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Economic comparison of fuel cell powered forklifts to battery powered forklifts

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ABSTRACT

This paper presents an economic comparison of fuel cell powered forklifts to various types of battery powered forklifts. The total costs of ownership of each technology is calculated and compared over their economic lifetimes and at varying workloads to determine the economic costs or benefits associated with each technology. The study is novel compared to the previous literature in that all data sources are referenced, it includes a model that is scalable by facility workload, and it includes the economic costs of hydrogen storage and charging infrastructure. