Electric Bike Sharing--System Requirements and Operational Concepts

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ABSTRACT

Bike sharing is an exciting new model of public-private transportation provision that has quickly emerged in the past five years. Technological advances have overcome hurdles of early systems and cities throughout the globe are adopting this model of transportation service. Electric bikes have simultaneously gained popularity in many regions of the world and some have suggested that shared electric bikes could provide an even higher level of service compared to existing systems. There are several challenges that are unique to shared electric bikes: electric-assisted range, recharging protocol, and bike and battery checkout procedures. This paper outlines system requirements to successfully develop and deploy an electric bike sharing system, focusing on system architecture, operational concepts, and battery management. Although there is little empirical evidence, electric bike sharing could be feasible, depending on demand and battery management, and can potentially improve the utility of existing bike sharing systems. Under most documented bike sharing use scenarios, electric bike battery capacity is insufficient for a full day of operation, depending on recharging protocol. Off-board battery management is a promising solution to address this problem. Off-board battery management can also support solar recharging. Future pilot tests will be important and allow empirical evaluation of electric bike sharing system performance.

INTRODUCTION

Bike sharing has emerged as an innovative form of public transport to provide urban short-distance transportation services that are often underserved by other forms of public transportation. Bike sharing couples the benefits of shared ownership and expense with personal and demand responsive transportation. This model, driven by improved technology and advances in other shared vehicle platforms has filled an important niche in the transportation system of many global cites, improving sustainability of transportation services and accessibility in urban areas.

Electric bikes are a technology that has emerged in parallel with the rising popularity of bike sharing. Reborn in China in the past decade, electric bike technology has evolved and over 100 million have been sold since the early 2000's *(1)*. Electric bikes, particularly pedal assist electric bikes, appear and operate much like traditional bicycles (Figure 1). Pedal assist electric bikes require the rider to pedal and on-board control technology assists the rider by supplementing the rider's effort with electromechanical power. This effectively increases the range of the bike and reduces fatigue barriers, particularly in hilly terrain. These benefits make electric bikes more attractive to casual riders, who might otherwise avoid traditional bicycles.

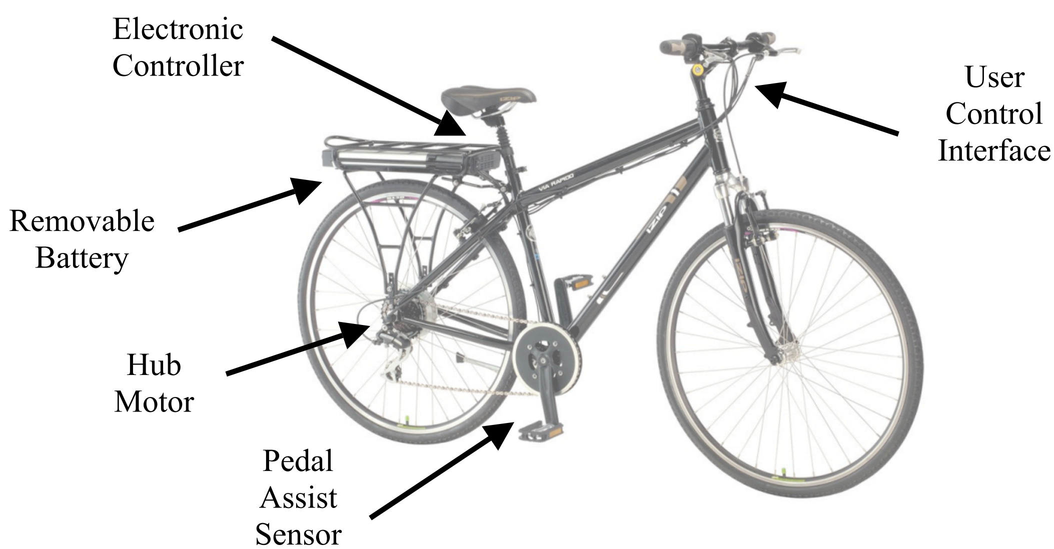

FIGURE 1 Typical Pedal Electric Bike

Some of the goals of bike sharing include attracting casual bike riders; those who don't own bikes, commute by car, or use transit. Much of the commuter market is not pre-disposed to commuting by bike for a number of reasons. Electric bikes can overcome some barriers to bicycling for viable, expanded market of commuters. However, electric bikes are generally significantly more expensive than similar quality non-electric bicycles. As such, the electric bike market has not grown as rapidly in the US as compared to other countries. Sharing electric bikes can overcome price barriers by spreading the cost over many users. Including electric bikes in a shared environment also casually introduces the technology to users without the pressure or commitment of a purchase.

