UrJar: A Lighting Solution using Discarded Laptop Batteries

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ABSTRACT

Forty percent of the world's population, including a significant portion of the rural and urban poor sections of the population in India, does not have access to reliable electricity supply. Concurrently, there is rapid penetration of battery-operated portable computing devices such as laptops, both in the developing and developed world. This generates a significant amount of electronic waste (e-waste), especially in the form of discarded Lithium Ion batteries which power such devices. In this paper, we describe *UrJar*, a device which uses re-usable Lithium Ion cells from discarded laptop battery packs to power low energy DC devices. To understand the usability of *UrJar* in a real world scenario, we deployed it at five street-side shops in India, which did not have access to grid electricity. The participants appreciated the long duration of backup power provided by the device to meet their lighting requirements. To conclude, we present an ecosystem which consists of a community-level energy shed and *UrJar* devices individually owned by households, as a mechanism for DC electrification of rural areas in developing countries. We show that *UrJar* has the potential to channel e-waste towards the alleviation of energy poverty, thus simultaneously providing a sustainable solution for both problems.

Keywords

computing for development; DEV; ICTD; e-waste; sustainability; discarded laptop battery; lighting device; energy poverty

Categories and Subject Descriptors

B.0 [**Hardware**]: General

1. INTRODUCTION

Over the past decade, several smart grid technologies have been proposed aiming to deliver high-quality, reliable electricity to consumers while simultaneously improving the efficiency of the generation and distribution network [12]. However, there is a significant portion of the world, where grid-based electricity has either not permeated down yet, or is unavailable for significant durations every day. In 2012, 23.9% of the developing world did not have access to grid-based electricity [23], which accounts for 20% of the world population, and includes more than 400 million people in India [33]. India suffers from an electricity deficit of around 8.5% which results in long power outage periods - upto 15-20 hours at a stretch - even in areas which have been declared 'grid connected' [3]. 44.7% of rural households in India do not have any access to electricity [20]. Most of these people cannot afford expensive power backup solutions, thus necessitating a dependence on kerosene oil to power their essential energy needs such as lighting. 43% of rural households in India still use kerosene to meet their lighting requirements [4]. The use of kerosene for lighting has adverse health, safety, economic and environmental implications.

On the other hand, a large amount of electronic waste (e-waste) is created around the world daily, both in developed and developing regions of the world. In the US alone, 142,000 computers are discarded on an average per day [16]. In India, it is estimated that more than 8,00,000 tons of e-waste is generated every year [8]. With an estimated 58,824 registered Information Technology (IT) companies in India as of January 2011, India is increasingly becoming an IT hub [2]. Lithium Ion (Li-Ion) batteries, which power portable devices such as laptops and mobile phones, form a key constituent of e-waste. In 2013, the India operations of just one large multinational IT company resulted in more than 10 tons of discarded laptop batteries[1]. Recycling of Li-Ion batteries is a complex, labour-intensive and costly process, which includes collection, transport, sorting into battery chemistries, shredding, separation of metallic and non-metallic materials, neutralizing hazardous substances, smelting, and purifying the recovered materials [10]. Hence, recycling Li-Ion batteries is not commercially viable. Though efforts are underway at developing new battery designs and improving the efficiency of Li-Ion recycling processes [5], reports [10, 16] estimate that it still takes 6 to 10 times more energy to reclaim metals from recycled Li-Ion batteries as it does to produce these materials through other means, including fresh mining. Despite the difficulty associated with recovering metals from Li-Ion batteries, it has been estimated that as many as 90% of returned phone batteries are in good shape or can be restored with a simple service [10]. These batteries are often discarded because of misdiagnosis of device performance problems. Recently, some entrepreneurs have leveraged this finding as a business opportunity [19,26], wherein they identify batteries which are still usable, and recirculate them (e.g., inside refurbished phones), with or without battery reconditioning.

Battery packs used in laptops consist of Li-Ion cells arranged in a series-parallel configuration. A study on discarded laptop batteries undertaken by us revealed that some of the Li-Ion cells in discarded

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[1]Data communicated through sources inside the organization.

battery packs can still provide a satisfactory terminal voltage level, suggesting that when a battery pack is discarded, not all of its constituent cells are 'dead'. It was also observed that in some cases, the battery pack can be reused directly after removing the battery conditioning circuit, indicating that sometimes battery packs are discarded because of a failure/fault in the conditioning circuit. Therefore, similar to discarded phone batteries, discarded laptop battery cells also have reuse potential. However, unlike mobile phone batteries, this potential has not been exploited. Used laptop battery collection services around the world and in India [11, 14] have had limited success so far, with an estimated collection rate of less than 5% [18]. Therefore, most discarded laptop batteries today end up in landfills or incinerators, which results in an adverse environmental impact.

We believe that novel use cases of discarded laptop batteries can alleviate their environmental impact by creating an ecosystem that has a demand for such batteries. This paper presents one such attempt, embodied in the form of a backup power device - called *UrJar* - that seeks to simultaneously address the problems of proliferation of laptop battery e-waste, and the prevalence of energy poverty in developing countries. It uses discarded but still usable laptop battery cells to power low energy DC appliances. The device is aimed at 'bottom-of-the-pyramid[2]' users, especially people in rural or semi-urban parts with access to intermittent power. *UrJar's* target users are (a) home-owners in rural India, who can charge *UrJar* during the few hours when grid power is available, and (b) roadside vendors with mobile carts, who can charge *UrJar* at home using grid electricity and use it during business hours. The device is primarily aimed at powering a DC light bulb, since lighting represents an essential load for this population. Moreover, it also has provision to power secondary loads such as a DC fan and a mobile charger. To develop this device, we first conducted a survey of lighting solutions being used currently by our target end users in India based on which we identified the design considerations for *UrJar*. We then developed a few prototypes of *UrJar* and evaluated them through real world deployments. The key benefits offered by *UrJar* are: (i) a means to addess the proliferation of Li-Ion e-waste, (ii) a mechanism to meet the essential energy requirements of bottom-of-the-pyramid population in developing regions such as lighting, and (iii) enablement of an ecosystem to electrify rural areas.

