Power in a Portable World: Usage Patterns and Efficiency Opportunities for Consumer Battery Chargers

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ABSTRACT

Portable functionality has become a principle driver in the marketplace for consumer electronics. Appliances containing rechargeable batteries include rapidly evolving high-tech products such as notebook computers and cellular phones, commodity items such as cordless phones and power tools, and a variety of others, and are becoming pervasive and central tools in our daily lives, with implications for electricity loads related to battery charging. The chargers associated with these devices typically spend the majority of the time in one of several distinct power modes. However, no detailed estimates for the energy consumption or demand characteristics have been developed for battery charging.

This paper combines survey-based usage pattern information and measured load data for the most common battery-powered devices to estimate the impact of small battery chargers in California's residential sector.[1] First, the results are presented for an in-depth survey of 34 California households. Survey results are compared with macro-level penetration estimates and existing assertions of usage patterns from industry and other sources. Second, electric demand was measured for a range of common chargers and rechargeable devices. Together these data sets are used to construct an aggregate load profile for each device type and to create bottom-up estimates for total energy and demand impacts of small battery chargers in California's residential sector. We estimate that there are over 106 million small chargers in California homes, that their peak-coincident load is 160MW, and that their annual consumption is 1600 GWh or about 2.0% of total statewide residential electricity use. Further, over 75% of this consumption occurs when the battery is already fully charged. Finally, fertile areas for potential savings are described taking into account recent developments in battery and charger technologies and the evolution of the marketplace for these devices.

Introduction

Consumer electronics is one of the fastest growing sectors of energy consumption in the U.S., accounting for around half of the growth in so-called "miscellaneous" energy use in the residential sector during the 1990's. Additionally, it is estimated that nearly half 50% of all electronics energy is consumed in standby mode, that is, while not in active use (Sanchez 1998). Within electronics generally, one of the highest growth and least studied areas is that of portable, rechargeable devices; the charging function can be mostly categorized as low power mode (LPM) energy use. However, since devices vary in configuration and some chargers may not possess an active usage mode, we use the simpler term Power Mode (PM). While manufacturers, particularly of high-end items such as cell PDAs and notebooks, may be investing heavily in

[1] The authors wish to thank the University of California Energy Institute for its support of this research, as well as UC-Berkeley's Renewable and Appropriate Energy Laboratory for its assistance. For further information, contact amcallis@socrates.berkeley.edu.

efforts to optimize the power needs of their devices—in order to improve battery autonomy and enable more and better features—less effort is being put towards improving the battery chargers accompanying these devices. Preferences for lower initial costs over lifetime costs or energy efficiency tends to lead to the use of cheap, simple battery chargers, which can be inefficient and may continually draw power whenever they are plugged in, no matter the state of charge of the battery or even the presence of a battery to be charged. Many of these devices (e.g. cordless phones, security systems) are plugged in all the time, so that small efficiency improvements may result in relatively large benefits. This has led to concerns about the potential for very large numbers of cheap, inefficient battery chargers to unnecessarily increase electricity demand and consumption.

Battery charging systems vary widely according to the particulars of each application, in performance requirements, battery chemistry and resultant charge/discharge parameters, safety requirements, and thermal characteristics, to point out just a few dimensions. They have several possible operating modes, complicating the estimation of realistic load profiles. Table 1 defines a few relevant terms, including the three principle power modes for battery chargers.

Table 1. Charger-Related Power Modes

Term	Definition
1. *No-load* Power Mode	Charger plugged in; battery not inserted in the charger (e.g. telephone handset out of cradle). For many devices this mode corresponds to standby. For others (e.g. many shavers) this mode is 0W, equivalent to the disconnected state. For still others (e.g. security systems) it does not apply in practice, since the battery is hard-wired.
2. *Charging* Mode	Charger plugged in; battery inserted in the charger, with charging taking place. Charging will occur after the battery has been discharged during device use. A relatively short time (i.e. hours or fraction thereof) will usually allow full recharge.
3. *Charge Maintenance* Mode	Charger plugged in; battery inserted in the charger, battery fully charged. A continuous small charge may be applied to the battery whenever in place. This mode dominates in devices that are plugged in 24 hours.
Standby Power	By definition, standby power is the lowest of a device's Power Modes. The standby condition varies by appliance and thus lacks specificity; the term is avoided here for clarity, except where used by others.