There are many challenges and opportunities associated with including electric bikes into a bike sharing model. Foremost of those is range limitations and recharging protocol. Electric bikes are effectively hybrid vehicles (i.e., if the battery dies, the rider can still pedal the bike to his or her destination). Still, an effective electric bike sharing system should ensure that the user of the system has a maximum amount of range available. Since most electric bikes have a range that is below the demand demonstrated by many shared bike systems, it is possible that range will diminish over the day. Recharging is also complicated in a shared environment. Existing bike sharing systems employ mechanical connections to automatically secure bikes. Electric bike sharing systems have to develop electrical connections that are safe and automatic (rather than relying upon the user to manually plug in the vehicle). Vending bikes and batteries and securing components of the bike away from the station are further complicating factors. Finally, many commercially available electric bikes have a retail value of more than $2000, making theft reduction, asset management, and appropriate business model development more important. Many of the challenges associated with integrating electric bikes into bike sharing systems remain unaddressed. There are a number of operational models that can be developed; yet there has been little attention to models that are deployable.

This paper discusses several of the key characteristics of deploying electric bikes in a shared system. It focuses on unique operational requirements and proposes a system architecture and concept of operations for electric bike sharing in the context of existing third or fourth generation bike sharing system designs. A preliminary analysis of battery management requirements is illustrated and finally conclusions and a future electric bike sharing pilot are discussed.

LITERATURE REVIEW

Car Sharing

Advanced share-use vehicle systems have emerged in parallel throughout the world in the past decade. Car sharing is a class of shared use vehicles that has matured and become commercialized globally *(2)*. Car sharing history has been well documented, with shared cars operating in the niche between taxi use and daily car rental, with a focus on improving access, flexibility, and cost for car share users *(3-8)*. Several studies have shown it to be promising strategy to reduce travel demand and car ownership *(3, 9-11)*. While car sharing is unique from bike sharing in many ways, they share many common operational characteristics. Particularly, vehicle allocation challenges are inherent, especially in a system dominated by one-way trips. Fleet size and distribution of vehicles are perhaps the most significant operational challenges *(12, 13)*. Technology has assisted in fleet management and has also improved the viability of shared electric cars *(14-17)*.

Bike Sharing

Formal car sharing systems are relatively new and well studied. Formal bike sharing, on the other hand, has existed for nearly half a century, with various levels of success. Few studies have systematically estimated demand or defined operational parameters *(18)*. There have been three generations of evolution, driven mostly by advances in technology. The first generation began in Amsterdam in 1965, where stationless bikes could be borrowed and left anywhere in the city, to be borrowed again by the next individual. It was quickly unsuccessful due to vandalism and theft. The second generation, born in Denmark in 1991, allowed bikes to be picked up and returned to several central locations with a coin deposit. Theft was also a problem largely due to the anonymity of the user. Third generation bike sharing was born in Portsmouth University in England and involved several technological improvements such as bike racks that locked electronically, on-board electronics, swipe cards, and telecommunication capabilities. In 2005 and 2007 respectively, Lyon and Paris, France launched highly successful third generation bike sharing programs that grew to over 15,000 and 20,000 bikes respectively. Today, one bike share program per month is being created somewhere in the world *(19, 20)*.

Beginning in 2008, cities outside of Europe began to launch third generation programs. Rio De Janiero launched a pilot public bicycle sharing program in 2009. In the first eight months, 4,316 trips were made. Several others followed in South America and Asia. Some of the largest bike sharing networks are in cities such as Beijing, Hangzhou (40,000 bikes and 1,700 stations), and Wuhan, China (13,000 bikes and 516 stations). In North America, Montreal, Denver, and Washington D.C. have launched successful third generation bike sharing programs in the past two years. Dozens of other North American cities are in planning stages for bike sharing system *(21)*.