2. STUDY OF CURRENT PRACTICES

To understand the current lighting solutions being used by underprivileged people in developing regions, who do not have direct access to grid, we conducted a study with 25 participants. A total of 35 lighting devices were discussed in this study. The aim of our study was to elicit a detailed picture of participants' current and previous lighting devices, including shortcomings of such devices and additional features desired by the participants.

2.1 Methodology

The interviewers walked around a few neighborhoods in Bangalore, India during evening hours to identify participants. Road-side vendors (who were not too busy with their customers) and slum dwellers, who did not have access to grid electricity to meet their ligting requirements were selected as participants. However, the interviewers did not include people meeting their lighting needs using *parasitic* sources, e.g., street lights for lighting their own business area.

Participants were interviewed based on aspects relating to their current and previous lighting devices, including costs, duration of usage, benefits obtained, problems with the devices, and any 'good-to-have' additional features. Two authors who were fluent in Hindi and English conducted the interviews. A majority (17) of the interviews were conducted in Hindi, while two were conducted in English and six in Kannada with the help of a translator. Each interview lasted for 20 to 30 minutes.

All interviews were voice recorded. The interviewers took extensive notes during each interview, and clicked pictures of participants using their devices. All interviews were transcribed, after translation, if required. Both notes and transcripts were used for data analysis. The interview coding and analysis was done in an iterative fashion following methods taken from informed grounded theory [34]. Transcriptions were open coded by one author. Two authors then jointly conducted selective coding to identify themes that were representative of the data.

2.2 Participants

Semi-structured interviews were conducted with 25 participants (21 male, 4 female), during the summer of 2014. All participants were using one lighting device each, except one participant who was using two devices at a time (Fig. 1b). In total, we collected data related to 35 devices, which includes 26 devices that were in use currently by the participants and 9 devices which participants claimed to have used earlier. A majority of the participants (21) were street side vendors, while four participants were slum dwellers. Out of 21 vendors, 10 shops sold food items such as noodles, fruits, sweets and fried snacks, 5 sold tea and cigarettes, and the remaining 6 sold apparel such as clothes and shoes. A majority of the shops (14) were set up on a cart and hence were mobile , while the remaining 7 were set up in stationary tin shacks. The 4 slum dwellings were made up of tin, bamboo, plywood and tarpaulin. The age of the participants varied from 20-45 years, with 5 participants between 20-25 years of age, 4 betwen 25-30 years, 7 between 30-35 years, 6 between 35-40 years, and 3 between 40-45 years old. Only two particpants had an undergraduate degree, while 15 had attended high school and the remaining 8 had only attended primary school.

2.3 Findings

In our study, we found that 23 devices were battery-powered wherein batteries were charged by the participants at home using AC grid power (Fig. 1a, 1b, 1e, and 1g), 5 devices required solar-based DC charging (Fig. 1c, 1d, and 1f), and the remaining 7 were powered directly by fossil fuels such as Liquified Petroleum Gas (LPG) or kerosene oil (Fig. 1h). Based on these sources of power, we categorize the different kinds of lighting devices as explained below.

2.3.1 AC-charged Devices

We found that a majority of the devices (23 out of 35) had two parts - a box carrying a battery and charging circuit (referred to as 'UPS' by the participants), and a light source (CFL, LED, or tube lights). The participant charged the device at home using AC power from the grid. 15 out of these 23 devices were 'CFL powered by battery' where the CFL and the battery were separate units (Fig. 1a, 1b, price range = INR[3] 1200-2800, mean price = INR 1917, standard deviation of price = INR 525.70), 5 devices were 'emergency lights' where the light and the battery were packaged together (Fig. 1b, price range = INR 350-2000, mean price = INR 1188, sd = INR 721.40), 2 devices were 'LED powered by battery' (Fig. 1e, priced

[2] A country's poorest socio-economic group

[3] Indian National Rupees. 1 USD is approximately equal to 60 INR.

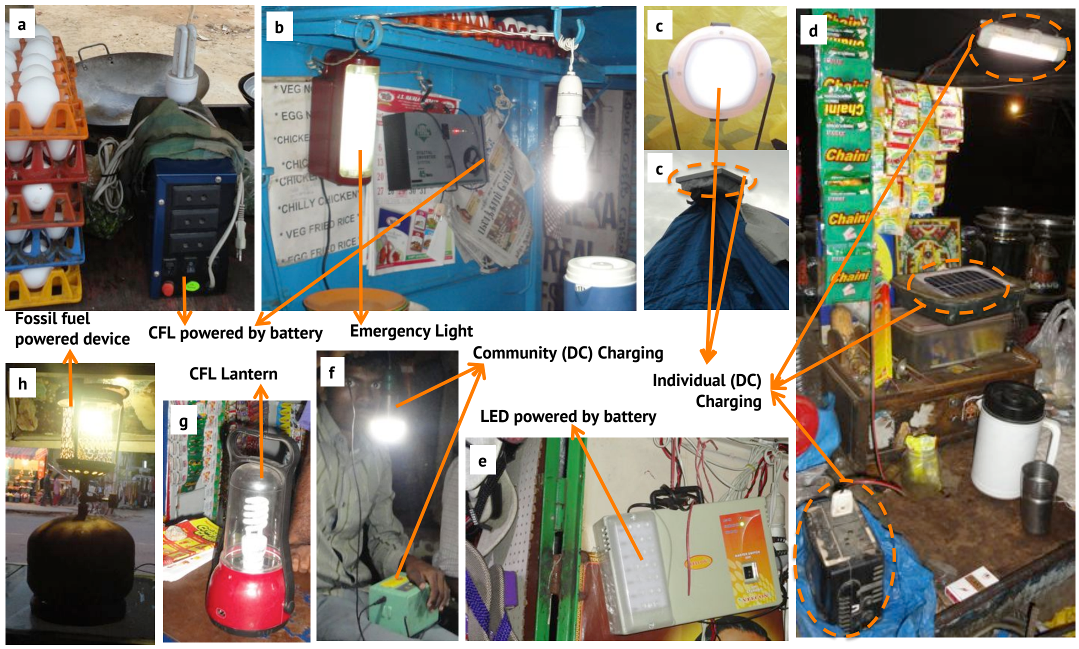

Figure 1: Current lighting devices

at INR 1000 and INR 2000 respectively), and one device was a 'CFL lantern' (Fig. 1g, priced at INR 1400).

