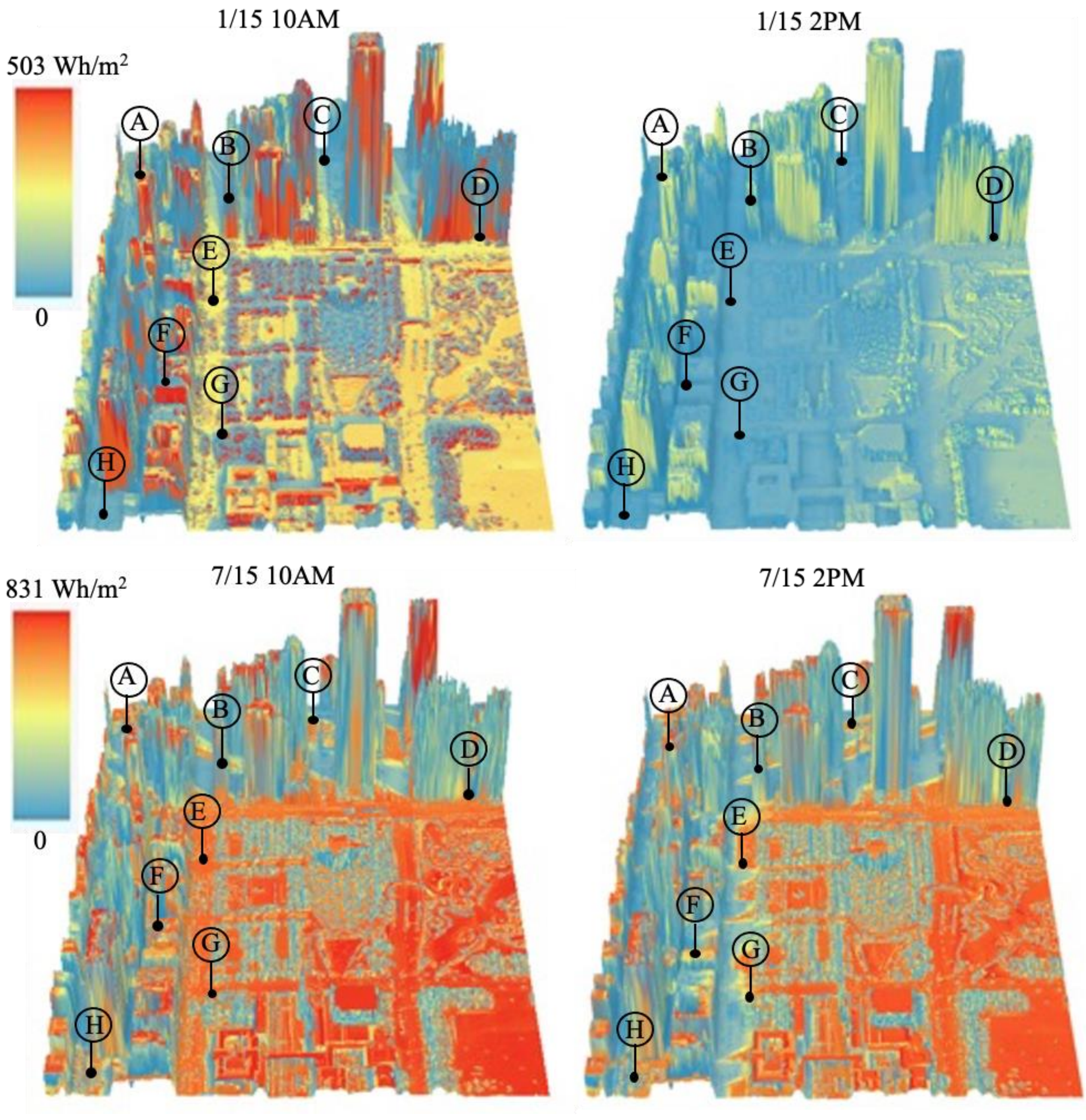


Figure 6. Hourly solar radiation distribution at 10 AM and 2 PM on January 15 and July 15, 2019, for the Chicago Loop area (in CBD). Divvy stations in this area include (A) Wabash Ave & Wacker Pl, (B) Michigan Ave & Lake St, (C) Stetson Ave & South Water St, (D) Columbus Dr & Randolph St, (E) Michigan Ave & Washington St, (F) Michigan Ave & Madison St, (G) Millennium Park, and (H) Wabash Ave & Adams St.

These results show how locations could significantly impact energy independence of a station. When designing and siting a bike share system, it is necessary to take PV generation and energy demand into account to improve system sustainability. Avoiding placing stations in or near the shadows of tall buildings and trees can help improve PV electricity production. For example, moving some stations to the other side of the street could significantly increase solar radiation (Figure S6). Furthermore, while the current system configuration has the same PV panels for all stations regardless of their energy demands, sizing PV panels based on anticipated energy demand and station capacity could be beneficial (more discussions in Section 3.3.3).

Although stations could not fully achieve independence from grid electricity, from the energy perspective, it is still worth installing PV-battery systems on most bike share stations. Most stations (around 75%) had an EPBT below 7 years, indicating that they can produce more energy than the invested energy within 7 years (Figure 5b). As of July 2022, around 75% of stations have paid back their energy investment, and on average, stations have had around 0.8 years of net energy gain (Figure S8). However, in the CBD areas, some PV-battery systems have not paid back their energy investment and will not be able to do so within the 10-year lifetime of the station [22]. One station's EPBT was over 100 years due to extremely low PV production because it is surrounded by very tall buildings and was mainly powered by grid electricity from battery replacements. Stations like this may not need PV panels at all, which can reduce system capital investment. Compared with stations in CBD, stations outside CBD had shorter EPBT due to higher PV electricity generation.

3.2 "No Extra Effort" Scenario

Because replacing the depleted batteries as soon as they are depleted is unrealistic, we evaluated the "no extra effort" scenario in which the batteries were only replaced with rebalancing visits at the stations with no dedicated battery replacement trips. The different battery replacement frequencies and times may change the energy self-sufficiency level and EPBT (Section 3.2.1). When the battery replacement needs were not met, some stations would experience downtime (Section 3.2.2).

3.2.1 Energy Self-sufficiency Level and EPBT

Despite the significantly fewer battery replacements, the self-sufficiency levels of stations in the "no extra effort" scenario were similar to those in the "zero downtime" scenario (Figure 7). This similarity is expected because both scenarios had the same PV electricity generation and energy demand, and the main difference came from the amount of PV energy being consumed by the stations, or in other words, the amount of wasted PV energy. If the "no extra effort" scenario caused more PV energy to be wasted (e.g., the battery is too full to be charged after replacements), it would result in a lower self-sufficiency level (negative difference value) and vice versa.

