Field Study of Industrial High Frequency Battery Chargers

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Executive Summary

Battery-powered lift-trucks are utilized throughout manufacturing facilities, airports, warehouses, and retail buildings for material handling. The number of battery-powered lift-trucks used in Minnesota is quite large: in the industrial sector alone, it is our experience that the typical manufacturer has at least one battery-powered lift-truck, and the state of Minnesota has approximately 7,300 businesses that are classified by NAICS code as manufacturing[1].

There are three types of battery chargers commonly used to power lift-trucks: ferroresonant (FR), silicon-controlled rectifier (SCR), and high frequency (HF). Local suppliers estimate that the vast majority of industrial battery chargers used in Minnesota today are silicon-controlled rectifier (SCR) or ferroresonant (FR) chargers. These battery charging types have long been in existence and proven to be very reliable for high power applications. However, high frequency (HF) chargers, the newest technology of the three, have quickly gained a market foothold in recent years. HF chargers are typically promoted as being more energy efficient than conventional chargers, and are usually sold at a higher cost. A landmark study by the Pacific Gas and Electric Company (PG&E) in 2009 (Ecos 2009) involving standardized testing of a large number of industrial battery chargers demonstrated that HF chargers can offer significant energy efficiency improvements over FR or SCR chargers.

Some manufacturers also promote HF chargers as providing opportunity charging capability, in which batteries are charged at a very high rate during breaks in the workday. In contrast, under a conventional charging approach, batteries are run down to low levels, then slowly charged overnight and/or during off-peak hours. Opportunity charging can offer productivity and safety benefits for some businesses by avoiding the need to change batteries when depleted.

This study set out to evaluate the actual performance of HF chargers in the field. Field testing was completed at a total of 9 facilities across Minnesota and South Dakota, comprising a total of 13 charging stations. At each site, energy loggers were installed to monitor existing FR or SCR chargers for a period of two weeks of normal production activity. Next, HF chargers were installed, and energy loggers were installed to monitor the new HF chargers over an additional two weeks of normal production activity. The resulting pre- and post- energy logging data was then analyzed to determine energy savings. We also analyzed the data to detect any impacts on peak demand from installing the HF chargers, which could occur if lift-truck operators switched to opportunity charging.

The field test results were puzzling. Installing HF chargers did not consistently reduce the energy consumed per charge cycle, or total energy use per day, which would have been expected from the PG&E results; in some sites, energy consumption actually increased with the HF chargers. There was also no consistent impact on peak demand, though operators generally did not take advantage of the ability to opportunity charge with the new HF chargers. However, the testing arrangements generally had

[1] US Census, 2011 *County Business Patterns.*

significant limitations, which make it difficult to draw conclusions from our results on the actual impacts on energy and peak demand.

Many utilities currently offer custom incentives for HF industrial battery chargers. Because of the limitations of this study, there is insufficient evidence from our findings alone to discontinue this practice, especially given the previous work by PG&E demonstrating significant energy savings on average for replacement of FR and SCR chargers. However, the PG&E results indicate significant variability in key energy efficiency metrics across each charger type. This suggests that HF chargers are not necessarily be a cost-effective investment option for every business. Proposed installations should be carefully evaluated in relation to existing charger performance to ensure that minimum return on investment requirements will be achieved. If opportunity charging is desired, special consideration should be given to potential peak demand impacts as a result of the faster rate of charging.

Introduction

Battery-powered lift-trucks are utilized throughout manufacturing facilities, airports, warehouses, and retail buildings for material handling. The number of battery-powered lift-trucks used in Minnesota is quite large: in the industrial sector alone, it is our experience that the typical manufacturer has at least one battery-powered lift-truck, and the state of Minnesota has approximately 7,300 businesses that are classified by NAICS code as manufacturing[2].

The energy needed to power a battery-powered lift-truck is substantial: according to one estimate, the typical charger consumes approximately 15,000 kWh per year, resulting in a total utility cost of $1,500 annually (Ecos 2009)[3]. For a large facility with many lift-trucks, the total cost can be very large relative to other end-use equipment often targeted for energy efficiency improvements.

Local suppliers confirm that the vast majority of industrial battery chargers in use today are silicon-controlled rectifier or ferroresonant chargers. These battery charging types, collectively referred to as “conventional” chargers in this report, have long been in existence and proven to be very reliable for high power applications. However, high frequency chargers, the most recent entrant to the industrial battery charging market, are available and have quickly gained a market foothold in recent years. High frequency chargers are typically promoted as being more energy efficient than conventional chargers, and are usually sold at a higher cost.

Some manufacturers have also promoted high frequency chargers as offering faster charging capability than conventional chargers, allowing users to “opportunity charge” during breaks in the workday and still maintain sufficient battery power. In contrast, conventional charging has traditionally meant running batteries down to approximately 20% capacity, and then recharging slowly (typically during off-peak/overnight hours) to 80% capacity. Some facilities with very heavy lift-truck usage are forced to swap out batteries daily to maintain lift-truck usage due to the slow charging rates under conventional charging. This is a non-value added activity that increases maintenance costs and impacts productivity.

Standardized tests developed under the auspices of the California Energy Commission have demonstrated the potential for significant energy savings through replacement of conventional chargers with HF chargers. However, there is relatively little information in the public domain on the actual performance of HF chargers in the field. This study set out to evaluate the performance of HF chargers deployed across manufacturing facilities located in Minnesota and South Dakota.[4] Of special interest was whether the ability to opportunity charge would have a detrimental impact on a facility’s peak demand charges, offsetting any savings from the higher energy efficiency of HF chargers. We also

[2] US Census, 2011 *County Business Patterns.*

[3] Assumes a blended rate of $0.10 per kWh, in our experience an average rate for Midwest utilities.

[4] All but one facility was in Minnesota. The South Dakota facility was chosen because of the facility manager was interested in evaluating high frequency charger performance, and the facility had heavy lift-truck usage, so we anticipated being able to capture a large number of charging cycles.

wanted to understand what non-energy benefits, if any, the HF chargers offered to the facilities through faster charging capability.

Background

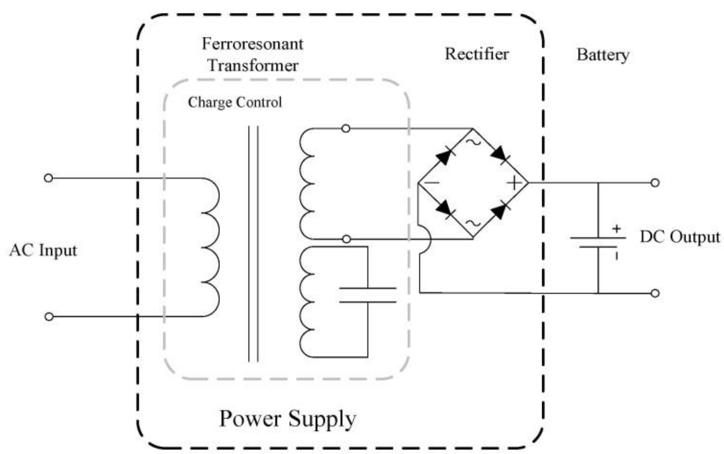
Technology Description

There are four types of industrial battery chargers: ferroresonant (FR), silicon-controlled rectifier (SCR), hybrid, and high frequency (HF). FR and SCR are the most common types in use today, though the market share of HF chargers is growing. Every type of charger performs the same basic function: conversion of alternating current (AC) electricity from the utility to direct current (DC) electricity at the battery terminals; for large industrial battery chargers, three phase AC power is usually supplied. However, the specific way power is converted and delivered to the battery varies by technology.

Ferroresonant (FR) Chargers

Ferroresonant (FR) charger designs utilize a ferroresonant transformer circuit. A representational circuit schematic is shown in Figure 1. While they have a proven track record of reliability, FR chargers have relatively low power conversion efficiencies, averaging approximately 85% (Ecos 2009). Eddy current and magnetic saturation losses in the transformer core are responsible for the low conversion efficiencies. Despite this shortcoming, FR chargers are still widely used today, owing to their relatively low cost and proven reliability.

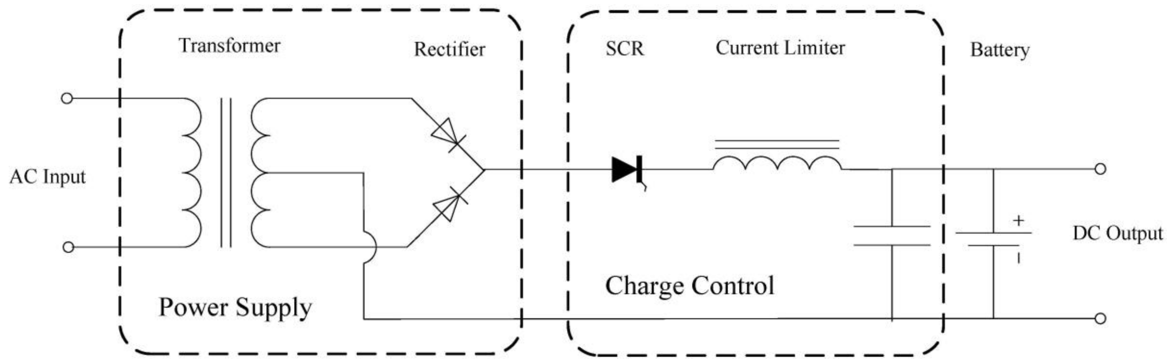
Figure 1. Single-phase Ferroresonant Battery Charger Circuit



Silicon-controlled Rectifier (SCR) Chargers

This type of charger uses a silicon-controlled rectifier to regulate voltage and current to the battery, as indicated in Figure 2. Like FR chargers, SCR chargers are a mature technology with proven reliability in high power applications. However, conversation efficiency is generally lower than HF chargers, owing to the limited switching speed of the SCR.

Figure 2. Single-Phase SCR Battery Charger Circuit



Hybrid Chargers

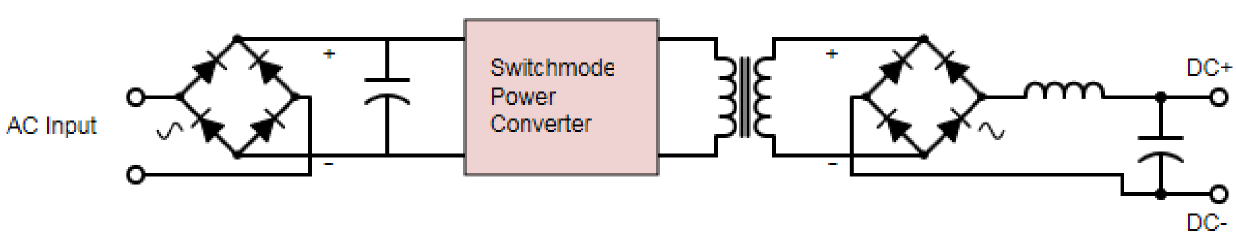
Hybrid chargers are similar to FR chargers, but use a switching circuit in place of the capacitor shown in Figure 1. While more efficient than FR or SCR on average, hybrid chargers are not widely used.