CFL powered by battery: All the participants using CFL powered by battery were street side vendors, who were using it for the last 3 to 48 months (mean = 12.1 months, sd = 14.1 months) from evening till late night for 2.5 to 6 hours (mean = 3.7 hours, sd = 0.9 hours) daily. Participants were satisfied with the long battery life, which they reported to be between 6 and 12 months. All of them charge the battery for 5 to 7 hours overnight at home. There was significant variation in the power rating and the cost of the CFL. The power range was 3 to 25 W (me = 9.5 W, sd = 5.9 W) and the cost range was INR 150 to 230 (m = INR 170.5, sd = INR 25.6).

All the users in this category expressed a high level of satisfaction with their lighting devices, due to "*minimal maintenance*", "*no problem so far*", "*12-months warranty*", and "*multiple power outlets at the back, hence can use for mobile charging and/or radio*". However, none of these participants used the battery for powering multiple lights or for any other use besides lighting, as they were concerned about the potential reduction in backup power availability duration. Six of these participants moved from fossil fuel based lighting solutions (Section 2.3.3), and were satisfied with the associated reduction in cost, ease of recharging the device, and longer life of the lighting device.

There were two problems reported by the users of CFL powered by battery. Firstly, the battery inside the box needs to be replaced every year, which costs INR 600 to 900. Secondly, the power backup duration was not sufficient in some cases, as "*even with 5 to 6 hours of charging, it only works for 3 to 4 hours*". One of the participants mentioned that the battery pack broke when it was dropped by mistake, forcing him to buy a new device (Fig. 1e), while another participant had connected an external audio speaker to this device at home, which resulted in speaker malfunction, "*may be due to a short circuit*". Another interesting observation was that a majority of these participants (12 out of 15) had hidden the battery from view by placing it behind the cart, behind bisuit jars, below the shelf, *etc.*such that only the CFL bulb portion of the device was visible. They mentioned two reasons for this: (a) the battery boxes were not aesthetically-pleasing, and (b) they were expensive, hence were not safe to be left in the open.

Emergency Light: Five participants shared their experience with emergency lights (packaged light and battery unit), which they were using for 2 to 36 months, for 1.5 to 4.5 hours per day, after charging for 6 to 7 hours per day. The major issue reported with these devices was their life, as they usually "*lasted only 3 to 5 months and come with no warranty*", which makes it expensive. Another issue reported was the short backup power duration, with one participant switching from *emergency light* to CFL powered by battery, as "*it (emergency light) used to get over in 2.5 to 3 hours, hence forcing the shop to be closed earlier in the night than desired*". Also since this device is a single packaged unit, the entire unit would need to be replaced even if only the light failed. Another complaint reported by two participants was that, "*it can not be hanged from the roof, hence the spread of light is limited*".

LED powered by battery: We found two different kinds of devices being used in this category. The first device had 3 parts - a central unit with a 7x3 LED light array (Fig. 1e) and two separate 7x3 LED arrays which were connected to the central unit with wires. It also had outlets for mobile charging. The second device was a single packaged unit with battery on the back and a 10x3 LED array on the front. The former was being used by the participant for the past one month for 4 hours per day, after charging for 6 hours per day, while the latter device was being used for the past one year, for 2 hours per day after charging for 6 hours per day. The user of the former device was highly satisfied with the device, while the later complained of small duration of backup power availability and wanted a device which can provide lighting for at least 4 hours per day.

CFL Lantern: We found only one participant using a CFL lantern (Fig. 1g). The device came with a 12-month warranty, and had a 7 W CFL costing INR 150. The participant was using it for the last 7 months for 3 hours daily, after charging for 6 hours per day. The major issue reported was the insufficient duration of backup power availability: "*It runs for 3 hours at max, because of which I have to close my shop by 9 (PM). Ideally I would like something which works for 4 to 5 hours*" Moreover, he expressed a desire for power outlets for mobile charging and radio. Besides these issues, the participant was satisfied with the product, mentioning that there were "*no problems so far*" and that the device was "*very durable*".

2.3.2 DC-charged Devices

Out of the 35 devices surveyed, 5 devices were charged by DC electricity using renewable energy from solar panels. All such devices had multiple parts - a solar panel, a battery, and a LED light (usually a 5 W LED bulb). Three of them were charged using community level solar panels (Fig. 1f), while remaining two were charged using individual solar panels (Fig. 1c, and 1d).

Community Charging: Community charged solar-based lighting devices were provided by SELCO [30] in a slum community of 40 residents. We interviewed three residents to understand SELCO's model. SELCO has appointed a *community supervisor*, whose role is to maintain the community charging station, which has 6-large solar panels on the roof. The community supervisor collects batteries (green-colored box in Fig. 1f) from each resident in the morning at 6 AM, and connects it to the charging station. In the evening at 6 PM, the supervisor then distributes the charged batteries back to the residents, so that they can connect the LED bulb with the battery to meet their lighting needs at night. The three residents we interviewed were using SELCO's lighting solution for the past 7 to 8 months, and keep the bulb switched on for 12 hours daily (6 PM-6 AM). SELCO follows a subscription-based pricing model, wherein a resident has to pay INR 200 per month for a light source. This price includes complete warranty and replacement of any part(s) of the lighting device; however the hardware is completely owned by SELCO. Such community based battery charging stations (BCS) have been around for 15 years in rural areas of Asia and Africa [22, 35]. All the participants interviewed were satisfied with SELCO's lighting solution as they "*get light during dinner*", "*children can study at night*", and "*it helps in avoiding rats and insects at night*". However, one of the participants complained about the wear and tear of the wire connecting the battery and the bulb, while two participants asked for a way to "*charge mobile phones*". The SELCO supervisor mentioned that with phone charging, the batteries would not provide 12 hours of lighting, hence they could not provide that feature.