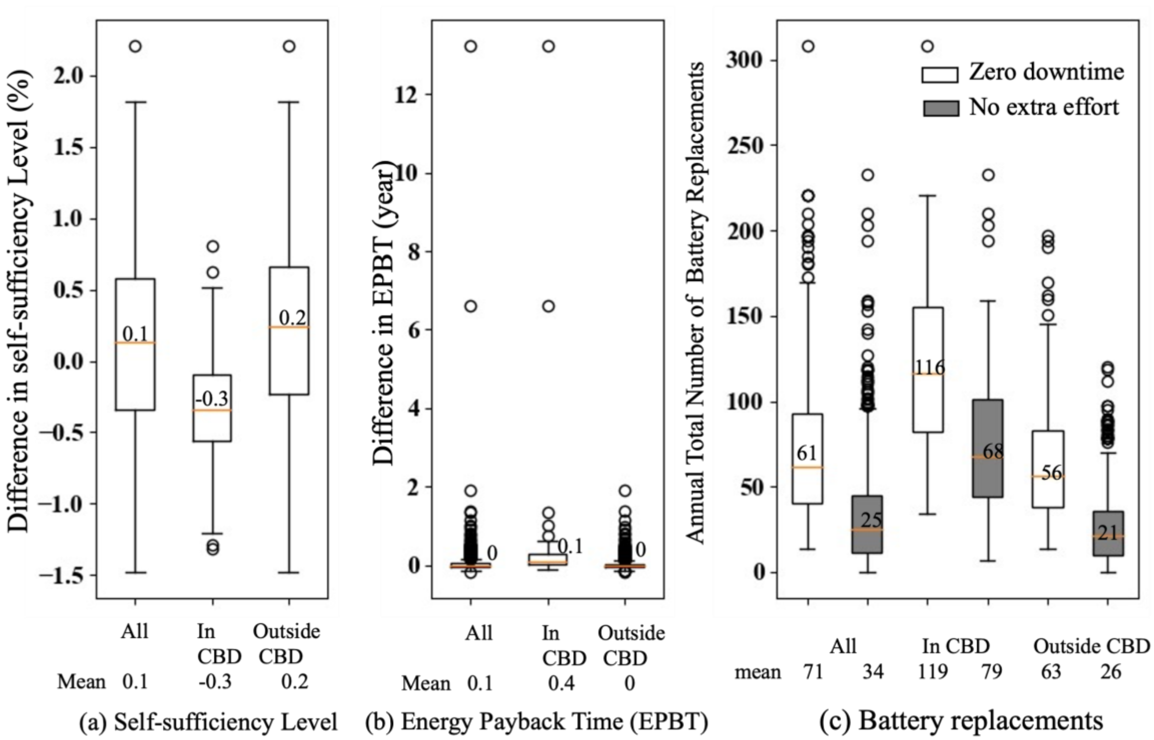
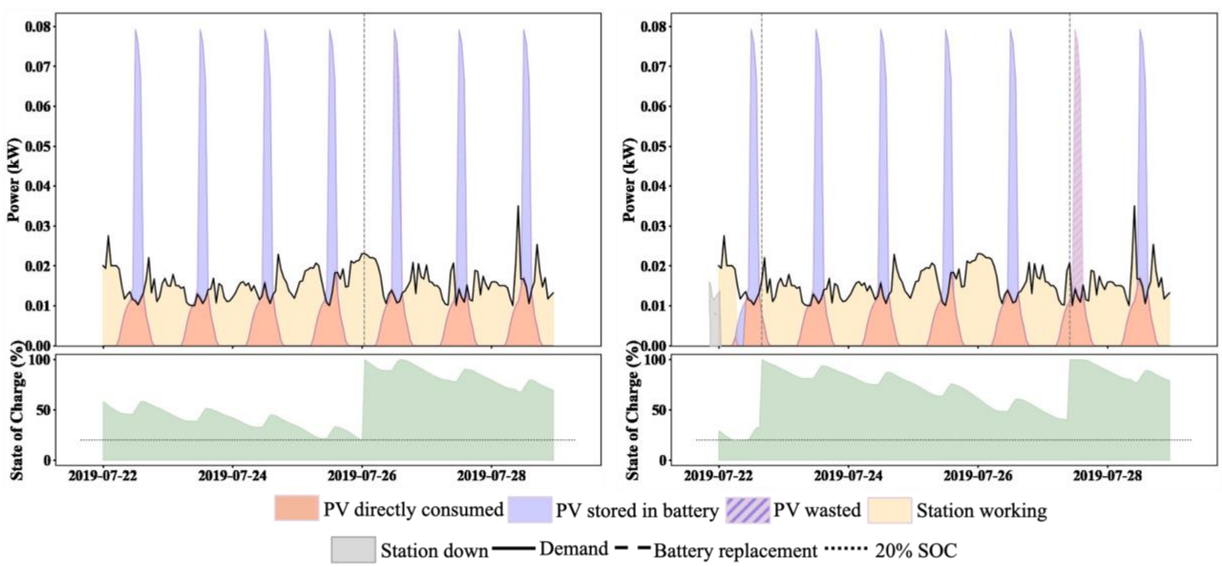


Figure 7. Boxplots of distribution of the difference in (a) self-sufficiency level and (b) Energy Payback Time (EPBT) between "zero downtime" scenario and "no extra effort" scenario for all stations, stations in CBD, and stations outside CBD, labeled with median values. The differences were calculated by subtracting values of "zero downtime" scenario from those of "no extra effort" scenario. (c) Boxplots of total battery replacement in a year for "zero downtime" scenario where new batteries were installed as soon as the charge level reached the cut-off point, and "no extra effort" scenario where batteries with low charge level were replaced during bike rebalancing for all stations, stations in CBD and outside CBD respectively.

Most stations (> 80%) in CBD have lower self-sufficiency levels in the "no extra effort" scenario (negative values of difference). Because stations in CBD tend to have more rebalancing visits (Figure S2) which are normally conducted during the day, the high SOC of the replaced battery resulted in missed opportunities to charge using PV energy. For example, during the week in Figure 8, the "zero downtime" scenario had only one battery replacement, while the "no extra effort" scenario had two. The second battery replacement occurred in the morning and the battery was too full to store the generated PV energy, wasting solar electricity. For this station, because the "no extra effort" scenario replaced most of the batteries during the daytime, while the "zero downtime" scenario replaced them during the night (Figure 9a), this station's self-sufficiency level of the "no extra effort" scenario was 1.31% less than that of the "zero downtime" scenario. Overall, this temporal pattern could also be found in all stations (Figure 9b).



(a) "Zero downtime" scenario (b) "No extra effort" scenario

Figure 8. PV energy consumption, storage and waste and battery State of Charge (SOC) from July 22 to July 29, 2019, for the station at Well St & Polk St in (a) "zero downtime" scenario and (b) "no extra effort" scenario with battery replacements

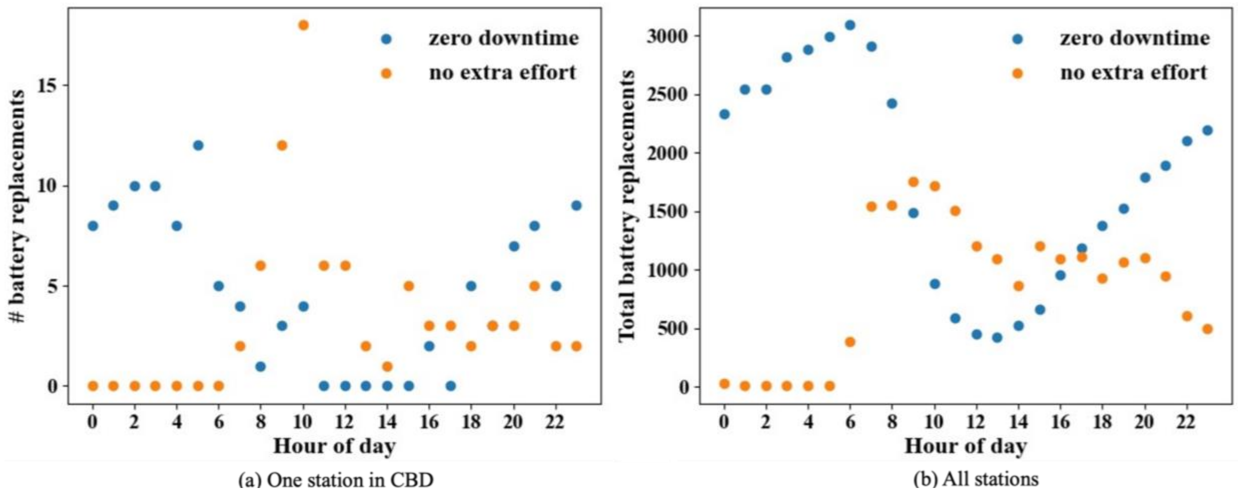


Figure 9. Total battery replacements in a year by the hour of the day with "zero downtime" and "no extra effort" scenarios for (a) one station at CBD (Well St & Polk St) and (b) all stations