Since this is a new model, travel demand estimation is difficult, particularly since established private bike sharing system demand data are often proprietary. A recent demand analysis was conducted for the program in Philadelphia. This analysis used a geographic information systems (GIS) analysis approach to determine a geographic market area for a bike sharing system, and applied bike share trip diversion rates observed in peer European cities to estimate the number of bike share trips. This study estimated daily usage in Philadelphia to be from 6,000 to 23,000 trips *(22)*. Proposed improvements to third generation systems include increased interoperability with other transportation modes and advanced user information to control fleet distribution.

Challenges with theft and fleet management persist with bike sharing systems and the evolution of low-cost mobile technology has influenced the rise in third generation bike sharing systems. Electric bike sharing has been proposed by several, but presents many challenges in the context of a vehicle sharing system. In particular, relatively short range coupled with relatively long recharge time in a heavily subscribed systems requires improved fleet management. It is no longer sufficient for stations to have vehicles available, but appropriately recharged vehicles are required. Electric bike systems and concepts have been proposed, but few have been successfully deployed *(23)*.

ELECTRIC BIKE SHARING

System Components

A typical electric bicycle sharing system consists of bicycles, a vending and charging station, and support system (Figure 2). The core of an electric bicycle sharing system and the most costly component is the electric bicycle. The simple fact that the batteries must be recharged, coupled with the relatively higher bicycle unit cost as compared to non-electric bicycles, all but requires a system with stations. Bicycle design specifics vary greatly, but whether the battery is fixed or removable is a key parameter in determining the design parameters of the stations. One electric bicycle design parameter that may significantly impact battery use, and therefore charging demand, is the way electric power is controlled. The two primary motor control concepts are “twist and go” and pedal assist. The “twist and go” concept simply gives the user control of the electric motor through a twist throttle. Electric motor output is proportional to the position of the twist throttle. This control method typically does not require the cyclist to exert any pedaling effort, and therefore may reduce potential health benefits to the rider and decrease electric-assisted range. Pedal assist bicycles include a sensor to measure pedaling effort and add electric power to reduce or limit maximum user effort. This system helps the rider overcome steep hills and long grades without eliminating the need for the rider to pedal. The increased rider input would increase the electric assisted range and still provide some health benefits to the rider.