Individual Charging: Two participants were using individual solar-charging based lighting devices - Sun King Pro 2 (Fig. 1c) [21] and a locally built solution (Fig. 1d). The local solution was being used by a street side vendor, who had purchased it for INR 3000. It had three parts - a solar panel, a battery, and a light source consisting of an array of 5-LEDs (Fig. 1d). It was in use for a year, with the lighting turned ON for 7 hours (5 PM-12 PM), "*without any issues*". She charges the battery through out the day by keeping the solar panel on the roof of her shop. The device offers a 12-months warranty, including "*a phone number wherein a person will come and fix it*". The other participant was using the Sun King device for the past two weeks. The device has two parts - a light bulb with a 3000 mAh, 3.3 V Lithium Ferro-Phosphate (LFP) battery at its back (Fig. 1c top), and a 3.3 W, 5.8 V polycrystalline solar panel which the participant placed on the roof of his house (Fig. 1c bottom). This participant had switched from SELCO's solution to Sun King due to several reasons - a) cost, as Sun King costs INR 2400 and offers 12-months warranty, "*so even if it lasts just a year, it is the same price as SELCO... also the hardware is ours*", b) it offers two-USB mobile charing points, c) "*no dependency on SELCO people... I can even use it during day time*", d) "*light has 3 levels of brightness*", e) "*comes with a nice stand to fix the light*", f) very compact, and g) aesthetically pleasing. Similar to Sun King, there are many devices available in the market, such as d.light [15], Mighty Light [13], and SunLite [31], which are powered by solar energy and use LED light.

2.3.3 Fossil fuel powered devices

Only one of the participants was using a LPG based *Petromax* device (Fig. 1h); and six participants mentioned that they had used LPG based (three participants) or kerosene oil based (three participants) devices in the past for several years (m = 6.1 years, sd =4.6 years), but had switched to 'CFL powered by battery' devices within the last two years. Though the capital cost of fossil fuel based devices is very low (INR 300 to 600), the fuel cost as mentioned by the participants varied from INR 25 to 40 per day (*i.e.*, INR 750 to 1200 per month). Apart from a high fuel cost, participants also complained of maintenance issues with these devices, including "*mantle blows up almost every month... it then costs INR 40 to replace*". Other issues mentioned were "*have to travel 1 to 2 kms every week to re-fill LPG*", "*it is very heavy*", oil/gas is unsafe to use and bad for health, the device is not aesthetic, and "*light is not bright enough for children to read... or use for education*".

3. DESCRIPTION OF URJAR

In this paper, we differentiate ourselves from the above mentioned technologies by focusing on the e-waste problem. Our proposed solution re-uses discarded laptop batteries to address the energy poverty prevalent in developing countries. The design, construction and evaluation of *UrJar* is the key contribution of this paper.

We first report findings from an experimental study to quantify the reuse potential of discarded laptop batteries. Next, we list key attributes obtained from study of current lighting devices, which were considered while designing the proposed device. This is followed by technical details of *UrJar* prototypes, that were built for the evaluation studies described in Section 4.

3.1 Reusing discarded laptop batteries

Continued use (cycling) of batteries reduces the maximum amount of charge that they can hold at any one time. This maximum level is also known as the *charge capacity* of the batteries. When the charge capacity of a laptop battery pack falls below a satisfactory threshold, the user discards it and replaces it with a new battery pack. In order to find at what charge capacity laptop batteries are usually discarded, we performed an experiment. We tested 32 laptop battery packs that were discarded by a business division of a large multinational IT company in India. Each of these battery packs had been used for at least 3 years. We used the WMI Code Creator tool in Windows [7] to test the residual charge capacity of these packs. 15 battery packs were from the Lenovo Thinkpad T60 series, and the remaining 17 were from the Lenovo Thinkpad W500 series. Each pack was in a 6-cell configuration with a rated charge capacity of 85 Wh. Fig. 2 shows the charge capacity as a percentage of designed capacity for the investigated laptop battery packs. We found that although there was a significant variation in the residual capacities, the mean value was 64% while the median was 73%. The mean value corresponds to more than 50 Wh of capacity for the batteries tested, which is sufficient to power a 3 W LED light bulb, a 6 W DC fan and a 3.5 W mobile phone charger simultaneously, for around 4 hours. Therefore, discarded laptop batteries appear to have satisfactory potential for reuse as backup energy sources to power low energy DC devices.

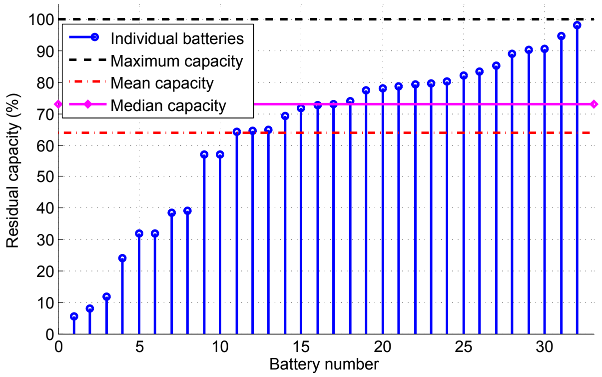

Figure 2: Residual capacity of a sample of discarded laptop battery packs

3.2 Design considerations for UrJar

We exploit the above finding by proposing an energy backup device, *UrJar* (*urja* + *jar*). Here, *urja* is the *Hindi* word for energy and *jar* represents a box. Hence the name *UrJar* reflects the fact that it is a box which provides energy (by re-using discarded laptop batteries) to run essential devices such as lights, fans and phone chargers. The key design considerations for such a device are listed below. Some of these considerations are based on findings from the study in Section 2.

Lighting: *UrJar* should primarily meet lighting needs of around 6 hours daily. It should also allow the user to meet other secondary needs such as mobile charging.

AC/DC charging: Depending on user's requirement, *UrJar* should allow charging from an AC power source or a DC power source. A rural household might not have access to grid and hence needs a solar based DC charging, while a street-side vendor in a city might have electricity at home and hence would prefer AC charging. A high charging efficiency is also desirable.

Minimize conversion losses: Each of the appliances that can be connected to *UrJar*, such as a light, fan and phone charger, should be DC so as to minimize conversion losses. Ports with appropriate connector pins should be provided to allow users to connect appropriate DC devices to *UrJar*.

Modular design: *UrJar* should be made up of multiple modular parts, so that each part is easily replaceable, instead of buying the whole product again. For instance, in case of 'emergency light' (Section 2), even if the light fails, the whole unit needs to be replaced. Moreover, multiple parts would enable hanging the light separately from the device resulting in wider spread of light, and would allow hiding the aesthetically non-pleasing device parts.