Battery charging systems consist of two main components: the power supply and the charging circuitry.[2] As with all electronics, battery chargers require a power supply to convert AC mains power to low-voltage DC. A traditional power supply (external supplies are also called wall packs or adapters) contains an iron core linear transformer. Losses are on the order of 40-70% (Ecos 2004). Newer switching power supplies are electronic and operate at high frequency, avoiding the use of a potentially inefficient linear transformer. Switching supplies in general have lower losses than their linear equivalents.

Charging circuitry controls the current and voltage provided to the battery at each moment. The simplest controls provide a constant charge to the battery[3], and thus create the possibility of high proportional losses if the user fails to unplug the device after an appropriate

[2] The power supply may be external or internal to the device. Charge circuitry is usually internal, even on the same circuit board as the rest of the device (e.g. cordless phone). Exceptions are devices that come with a separate battery charger (e.g. power tools).

[3] Simple chargers are usually found with NiCd batteries, though not all NiCd-powered devices have "dumb" chargers, e.g. contractor-grade power tools designed for heavy cycling and quick charging.

time. At the other extreme are sophisticated algorithms that continually tailor the charge to the battery's requirements, which can greatly reduce heating and other losses associated with overcharge. Newer battery chemistries (NiMH, Li-ion or Li-polymer) generally do not allow use of the simplest charge algorithms for reasons of safety and battery health, and their chargers tend to be somewhat more efficient, though there is still room for improvement.

Over 350 million small rechargeable batteries (including sealed lead-acid batteries under 1kg) are sold each year in the US (USEPA 2002, 1). For example, annual U.S. sales of cordless phones are around 43 million, and each has a small rechargeable battery pack, usually nickel-cadmium. The increasing penetration of portable computing and communications devices, cordless power tools, personal care items and other rechargeable appliances is notable as well. However, reliable and/or disaggregated energy usage data for these devices is rare. The Department of Energy Residential Energy Consumption Survey (RECS) includes just one category for all rechargeable devices, and underestimates their actual quantity. The 2001 RECS reports only 48 million "rechargeable appliances" in use in the US in 2001 (DOE RECS 2001, Table HC5-7a); this is roughly equal to the number of cordless phones sold in that year alone.

The earliest study of the standby power use of battery-operated consumer appliances measured instantaneous power draw for 56 products with embedded chargers, including telephones, personal care devices, power tools, retail battery chargers and home security systems (Floyd and Webber 1998). The authors found a range of several watts within each category, with an average demand of 3.1W across all rechargeable devices measured. An extensive survey and measurement project in Australia found an average standby power of 1.9W for rechargeable devices; this study reported ownership of 3.5 rechargeable devices per home (Harrington 2001).

Ross and Meier used a "whole-house" approach to identify standby loads in ten Bay Area homes, and determined that total standby power (from all devices, not just chargers) accounted for an average of 9% of annual electricity usage (Ross & Meier 2001). Two other standby power studies included some rechargeables in their estimates of overall standby consumption (Sanchez et al 1998; Lebot et al 2002). None of these studies examine the usage patterns of particular device types. A 2002 roundtable on standby power identified energy consumption by battery chargers as an important research gap, and noted that behavioral issues—i.e. how people use these devices—were in particular need of investigation (ACEEE 2002; Meier 2002).

Only through systematic measurement and reporting will researchers establish such energy consumption figures for each appliance type, and only then will potential savings be quantifiable with a known level of uncertainty. This paper provides some insight into the level and character of electricity demand by consumer devices that utilize small battery chargers.