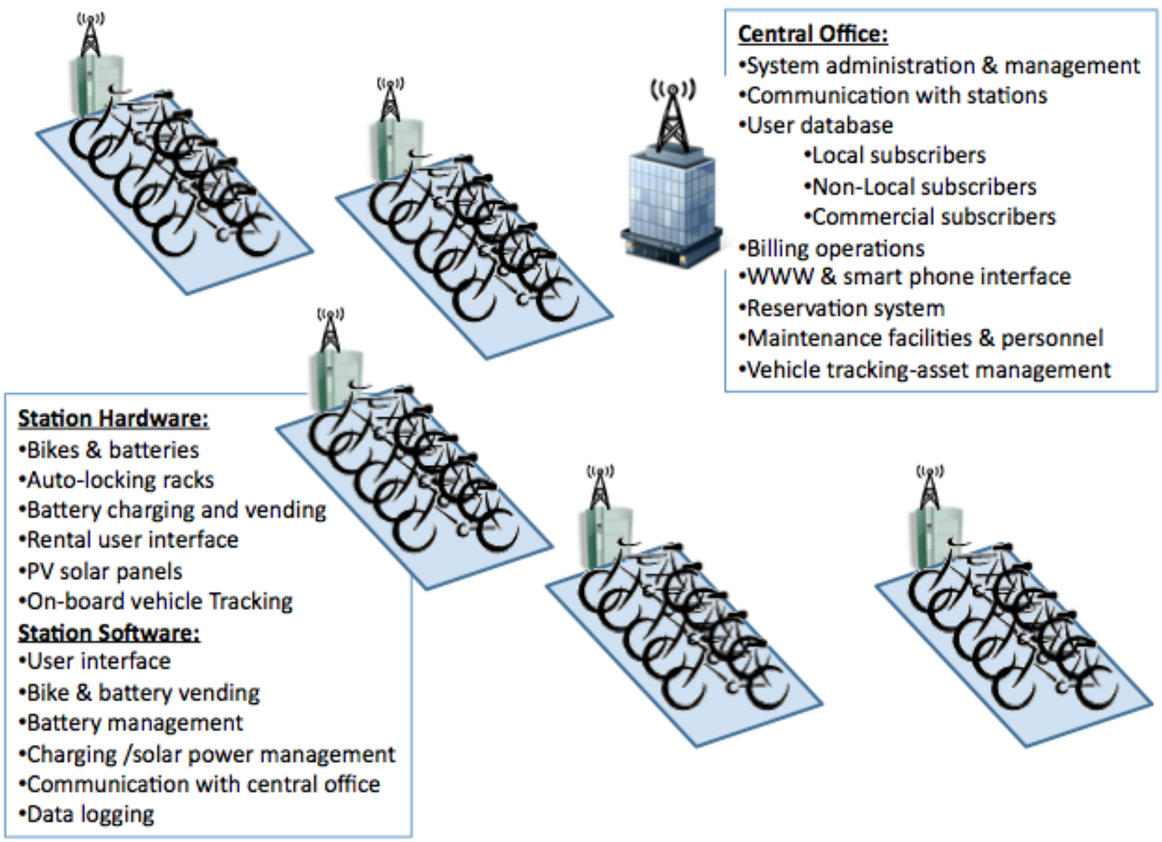

FIGURE 2 System Components of Electric Bike System

The stations in an electric bicycle sharing system serve three main purposes: physical security, vending, and charging. The first two functions are shared with station-based, non-electric bike sharing systems. The station must physical secure the bicycles. This could be as simple as a traditional bicycle rack where the users would be required to manually secure the bicycles when returning them to the station. However, an electromechanical locking system would simplify the return process and provide an opportunity to verify that a bicycle has been returned and properly secured.

Along with providing theft security, the stations must provide access to the bikes by system users. The vending system must identify a user and provide access to a bicycle, typically by unlocking an electromechanical lock. This component is the heart of business operations and collects the usage data necessary to bill users. The vending system must also identify the bicycle when it is returned, should confirm it is secured properly, and record that the user has returned the bicycle. If the system consists of more than one station and the user is allowed to return a bicycle at any station, the stations must be linked to coordinate operations across stations. This linkage could most easily be established using cellular or wireless internet technology, but wired telecommunications could also be used. The shared data in a multi-station system can be used to track the distribution of bicycles throughout the system to ensure both bicycles and spaces for returns are available throughout the system. The stations can also allow the user to enter information about bicycle serviceability to prevent unserviceable bicycles from being vended and queue maintenance personnel to provide necessary repairs. In addition to these core functions, the stations may also include an overhead cover to protect system components from the weather and provide safety lighting.

Battery charging is the primary difference between electric and non-electric bicycle sharing stations. The need to charge batteries requires access to a reliable source of energy. The most reliable source is a connection to an electric utility. However, this complicates selection of station sites and increases installation cost. The need to store solar energy in batteries or other devices is a common disadvantage of solar-based system, primarily due to the expense of the storage components. Since battery charging is the primary power consumption in this application and the batteries are an integral component of the system, an electric bike sharing system may be a near ideal application for solar power. However, sufficient reserve energy capacity must be provided to ensure uninterrupted service in periods of inclement weather. The fact that usage and power is expected decrease during inclement weather may offset this limitation. Hybrid grid and solar power would provide both uninterrupted service and the benefits of a renewable energy source. Solar powered stations could also provide additional revenue by net-metering surplus power onto the power grid.

Charging profiles are largely dependent on battery chemistry. The selection of battery chemistry for an electric bicycle is dominated by energy density (energy per unit mass) of the battery. Lithium ion, nickel metal hydride, nickel cadmium, and sealed lead-acid battery chemistries are all used, but lithium-based batteries are the most common primarily due to a relatively high energy density. Regardless of chemistry, charging time of batteries can be classified as quick-charging or slow-charging. In general, a slower charge rate extends battery life, maximizes stored energy, and minimizes the risk of overcharging or overheating the battery. Commercial electric bike battery rechargers typically balance charge time and battery life, with typical charge times ranging from four to six hours. The battery charging system in a station could utilize any of these charging profiles or a combination of more than one profile. The battery management system would ideally be able to track or historically predict both demand and storage in the system and choose an appropriate charging profile to maximize battery life while maintaining an acceptable level of charged battery availability.