Pricing: It is a well known fact that people at the 'bottom-of-the-pyramid' usually pay higher prices for basic goods and services compared to wealthier people [25]. We found participants spending around INR 800 per month just for re-fuelling fossil fuel based devices to provide lighting for 3-5 hours per day. Hence, they were comfortable spending INR 2000 to INR 3000 (USD 40 to USD 55) for battery based lighting devices with one year warranty, providing the basic necessity of uninterrupted light for 3 to 6 hours after recharge. An interesting finding from our study was that for the same total amount of money, participants preferred paying in one lump sum as opposed to multiple recurring weekly or monthly payments. Based on this finding, it is desirable that *UrJar* should have minimal recurring cost component associated with it. Also, *UrJar* should have a smaller one-time cost than that of the existing battery based lighting devices to facilitate its adoption by users.

Clear instructions: A list of appliances that can be plugged into *UrJar* should be clearly marked to prevent malfunctioning of the device and/or the connected appliances.

Safety: The device should have appropriate safety features built-in to minimize risks such as fire hazards associated with Li-Ion batteries [6].

Portability: *UrJar* should be light weight and portable so that users such as street side vendors can easily carry it from their shop to their home for charging.

3.3 Prototypes built for evaluation

A few protypes of *UrJar* were built based on the abovementioned design considerations (Figures 3, 4 and 5) using the following steps:

Step 1: Source used laptop battery packs from e-waste.

Step 2: Disassemble packs to extract individual Li-Ion cells that can still deliver power.

Step 3: Connect re-usable cells to build a refurbished battery pack.

Step 4: Build a box which contains a charging circuit for the refurbished pack, step-up/step-down converters and other electronics to power extrenal devices such as a LED light bulb, a DC fan, and a mobile charger.

These prototypes have the following features:

Appliances: The prototypes power a DC light bulb (LED), a DC fan and a mobile charger.

Refurbished battery packs: Refurbished battery packs were built by extracting Li-Ion cells from discarded laptop batteries exhibiting terminal voltages of more than 3.7V. The cells were arranged in a 3S2P configutation, and the refurbished pack delivers DC power at around 12 V.

Battery charger: A 6W charger based on FSEZ1216 IC from Fairchild Semiconductor [17] is used as the off-line battery charger. The IC uses primary-side sensing which reduces the number of components enabling a compact design. The IC was chosen from a readily available inventory since it provides Constant Voltage and Constant Current control which is ideal for battery charging. The charging efficiency is close to 75%. Charging current is limited to 500 mA to ensure that batteries are not damaged due to higher charging currents. Since these batteries are not new, their ability to handle abuse is reduced and therefore, charging cut-off is kept between 4.0 to 4.1 V per cell.

Mobile charger: A sychronous DC-DC buck converter operating at 1 MHz is used for conversion from battery voltage to 5V needed for mobile charging. The output is a constant 5V output with a maximum current of 1A. Since the current is small, a sychronous regulator with internal MOSFETs is used. This reduced the footprint for the mobile charger. Operating at 1MHz reduced the power inductor size and current handling requirements. The efficiency of conversion was close to 90%.

Fan: Brushless DC motor based personal table fan is used. A similar buck converter topology, as above, with higher current is used.

Light: A buck regulator in continuous conduction mode is used for buck regulation. The regulator uses a current sense of 100 mV to precisely regulate LED current. High Power, high efficiency LEDs with 120 degree beam width is used. A frosted shell minimises glare. The regulator output drives three 1 W LED bulbs in series, housed in a 3 W LED bulb enclosure, at 100mA. A single LED driver at 350 mA could be used to lower costs further.

Cost: At a volume of 1000 pieces, we estimate the bill of material cost for each of these protoypes to be around INR 600. The pricing includes the enclosure, electronics, a 3 W LED light bulb, and a mobile charger but does not include a fan.

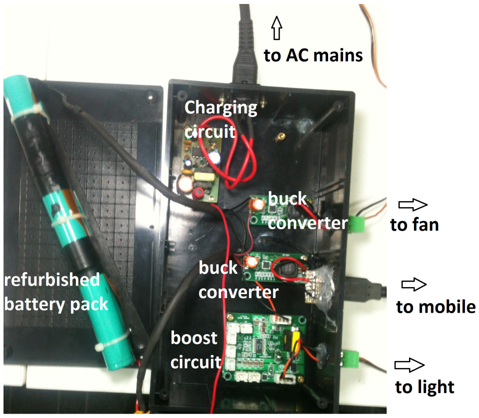

Figure 3: Component details of an *UrJar* prototype built using discarded laptop batteries.

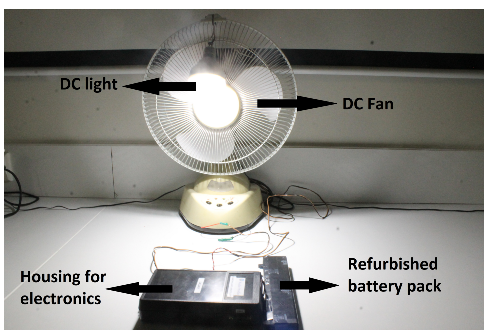

Figure 4: An *UrJar* prototype with DC appliances connected.

4. FIELD EVALUATION

To understand the usability of *UrJar* in a real-world scenario, we developed three prototypes of it (Fig. 5) based on the design described in Section 3. The number of prototypes built was limited due to cost constraints. The prototypes were handed to five participants to be used in unsupervised settings for one week or more. Four participants were interviewed after a week of usage, while one participant was interviewed after 3 months of usage as initially we only had one prototype of *UrJar*.