On the other hand, some battery replacements in the "zero downtime" scenario could also cause wasted PV energy and resulted in a lower self-sufficiency level compared to "no extra effort" scenario. For example, the station at Washtenaw Ave & Ogden Ave had 38 battery replacements in a year in the "zero downtime" scenario and only 9 in the "no extra effort" scenario. Figure 10 shows one battery replacement in the "zero downtime" scenario led to wasting PV energy, while none was wasted in the "no extra effort" scenario because no battery replacement occurred (but there was station downtime during this period, more discussions in Section 3.2.2). Optimization of battery replacement planning with predicted solar energy production using local weather forecasts could reduce wasted energy, but this is beyond the scope of this study. In total, for the entire system, 9.6% of the PV energy is wasted in the "zero downtime" scenario and 8.7% in the "no extra effort" scenario.

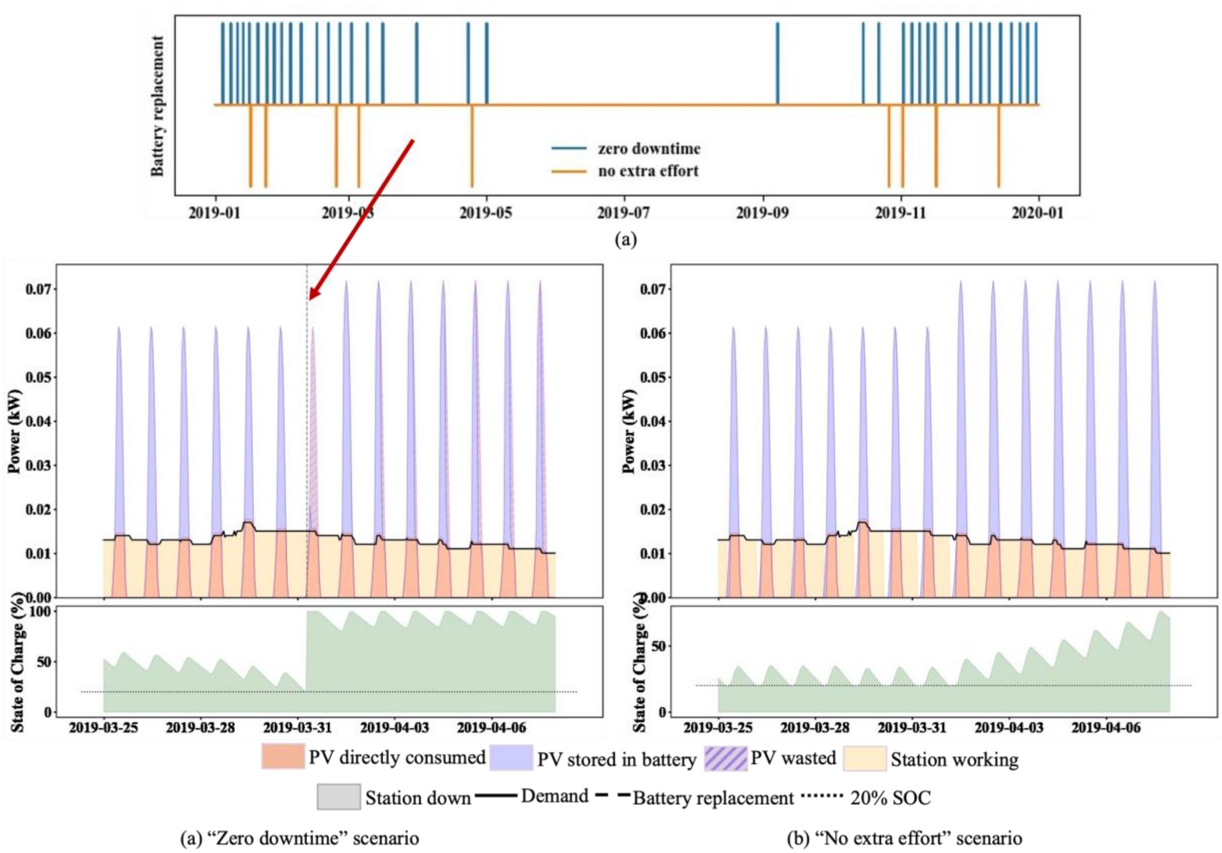


Figure 10. (a) Battery replacements over the year for "zero downtime" and "no extra effort" scenarios for a station outside CBD (Washtenaw Ave & Ogden Ave); PV energy consumption, storage and waste (upper sub-figure) and battery State of Charge (SOC, lower sub-figure) for this station from March 25 to April 8, 2019, in (b) "zero downtime" scenario and (c) "no extra effort" scenario.

Similarly, the EPBT values in both scenarios did not have significant differences (Figure 7c). The outlier stations that had very low PV energy generation and consumption, such as the station at LaSalle St and Adams St as discussed in Section 3.1, would have high absolute difference values (increasing its EPBT from 160 years to 173 years).

3.2.2 Downtime due to Insufficient Energy

When the battery was depleted without rebalancing visits to replace the battery, the system would shut down due to insufficient energy. The station downtime varies spatially, with an average annual station downtime for all stations at 24% (Figure 11a). Most stations with over 60% downtime were outside CBD in the suburbs, where rebalancing vehicles visited less frequently (Figure S2). Although these stations need fewer battery replacements (Figure 7c), the current rebalancing activities were insufficient to meet their battery replacement needs (Figure S9), resulting in more downtime. Although stations in CBD had more battery replacements from frequent rebalancing activities than those outside CBD (Figure 7c, Figure S10), solely relying on rebalancing still could not meet all battery replacement needs. Downtime at these popular stations would cause significant customer loss.

Station downtime exhibits strong seasonality and temporal patterns, with over 40% of stations down on average in winter months (Jan, Feb, Nov, Dec), and fewer than 5% in summer (May, Jun, Jul, Aug) (Figure 11b). Also, no station could remain operational all year round without additional battery replacement beyond rebalancing visits (Figure 11c). Each station had varied operational and downtime at different time of the year, with some stations being down for most of the year (Figure 11c). Due to the seasonality of solar energy, the number of battery replacements in the "zero downtime" scenario had a strong seasonal pattern, while that of the "no extra effort" scenario did not fluctuate from month to month (Figure S11). These results show the need for additional battery replacement trips besides rebalancing, especially during the cold months. During the day, the percentage of stations that were down decreased from 8 AM until 1 PM, and then it started to increase (Figure S12). Generally, more stations were down during the night when fewer people were expected to use the system than during the day when more people used it. This pattern was consistent throughout the year (Figure S12).