High Frequency (HF) Chargers

HF chargers, illustrated in Figure 3, include a switching circuit built from insulated gate bipolar transistors (IGBTs), which are capable of much faster switching than SCRs. They are capable of achieving higher power conversion efficiency than FR or SCR technology, in excess of 90% according to studies by the Pacific Gas and Electric Company (PG&E) (Ecos 2009). These studies also found that HF chargers produce higher power factors on average than conventional chargers, which can be an important consideration for facilities with a large number of chargers and heavy lift-truck usage.

While HF chargers are the newest large battery charging technology on the market, they have been commercially available since at least 1996 (Stanbury 2013). It was not until the late 2000s that utilities began widely promoting HF chargers as an energy efficiency measure, however, following adoption of a standardized test procedure for industrial battery chargers by the California Energy Commission. More information is provided on this project under Review of Past Studies.

Figure 3. Single-Phase HF Battery Charger Circuit



Technology Summary

Table 1 provides a synopsis of the four types of industrial battery chargers with typical power conversion efficiencies, cost, and estimated market share.

Table 1. Summary of battery charger technologies[5]

Technology	Approx. Percent of Existing Stock[6]	Average Power Conversion Efficiency	Cost
Ferroresonant (FR)	50%	85%	$1,500-$2,300
Silicon-Controlled Rectifier (SCR)	30%	85%	$1,300-$2,700
Hybrid	5%	86%	$2,000-$3,500
High Frequency (HF)	10%	92%	$2,000-$3,500

Energy Efficiency Metrics

Test procedures developed by the California Energy Commission identified several energy efficiency metrics which characterize industrial battery chargers:

- *Charge Return Factor,* the ratio of amp-hours returned during a charge cycle to amp-hours delivered by the battery during discharge. This factor characterizes how well a charger controls charging according to a battery's depth of discharge (DOD); the ideal range is 1.05 to 1.15 for battery health. Overcharging beyond 1.15 hurts the life of the battery and wastes energy.
- *Power Conversion Efficiency,* the ratio of DC output power to AC input power.
- *Maintenance Power,* the average AC power consumed by the charger when the battery is connected but not actively charging.
- *No Battery Power,* the average AC power consumed by the charger with no battery connected.
- *Power Factor,* the ratio of active (useful) power in Watts to apparent power in Volt-Amperes for AC electricity. Power factor varies between 0 and 1 and measures the extent to which the voltage and current phases are coincident. From a utility standpoint, the ideal Power Factor is 1.

For most installations, charge return factor and power conversion efficiency are the most impactful energy efficiency metrics. Charge return factor, maintenance power, and no battery power primarily related to how well the charger control circuitry is designed; any one product can be designed to perform well in these metrics regardless of the underlying technology type (HF, FR, or SCR). However, HF

[5] All figures are from the 2009 Ecos Consulting study of industrial battery chargers on behalf of PG&E (Ecos 2009).

[6] Feedback from the three main Minnesota suppliers of industrial battery chargers indicated that the estimated distribution of charger types in California was similar to what Minnesota has.

chargers tend to have an inherent advantage in terms of power conversion efficiency and power factor over FR and SCR chargers (Ecos 2009).

Review of Past Studies

Much of the information on the energy efficiency of HF industrial battery chargers in the public domain is the result of standardized testing performed by PG&E through its Emerging Technologies Program. These efforts grew out of a 2003 initiative of the California Energy Commission's (CEC) Public Interest Research Program to develop a standardized test procedure for small consumer battery chargers for products such as power tools, electric toothbrushes and shavers. The test procedure for consumer battery chargers is conceptually similar to industrial battery chargers in that similar energy efficiency metrics are measured such as power conversion efficiency and maintenance power.

While development of the consumer battery charger testing standard was ongoing, PG&E and Southern California Edison (SCE) began collaborating on development of a modified test procedure for large three phase industrial battery chargers. This procedure was eventually formalized and combined with the consumer battery charger procedure. The combined document was then reviewed through a formal rulemaking process and officially adopted by the CEC in December 2008 (Ecos 2009).

Using the new test procedure, PG&E completed a study of 28 industrial battery chargers covering all four types with the goal of evaluating relative energy efficiency performance. The results, summarized in Table 2, indicated that HF chargers were on average 5%-6% more efficient than FR or SCR chargers in power conversion efficiency. With regard to charge return factor, the other factor most closely linked to energy consumption, all charger types had an average value within the ideal 1.05-1.15 range except SCR. HF chargers had the highest average power factor, though the range of FR power factors was similar. The average values for each parameter were used to estimate average savings and paybacks for replacement of FR, SCR, and Hybrid chargers with HF as indicated in Table 3.

