Dynamic, data-driven optimization of solar powered charging kiosks for crisis response

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ABSTRACT

In this paper, we describe methodologies for using portable, solar powered charging kiosks to provide mobile phone charging to communities following a disaster. We do not strive to provide a comprehensive alternative to grid power, rather we focus on charging mobile phones and other battery-powered devices. The small size of portable solar systems come with a trade-off: demand for power may exceed battery capacity and solar power generation. In such cases, power output must be regulated in order to maintain the functionality of the system, or the system may be modified to produce more power by adding more solar panels, or to store more power by adding additional batteries. We model user demand for power and kiosk power generation, battery status, and power output to inform the development, deployment, operation and reconfiguration of such kiosks following a disaster.

Keywords

Solar power, charging kiosk, emergency power, current limiting, rapid reconfiguration.

INTRODUCTION

Following an emergency or disaster, electricity is a critical need for citizens in the impacted area. Unfortunately, disasters often reduce the availability of electrical power, impacting communication, lighting, and reconstruction. Many of these power outages persist for days or weeks, or even months. For example, the day following Hurricane Sandy's landfall on October 29th, 2012, about 8.7 million customers on the east coast of the United States were affected by power outages (Mühr, Kunz-Plapp, Daniell, Khazai, Vannieuwenhuyse, Comes, Elmer, Schröter, Leyser, Fohringer, Münzberg, Trieselmann, and Zschau, 2012). On November 6, hundreds of thousands of residents in New York and New Jersey were still without power, along with thousands of residents across six other states, from South Carolina to Michigan (Mühr et al., 2012). Being left without power can remove a victim's ability to communicate, as the internal batteries in communication devices such as cellular phones are depleted and few or no functional power outlets are available to recharge those batteries. Additionally, lack of power reduces standards of living, as users may not have sufficient lighting to function indoors or at night, and cannot use items such as power tools for reconstruction or damage mitigation.

One solution to this problem is to deploy emergency generators, charging kiosks or charging stations following an emergency or disaster. Companies such as AT&T charging trailers within days of Hurricane Sandy, providing phone charging to those affected by electrical outages (Merritt, 2012). However, this approach works best in developed countries, with mostly functional infrastructure. Truck-based charging relies on the availability of fuel to run generators. Additionally, functioning road infrastructure is also required, to move a kiosk to where it is needed and to regularly re-supply the kiosk's generators with fuel. Such an approach would not work following disasters such as the April 2015 Gorkha earthquake in Nepal, which severely damaged road networks. Sagar Mani Parajuli, Joint Secretary for Nepal's Home Ministry, reported "Given Nepal's geographical terrain we cannot use surface transport much but we are using it" (Ng, 2015). For rural villages, relief supplies were typically delivered by helicopter or on foot.

We therefore see the need for smaller-scale charging kiosks, which are portable enough to be transported by individuals on foot, provide sufficient power for charging phones, and do not require regular fuel delivery for continued operation. We designed a battery-backed, solar powered charging kiosk which meets these requirements. We constructed an 'ideal' kiosk in the United States, and deployed it in Nepal as part of the relief efforts following the Gorkha earthquake. While in Nepal, we constructed a second kiosk, using locally sourced materials, to evaluate the feasibility of constructing such kiosks in developing countries following a disaster. We worked with a non-governmental organization to deploy the kiosks in the mountainous Sindhupalchok District of Nepal in July of 2015.

In the process of creating these kiosks, we learned about how such kiosks are likely to operate following a disaster. We find that without regulating power output in some way, such a kiosk will not provide a fair and reliable source of power to a large group of users. To design a system that does so, we model the design and operation of such kiosks, combining observations of kiosk utilization with current and voltage sensing. Our goal is to balance demands for power with battery capacity limitations to inform a kiosk's operation.