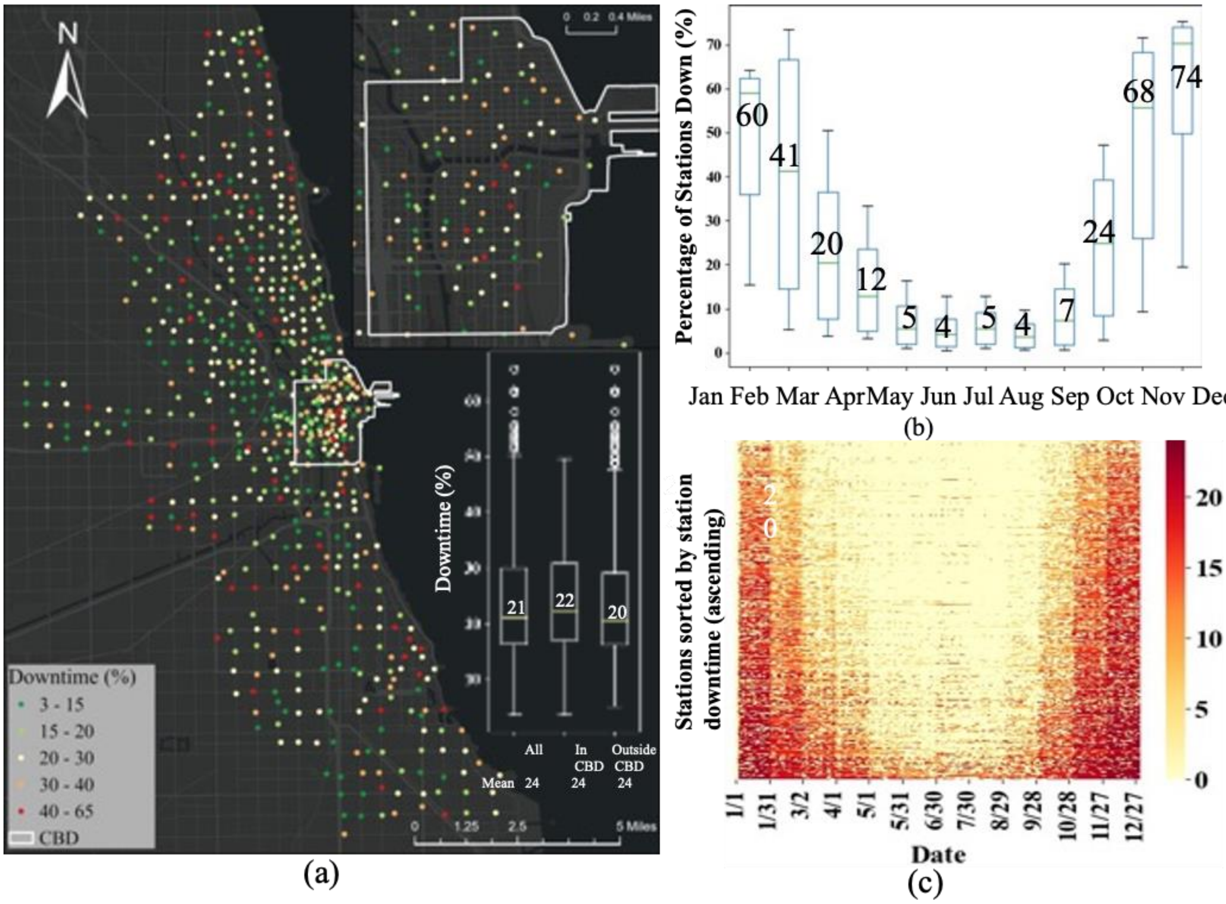
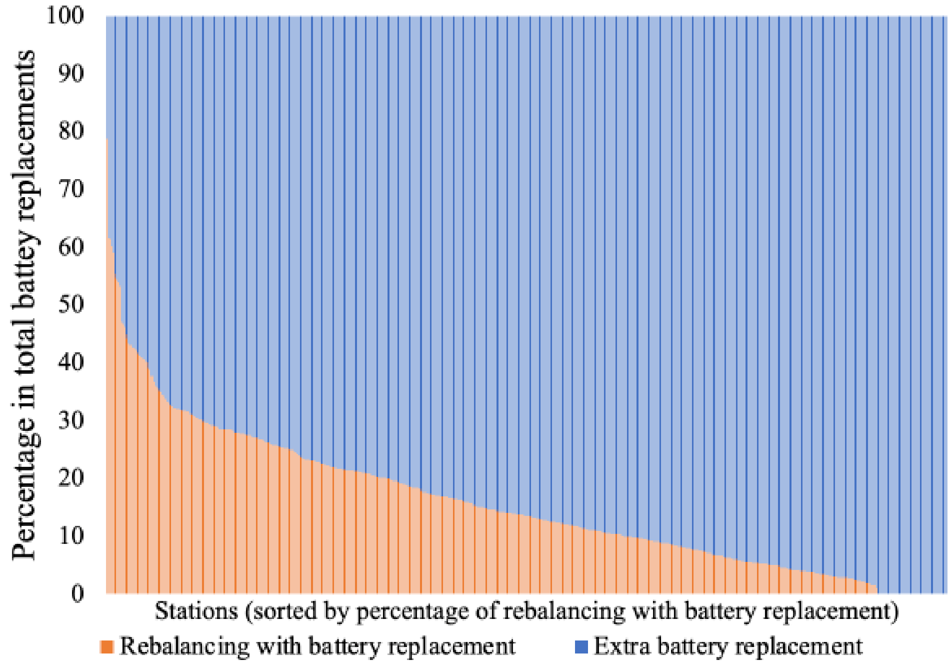


Figure 11. (a) Map of Divvy stations with color representing station downtime due to insufficient energy over a year (%) (1 mile = 1.6 kilometers) with boxplots showing the distribution of the values for all stations, stations in CBD, and stations outside CBD, labeled with median values while mean values are placed below the chart. (b) Boxplots of the average percentage of stations down for each month, labeled with median values. (c) The number of hours of downtime for stations every day in a year is sorted ascending by total yearly station downtime due to having insufficient energy.

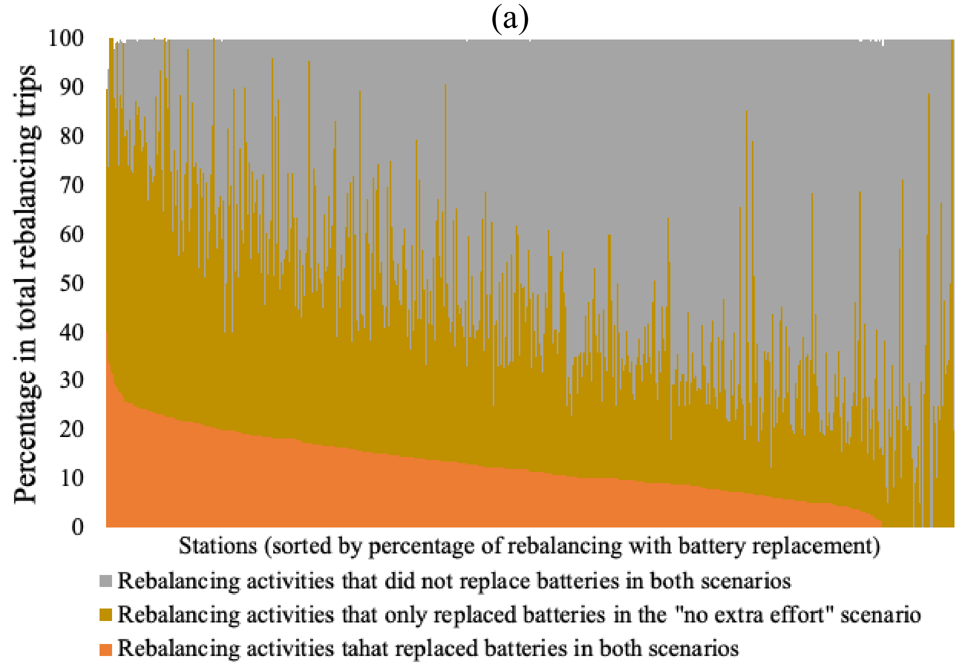
3.3 Strategies for Improvement

3.3.1 <u>Hybrid Strategy</u>

To eliminate downtime, the hybrid strategy would replace depleted batteries as needed with dedicated battery replacement trips besides rebalancing trips. With this strategy, on average, only around 15% of total battery replacements were from rebalancing trips while the rest was fulfilled by dedicated trips (Figure 12a). Adding the dedicated battery replacement trips would also take away some opportunities for using rebalancing trips to replace batteries, because after the dedicated battery replacement, the battery SOC would be higher than the cut-off threshold when the rebalancing occurred. In the “no extra effort” scenario, about 35% of the rebalancing trips replaced batteries, while only 12% did so with the hybrid strategy. Among the rebalancing trips without battery replacement, on average 35% of them replaced batteries in the “no extra effort” scenario (Figure 12b), but not with this hybrid strategy. This result shows the tradeoff between maintaining system operation and saving costs through leveraging rebalancing trips to replace batteries.