Table 2. PG&E Test Results by Charger Technology[7]

Orange fill indicates within ideal range
Yellow fill indicates best (highest or lowest)

Technology		Charge Return Factor	Power Conversion Efficiency	Maintenance Power (W)	No Battery Power (W)	Average Power Factor
FR	Range	1.12 - 1.21	84% - 87%	7.0 - 293.5	7.0 - 39.5	0.91 - 0.97
	Average	1.15	85%	81.7	18.2	0.92
SCR	Range	1.09 - 1.35	81% - 88%	10.0 - 262.8	10.0 - 285.0	0.60 - 0.85
	Average	1.18	85%	137.1	125.3	0.76
Hybrid	Range	1.10 - 1.14	80% - 89%	53.0 - 73.9	6.0 - 19.0	0.87 - 0.97
	Average	1.12	86%	62.3	14.1	0.91
HF	Range	1.06 - 1.29	91% - 92%	23.8 - 108.0	23.8 - 108.0	0.93 - 0.99
	Average	1.15	92%	48.4	48.4	0.96

Table 3. PG&E Average Savings Results by Number of Lift-Truck Shifts

Technology Replaced	Average Savings Achieved from HF Charger (per Unit)	(1) 8-hour shift	(2) 8-hour shifts	(3) 8-hour shifts
FR	Annual kWh Savings	1,035	2,125	2,911
	Peak kW Savings	1.3	1.3	1.3
	Payback: Incremental Cost (years)	8.5	4.2	3.0
	Payback: Full Replacement Cost (years)	16.2	7.9	5.7
SCR	Annual kWh Savings	2,169	3,627	4,849
	Peak kW Savings	0.4	0.4	0.4
	Payback: Incremental Cost (years)	2.5	1.5	1.1
	Payback: Full Replacement Cost (years)	8.8	5.3	3.9
Hybrid	Annual kWh Savings	149	439	575
	Peak kW Savings	1.1	1.1	1.1
	Payback: Incremental Cost (years)	16.3	5.5	4.2
	Payback: Full Replacement Cost (years)	155.3	52.6	40.2

While the California standard was under development, the Electric Power Research Institute (EPRI) was undertaking research on the benefits of fast charging in large manufacturing facilities. Demonstration projects were completed in 2002-2004 of fast charging in automobile assembly plants in Illinois, Alabama and Tennessee, all facilities with heavy lift-truck usage where batteries were changed daily (EPRI 2002, EPRI 2003, EPRI 2004). New chargers with fast charging capability were installed in each

[7] Source: (Ecos 2009).

facility in order to test acceptance of the technology and evaluate the impact on productivity. The results were very positive. Major findings included:

- Increased productivity and reduced labor costs from not having to change batteries between shifts or at the end of the day
- Improved safety through reduced risk of injury associated with battery change-outs, and reduced risk of vehicle collisions in battery changing areas
- Parts and maintenance savings generated by not having to purchase extra batteries and better part protection
- Battery and part protection, as batteries were less likely to go below 20% of charge capacity, which can damage batteries, brushes and connection points

It should be emphasized that the facilities in the EPRI studies were large automobile assembly plants with very heavy lift-truck usage. As such, they are not representative of the typical facility using electric lift-trucks. Many small to mid-sized facilities, which are most numerous in Minnesota, have only 1-2 lift-trucks that are used daily but on a much more sporadic basis. Even facilities with regular lift-truck usage may not need to change batteries daily. In both types of situations, the case for HF chargers is less compelling from an O&M standpoint.

Inclusion in DSM programs

As a result of the PG&E studies, many utilities began to promote HF industrial battery chargers, typically through custom incentive programs. A handful of utilities currently offer prescriptive rebates for HF industrial battery chargers, as listed in Table 4.

Table 4. Prescriptive Offerings for HF Industrial Battery Chargers

Utility Program	States	Incentive
ComEd Energy Impact Illinois	IL	Up to $230 per charger for newer technology industrial battery charger (minimum power conversion efficiency of 92% and minimum 8-hour shift operation five days per week). New charger must replace either a Ferro resonant or SCR charger.
Consumers Energy Business Energy Efficiency Programs	MI	$350 per HF charger per shift.
Energy Smart - C&I, offered to 20 Municipal Utilities in Michigan	MI	$100 per HF charger per shift.
Missouri River Energy Services Bright Energy Solutions	IA, MN, ND, SD	$100 per HF charger replacing FR or SCR charger (1 or 2 shifts fork lift operation). $300 per HF charger replacing FR or SCR charger (24-hour forklift operation).
Northwestern Energy ePlus	MT	$25 per unit for HF battery charger
PNM Commercial Energy Efficiency Rebate Program	NM	$200 per unit for 3-Phase HF industrial battery charger

Methodology

Field Testing Procedure

The objective of this study was to evaluate actual charger performance in the field. Testing took place in a total of 9 industrial facilities located throughout Minnesota and South Dakota that utilized electric lift-trucks. There were a total of 13 charging stations metered across the 9 facilities; the number of metered charging stations per site varied from one to three. The participating facilities were recruited with help from utilities and our subcontractor. Early in the study, we also reached out to local distributors for help with leads but struggled to get traction.

The intent of field testing was to perform a pre- and post-comparison of energy use between a facility's existing chargers and new HF chargers under actual operating conditions. The pre- and post-monitoring periods were to include all modes of operation: active charging, maintenance power, and no battery power. Following the pre-monitoring period, HF frequency chargers would be installed, and post-monitoring would commence under similar conditions. The pre-and post-monitoring period durations were intended to be a minimum of two weeks each.