4.1 Methodology

This study was conducted in three stages. First, each participant was asked to connect the three separate parts of UrJar - circuit box (black-colored box in Fig. 5a), laptop battery (the green colored bar in Fig. 5a), and the LED bulb - as per their intuition. Second, participants were given a 15 minute training on the device, including how to use it, how to connect the three parts, and how to charge it. After the training, they were handed *UrJar* to be used in a completely unsupervised setting for one week or more. Third, after a week (3 months for one of the participants), two authors who deployed *UrJar* at the first place, conducted a 30 minute long semi-structured interview. The interview questions primarily focused on

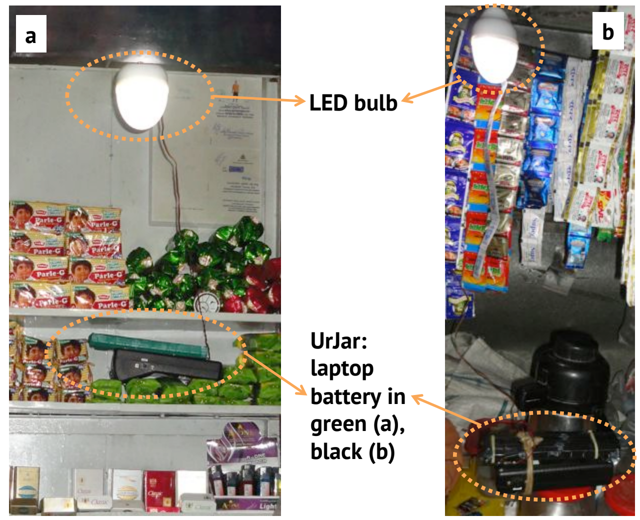

Figure 5: *UrJar* protoypes deployed at street-side shops in India.

the users' experience with *UrJar*, including usage time, charging time, benefits, problems, shorcomings, additional 'good-to-have' features, and the amount of money they were willing to spend to buy it.

Five participants were selected for this study from the participants who participated in study of current lighting devices in Section 2, and were interested in using a 'new' lighting device protoype for a week and provide feedback. We selected these participants from different groups based on their current lighting devices, one each from CFL powered by battery, Emergency Light, CFL Lantern, Community DC-charging, and Fossil Fuel powered device.

The same two co-authors who previously conducted state-of-the-art interviews also conducted this deployment study. Two interviews were conducted in English, one in Hindi, and two in Kannada. Interviews in Kannada were conducted with the help of a translator. The same methodology as that described in the interviews in Section 2 was used to conduct, record, and analyze these interviews.

4.2 Participants

Five users (4 male, 1 female) participated in this study. Only one was a residential consumer, while the remaining were street-side vendors - two of them selling fast-food items, and two selling tea and cigarettes. One participant was between 20-25 years of age, three between 30-35 years, and one between 40-45 years. Two participants had an undergraduate degree, while one went to higher school, and two had only attended primary school.

4.3 Findings

The first *UrJar* prototype was provided to a female tea and cigarette vendor, who has been using it for 3 months now (Fig. 5b). Even after 3 months of usage, she was very happy and satisfied with *UrJar*, as it had "*no problem at all*". The remaining two prototypes were rotated among four participants for a week each. Each participant used *UrJar* for 4 to 6 hours daily, except one who used it for 12 hours daily. Similar to CFL powered by battery, all the participants liked the mobile charging feature of *UrJar*, but no one used it for actually charging their phones. All, except one, participants were satsified with *UrJar*. When asked how much they were willing to pay for it, they claimed that they were willing to spend INR 1000 to buy the device with 1-year warranty. The key aspects described by the participants based on their experience of using *UrJar* are summarized below.

Long Lighting Hours: The major benefit of *UrJar* mentioned by participants was long lighting hours after a single recharge. Three participants explicitly mentioned and appreciated this. For instance, "*my (previous) emergency light needed charging everyday; with just one day of charge, UrJar works for 2-3 days, from 6:30 to 11 PM*" Another participant who was initially hesitant to replace his CFL lantern with UrJar due to UrJar's low brightness, finally replaced it due to UrJar's long backup hours. The CFL lantern required charging every day, while UrJar worked for 2-3 days with one charge. Moreover, "*the lantern only used to last for a maximum of 2.5 hours daily, and hence I had to close my shop by 9 (PM)...now with UrJar I can keep it open until 11 PM*".

Brightness: Two participants mentioned that the brightness provided by *UrJar* was greater than their previous lighting solutions, *i.e.*, emergency light and CFL powered by battery, while the other three participants complained of *UrJar's* low brightness. One of the food cart vendors who used LPG based light, needed more brightness "*to attract customers*". Moreover, he claimed that he willing to pay only INR 500 for *UrJar* with the current level of brightness, but was willing to pay INR 1000 with a brighter bulb.

Connecting Parts: Three out of five participants were able to correctly perform the first task of connecting the three parts of *UrJar* without any help. After the training, all the participants were able to perform the connections easily, and even mentioned that the device was "*easy to use*".

Customizable and Usable: As *UrJar* was loaned to the participants, they took extra care of the device, and even implemented simple work-arounds to make it more usable. For instance, tying the circuit box and battery together using a coconut rope (Fig. 5b), so that both the parts are easily carried back home for charging purpose. Three participants hid the device behind shop items, may be due to aesthetic reasons or to pevent theft.

Overall, the participants mentioned that *UrJar* is safer, cheaper, and easier to use, compared to their existing solutions. However, they asked for features such as increased brightness, thicker connecting wires so that "*rats cannot cut them easily*", option for plugging a FM radio, and a more durable enclosure.

5. DISCUSSION AND ADDITIONAL CONSIDERATIONS

5.1 Additional design considerations

Based on the evaluation study, the following list of design impications were derived for future improvement to *UrJar*:

Higher durability: Participants complained of rats cutting wires in their house, mishandling of lighting devices at home by children, and fear of breaking the device while moving the mobile cart or carrying the device back home for charging. Hence, *UrJar* should be highly durable, with minimal maintenance. Moreover, even the connecting wires and connectors should be of high strength.

Low battery and dead battery indicators: Using battery capacity sensing technology [9], low battery indicators can be provided. This would allow the user to accomplish timely charging before the battery completely drains out. Besides low battery cut-off indicators, dead battery cell indicators can also be included. These indicators can be implemented by comparing the current maximum state of charge achieved by a cell at the end of a full charging cycle to its design state of charge. If this ratio is less than a predetermined threshold (e.g. 10%), the cell can be deemed dead and an LED light can be made to flash to indicate the user to replace it. This feature is especially useful since recycled batteries have high capacity variations (see Fig. 2).