(a)



(b)

Figure 12. (a) Percentage of extra battery replacement and rebalancing with battery replacement; (b) the percentage of rebalancing trips that replaced batteries in the "no extra effort" scenario and with the hybrid strategy.

Although more battery replacements could decrease downtime, the dedicated trips for battery replacements would generate additional operational fleet Vehicle Miles Traveled (VMT) and increase use phase emissions. Previous research on bike share operation modeling has only considered bike rebalance needs, ignoring these additional trips to meet battery replacement needs [63]. These trips could either be routed separately or added as additional stops for the rebalancing vehicle. Considering both battery replacements and rebalancing in bike share system modeling could improve the estimation of the operational cost, VMT, and emissions of bike share systems, which had been underestimated.

3.3.2 Double Panel and Double Battery Strategies

If implementing the same upgrades to all stations, we could either double the PV panel to generate more PV energy or double the battery capacities to store more energy. For all stations, the double panel strategy is more effective at increasing self-sufficiency level with less impact on EPBT (Figure S13). The stations generated more power from PV panels and need less energy supplement from battery replacement, leading to enhanced independence from grid electricity. Also, with less impact on EPBT, all stations should choose double panel from the energy perspective. Furthermore, for around 67% of the stations, double panel was more effective at mitigating system downtime, and thus double panel should be chosen from both energy and operation perspectives. However, double battery worked better for about 33% of the stations, mostly located in CBD (Figure S14). If minimizing downtime has higher priority, double battery should be selected at the expense of self-sufficiency level and EPBT. The overall better performance of the double panel strategy shows that PV production is more of a bottleneck than energy storage. However, stations relying mostly on battery replacements with frequent rebalancing visits could benefit more from doubling battery capacity.

3.3.3 Customized Strategy

If customized design and upgrades could be an option, the stations could either keep the current setting, remove the PV panels, double the PV panel size, or double the battery capacity (Figure 13). With the customized strategy, 84% of the stations would double PV panel size, with the majority favoring this option for all three performance metrics as discussed in Section 3.3.2, and located outside CBD. 4% of the stations, mostly in CBD, would double the battery capacity for better performance with the cost of lower self-sufficiency level but less than 10-year EPBT.

Approximately 11% of the stations, mainly in CBD, would remove the PV panel because they could not pay back the energy investment with the station's lifespan. The PV panels removed could be repurposed or installed on the stations that would benefit from having double panels. This result can help inform the planning of new systems to avoid installing PV panels at such stations in the first place. One station would also keep the current configurations because neither upgrade could significantly enhance its performance. Different from the stations outside CBD which mostly used double panel, stations in CBD employed a variety of strategies, showing that stations in CBD could particularly benefit from having customized configurations. Many of the stations in CBD that chose double battery in Section 3.3.2 would remove the PV panel or double panel size with a customized strategy (Figure S15). The modeling framework proposed by this study could help guide designing the customized station configurations to optimize system performance and sustainability.

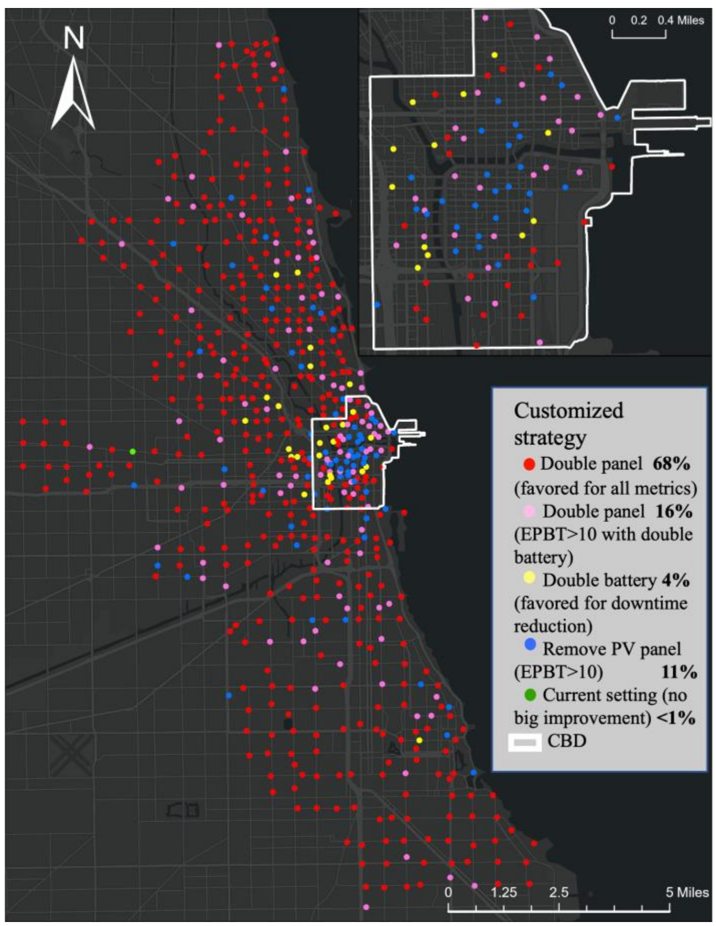


Figure 13. Map of stations with customized strategy (1 mile = 1.6 kilometers)

3.3.4 Strategy Performance

At the bike share system level, the hybrid strategy had minimal influence on the self-sufficiency level and EPBT compared to "zero downtime" and "no extra effort" scenarios (Figure 14a), because no additional PV energy was generated. However, with additional battery replacement trips (Figure 14d), the downtime was reduced to zero. Double panel is the most effective strategy to improve self-sufficiency with an average increase of 20% (Figure 14a), enabling 75% of stations to have over 70% self-sufficiency level. Without significant impact on EPBT (Figure 14b), on average it decreased downtime by over half (55%), bringing it down to 12% (Figure 14c). Some stations (1%) could reach close to zero (<1%) downtime. It also reduced the average number of battery replacements to 19 times/year (Figure 14d). Double battery was not as efficient as double panel. It could only slightly improve self-sufficiency (1%) but increased EPBT with an average of 3.3 to 10.1 years (Figure 14a-b). Downtime was also reduced by a lesser degree to 16% (Figure 14c), and the number of battery replacements was decreased to 23 times/year (Figure 14d).

Because around 84% of the stations in customized strategy employed double panel, the overall performance of customized strategy was comparable to that of double panel. It considerably boosted the self-sufficiency level (Figure 14a) while reducing downtime (Figure 14c) and the number of battery replacements (Figure 14d). The customized strategy had a heavier tail with more stations having high downtime compared to double panel strategy, which could cause revenue loss at these stations. This was because some stations did not upgrade to double panel or double battery as the EPBT would exceed the 10 years' station lifespan. The EPBT in customized strategy was below 10 years since stations having EPBT over 10 years had their PV panel removed, and EPBT no longer applied. The capital investment saving from not installing these PV panels were not quantified in this study.