AC input power was measured using a three-phase energy logging device such as a Fluke 1730 combined with current transducer (CT) clamps which could be fitted around the power cables within each charger assembly. The AC input power to each charger was logged at either 1 minute or 5 minute intervals, depending on the specific instrumentation used at each site. The parameters recorded by the loggers included voltage, current, and power factor. Following completion of pre- and post-monitoring at each site, the data from each logger was exported and opened in Microsoft Excel for analysis.

The field testing protocol also called for measuring the power conversion efficiency of the existing and new chargers. This would have required simultaneous monitoring of the DC output power from each charger. However, we struggled to find an instrument with this capability that could be safely installed with minimal impact. Eventually, we discovered that the Douglas DataTrac, a small battery monitoring device, could be used for this purpose, albeit with some limitations. A cable assembly, shown in Figure 4, was rigged around the DataTrac and embedded in one of the two lift-trucks in Site 8. Unfortunately, the DataTrac could not provide interval data, but by comparing the device's time-stamped event summary of amp-hours delivered per charge to the AC log data, it was possible to get a rough estimate of the power conversion efficiency over each charging cycle.

Figure 4. Battery Monitoring Device and Embedded Test Assembly

Customer Interviews

Facility managers at Sites 8 and 9 were interviewed to assess operator acceptance of the HF chargers and to gather information on any productivity and other non-energy benefits from the ability to opportunity charge using the new HF chargers. Summaries of the interviews at each facility are included in Appendix A, with the customer names and facility locations removed for privacy.

Findings and Analysis

Finding good test sites was a major challenge during this study. Many potential sites were rejected for not meeting minimum conditions, and many of the sites we did select were less than ideal.

The ideal test site would have been a small manufacturer or warehouse with regular lift-truck and charger usage. It would have had only 1-2 chargers that would each be replaced with new HF chargers following pre-monitoring. To the extent that the total energy expended by the lift-trucks during the pre- and post-monitoring was equivalent, an accurate determination of the energy savings from switching to HF chargers could have been made.

In addition, the ideal test site would have shifted from conventional charging to opportunity charging with the new HF chargers. This would have allowed us to assess the peak demand and productivity impacts of opportunity charging compared to conventional charging.

Unfortunately, none of the test sites met all of these criteria. One shortcoming was that we were not able to disable all existing chargers at each station and replace them all with HF chargers for the post-monitoring: we generally just had one HF “loaner” charger to work with. This meant that operators could still use one or more old chargers during the post-monitoring phase, confounding the energy savings calculations. If the battery charger output could have been monitored directly, then energy consumption could have been normalized by energy delivered, which would allow for correcting for differences in charger usages between the pre- and post-periods. However, as we describe under the Field Testing Procedure, we were not able to find a test instrument with this capability that could be installed in the charger without voiding the manufacturer’s warranty.

Furthermore, of the two sites interviewed, only Site 9 had a possible need for opportunity charging; Site 8 had relatively light lift-truck usage. Neither site changed its charging behavior to take advantage of opportunity charging with the HF chargers so we were unable to assess productivity or other non-energy impacts.

AC Input Power

Table 5, Table 6 and Table 7 summarize the AC power data collected at each site. For two of the sites, Site 5 and Site 7, we were not able to complete both pre- and post-monitoring. Site 5 had only one lift-truck that was used sporadically and no charging was performed during pre-monitoring. At Site 7, there was an expectation that the customer would be installing HF chargers, which would have allowed us to do post-monitoring, but this did not occur. Pre- and post-monitoring was completed at the remaining sites. Key metrics were calculated from the logging data including average power factor, peak demand, estimated kWh per charge, and estimated kWh per day. In the tables, Changes Pre-Post summarizes changes in key parameters between the pre- and post-periods, with green highlighting significant increases, and red highlighting significant decreases.

A careful review of the site by site results yields some puzzling observations. First, the average kWh consumed per charge was not consistently lower with the HF chargers; while significant reductions occurred at Site 1/Station 1 and Sites 3, 6, 8, and 9, it changed minimally or increased significantly at other sites. This finding is counter to the expectation that HF chargers have higher conversion efficiencies than FR or SCR chargers. An increase in the average time per charge cycle could be one explanation for higher average kWh per charge: a longer average charge cycle may imply that batteries were in a more depleted state on average at the start of each charge cycle. However, there is no consistent relationship between changes in the average length of charge and the average kWh per charge.

Second, our findings did not show a consistent advantage for the HF charger power factors over the incumbent chargers: at Sites 1, 3, 4, and 6 the existing FR chargers had a high power factor of 0.90 or greater, and a significant increase in power factor for the HF charger was only seen at Site 9. This is actually not surprising since the PG&E findings in Table 2 show overlapping ranges for FR and HF power factor values. However, the very low power factors measured for the HF chargers at Sites 4 and 8 (0.75 and 0.62) are quite surprising as they are significantly lower than minimum HF values in the PG&E results.

Finally, there was no consistent relationship between change in average charging time and change in peak demand: if the average charging time decreases, then it might be expected that the peak demand would increase accordingly because the same energy would be delivered to the battery in less time. There are at least three possible explanations for this. First, the HF charger may not have had faster charging capability than the existing charger; in the course of our research, we found several examples of FR or SCR chargers that are marketed as having fast charging and/or opportunity charging capability. Second, some HF chargers used in the study were later discovered to have an opportunity charging mode that was not enabled in all cases, limiting the unit to conventional charging speeds. Finally, there may have been differences in the average starting charge level of batteries between the pre- and post-phases; as cited previously, this factor could not be controlled under the testing protocols for this study.