Methods

Three of the key steps for developing a bottom-up estimate of appliance end-use consumption are (Rosen 2001):

1. Estimate typical usage patterns, i.e. how much time the product spends in each mode
2. Collect power measurements for the most commonly used modes for each product
3. Estimate the number of units in the California residential sector

This paper focuses on these steps for consumer battery chargers. In particular, we focus on understanding the behavioral issues around rechargeable devices. Information on penetration rates and typical usage patterns is essential to understanding the system wide impact of charger-based appliances, but little is known about this component of the equation.

To fill this gap, we developed and applied a survey to a random sample of 34 Bay Area households (HHs). While the sample is not so large as to have statistical power, it includes a reasonable range of household types and electricity consumption levels, so that it should help to develop understanding of ownership and usage patterns of battery-powered devices in U.S. homes. Electricity consumption data was available from PG&E for 30 of the 34 respondent households; this information was used to verify the representativeness of the sample population and to examine the relationship between charger consumption and household totals. In addition, we measured the power draws in the three power modes for a group of 85 new and in-use rechargeable devices. Finally, we assembled market and usage data for each device of potential interest from a variety of sources including trade associations, manufacturers and publications.

The survey tool was pretested in winter of 2003, and modified to improve question clarity, logical flow and ease of use. Subjects for the survey were recruited by telephone from a randomly selected group of listed numbers from four San Francisco Bay Area area codes (415, 510, 925 and 650). Residences were called in sequence to schedule an in-person interview. These surveys were conducted from January through April 2004, all but one in the respondent's home.

In short, the survey was primarily conceived to collect information that would permit construction of weekday and weekend hourly usage pattern for each device encountered in each HHs. With this information, the daily profile for each of the three main charger power modes could be constructed for that charger. For example, a shaver that is charged for two hours every three days (at the same time of day) would have two hourly charge mode "usage factors" of 0.33. Since the four possible charger power modes (three modes listed in Table 1, plus "disconnected") are exclusive—that is, a device can be in only one of the modes at a time—the hourly usage factors can be added for an overall usage profile for that device. Summing these 24-hour usage profiles by HH and by device type provides understanding of aggregate behavior.

In parallel with the surveys, we conducted load measurements of the three primary charger modes (no-load, charging and charge maintenance) for a variety of representative devices, following a test procedure adapted from IEC draft standard 62301 "Measurement of Standby Power." Both new and older equipment was tested, so that the range of products corresponded generally to those actually in use in homes. A Power Line Meter PLM1-LP, manufactured by Electronic Product Design, Inc. was used to make these load measurements.

Finally, load curves were constructed by multiplying the device usage information by the measured data for each device type. Aggregate load curves can improve understanding of the overall impacts of these devices in the state and beyond.

Results

The respondent population includes both urban and suburban residents and a wide variety of income levels, and would seem to be fairly representative of typical residences throughout the more densely populated areas of the state. The relatively mild climate of the survey area might be expected to result in lower average energy consumption in the sample than for the state or nation as a whole. Indeed, average consumption for the sample was 450 kWh/month (including one very high consumption HH at 2500 kWh/month), while statewide average residential consumption is 540 kWh. Since usage of battery chargers does not tend to be climate-dependent, selection bias likely does not impact the results of this survey in any meaningful way. Average household size for the sample of interviewed households was 2.25, somewhat smaller than the statewide average of 2.78; of the members in the HHs surveyed, 22% were children, slightly less than the 29% proportion in California as a whole (CA Dept. of Finance 2003).

On average, the households surveyed owned 8.4 chargers. Maximum household ownership was 21, and the minimum was 0. Perhaps not unexpectedly, cellular and cordless telephones were the two most common rechargeable devices. Table 2 contains a summary of relevant information collected through the survey for these and other devices.