Pleasing aesthetics: As the current version of *UrJar* is a proof of concept, it was not in a product form during the deployment study. In most of the shops, we found that only the light was visible to the customers, while lighting device and battery were hidden. This could be because of aesthetic reasons. Hence an aesthetically pleasing device might be appreciated by street-side vendors, especially shops selling apparel.

Support: As most low-income people can not read English, the product manuals should be figure-based, or in the local language of the region where the product is being sold. Moreover, instruction sheets should contain all details, including steps to connect the different parts of *UrJar*.

5.2 Variants of UrJar

Apart from the version of *UrJar* described in Section 3, several other variants are possible by including one or more of the following features. It should be noted that the addition of these features can increase the cost of the device. Therefore, an economic analysis should be undertaken before incorporating any such feature(s).

Direct solar charging: The prototypes described in Section 3 are charged using AC power. However, a version which allows direct DC charging can be built. This could be useful to enable the ecosystem described in Section 5.3, with solar-based community charging station, as is becoming common in India [27]. The direct DC charging circuit would primarily entail appropriate voltage step up or step down converters which are easily available.

Other types of battery packs: Although the prototypes were built using discarded laptop batteries, other types of batteries, including discarded cellphone batteries can be used after appropriate modifications to the underlying hardware of *UrJar*. Similarly, new batteries can also be used instead of discarded batteries in situations where the requirement of having reliable power acquires greater importance than the cost of the solution. Instead of a small battery pack, a larger battery rack could be built where different batteries can be mechanically mounted and energy can be pooled from them to power external devices. This setup can be advantageous because it provides redundancy.

Inclusion or removal of one or more DC devices: The prototypes described in this paper were built to power three specific appliances - a light, a fan and a mobile charger. However, the modularity of the circuit design (Fig. 3) facilitates easy addition or removal of one or more appliances. For instance, if in a particular climate zone, the fan is not needed, the step down converter for the fan can be mechanically removed without affecting other parts of the circuit. Similarly, if an additional light bulb is needed, another step up converter can be easily added. Other appliances, for instance electronic mosquito bats [1], can be included in a rural setting to keep flies and insects away from infants while parents are working in the field.

5.3 Ecosystem for rural electrification

Rural electrification is a costly affair, with the World Bank estimating the cost of extending the grid to be between USD 8,000 and USD 10,000 per kilometre [29]. In recent years, there has been a sustained downward trend in the cost of solar energy [24], coupled with an upward trend in the cost of grid extension (due to factors such as increasing cost of raw material [28]). These developments have created new and promising opportunities for implementing innovative and economically viable energy ecosystems in rural areas of developing countries. Here, we describe one such en-

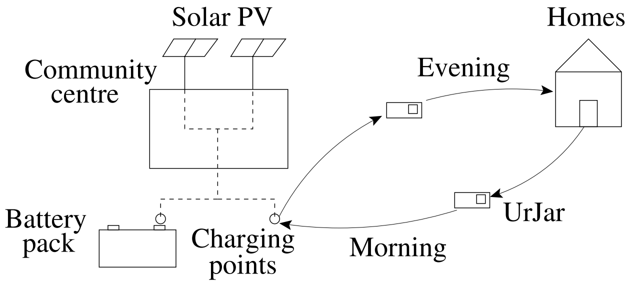

Figure 6: Illustration of system architecture

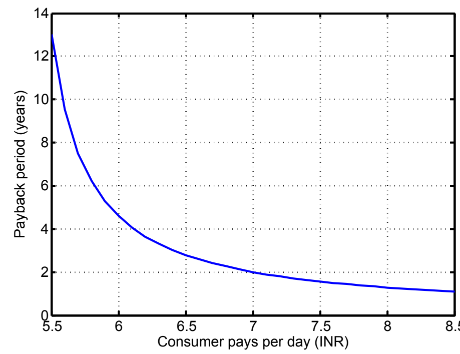

Figure 7: Estimated payback period for given user price per day

ergy ecosystem which leverages *UrJar*. The system architecture for this solution is described, followed by a cost analysis of the system components.

5.3.1 Ecosystem architecture

The architecture of the described eco-system is illustrated in Fig. 6 which is similar to the SELCO model. It consists of a centrally located community charging station and a set of *UrJar* devices. A community charging station is a facility that can provide power at certain times of a day. Such a station would consist of three parts: (i) a source of energy, for example an array of solar PV panels, (ii) power electronics to output power within a prescribed voltage range, and optionally (iii) batteries to store energy if needed. The most common manifestation of a community charging station is a solar powered station, but other manifestations could also exist such as a bank of one or more diesel generators, or wind turbines. The specific choice of the community charging station would be dictated by factors such as renewable potential of the region, capital cost, operating cost, environmental emissions, ease of hardware procurement, and ease of setting up. In the described ecosystem, each household served by the community center can be given an *UrJar* device, which they can recharge from the charging station for a nominal fee.

5.3.2 Cost analysis

We denote the capital cost needed to set up the charging station as x_1, and the operational cost (including maintenance cost) as x_2 per year. Suppose there are n households in the village, and each consumer is provided an identical *UrJar* device, with battery capacity of C_B Wh (assuming one battery pack per household), cost p, and residual lifespan of N years. We assume that the capacity is sufficiently large so that each consumer only requires 1 trip to the charging station per day. Each consumer is charged at the rate of c per Wh of energy withdrawn from the station. Battery charging efficiency is denoted as η_B.

Let y be the number of years to reach the break even point for the investment (we assume y to be less than 20 years - which is taken as the life span of the solar panels):

$x_1 + x_2 \cdot y + n \cdot p \cdot y/N = n \cdot C_B \cdot c \cdot 365 \cdot y/\eta_B$

The left hand side denotes the cost factors and the right hand side denotes the income factor. Assuming a new 6 cell laptop battery pack provides 48 Wh and that the battery pack is discarded at 60% of the battery capacity when given to the consumer: $C_B = 0.6 \times 48 = 28.8$ Wh.

Capacity of charging station needed, assuming each consumer brings *UrJar* completely discharged to the charging station: $C = \frac{C_B \cdot n}{\eta_B} Wh = \frac{28.8}{0.8} \cdot n = 36n$ Wh.