Table 5. Field results for Sites 1-2.

Site	1		2		
Charging Station	**1**	**2**	**1**	**2**	**3**
Old Charger Type	FR	FR	FR	FR	FR
3-Phase AC Voltage	240V	240V	277/480V	277/480V	277/480V
Pre-monitoring duration (days)	31.17	31.17	6.37	6.74	6.85
% of time charging	44%	35%	7%	29%	26%
No. of Charging Events	134	122	4	6	6
Avg. Length of Charge(hrs)	2.43	2.14	2.58	7.69	7.14
Peak Demand, kW	8.95	10.15	4.37	4.51	4.48
Average Power Factor	0.97	0.98	0.84	0.90	0.89
Average # Charges/Day	4.30	3.91	0.63	0.89	0.88
Average kWh/Charge	11.53	11.18	9.93	25.92	26.58
Average kWh/Day	49.56	43.78	6.24	23.08	23.28

New Charger Type	HF	HF	HF	HF	HF
3-Phase AC Voltage	240V	240V	277/480V	277/480V	277/480V
Post-monitoring duration (days)	17.41	17.41	6.40	6.77	6.99
% of time charging	13%	33%	27%	22%	25%
No. of Charging Events	37	63	7	7	7
Avg. Length of Charge(hrs)	1.43	2.20	5.86	5.06	5.24
Peak Demand, kW	10.80	10.80	7.64	7.65	7.63
Average Power Factor	0.93	0.96	0.90	0.90	0.90
Average # Charges/Day	2.13	3.62	1.09	1.03	1.00
Average kWh/Charge	6.79	12.31	30.54	29.23	30.11
Average kWh/Day	14.44	44.57	33.42	30.23	30.17

Changes Pre-Post

Avg. Length of Charge(hrs)	-1.00	+0.06	+3.29	-2.63	-1.90
Peak Demand, kW	+1.85	+0.65	+3.26	+3.14	+3.15
Average Power Factor	-0.03	-0.02	+0.06	-0.00	+0.01
Average # Charges/Day	-2.17	-0.30	+0.47	+0.14	+0.13
Average kWh/Charge	-4.74	+1.13	+20.61	+3.31	+3.52
Average kWh/Day	-35.12	+0.80	+27.19	+7.15	+6.89

Table 6. Field test results for Sites 3-6

Site	3	4	5	6	
Charging Station	**1**	**1**	**1**	**1**	
Old Charger Type	FR	FR		FR	
3-Phase AC Voltage	277/480V	277/480V	277/480V	277/480V	
Pre-monitoring duration (days)	21.78	22.13		5.39	
% of time charging	46%	13%		13%	
No. of Charging Events	68	26		10	
Avg. Length of Charge(hrs)	3.57	2.58		4.70	
Peak Demand, kW	9.69	6.07		8.33	
Average Power Factor	0.94	0.99		0.90	
Average # Charges/Day	3.12	1.17		1.85	
Average kWh/Charge	21.31	14.75		27.10	
Average kWh/Day	66.53	17.33		50.26	

New Charger Type	HF	HF	HF	HF	
3-Phase AC Voltage	277/480V	240V	277/480V	277/480V	
Post-monitoring duration (days)	21.91	48.91	21.90	28.04	
% of time charging	44%	40%	15%	5%	
No. of Charging Events	38	199	64	13	
Avg. Length of Charge(hrs)	6.06	2.35	1.19	2.80	
Peak Demand, kW	7.49	10.80	11.62	3.12	
Average Power Factor	0.94	0.75	0.95	?	
Average # Charges/Day	1.73	4.07	2.92	0.46	
Average kWh/Charge	27.36	11.73	7.51	11.58	
Aveage kWh/Day	47.45	47.74	21.94	5.37	

Changes Pre-Post

Avg. Length of Charge(hrs)	+2.49	-0.23		-1.90	
Peak Demand, kW	-2.20	+4.73		-5.21	
Average Power Factor	-0.00	-0.24			
Average # Charges/Day	-1.39	+2.89		-1.39	
Average kWh/Charge	+6.05	-3.01		-15.52	
Average kWh/Day	-19.08	+30.41		-44.89	

Table 7. Field test results for Sites 7-9

Site	7		8	9
Charging Station	**1**	**2**	**1**	**1**
Old Charger Type	SCR	SCR	SCR	FR
3-Phase AC Voltage	277/480V	277/480V	277/480V	277/480V
Pre-monitoring duration (days)	13.93	13.92	6.94	14.75
% of time charging	91%	33%	7%	20%
No. of Charging Events	10	10	3	9
Avg. Length of Charge(hrs)	1.26	1.86	4.02	8.00
Peak Demand, kW	8.22	1.77	11.76	7.02
Average Power Factor	0.65	0.65	0.85	0.68
Average # Charges/Day	0.72	0.72	0.43	0.61
Average kWh/Charge	6.93	2.21	45.89	48.37
Average kWh/Day	4.97	1.59	29.55	26.22