Table 2. Survey Summary

n = 34 households Device	Survey Population	Ownership (# per HH)	Penetration (% possesing)	Average Age (years)
Cellular Telephone	57	1.68	79%	0.9
Cordless Phone	54	1.59	82%	4.0
Notebook Computer	29	0.85	62%	2.6
Cordless Power Tool	28	0.82	47%	5.4
Rechargeable Toothbrush	23	0.68	47%	3.0
Video Camera	15	0.44	38%	3.9
Other Rechargeable	15	0.44	32%	4.5
Cordless Shaver	11	0.32	32%	3.0
Security System	10	0.29	29%	8.7
Cordless Vacuum	10	0.29	29%	3.4
Digital Camera (rechargeable)	9	0.26	24%	1.5
Emergency/Utility Light	7	0.21	15%	5.0
Rechargeable Toy	7	0.21	15%	2.5
PDA (rechargeable)	5	0.15	12%	1.5
MP3 Player	3	0.09	6%	1.0
Stand-alone Charger (e.g. AA)	3	0.09	9%	8.0
TOTAL	286	8.41		

From the survey data, we created an hourly usage profile for each of the three applicable modes for each specific device, based on the respondent's description for usage of that device. These profiles were aggregated by device category and by HH to determine overall usage patterns. The mode-specific profiles were then multiplied by the measured load data to create load profiles and calculate estimated energy consumption by device and HH.

Figure 1 shows the average number of battery-powered devices plugged in during each hour in a single residence, disaggregated by power mode. That is, a given home has a number of devices plugged in at any moment, each with a distinct charge charging pattern—changing between the four modes (including "disconnected") throughout the day depending on the device type and particulars of usage. On average, over five rechargeable devices are plugged in at any given time, and the dominant power mode is that of charge maintenance. The bulk of actual battery charging ("charge" mode) is accomplished in evening and early morning, typically off-peak periods. This reflects heavier daytime and early evening usage of portable devices, which seems reasonable for weekday residential sector load. The survey data also reveal a substantively similar pattern for weekend days as well, with much of the charging done during late evening.

Generalizing from the survey sample is one way of estimating statewide populations for each device type. Given the relatively small sample population, it is useful to compare these results with other sources of information, such as sales and penetration figures from trade magazines, manufacturers and the like. Table 3 shows these estimates.

Sales figures available from industry sources tend to be national figures, and so may not reflect purchase patterns in California, though on the other hand the greater Bay Area may not be representative for some devices—such as notebooks and perhaps electric toothbrushes. Industry-reported saturations for very common devices may underestimate the number of devices, since HHs with more than one similar device tend to be counted only once. Ownership of multiple units of the same device type was quite common among respondent HHs. In total, we estimate that there are over 106 million small battery chargers in homes throughout the state.

Figure 1. Average Energized Devices per Household

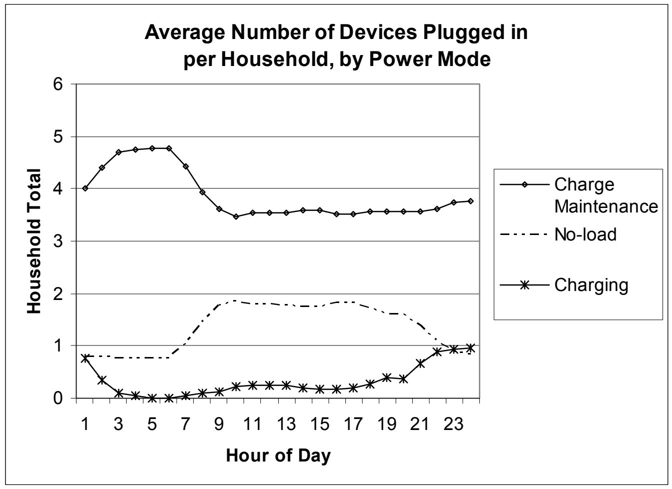


Table 3. Estimated Numbers of Devices in CA

Device	Est. Statewide Totals (millions)	Estimated from Industry Sources†
Cellular Telephone	21.2	17.3
Cordless Phone	20.1	26.4
Notebook Computer	10.8	7.6
Cordless Power Tool	10.4	7.1
Rechargeable Toothbrush	8.6	4.8
Video Camera	5.6	5.2
Other Rechargeable	5.6	
Cordless Shaver	4.1	4.9
Security System	3.7	
Cordless Vacuum	3.7	3.3
Digital Camera (rechargeable)	3.4	
Emergency/Utility Light	2.6	2.8
Rechargeable Toy	2.6	
PDA (rechargeable)	1.9	2.3
MP3 Player	1.1	
Stand-alone Charger (e.g. AA)	1.1	
TOTAL	106.5	