KIOSK COMPONENTS AND DESIGN

Each charging kiosk is a stand-alone off-grid solar power system. Figure 1 shows a reference system, similar to one we deployed in Nepal. The core components of the kiosk are a 12 volt, 35 Amp-hour sealed lead acid battery, a charge controller, and a power distribution module, and a waterproof toolbox. To allow the kiosk to provide power through USB ports, a 12V to 5V DC-DC regulator and a 10 port USB hub are used. A microcontroller uses a three-channel current and voltage monitor to measure power flow between the solar panel and the charge controller, the charge controller and the battery, and the battery and power outputs. A compact Wi-Fi router running OpenWRT, a minimal Linux distribution, uses power measurements to monitor the kiosk, and instructs the microcontroller to adjust the maximum current draw allowed from the USB ports. A 100W solar panel provides power to the system. The system is designed to be modular. Depending on demand for power, cost, and availability of components, the size of solar array and number of batteries may be adjusted.

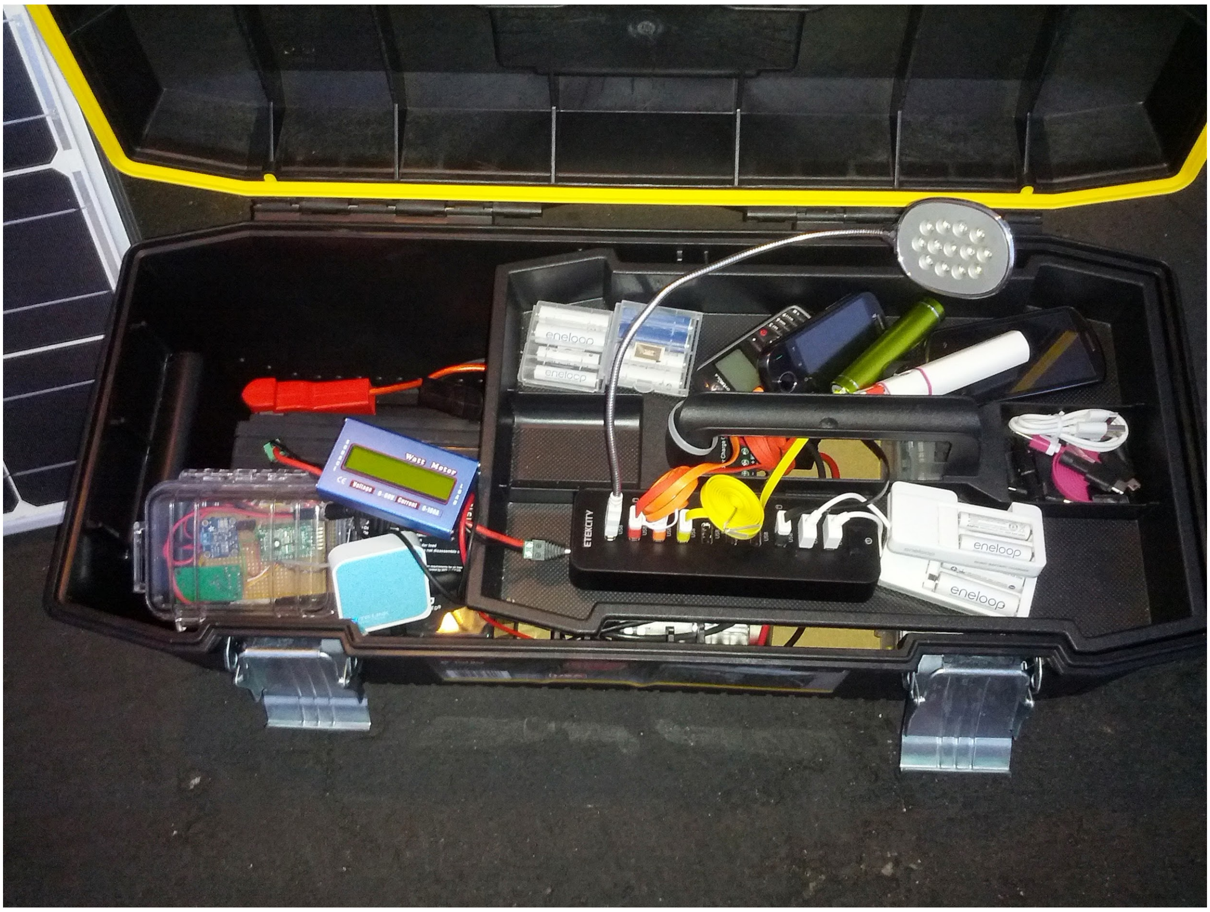

Figure 1. A reference charging kiosk, containing current and voltage sensing and control equipment (left), tray with 10 port USB hub, LED light, phones, batteries, and flashlights (right), battery, charge controller and power distribution unit (below other items), and 100W solar panel (background).