New Charger Type			HF	HF
3-Phase AC Voltage			277/480V	277/480V
Post-monitoring duration (days)			28.00	18.11
% of time charging			4%	14%
No. of Charging Events			4	9
Avg. Length of Charge(hrs)			6.10	6.99
Peak Demand, kW			3.46	7.09
Average Power Factor			0.62	0.93
Average # Charges/Day			0.14	0.50
Average kWh/Charge			18.79	32.36
Average kWh/Day			17.65	16.08

Changes Pre-Post

Avg. Length of Charge(hrs)			+2.09	-1.01
Peak Demand, kW			-8.30	+0.07
Average Power Factor			-0.23	+0.24
Average # Charges/Day			-0.29	-0.11
Average kWh/Charge			-27.10	-16.01
Average kWh/Day			-11.90	-10.14

Power Conversion Efficiency

Power conversion efficiency, the ratio of output power delivered to input power consumed, was measured for the existing SCR charger and new HF charger at Site 8 by combining the AC log data with the time-stamped event summary from the Douglas DataTrac, which was embedded in one of the lift-trucks as described under Methodology. One charging cycle was completed with the Douglas DataTrac with the existing SCR charger, and two charging cycles were completed with the new HF charger.

As shown in Table 8, the results of this procedure demonstrate a higher conversion efficiency for the HF charger, but the calculated values are questionable: a conversion efficiency of 51% is much lower than would be expected for an SCR charger from the PG&E results, and the first charging cycle for the HF charger indicates a charging efficiency over 100%, which is impossible. These results point to the difficulty of combining the Douglas DataTrac event summary data to the energy logger input data; differences in calibration or the underlying calculation methodology in the DataTrac software may account for the calculated efficiencies. Nonetheless, the results do demonstrate a significant efficiency improvement with the HF charger.

Table 8. Conversion Efficiency Results for Site 8..

Date	Charger	Time On Charge	Net AHRs Delivered	Battery Voltage	DC kWh Out	AC kWh In	Conversion Efficiency
Fri May-13-2016	SCR	06H 16M	733	36.0	26.4	51.4	51.3%
Wed Jun-08-2016	HF	07H 59M	660	35.3	23.3	21.8	106.8%
Fri Jun-17-2016	HF	07H 59M	678	34.2	23.2	23.3	99.4%

Interview Results

Interviews were completed with facility managers at Sites 8 and 9, where HF chargers were installed on a temporary basis for this study. Table 9 provides a summary of lift-truck usage at each facility.

Table 9. Summary Information on Interview Sites

	Site 8	Site 9
Business Type	Commercial printing	Medical device manufacturer
Lift-Truck Functions	Stacking, moving, loading/unloading	Material handling and warehousing
No./Type of Chargers	2 SCR	35 FR
No. of Battery-Powered Lift-trucks	2	30

Summaries of each interview are included in Appendix A. As indicated, the questions posed focused on operator satisfaction with the new HF charger, any productivity impacts realized from the ability to opportunity charge, and what factors are most important when evaluating chargers. The managers were interviewed immediately following conclusion of post-monitoring so they had no knowledge of the energy savings results.

Regarding satisfaction with the HF charger, operators were generally indifferent because they simply continued charging as they normally would with their old chargers. One operator at Site 8 was unhappy with the HF charger because it was programmed to only charge to 85% instead of 100%; the distributor had set it up this way prior to installation as it is common to set a maximum charge level of 80% or 85% for battery protection (for any charger type). No productivity changes were seen at either site with the HF chargers because no opportunity charging occurred, though managers were made aware of our desire to study this approach. Apprehension over potential battery damage and a general reluctance to change their charging habits and risk impacting production appear to have been possible reasons.

Regarding what factors are most important for considering new chargers, both respondents indicated that reliability was their chief concern. Site 9 indicated that better battery life and energy savings were also important, but expressed concern regarding the serviceability of HF chargers by their in-house technicians, who were not familiar with the technology. This respondent also expressed interest in higher charging speed as a consideration given they are a 24/7 operation, but indicated that they needed to investigate HF products more closely to ensure charging speeds would be high enough to meet demand if they switched to opportunity charging.

Conclusions and Recommendations

Considering the conflicting results seen across the test sites and the testing limitations described previously, it is difficult to draw any conclusions on the actual performance of HF chargers in the field from this study alone. The Site 8 combined test results do indicate a higher conversion efficiency for the HF charger over the existing SCR charger. It is also difficult to draw any conclusions on what impact HF chargers might have on peak demand in the field. Moreover, the premise that HF chargers alone enable opportunity charging, which could potentially increase peak demand, may be flawed, given that there appear to be FR and SCR chargers available that provide this capability as well.

Power factor is one parameter where our results are more robust. We found that there was no clear advantage for the HF chargers over the conventional chargers in this area. We also found a wide range of variation in this parameter. Facilities with heavy lift-truck usage should evaluate proposed equipment to ensure that their power factor requirements will be met, rather than making an assumption based on HF technology or sales literature.

Given the uncertainty in our results and the existing body of research showing high energy savings potential for HF chargers, we would not recommend utilities discontinue rebates for HF units as a replacement for FR or SCR chargers. However, technology type alone should not be used as the basis for rebate eligibility.

Rebates for high efficiency chargers may best be handled on a custom basis given the many variables that affect energy consumption, from energy efficiency metrics such as power conversion efficiency to operational factors such as average charge cycles per day. The performance of both the old and new chargers should be carefully modeled to ensure that cost-effective savings will be produced before any rebate is approved.