†Appliance Magazine 2003a, 2003b; Consumer Electronics Association

In the second component of this research, power measurements were made on 85 rechargeable devices, including several from each of the most common devices types encountered in the survey population. The average power draw in each mode for the measured devices is shown in Table 4.

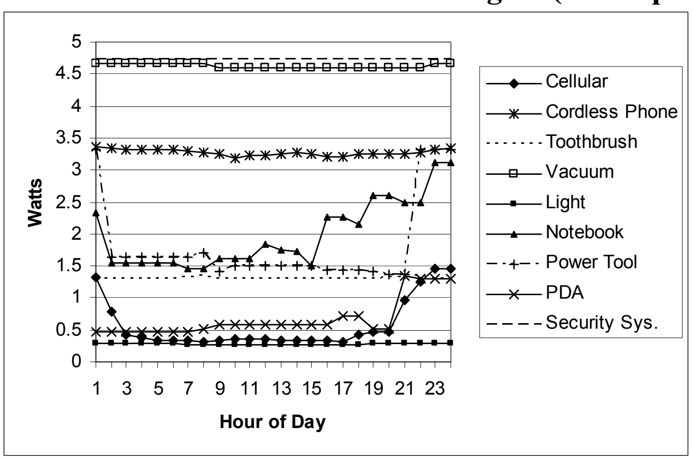
For each device tested, specifications were noted including battery type and capacity (where labeled), external power supply type (linear or switching), and power supply output wattage. Each of these factors may prove a useful variable for analysis of the determinants of energy usage within each device category. For example, of the 52 devices tested that had external powers supplies, at least 34 (63%) were linear. Linear power supplies add around 1W or more to the load of a given device; and the low-wattage (<5W) linear transformers that are so common in small consumer electronics are in fact the least efficient (Ellis 2004).

By combining the usage pattern and measurement information by power mode, we estimated electricity demand by battery charging devices in residences in California. An hourly load profile was created for each device; these load profiles were aggregated by power mode and by device. The results of this process are presented in Figures 2, 3 and 4, and Table 5 below.

Table 4. Summary of Charger Measurements

		Power Draw in Three Principle Power Modes (W)		
Device	**n**	**No-load**	**Charging**	**Charge Maintenance**
Cellular Phone	9	0.45	3.72	0.53
Cordless Phone	11	2.42	3.99	3.37
Cordless Shaver	8	0.29	2.31	0.68
Cordless Vacuum	4	0.80	4.66	3.69
Digital Camera	2	0.20	3.00	0.20
Emergency/Utility Light	3	0.26	0.34	0.34
MP3 Player	3	0.26	3.68	0.62
Notebook Computer	10	1.27	44.53	2.25
PDA	2	0.58	4.73	0.61
Power Tool	12	0.89	15.85	3.61
Rechargeable Toothbrush	5	1.66	1.65	1.58
Security System	3	n/a	16.92	4.73
Stand-alone Charger	9	1.25	11.82	3.08
UPS	2	n/a	10.85	5.45
Video Camera	2	0.37	9.60	0.39
Total	85			

Figure 2. Load Curves for Common Chargers (Watts per Unit)



Charge maintenance mode—when the battery is full but still in place—is the dominant mode throughout the day, in fact accounting for about 75% of all charger energy consumed. Another 10% is used in the “no-load” condition, so that only about 15% of the total energy is used during active battery charging.