The physical implementation of the battery charging system can either require the users to remove the battery from the bicycle for charging or connect the charging system to the bicycle without removing the battery. Charging the battery on the bike simplifies the bicycle check-out process and hardware, but has the major disadvantage of taking the bicycle out of service while charging. Charging the battery after removing it from the bicycle requires the ability to dispense and return the batteries but allows all available bicycles to remain in service while the battery is recharged if there are more batteries than bicycles in the system. A system with “surplus” batteries also make a solar energy source more feasible since the peak demand for bicycles and peak availability of solar energy tend to coincide. A battery management system would include slots to house the batteries while charging, provide physical security for the battery, and provide access to users when checking out a bike. If commercially available batter packs are used, the battery management system would also need to identify the battery as belonging to the system to prevent battery theft and replacement with an empty case or privately owned unserviceable batteries.

In addition to the core components, additional components may be necessary depending on the operational concept of the electric bicycle sharing system. In some systems it may be necessary to secure the bicycle at a location other than a vending station. For those systems it may be advantageous to provide user with a reliable means of securing the bicycle in conventional bicycle racks. Also, it may prove cost effective to include an active tracking system to discourage theft and aid in recovery of stolen bicycles.

The support system would include a data network, administrative support, and maintenance support. The data network would transfer information between the stations and a central control node. In addition to user data and billing information, this system could transfer information regarding the disposition of the bicycles (location, serviceability, usage, etc.) and overall system status (station maintenance status, bicycle distribution at stations, available return slots, battery status and distribution, etc.). This information could prove extremely valuable to managing the overall system. Anti-theft tracking devices could also be integrated into the management data network to alert personnel to theft and aid in recovery. The integration of web and mobile phone applications as a user interface would also be very beneficial in marketing the system and ensuring a high level of user information and ultimately satisfaction.

Operational Concepts

Bike sharing system operations and terms of use are diverse and vary by system. Under most third generation systems, a user (usually a subscriber) checks out a bike by entering his or her credentials at a bike sharing station. The system checks the credentials of the subscriber and issues a bike automatically. That bike is assigned to the user and the user is responsible for returning the bike to the same or another station, usually within a pre-defined time period. Under most systems, the bike can be returned to any station within the system. The user identifies a station with available parking capacity at his or her destination and returns the bike to an automatically locking rack. The system identifies the bike automatically, or the user re-enters his or her credentials to return the bike. Some systems allow maintenance flags and will make a bike unavailable if a maintenance problem is detected. Upon check-in, the bike is restored to service for the user community to check out again.

Many of the operations of an electric bike sharing system are similar to those of traditional bicycle sharing systems, except that electric bike sharing models require careful consideration to manage battery charging. One concept integrates the battery with the bike and battery recharging is conducted on the bike (through the rack). The system can assign bikes to users based on the level of charge in each bike, distributing bikes that have the highest level of charge first. This model operates like a third generation bicycle sharing system but is limited because the bike is out-of-service if the battery is depleted, until the battery can be recharged through the rack. This effectively limits the fleet availability particularly in a high-use environment.

The other concept includes a removable battery and allows the system to exchange depleted batteries for recharged batteries in a battery management kiosk. Because electric bike batteries are lightweight, users are able to exchange batteries as a part of the bike share checkout process. This is an important distinction compared to electric car sharing concepts. Under this concept, the user checks out an electric bike, which is unlocked automatically. Simultaneously, a battery is distributed from a separate battery management system and the user physically inserts the battery on the bike. The system can identify the battery with the highest state of charge and will maintain more batteries than available bikes, allowing batteries to be recharged even when the system is at peak use levels. When the user returns the bike, he or she will also return the battery and it will be place in a virtual distribution queue with the other batteries depending on its state of charge.

Electric Bike Demand and Battery Charge Management

The ratio of bikes to active subscribers varies by subscription types and fees. Though little data are publicly available, systems with annual subscription fees coupled with pay-per-use fees share one bike between about 10-20 subscribers. Shared vehicle systems with very low annual subscription fees maintain many more administrative users who are not active participants. Among these users, bike sharing systems yield 4-6 trips per bike per day, ranging from 4-6 kilometers each *(20)*. Depending on system use rules, these bikes can be away from the stations for several hours a day. Based on these baseline estimates, shared bikes require 25 km range availability per day *on average*. Since there is little empirical evidence of electric bike demand characteristics in a shared system, it is difficult to estimate the range requirements. Because electric bikes have higher utility, one could speculate that electric assisted bikes trips would be longer on average and/or the trip rate would be higher, resulting in more demand per bike.