Prescriptive rebates for high efficiency chargers and/or Technical Reference Manual (TRM) inclusion could be considered as long as special attention is given to rebate eligibility requirements, both for the proposed equipment as well as the operating conditions. Technology-neutral minimum requirements for charger performance should be set including power conversion efficiency, charge return factor, and power factor to ensure that cost-effective savings are produced. These parameters should be rated using the test procedures established by the State of California.

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Appendix A. Interview Summaries

Site 8.

1. **Please describe how forklifts are currently used in your business operations.**

   Stacking, bins, bales, loading unloading trucks. Lifting cages.

2. **How convenient was the new charger to use?**

   ☐Extremely convenient
   ☐Very convenient
   ☒Moderately convenient
   ☐Slightly convenient
   ☐Not at all convenient

3. **Please describe how the charger is more (or less) convenient.**

   No difference.

4. **What do you see as the primary benefits of your HF charger?**

   None- we do not do opportunity charging. We like to let it run down and then charge. We wonder whether it is good for the battery to do opportunity charging.

5. **Are there any drawbacks of the HF charger versus your SCR chargers?**

   We didn't see any, except that one operator didn't like how it only charged to 85%.

6. **How does the new charger's speed compare to your previous charger's speed for charging applications?**

   We didn't notice any difference because we charge overnight.

7. **How have forklift operators changed their charging habits, if it all, with the new HF charger?**

   They didn't change their habits.

8. **Has the HF charger produced a net impact on productivity?**

   ☐Much higher productivity
   ☐Somewhat higher
   ☒No change
   ☐Somewhat lower
   ☐Much lower productivity

9. **Please rank the following performance characteristics in order of importance:**
   1 Reliability
   3 Speed
   2 Energy Savings

   Reliability is our main concern. Speed is not a factor for our operation. We don't see the utility bills, but energy savings would be important to justify the purchase with the "bean counters".

10. **Did you consider whether switching to a HF charger might impact your peak demand charges?**

    We charge overnight so it is not a factor.

11. **What type of party was the seller of your current chargers?**

    ☐Manufacturer
    ☒Distributor
    ☐On-line Retailer
    ☐Other

12. **How likely are you to change out a battery charger before it starts to fail?**

    ☐Extremely likely
    ☐Very likely
    ☒Moderately likely
    ☐Slightly likely
    ☐Not at all likely

13. **How likely are you to recommend your new high frequency battery charger to others?**

    ☐Extremely likely
    ☐Very likely
    ☐Moderately likely
    ☒Slightly likely
    ☐Not at all likely

Additional Comments: We would like to see the report to see if there is a return with the new chargers in terms of energy savings. Would like preliminary results when available.

Site 9.

1. **Please describe how forklifts are currently used in your business operations.**

   Handling and transportation of semi-finished and finished materials between manufacturing lines and warehouse.

2. **How convenient was the new charger to use?**

   ☐Extremely convenient
   ☒Very convenient
   ☐Moderately convenient
   ☐Slightly convenient
   ☐Not at all convenient

3. **Please describe how the charger is more (or less) convenient.**

   It was no more or less convenient than our existing Ferro chargers. Employees plugged in batteries and walked away.

4. **What do you see as the primary benefits of your HF charger?**

   Possibly better battery life and energy savings.

5. **Are there any drawbacks of your HF charger versus your Ferro or SCR chargers?**

   Possibly serviceability by our in house technician. Technology would be new for us. Actual product life unknown. The existing Ferro chargers are tried and tested.

6. **How does the new charger's speed compare to your previous charger's speed for charging applications?**

   ☐Much faster
   ☐Faster
   ☒About the same
   ☐Slower
   ☐Much slower

7. **How have forklift operators changed their charging habits, if at all, with the new HF charger?**

   No noticeable change during trial.

8. **Has the HF charger affected forklift driving habits, and if so, how?**

   No noticeable change during trial.

9. **Has the HF charger produced a net impact on productivity? Please select from the following options:**

   ☐Much higher productivity
   ☐Somewhat higher productivity
   ☐No change
   ☐Somewhat lower
   ☐Much lower productivity

10. **Please rank the following performance characteristics in order of importance, with 1 being most important:**
    ___ Reliability
    ___ Speed
    ___ Energy Savings

11. **Have you considered whether switching to a HF charger might impact your peak demand charges? Please explain.** Yes – but we're a 24/7 operation. There is some concern that not charging during the day will create a shortage on fully charged batteries. We need to study the possible benefits more.

12. **What type of part was your seller?**

    ☐Manufacturer
    ☒Distributor
    ☐On-line Retailer
    ☐Other ____

13. **How likely are you to change out a battery charger before it starts to fail?**

    ☐Extremely likely
    ☐Very likely
    ☐Moderately likely
    ☒Slightly likely
    ☐Not at all likely

14. **Overall, how satisfied are you with the new charger?**
    ☐Extremely satisfied
    ☐Moderately satisfied
    ☒Neither satisfied nor dissatisfied

☐Moderately dissatisfied
☐Extremely dissatisfied

15. How likely are you to recommend your new high frequency battery charger to people you know?

☐Extremely likely
☐Very likely
☐Moderately likely
☒Slightly likely
☐Not at all likely

Additional comments: When reviewing the above information, please keep in mind we had the HF charger for only 2 to 3 weeks so our data and experience with the unit is limited. As such, I intentionally did not answer question #9 and #10. At the time of this writing, final performance data had not yet been reviewed.