MODELING KIOSK STATE

We model our kiosk as an independent agent, which seeks to maximize the amount of power it distributes and the number of people it distributes power to. However, the kiosk's attempts to maximize these two properties must be balanced by an understanding of the kiosk's constraints, including battery capacity and daily power generation. In order to achieve its goals, a kiosk may modify only the current it allocates to its output ports.

In meeting its goals, the kiosk must avoid several failure cases. The kiosk must maintain reliable operation, that is, the kiosk should be able to provide some electricity to any user whenever they request it. The kiosk should not allow itself to be over-discharged to the point where its low voltage disconnect is triggered and it cannot provide any service at all.

In the following subsections, we describe how the kiosk can independently determine its own state, and use this information, along with predicted and past information about the kiosk's users and solar power generation, to distribute as much power as possible among as many users as possible without damaging itself. For the purposes of our concrete examples, we will consider our 100W solar panel, 35Ah battery, 10 USB port reference design.

Understanding battery state

Our kiosk uses sealed lead acid batteries, a type of deep cycle battery. Deep cycle batteries lose capacity when they are discharged, with the amount of damage done correlated to the depth of discharge in a given cycle, that is, the percentage of available battery capacity utilized before recharging (Thaller and Lim, 1987). Based on manufacturer and independent testing, depth of discharge below 50% is recommended to maximize battery lifespan. The manufacturer of our reference battery reports that a battery regularly cycled with 30% depth of discharge will retain 50% of its original capacity after 1200 cycles, while regularly cycling to 50% depth of discharge reduces the cycle count to around 500. Fully discharging the battery to 100% depth of discharge results in a cycle count of just over 200.

Limiting depth of discharge to the recommended values may not be possible in post-disaster scenarios. The available battery capacity when taking into account depth of discharge is a fraction of the stated size. For example, our 12 Volt, 35 Amp-hour battery should contain 12*35= 420 Watt-hours of power, but if the kiosk constrains itself to 50% depth of discharge, it should use a maximum of 210 Watt-hours of power for charging devices before recharging the battery. For very short deployments where the system lifespan is not a primary concern, the kiosk may permit an increased depth of discharge. However, if the kiosk seeks to maximize total power output over an indeterminate time-frame, ensuring the kiosk will continue to function well into the future, its battery management systems must prevent over-discharge and consider the effects of its past cycles on its present peak battery capacity (Michelusi, Badia, Carli, Corradini, and Zorzi, 2013).

Regulating power consumption

A kiosk's microcontroller uses current and voltage sensors to monitor the state of the battery and the operation of the charge controller. The kiosk can observe both how much energy is taken from the battery, and how much is put back in, allowing it to estimate depth of discharge at all times. During charging, when the charge controller reaches the float stage of charging, the battery will reach a constant voltage and the input current being provided will drops drastically. When the kiosk observes this pattern of behavior, it knows its battery is fully charged and it can reset its 'current depth of discharge' variable to 0. If the power being generated by the solar panel is less than the power being provided through the USB outputs, the battery will discharge. When the kiosk is operating on its battery reserve, it has the goal of discharging at most P_{MAX} Watts of power before charging resumes, where P_{MAX} is defined as:

(1) P_{MAX} = (1- current depth of discharge) * (estimated capacity * permitted depth of discharge).

The kiosk will then apply a current limit on its outputs, using a simple formula for constant current power distribution:

(2) $I_{MAX} = P_{MAX}$ / number of hours until recharge begins

This reserves an equal amount of power for each time window, preventing an advantage to users who can visit the kiosk at less busy times. I_{MAX} may be re-computed at any time, and should be re-computed frequently using the current depth of discharge. This ensures that if users do not use the reserved power in the early evening, later users may use more power in the later evening or early morning. Conversely, even if many users consume the maximum allowed amount of power in the early evening, there will still be power left for later users.