Therefore, the capital cost incurred for setting up a charging station,

$$\begin{aligned} x_1 &= \text{Solar system cost in USD per W} \\ &\quad \times C/5 \text{ (assuming 5 hours of sunshine)} \\ &= 3 \times 36n/5 = 21.6n \end{aligned}$$

Annual maintenance cost for the charging station at 5% of capital cost $x_2 = 0.05 \times 21.6n = 1.08n$.

Further, we assume that the cost of *UrJar* provided to each household is p = USD 10 (an estimated price at high production volumes), and life span of each discarded battery pack is N = 0.33 years.

Hence, the break even point can be calculated using the following relationship (assuming $\eta_B = 100\%$)

$$\begin{aligned} 21.6 \cdot n + 1.08 \cdot n \cdot y + 10 \cdot n \cdot y/0.33 &= n \cdot 36 \cdot c \cdot 365 \cdot y \\ or, y &= \frac{21.6}{13140c - 31.08} \end{aligned}$$

Figure 7 depicts this relationship visually for the parameters selected above and shows that even a moderate payment of INR 6.5 per day by users can lead to a fairly quick return of 3 years on investment. For comparison, a family in an un-electrified rural India may spend between INR 5 - 15 per day on kerosene for lighting alone.

With regard to the energy ecoystem described, we predict a few initial operational challenges because it proposes a new paradigm for rural electrification. Crucial steps towards effective implementation include but are not limited to development of hardware for large-scale charging of battery packs, the design of the *UrJar* devices, methods for sorting discarded batteries, and the supply chain for discarded laptop batteries. Social acceptance of the solution will need to follow an adjustment period as people adjust their schedules to include daily trips to the community centre. The cost of logistics such as collection, storage and distribution of the devices also needs to be considered. Finally, the financial models for providing the devices and the charging tariffs will need to be tuned to suit local needs. For example, it may be necessary to subsidize the initial cost of *UrJar* in exchange for a slightly higher charging tariff, thus encouraging faster uptake of the technology.

We note that the cost analysis presented above represents back-of-the-envelope calculations with several assumptions. In particular, it does not consider any costs associated with logistics such as distribution and support related to the large scale handling of *UrJar*. A more accurate economic analysis inclusive of such factors would be attempted in future.

5.4 Benefits of UrJar

UrJar has the potential to provide the following benefits:

Environmental benefits: It attempts to mitigate the environmental and economic issues associated with e-waste in the following ways. Firstly, *UrJar* provides a means to utilize the latent residual capacity in laptop batteries, which would otherwise be wasted even if these batteries were properly recycled. Therefore, using this capacity can lead to a reduction in new battery capacity needed for energy needs. In particular, large scale adoption of *UrJar* can result in a reduced proliferation of e-waste from lead acid batteries which is more environmentally disparaging than Li-Ion e-waste. This is because during our study of existing devices in Section 2, we observed that a majority of the participants surveyed used lead acid battery based lighting devices. Secondly, if this technology is adopted commercially at a large scale, it can incentivize organized collection of e-waste. In 2012, despite the presence of around 77 e-waste recycling companies in India with a collective recycling capacity of 2,30,000 tonnes, these units ran significantly below their full capacity due to poor e-waste collection rates [8]. Around 95% of e-waste collection and recycling in India is still handled by the informal sector consisting of local garbage dealers, which poses safety and health problems since hazardous processes are involved in the recovery of recyclable parts and material [8]. Thirdly, *UrJar* provides a cleaner and potentially cheaper alternative than burning kerosene in order to meet lighting requirements. The use of kerosene poses safety concerns due to the risk of a fire hazard, health concerns because of the risk of tuberculosis by exposure to carbonaceous particulate matter and environmental concerns because each litre of kerosene, when burnt, results in 2.76 kg of greenhouse gas emissions [32]. In the context of the above benefits mentioned above, we note that an organized mechanism for collection of discarded *UrJar* battery packs is also needed to avoid the risk of these batteries being discarded individually by users through the informal sector. One way of achieving this is to provide monetary incentivies to users when they return such batteries to organized e-waste recycling units.

Business benefits: It offers potential business opportunity to companies which are engaged in rural and semi-urban electrification missions. The device does not require much capital investment and is easy to build. Although Li-Ion batteries are more expensive than other commonly used battery types such as lead acid, the fact that *UrJar* uses discarded Li-Ion batteries makes it a low cost alternative. Also, Li-Ion batteries inherently have a high charge density. This feature renders it compactness and a light weight, therefore enhancing its portability. *UrJar* can also provide economic benefits to users. For instance, a user can rent the device in fully charged state to another member of his community for a tariff, if he does not need to use the device for a few days (e.g., due to a travel).

Energy efficiency benefits: *UrJar* is a highly energy efficient device as it uses Li-Ion batteries, powers DC appliances, and in particular uses LED bulbs. Li-Ion batteries can sustain a higher depth of disharge than lead acid batteries, which implies a longer backup power duration before the need to charge again as well as longer life cycle. Also it powers low consuming DC appliances, and hence has a higher energy efficiency than other backup devices which are used to power AC appliances. This is because the latter require a DC to AC converter which usually has low conversion efficiency. The protoypes of *UrJar* built were used to power LED light bulbs which have a longer life cycle, as well as lower power requirement than the more commonly used CFL lights. This is expected to result in a low lifecycle cost of the device.

6. CONCLUSIONS

In this paper, we proposed a low-cost solution called *UrJar* to the problem of unreliable or unavailable electrical power in developing regions of the world. The novelty of this solution lies in the use of discarded lithium ion batteries as the source of energy. These batteries are employed to power lights, and additionaly fans and mobile chargers for the bottom-of-the-pyramid community in developing countries. We first performed a study of various lighting solutions currently being used by our target audience in India. Based on that, we developed *UrJar* prototypes and conducted real world field deployments. We found that the participants were generally satisfied with *UrJar*. To conclude, we described a vision for a community level ecosystem for disseminating and sustaining these devices, thus marrying economic incentives to the technological aspects. A simple calculation shows that judicious selection of the price of energy and the initial cost of the device will provide impetus for widespread dissemination of the technology. A combination of low initial cost, the ubiquity of discarded Lithium Ion batteries, and the economic incentive of increased comfort (or extended business hours) are expected to make this system an attractive proposition for both individuals and communities in developing regions.

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