Based on the estimated usage patterns and device measurements, we calculate that electricity use by small battery chargers in the average California home is around 117 kWh annually. Total annual electricity usage corresponding to these devices for the state’s 12,665,000 households is thus 1600 GWh, or about 2.0% of statewide residential electricity consumption. Table 5 shows the unit energy consumption (UEC) and estimated statewide energy use for the most common rechargeable devices in the residential sector.

Figure 3. Estimated Charger Load Curve

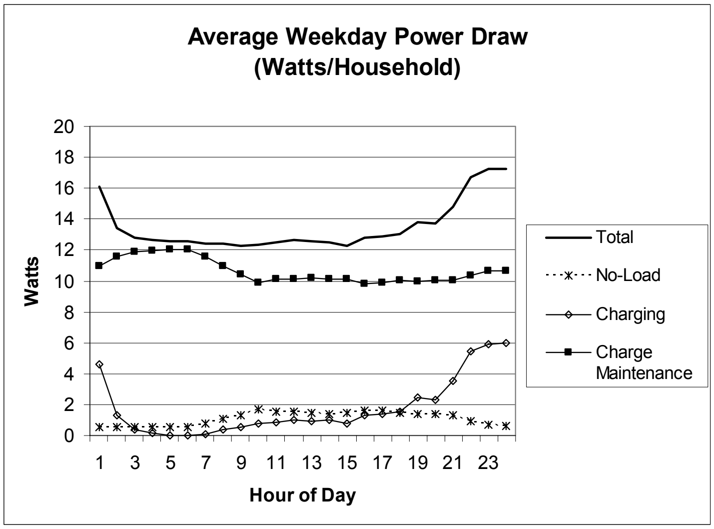


Table 5. Estimated Statewide Charger Energy Use by Device

Device	UEC kWh/year	Total Consumption in CA (GWh/yr)	Percent of Total Rechargeable Load
Cordless Phone	28.7	577	35.9%
Notebook Computer	17.0	183	11.4%
Power Tool	16.1	168	10.5%
Security System	41.4	154	9.6%
Cordless Vacuum	40.6	151	9.4%
Cellular Phone	4.9	103	6.4%
Other Rechargeable‡	12.6	103	6.4%
Rechargeable Toothbrush	11.5	99	6.1%
Digital Camera (rechargeable)	7.2	24	1.5%
Video Camera	2.3	13	0.8%
PDA (rechargeable)	6.1	11	0.7%
Emergency/Utility Light	2.5	7	0.4%
MP3 Player	5.6	6	0.4%
Cordless Shaver	1.0	4	0.3%
Stand-alone Charger	1.3	1	0.1%
TOTAL		1,604	100.0%

‡ Includes: toys, digital comm. backup systems, personal transport power systems, safety equipment, and a variety of other uncommon devices encountered.

By far the device with the largest aggregate charger consumption is the cordless phone, accounting for about 36% of the total. Other devices with important consumption are those with high penetrations and that tend always to be plugged in such as notebook computers, security systems and cordless toothbrushes. Chargers for which residential duty cycles tend to be low, such as for shavers and video cameras, have relatively small UECs.

For our sample, the portion of total electricity usage that corresponds to rechargeable devices ranged from 0% to 13.1%, with an average of 3.2%. The high average likely reflects the generally lower overall consumption of Bay Area HHs compared to the state as a whole; in absolute terms the respondent population likely reflects overall charger usage. Figure 4 shows charger electricity use relative to total household consumption for the 30 survey respondents for which utility data were available.

Figure 5 shows the estimated aggregate statewide load curve; "base" demand is around 160MW. The shape of this curve deserves note: its peak is in the evening and later, and so does not coincide with the typical system peak.