Utilizing Solar Power

Each kiosk should use a solar array large enough to fully recharge its battery bank in a day of sunlight, while utilizing any excess generation to charge user devices during the day. Energy not used to charge either the kiosk's internal battery or user device batteries is wasted, so users should be encouraged to visit the kiosk during the day, when the amount of current being distributed to their phones will be at its maximum.

(3) Total daytime current for users = (total solar generation current - kiosk battery charging current)

Our reference kiosk uses a 100W solar panel to charge a 35Ah sealed lead acid battery. The maximum charging current is 0.3 times the rated capacity. Charging the battery may consume up to 10.5A, or 126W. Therefore, if our kiosk is charging itself as fast as possible, it will not have any surplus power to provide to users. If we were to use a 200W array under ideal circumstances, we could charge the battery as fast as possible, while simultaneously providing 74W to charge user devices. So it is clear that in cases of high user demand, larger arrays will provide a superior daytime experience while maintaining a fully charged kiosk battery to provide a satisfactory nighttime experience.

To provide an ideal daytime charging experience the kiosk must strike a balance between providing power to users and reserving power to charge itself. It may minimize risk, by providing a minimal charging current to users until its own battery is fully charged. Once the kiosk's battery is fully charged, it can provide all solar power received to user devices. This will result in a worse experience for some users, as users who arrive while the kiosk is charging itself will experience lower rates of charging than those who arrive in the late afternoon, when the kiosk is fully charged. However, the kiosk is unlikely to enter evening without being fully charged.

Alternatively, the kiosk may attempt to maximize total power output to user devices, by assuming total power generation today (P_i) will follow solar irradiance models. This approach is based on the idea that power generation today should be similar to power generation yesterday, or power generation one year ago (that is, $P_i \approx P_{i-1} \approx P_{i-365}$). The kiosk may calculate the total expected power generation before sundown, based on models such as the Bird Simple Spectral Model, or by using historical solar irradiance values from historical databases such as those offered by the National Renewable Energy Laboratory. Both approaches allow us to estimate power output in Watt-hours per square meter of solar panels, allowing the kiosk to estimate power it should receive in a given day (Bird, 1986). The kiosk may then operate under the assumption that it will receive that amount of power, allowing it to provide more power in the early mornings, under the assumption that it will 'make up for it' in the afternoon. A simple approach to make such measurements more accurate is to weight them based on the difference between prior observations and prior estimations. So if yesterday's performance was 10% more than the model predicted, we will expect 10% more power today than the model predicts. This will also account for improperly deployed or shadowed solar panels. If yesterday's output was 30% less than the model predicted, today the kiosk will expect only 70% of the predicted power. We can calculate E_i, the power the kiosk expects to generate today, day i, using yesterday's actual power generation P_{i-1} and model-based estimates M_i and M_{i-1}:

(4) $E_i = M_i + (M_i * [(M_{i-1} - P_{i-1}) / M_{i-1}])$

The kiosk may now predict its expected surplus power S_i, by computing:

(5) $S_i = E_i$ - [(1 - current depth of discharge) * capacity in Wh]

The kiosk may now provide unlimited current to user devices until it has distributed close to S_i Watts of power, at which point it introduces strict current limits until its internal battery is fully charged. If the estimated power generation was too high, our kiosk will not be fully charged, resulting in a decreased P_{MAX} and lower nighttime charging rates. However even in this case, the kiosk battery should not be over-discharged, and tomorrow's S_i will be lower, reducing the chance of the kiosk going multiple days without fully charging the battery.

MEASURING USER DEMAND

While our kiosk is able to prevent itself from over-discharging by limiting current provided to users, this also prevents it from determining how much power users would utilize in an ideal world, and how quickly they would use it. When users are not using 100% of the allocated current limit, we can estimate how much power each device uses by observing the increase in power consumption corresponding to a device being plugged into the kiosk, and observing the decrease in power consumption when a device is removed. One option to estimate peak power demand during periods of current limiting is to periodically eliminate current limits, and observe the peak power consumption of the charging devices. An alternative approach, which should be more accurate, is to learn more about the devices we are charging, and their current battery levels at the time of the charge.