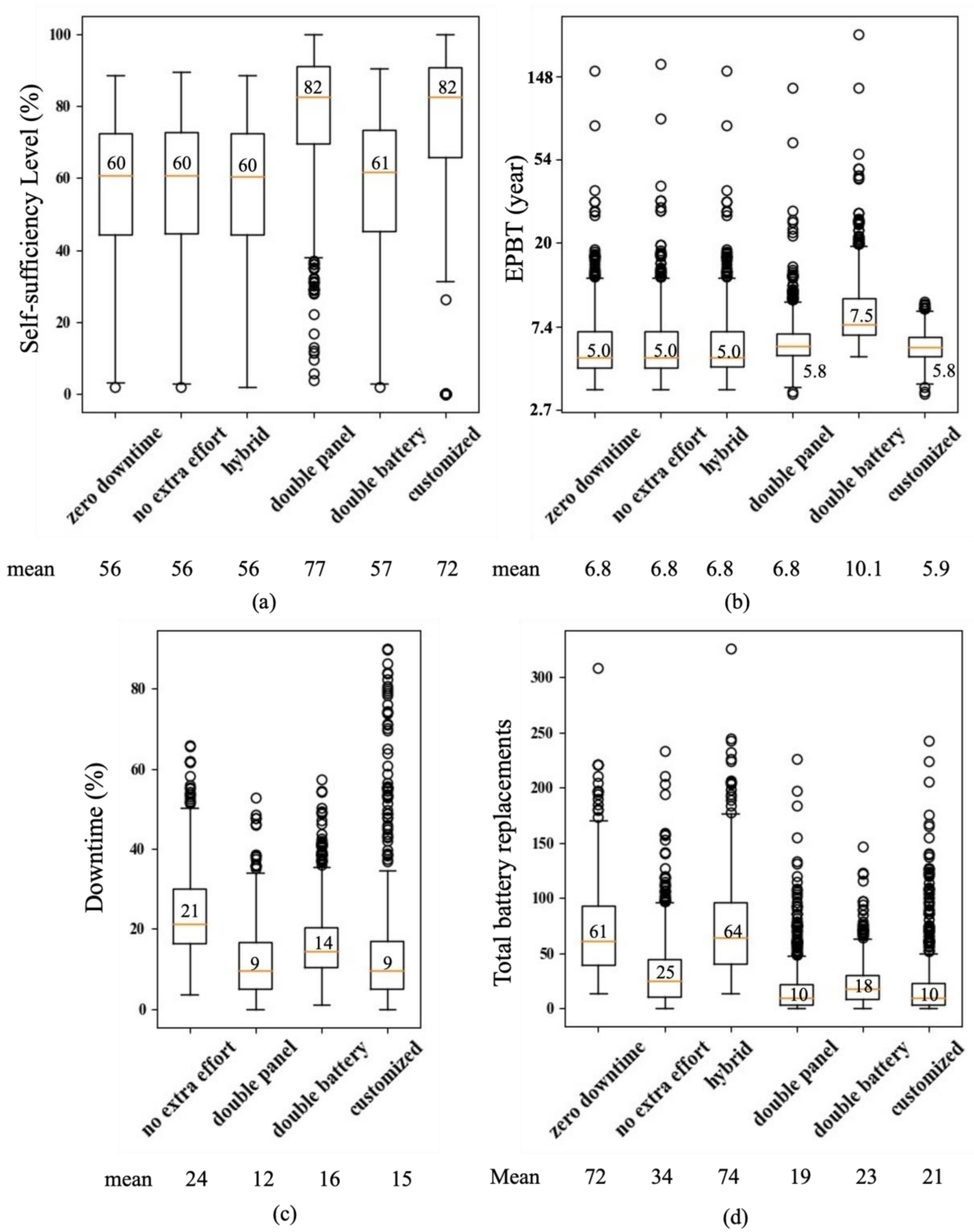


Figure 14. Boxplots of (a) self-sufficiency (b) EPBT (c) downtime (d) total battery replacements for all stations in "zero downtime" scenario, "no extra effort" scenario, hybrid strategy, double panel strategy, double battery strategy, and customized strategy

In summary, the four improvement strategies could all boost the system's performance and sustainability, however, to various degrees and at different costs. The hybrid strategy would enhance the operational performance with zero downtime, but could not improve energy sustainability and requires additional battery replacement trips. If stations would remain modular (i.e. all stations would install identical upgrades), double panel was more effective than double battery in improving system performance and sustainability. If customized station configuration is feasible, the capital cost could be saved by not installing PV panels or additional batteries at stations where the benefit was low.

4. Conclusions

This study assessed the performance of the PV-battery systems for bike share stations using a case study of Divvy bike share system in Chicago. The off-grid bike share stations use PV panels to power them, store excess energy in batteries, and receive additional grid electricity from battery replacements by the system operator. We conducted simulations of battery charging, discharging, and replacement, evaluated their performance, and proposed four improvement strategies. The results show that, without battery replacement, the current PV panels were unable to generate sufficient energy to meet all energy requirements for any station. None of the PV-battery systems were fully independent of grid electricity. In addition, most PV-battery systems had an EPBT of below 7 years, showing the feasibility to achieve net energy gain within the station's 10-year lifespan. However, some stations in the CBD with long EBPT were mostly powered by grid electricity via battery replacements due to extremely low PV production caused by the shadows of nearby buildings. Relocating these stations to nearby locations with higher solar radiation could help improve their performance and sustainability. We also found that to keep the stations operational, bike share operators had to make dedicated trips to replace batteries. Battery replacement during rebalancing operations was insufficient to meet all battery replacement needs, resulting in an average of 24% downtime. Another major finding was that, on average, doubling the PV panel size could reduce most stations' downtime by over half (55%) and improve their self-sufficiency levels by 20% without significantly increasing EPBT. Some stations outside CBD could remain operational without grid electricity with close to zero downtime with double panel, showing that the current PV panel size for these stations was sized too small and should be increased. If the customized configuration is an option, stations in CBD would particularly benefit from having different setups.

This study provides the first comprehensive assessment of the performance of PV-battery stations for bike share systems and generates insights and recommendations for the bike share system providers, operators, and policymakers on improving the sustainability of bike share systems. The results from the study show that the location of the stations is crucial, and when siting bike share stations, it is necessary to consider the potential shadow of surrounding buildings and tree canopies. Also, if feasible, the size of PV panels and capacity of batteries should be properly sized for each station, considering the station's solar radiation level, energy demand, and the frequency of rebalancing and battery replacements. Stations that receive very low solar radiation and frequent visits for rebalancing and battery replacement trips do not benefit from installing PV panels, whereas stations with strong solar radiation and fewer battery replacement trips should install larger PV panels. Additionally, this analysis demonstrates that bike share system modeling and operation planning should account for battery replacement needs, which was overlooked by previous research.