Electric bike range depends heavily on terrain, weight of the rider, and level of assist required. Most commercially available electric bikes advertise ranges between 30-40km, but all with the caveats of responsible power management (human assistance) and contingent on terrain, weight of the rider, and stop-and-go characteristics of the trip. Several instrumented test runs, on urban hilly terrain, with a 70-kg rider, yielded ranges between 20-25 km for a representative electric bike (240 Wh battery). It is expected that an urban, shared electric bike would deliver less range than advertised.

Under a traditional bike sharing system, the range of shared electric bikes would be insufficient to meet the average daily demand of the system unless trip durations were short and bikes are being recharged more than they are checked-out. Indeed, by the end of the duty period, a significant portion of the fleet could be out-of-service, particularly if electric bikes are introduced into a system where recharging stations are not ubiquitous and bikes are checked out for extended periods of time (and thus not recharged). A single two-hour round trip could completely deplete a bike battery and the bike would be effectively out-of-service for the rest of the service period. Recharge times range from 4-6 hours, but more advanced battery and recharging technologies can reduce recharging time to 30 minutes. Rapid recharging can significantly improve the operation of the bike share system.

In the case where electric bike demand is underestimated, or range is overestimated, there are few solutions to increase availability of service, short of increasing the size of the fleet. Another alternative to assure that electric bikes are always available is advanced, off-board, battery management. Each bike can always be available if an appropriate number of recharged batteries are available. With excess batteries, even if all bikes are checked out from a station, that station can still maintain a number of recharging batteries. Suppose a station supports ten bikes, but has capacity to recharge 15 batteries. If half of the bikes are checked out and returned with fully depleted batteries, those bikes can be immediately reintroduced to service. A more likely scenario is that the station (or system) will start with a specific energy capacity and draw from that capacity over the day as demand fluctuates. By the end of the day, the total capacity is lower than when started, but sufficient to provide service as the batteries recharge over night. This concept is easily scalable and demand responsive. It shares battery resources between bikes, rather than mounting an over-sized battery on each bike to meet daily energy demands for multiple short trips.

To illustrate, consider a hypothetical station with ten electric bikes and 15 batteries (240 Wh each). Suppose the travel demand of this station is 8 trips per bike per 12-hour day, each trip is 6 km. Each trip requires 60 Wh, or 480 Wh per bike per day. On average, the battery capacity of each bike is about half the daily demand. For this illustration, we assume high levels of utilization and little recharging during the day. We use a recharge rate that is about 1/3 the rate of energy demand, consistent recharge profiles of Li-ion batteries. By exchanging batteries, one can assure full use of all bikes in the fleet. If battery demand increases or decreases, rather than add bikes to the station to compensate for idle bikes, more batteries could be added or reduced. Figure 3 illustrates a simplified charge profile of this ten-bike station's battery capacity and demand. The figure shows that, under this simplified scheme, battery capacity will drop to 600 Wh by the end of the service period (19:00). If batteries were recharged on-board, all batteries (2400 kW) would be depleted by 17:00, before the end of desired service. Of course, real-world operations would vary considerably and future empirical studies are needed to estimate actual demand and capacity. Realistic demand profiles will vary over the time of day and day of week, with defined peak demand during weekdays *(18)*. The stochastic nature of transportation trips also complicates this illustration significantly.