One way the kiosk may obtain battery capacity information about user devices is through USB device IDs. When a user connects a mobile phone to the USB hub, the kiosk's Wi-Fi router may receive a USB device ID string, containing make and model information for a particular device. Battery capacities of popular devices are widely available online, or the user may be prompted to enter the voltage and capacity ratings from their device's battery pack into a webpage hosted on the kiosk's router.

Alternatively, the kiosk may request users install an Android or iOS app that report user battery status information to the kiosk. For Android devices, we can use the PowerProfile class to determine the maximum capacity of the device's battery in milliamp-hours (mAh), and the BatteryManager API to determine the device's current battery levels as a percentage of a full charge. For iOS devices, we can use the batteryLevel property from the UIDevice class to determine current battery percentage, and a simple look-up table of Apple device models to battery capacities to determine the maximum capacity of the user's battery. This allows us to express R_i, the power requested by a particular user *i* from the user group *U* as:

(6) $R_i = (1 - \text{battery\_percentage}) * \text{battery\_capacity}$

Even if we are unable to provide a full charge to these users, we can compute R_u, the amount of power required to provide a full charge to all users of the kiosk in the user group U, where a given user *i* visits the kiosk V_i times per day (i.e. a user who visits twice a week would have $V_i = 2/7 \approx 0.28$).

(7) $Ru = \sum_{i \in U} Vi * Ri$

If R_u is substantially more than P_i, the total power generated by the kiosk in a day, the operators of the kiosk may wish to install additional solar panels or increase the kiosk's battery capacity in order to provide a faster charging rate and make it more likely the kiosk can fully charge all user phones.

SIMULATING KIOSK UTILITY

To quantify the utility that a single kiosk can provide to disaster victims, we estimate the power production of a kiosk, and the power demands of users. For the purpose of the simulation, we base our power generation and storage capacity on our reference kiosk (35Ah battery, 100W solar panel) and model user power demand based on common phone models with 3.7V batteries, ranging from Motorola feature phones with 780 mAh batteries, to high-powered smart-phones such as the Motorola Nexus 6 with battery capacities as high as 3220mAh. Assuming all batteries are fully depleted, a user's demand for power would range from 2.886 Watt-hours for featurephone users to 11.91400 Watt-hours for smart-phone users.

Empirical measurements show average solar energy measuring 5.19kWh/m^2/day in the Kathmandu valley, near our deployment site (Pondyal, Bhattarai, Sapkota and Kjeldstad, 2011). Given our 100W panel has a surface area of 0.6471 square meters and an efficiency of 12%, we would expect our reference kiosk to generate about 403 Watt-hours of energy per day, during daylight hours. The kiosk would seek to store 210 Watt-hours of this in its internal battery, sufficient to recharge the kiosk from half capacity to full and permit 210 Watt-hours of nighttime consumption. This leaves 193 Watts-hours of power for charging phones during the day. The kiosk could therefore charge between 16 and 66 phones during daylight hours, and between 18 and 73 phones in the evening, for a total of 34 to 139 users per kiosk per day, depending on smart-phone penetration in the region.

Based on this analysis, our reference kiosk is likely sufficient for the rural areas we targeted, particularly if users tend to own featurephones. In such areas, user experience could most be improved by building additional kiosks in disparate population centers, reducing user travel time to the kiosk. In denser urban areas or refugee camps, being able to provide only 34-139 full charges per day would reduce the effectiveness of a kiosk. As the number of users approaches that threshold, charging rates would decrease, negatively impacting user experience. In such environments, multiple kiosks should be deployed, with supplementary solar and battery capacity apportioned to the kiosks detecting the most unique users.

CONCLUSION

In this paper, we generalize lessons learned from the construction of mobile phone charging kiosks following the April 2015 Gorkha earthquake in Nepal. We develop a set of current limiting rules based on a kiosk's battery state, current and voltage sensors, and solar insolation predictions in order to make solar powered phone charging kiosks more fair and reliable. We outline the rules than an autonomous charging kiosk may follow in order to avoid over-discharge of its batteries, and discuss mechanisms for measuring user demand for power to determine if a kiosk meets the power needs of its users or should be upgraded.

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