This study has the following limitations that could benefit from future research. First, the study estimated station energy consumption from the station status and kiosk use due to lacking actual energy consumption data. Having measured energy consumption data can help improve the analysis accuracy. Second, due to having no data on battery replacement activities, we evaluated an ideal situation with zero downtime and a more realistic scenario with no extra effort beyond rebalancing trips. However, actual system operation could differ from these scenarios. Having better information on battery replacements could help construct more realistic simulations in future research. Third, future research could optimize panel configuration including the tilt and aspect, and account for temperature's impact on panel efficiency to enhance PV electricity generation modeling. Including solar forecasting could also improve system planning strategies and guide battery replacement operations. Fourth, the battery charging and discharging model did not consider the battery degradation over time nor the impact of temperature on battery performance and can be further refined. The hourly simulation resolution can also be improved to produce more accurate simulation. Fifth, additional strategies exist to optimize the station configuration and worth future investigation, such as relocating stations to areas with higher solar radiation, further increase PV panel size, or considering connecting some stations to the grid. Last, this study only focused on the energy-related performance, without considering the economics factors. It would also be important to evaluate the economic benefits of using PV and compare the monetary cost of different improvement strategies.

As the first comprehensive assessment of PV-battery systems for bike share stations, this study evaluated their performances from operation and energy perspectives and identified their potential for energy self-sufficiency and sustainability. As electric bikes and scooters are becoming more popular in shared mobility systems, this study provides a modeling framework that could be extended to study how to use PV-battery systems to charge them. Moreover, this study shows the need to examine other smaller PV-battery systems similar to bike stations, which have been overlooked in solar PV research. Although each system is small, with their large quantities at scale, these systems have the potential to make solar PV energy widely accessible and help advance the United Nation's Sustainable Development Goal 7 to enable access to cheap, dependable, sustainable, and modern energy.

References

[1] Luo H, Zhao F, Chen W-Q, Cai H. Optimizing bike sharing systems from the life cycle greenhouse gas emissions perspective. Transp Res Part C Emerg Technol 2020;117:102705. https://doi.org/10.1016/j.trc.2020.102705.
[2] Use of energy in explained - U.S. Energy Information Administration (EIA) n.d. https://www.eia.gov/energyexplained/use-of-energy/ (accessed July 6, 2022).
[3] Lovelace R, Beck SBM, Watson M, Wild A. Assessing the energy implications of replacing car trips with bicycle trips in Sheffield, UK. Energy Policy 2011;39:2075–87. https://doi.org/10.1016/j.enpol.2011.01.051.
[4] Zhang Y, Mi Z. Environmental benefits of bike sharing: A big data-based analysis. Appl Energy 2018;220:296–301. https://doi.org/10.1016/j.apenergy.2018.03.101.
[5] NACTO Bike Share Siting Guide. National Association of City Transportation Officials; n.d.
[6] Wamburu J, Raff C, Irwin D, Shenoy P. Greening Electric Bike Sharing Using Solar Charging Stations. Proc. 7th ACM Int. Conf. Syst. Energy-Effic. Build. Cities Transp., Virtual Event Japan: ACM; 2020, p. 180–9. https://doi.org/10.1145/3408308.3427621.

[7] Archive VA, feed G author R. CitiBike's rainy day blues: docs don't power up when it's cloudy. N Y Post 2013. https://nypost.com/2013/06/11/citibikes-rainy-day-blues-docs-dont-power-up-when-its-cloudy/ (accessed May 9, 2022).
[8] Cloudy weather crashed part of Boulder's solar-powered bicycle system. Denverite n.d. https://denverite.com/2017/09/29/half-boulders-bike-share-system-went-cloudy-solar-power/ (accessed May 9, 2022).
[9] Solar Radiation Basics. EnergyGov n.d. https://www.energy.gov/eere/solar/solar-radiation-basics (accessed May 10, 2022).
[10] Zhong Q, Nelson JR, Tong D, Grubesic TH. A spatial optimization approach to increase the accuracy of rooftop solar energy assessments. Appl Energy 2022;316:119128. https://doi.org/10.1016/j.apenergy.2022.119128.
[11] Noland RB, Smart MJ, Guo Z. Bikeshare trip generation in New York City. Transp Res Part Policy Pract 2016;94:164–81. https://doi.org/10.1016/j.tra.2016.08.030.
[12] Faghih-Imani A, Eluru N, El-Geneidy AM, Rabbat M, Haq U. How land-use and urban form impact bicycle flows: evidence from the bicycle-sharing system (BIXI) in Montreal. J Transp Geogr 2014;41:306–14. https://doi.org/10.1016/j.jtrangeo.2014.01.013.
[13] García-Palomares JC, Gutiérrez J, Latorre M. Optimizing the location of stations in bike-sharing programs: A GIS approach. Appl Geogr 2012;35:235–46. https://doi.org/10.1016/j.apgeog.2012.07.002.
[14] Frade I, Ribeiro A. Bike-sharing stations: A maximal covering location approach. Transp Res Part Policy Pract 2015;82:216–27. https://doi.org/10.1016/j.tra.2015.09.014.
[15] Conrow L, Murray AT, Fischer HA. An optimization approach for equitable bicycle share station siting. J Transp Geogr 2018;69:163–70. https://doi.org/10.1016/j.jtrangeo.2018.04.023.
[16] Kabak M, Erbaş M, Çetinkaya C, Özceylan E. A GIS-based MCDM approach for the evaluation of bike-share stations. J Clean Prod 2018;201:49–60. https://doi.org/10.1016/j.jclepro.2018.08.033.
[17] Kou Z, Wang X, Chiu SF (Anthony), Cai H. Quantifying greenhouse gas emissions reduction from bike share systems: a model considering real-world trips and transportation mode choice patterns. Resour Conserv Recycl 2020;153:104534. https://doi.org/10.1016/j.resconrec.2019.104534.
[18] Saltykova K, Ma X, Yao L, Kong H. Environmental impact assessment of bike-sharing considering the modal shift from public transit. Transp Res Part Transp Environ 2022;105:103238. https://doi.org/10.1016/j.trd.2022.103238.
[19] Li A, Gao K, Zhao P, Qu X, Axhausen KW. High-resolution assessment of environmental benefits of dockless bike-sharing systems based on transaction data. J Clean Prod 2021;296:126423. https://doi.org/10.1016/j.jclepro.2021.126423.
[20] Fan Z, Harper CD. Congestion and environmental impacts of short car trip replacement with micromobility modes. Transp Res Part Transp Environ 2022;103:103173. https://doi.org/10.1016/j.trd.2022.103173.
[21] Li X, Cottam A, Wu Y-J, Khani A. Can a bikesharing system reduce fuel consumption? Case study in Tucson, Arizona. Transp Res Part Transp Environ 2020;89:102604. https://doi.org/10.1016/j.trd.2020.102604.
[22] Luo H, Kou Z, Zhao F, Cai H. Comparative life cycle assessment of station-based and dock-less bike sharing systems. Resour Conserv Recycl 2019;146:180–9. https://doi.org/10.1016/j.resconrec.2019.03.003.