Figure 4. Consumption, Charger-only and Total Household

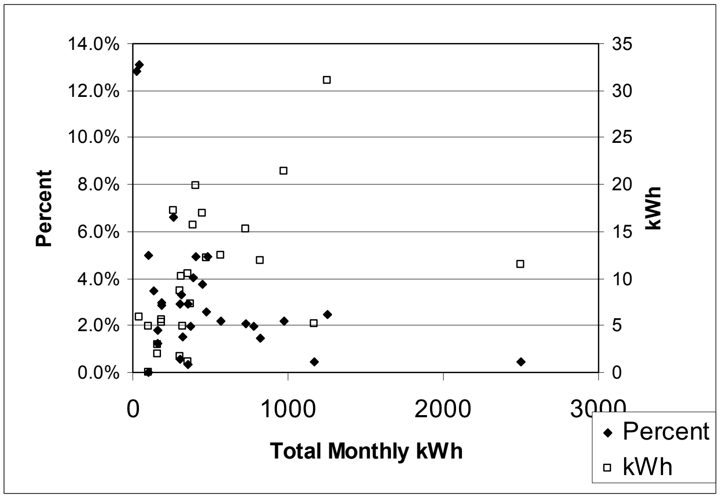
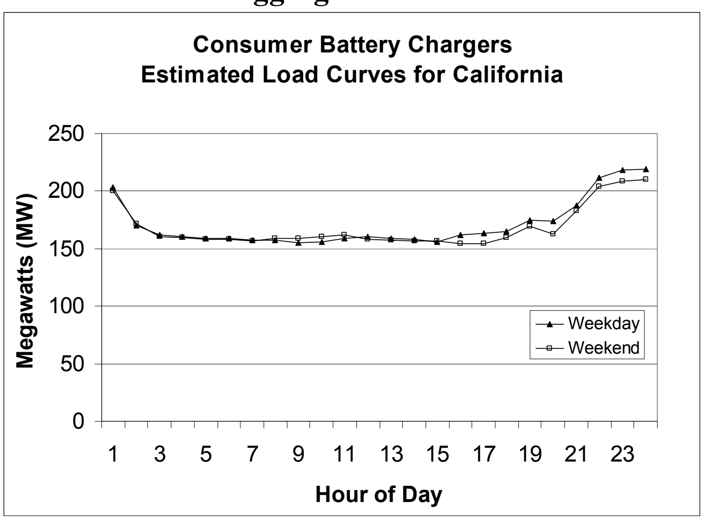


Figure 5. Estimated Aggregate Load Curves for California



The survey and measurement efforts reported here have uncovered interesting qualitative results as well. Some items are likely to be charged in multiple locations, with the most typical being home, work and car (for cell phones). Multiple chargers may be present for one device, increasing the no-load energy use associated with it; in this survey only residential energy usage was counted. A significant majority of people tend to leave their cell phone chargers plugged in all the time; the overall duty cycle for residence-based cell phone chargers is 70%. This means that the shift away from linear chargers that is currently underway is saving important amounts of energy—around 50-60 GWh per year in CA alone. Many of the Motorola chargers seen in the field and measured in the lab were of the switching variety, along with smaller percentages of other brands. PDA owners also mentioned a second charger at work.

Ownership of multiple identical devices (mainly cordless telephones, cell phones and toothbrushes) is relatively common—indeed packaging multiple units together is increasing as a retail marketing tool. In general these purchases increase penetrations and thus energy consumption, though where such packaging allows sharing of a single base unit between devices (e.g. toothbrushes) it may reduce charger duty cycles on a per-device basis.

Two personal styles of device management were observed: those that maintain devices plugged in only when in use (making sure that they are unplugged at other times), and those who keep chargers plugged in virtually all the time. Given that charge maintenance is the dominant mode in terms of energy consumed, the distinction is important. The percentage of owned devices that were plugged in at any one time varies widely from HH to HH, and seems to depend mainly upon habit and, for computer peripherals and multi-media devices, somewhat upon "outlet availability". A number of respondents expressed that the main reason they unplugged a given device was the need to access its place on the nearest power strip.