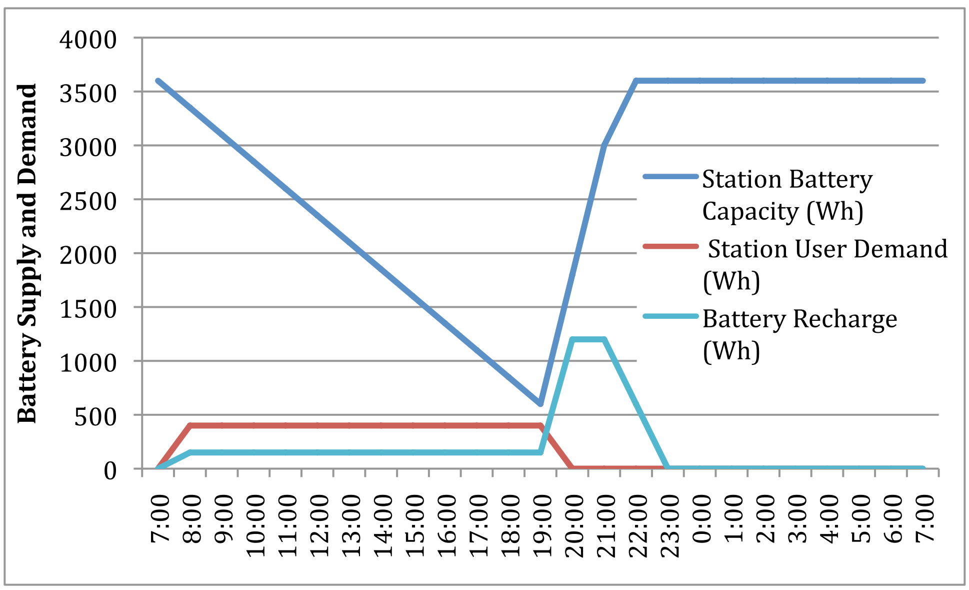

FIGURE 3: Illustrative E-bike Demand, Battery Capacity, and Recharge Profiles

Managing batteries does introduce another level of optimization in new fourth generation systems. One of the key features of fourth generation systems is more sophisticated redistribution of bikes, particularly by rewarding users for efficiently distributing bikes. Batteries also need to be efficiently distributed so that the battery capacity at all stations maintains a minimum state of energy storage to assure all stations have some level of fully charged batteries available. Users could be differentially rewarded for redistributing both bikes and batteries.

Another feature of the next generation of bike sharing systems is highly deployable and easily installed stations, or stationless systems. Reliably recharging electric bikes requires a reliable connection to a source of power, which precludes some of the features of deployable bike sharing stations. Solar powered bike sharing overcomes some of these problems, but requires more advanced battery management. Solar powered recharging does share some common characteristics with the battery management system proposed above. Bike sharing systems are most highly subscribed during the middle of the day, when solar generating capacity peaks. Charging a large storage battery, and recharging electric bike batteries from that battery is one solution that has been suggested for car-based solar charging stations. Because electric bike batteries are able to be exchanged, solar power can charge the electric bike batteries directly, without efficiency losses from inverting solar power or recharging batteries from other batteries. Exchanging to assure that a bank of batteries is available is essential and it is likely that a larger bank of batteries will be required than a grid-tied battery management system.

CONCLUSION AND NEXT STEPS

Electric bike sharing marries two emerging technologies that can improve the depth of penetration of traditional bike sharing systems to a new class of users by overcoming some barriers to traditional bicycling. Clearly, the current generation of bicycle sharing is in its infancy and there very little published empirical evidence on use patterns and demand. Electric bike sharing is less mature and it is unclear what impact electric bikes will have on system use. The concept of introducing electric bikes into shared systems has been proposed in other publication but to the authors' knowledge, there have been no studies of integrated system components required to overcome some of the challenges, nor has their been an outline of system operations that are unique to electric bike sharing systems. This paper is the first to provide a discussion of some of the challenges associated with developing an electric bike sharing system in the current context and poses some solutions.

The solutions proposed here are being incorporated into a proof-of-concept pilot test to develop a joint bicycle and electric bike sharing system on the University of Tennessee-Knoxville campus. This system will feature two stations hosting 15 electric bikes and six traditional bicycles that will be shared in the context of a controlled pilot test from Fall 2010-Spring 2011. Bikes will be equipped with a host of sensors to gather empirical evidence of daily energy demands on the bikes and the system and will aim to develop a robust and replicable electric bike sharing model that can be integrated with other bike sharing or multimodal systems. The UT campus is ideal for a bike sharing system because the campus is hilly and spread out, resulting in a large potential pool of customers that might ride an electric bike, but not necessarily a bicycle. As more data emerge, shared electric bikes could find a significant niche in our transportation system that reduces energy use and emissions while moving more individuals toward active transport modes.

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