[23] Bonilla-Alicea RJ, Watson BC, Shen Z, Tamayo L, Telenko C. Life cycle assessment to quantify the impact of technology improvements in bike-sharing systems. J Ind Ecol 2020;24:138–48. https://doi.org/10.1111/jiec.12860.
[24] Sun S, Ertz M. Can shared micromobility programs reduce greenhouse gas emissions: Evidence from urban transportation big data. Sustain Cities Soc 2022;85:104045. https://doi.org/10.1016/j.scs.2022.104045.
[25] Solar Energy: Mapping the road ahead. International Energy Agency; 2019.
[26] Zhong T, Zhang Z, Chen M, Zhang K, Zhou Z, Zhu R, et al. A city-scale estimation of rooftop solar photovoltaic potential based on deep learning. Appl Energy 2021;298:117132. https://doi.org/10.1016/j.apenergy.2021.117132.
[27] Sun Y, Hof A, Wang R, Liu J, Lin Y, Yang D. GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province. Energy Policy 2013;58:248–59. https://doi.org/10.1016/j.enpol.2013.03.002.
[28] Buffat R, Grassi S, Raubal M. A scalable method for estimating rooftop solar irradiation potential over large regions. Appl Energy 2018;216:389–401. https://doi.org/10.1016/j.apenergy.2018.02.008.
[29] Brito MC, Gomes N, Santos T, Tenedório JA. Photovoltaic potential in a Lisbon suburb using LiDAR data. Sol Energy 2012;86:283–8. https://doi.org/10.1016/j.solener.2011.09.031.
[30] Luthander R, Widén J, Nilsson D, Palm J. Photovoltaic self-consumption in buildings: A review. Appl Energy 2015;142:80–94. https://doi.org/10.1016/j.apenergy.2014.12.028.
[31] de Oliveira e Silva G, Hendrick P. Photovoltaic self-sufficiency of Belgian households using lithium-ion batteries, and its impact on the grid. Appl Energy 2017;195:786–99. https://doi.org/10.1016/j.apenergy.2017.03.112.
[32] Hernández JC, Sanchez-Sutil F, Muñoz-Rodríguez FJ, Baier CR. Optimal sizing and management strategy for PV household-prosumers with self-consumption/sufficiency enhancement and provision of frequency containment reserve. Appl Energy 2020;277:115529. https://doi.org/10.1016/j.apenergy.2020.115529.
[33] Liu Z, Yang A, Gao M, Jiang H, Kang Y, Zhang F, et al. Towards feasibility of photovoltaic road for urban traffic-solar energy estimation using street view image. J Clean Prod 2019;228:303–18. https://doi.org/10.1016/j.jclepro.2019.04.262.
[34] Binduhewa PJ. Alternative operation methods to reduce the energy demand of a traffic light controlled pedestrian crossing. 2011 6th Int. Conf. Ind. Inf. Syst., 2011, p. 533–8. https://doi.org/10.1109/ICIINFS.2011.6038127.
[35] Zhu R, Kondor D, Cheng C, Zhang X, Santi P, Wong MS, et al. Solar photovoltaic generation for charging shared electric scooters. Appl Energy 2022;313:118728. https://doi.org/10.1016/j.apenergy.2022.118728.
[36] Chicago Welcomes Divvy Bike Sharing System n.d. https://www.chicago.gov/content/city/en/depts/cdot/provdrs/bike/news/2013/jul/chicago_welcomesdivvybikesharingsystem.html (accessed February 28, 2023).
[37] Hu S, Xiong C, Liu Z, Zhang L. Examining spatiotemporal changing patterns of bike-sharing usage during COVID-19 pandemic. J Transp Geogr 2021;91:102997. https://doi.org/10.1016/j.jtrangeo.2021.102997.
[38] PVWatts Calculator n.d. https://pvwatts.nrel.gov/index.php (accessed May 11, 2022).

[39] Area Solar Radiation (Spatial Analyst)—ArcGIS Pro | Documentation n.d. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/area-solar-radiation.htm (accessed December 27, 2021).
[40] WI Kenosha-Racine Counties and IL 4 County QL1 Lidar; Classified Point Cloud n.d. https://chf.isgs.illinois.edu/distribute-east/cook/Cook_2017_metadata.xml (accessed December 26, 2021).
[41] Fu P, Rich P. Design and Implementation of the Solar Analyst: an ArcView Extension for Modeling Solar Radiation at Landscape Scales. Proc. Ninet. Annu. ESRI User Conf., 1999, p. 33.
[42] Hong T, Lee M, Koo C, Jeong K, Kim J. Development of a method for estimating the rooftop solar photovoltaic (PV) potential by analyzing the available rooftop area using Hillshade analysis. Appl Energy 2017;194:320–32. https://doi.org/10.1016/j.apenergy.2016.07.001.
[43] Dobos A. PVWatts Version 5 Manual. 2014. https://doi.org/10.2172/1158421.
[44] Isabelle Bettez V-L, Jean-SebastienBettez H. Bicycle Rental Systemad Station. US 9,076,136B2, 2015.
[45] Divvy Bicycle Stations | City of Chicago | Data Portal n.d. https://data.cityofchicago.org/Transportation/Divvy-Bicycle-Stations/bbyy-e7gq (accessed May 12, 2022).
[46] General Bikeshare Feed Specification 2022. https://github.com/NABSA/gbfs (accessed May 12, 2022).
[47] Divvy System Data. Divvy Bikes n.d. http://ride.divvybikes.com/system-data (accessed May 12, 2022).
[48] City of Chicago | Developers. Chicago n.d. httpshttp://dev.cityofchicago.org/open%20data/data%20portal/2019/07/10/divvy-datasets-frozen.html://dev.cityofchicago.org/ (accessed January 1, 2022).
[49] SD-1000-G Smart Dock Bikeep Smart bike Dock ver. G n.d. https://bikeep.com/architect/ (accessed May 12, 2022).
[50] Kiosk specifications THE GP2 KIOSK n.d. http://www.touch4.com/touch-screen-kiosks/specsheets/specsheet_gp2_v4.pdf (accessed January 2, 2022).
[51] NEC-KIOSK-PORT-S, 46" Silver Portrait Kiosk - Highlights & Specifications | NEC Display Solutions n.d. https://www.sharpnecdisplays.us/products/displays/nec-kiosk-port-s (accessed January 2, 2022).
[52] Cycloshare Bikeshare Solution Bikestation Data Sheet n.d. https://www.cycloshare.com/wp-content/uploads/2021/11/Cycloshare_Bikestation_Data_Sheet_Brochure_ENGLISH.pdf (accessed February 19, 2023).
[53] Quoilin S, Kavvadias K, Mercier A, Pappone I, Zucker A. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. Appl Energy 2016;182:58–67. https://doi.org/10.1016/j.apenergy.2016.08.077.
[54] Barnhart CJ. Energy and Carbon Intensities of Stored Solar Photovoltaic Energy. Compr. Guide Sol. Energy Syst., Elsevier; 2018, p. 351–60. https://doi.org/10.1016/B978-0-12-811479-7.00017-8.
[55] Sun R. Bike Share System - Rebalancing Estimation and System Optimization. Purdue University Graduate School, 2021.

[56] Frischknecht R. Methodology Guidelines on Life Cycle Assessment of Photovoltaic 2020 n.d.:33.
[57] Fthenakis VM. Life Cycle Analysis of Photovoltaics: Strategic Technology Assessment. Compr. Guide Sol. Energy Syst., Elsevier; 2018, p. 427–42. https://doi.org/10.1016/B978-0-12-811479-7.00022-1.
[58] Fthenakis V, Leccisi E. Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends. Prog Photovolt Res Appl 2021;29:1068–77. https://doi.org/10.1002/pip.3441.
[59] Wong JH, Royapoor M, Chan CW. Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. Renew Sustain Energy Rev 2016;58:608–18. https://doi.org/10.1016/j.rser.2015.12.241.
[60] Sullivan JL, Gaines L. A review of battery life-cycle analysis : state of knowledge and critical needs. 2010. https://doi.org/10.2172/1000659.
[61] How Long Do Solar Batteries Last? And What Impacts Their Lifespan? n.d. https://www.plicoenergy.com.au/blog/how-long-do-solar-batteries-last (accessed February 28, 2023).
[62] Fthenakis VM, Blunden J, Shields M, Betita R, Vinje R. Life Cycle Analysis of High-Performance Monocrystalline Silicon Photovoltaic Systems: Energy Payback Times and Net Energy Production Value n.d.:6.
[63] Shui CS, Szeto WY. A review of bicycle-sharing service planning problems. Transp Res Part C Emerg Technol 2020;117:102648. https://doi.org/10.1016/j.trc.2020.102648.