Notebooks showed similar patterns: units are either always plugged in as at a workstation/office ("desktop replacement" mode) or utilized (and charged) in a task-driven manner, which may include use as a second computer for HHs that own a desktop. A single HH demonstrated the two extremes: one spouse worked in a home office as if with a desktop; the other logged very little home usage, by using his laptop at home once per month—keeping it plugged in only when in use. Plugged use is the dominant residential mode, and would seem to diverge from business usage in which mobility is more important (Power Strategies 2003).

Two small uninterruptible power supplies (UPSs) were tested in the lab. While none was encountered in the survey population, they are certainly more common in the commercial sector, and their increasing presence in the major office supply retail chains would seem to point towards an important number in use. Since by design UPSs are meant to be plugged in at all times, the internal (sealed lead-acid) battery will remain fully charged, so the dominant power mode will undoubtedly be charge maintenance, at around 5-6W constant load. This internal load stays relatively constant at increasing load supplied through the UPS; that is, the AC output from the UPS is always 5-6W less than the AC input from the mains.

More than one in four HHs had an operational security system. This device has the largest UEC of any other device examined, due both to the high duty cycle (virtually 100%), and to the relatively simple chargers employed in these devices. Digital telephone systems employ a similar backup device, with a small sealed lead-acid battery to provide power during outages. While only two digital phone systems were encountered during the survey (included in the "Other" category), these are very likely to become more common in the coming years.

Conclusion

With relatively small power draw per unit, many residential battery chargers would not seem to be significant in terms of their power requirements. In aggregate, though, given that there are at least 100 million of them in the state, their load becomes significant. The overall dominant mode for most chargers is charge maintenance mode, so that most of the energy consumed when the battery is already charged.

This survey was concerned only with electricity usage by the battery charger, so the active usage component of a device (apart from the charger) is ignored. For example, the energy consumption of a notebook computer during use is not included in this study; we have tried to isolate the charger usage from the rest of the device. Note that for devices with internal charge circuitry (e.g. cordless phones), it can be very difficult to separate the power used in the charger from that used by other functions; further technical research would be required to disaggregate these components.

Better chargers can reduce energy use during charge maintenance mode. A wide array of charger designs can accomplish this, including timer-based approaches that turn off the charge circuit when appropriate, multi-stage chargers that dramatically reduce the charge current when the battery approaches full charge, and so-called "smart" chargers that use sophisticated charge algorithms to minimize overcharge and protect battery life. In some cases such improved chargers would also permit improved charge and battery status indicators, which provide users with relevant information for device management.

Improved power supplies would reduce the consumption of virtually all devices containing battery charging systems, not only in charge maintenance mode but in all modes, including during product use apart from the charging function. The California Energy Commission is moving towards the adoption of an external power supply efficiency standard to take effect in 2006. Energy Star recently unveiled a draft external power supply specification, and the EU Code of Conduct for external power supplies defines efficiency targets that will become relatively stringent on Jan. 1, 2005. Coordination is happening between manufacturers in China and specifiers and purchasers elsewhere, particularly in the US, Europe and Australia. Important steps to operationalize these agreements are taking place, including development of a standardized test procedure and the systematic efficiency testing of hundreds of power supplies in the US and Australia. These efforts will undoubtedly yield substantial energy savings in chargers and devices containing them

At the same time, similar steps are in the initial stages for battery chargers, and both DOE and the California Energy Commission are interested in pursuing potential efficiency opportunities, pending evaluation of the impacts of current power supply efforts.

The work reported here opens various pathways for further research relevant for the state and beyond, aimed at moving the market toward appropriate, responsive and cost-effective solutions to improved energy efficiency in battery chargers. One potentially fruitful area would be to investigate the environmental benefits of the move toward certain rechargeable technologies over others, for example using Life-Cycle Assessment and/or Design for Environment approaches to evaluate actual or proposed energy policies for batteries, chargers and other components of common products. In addition, the commercial sector is understudied with respect to standby power and is somewhat more complex in its end uses than the residential sector, and so presents a natural avenue for future efforts.

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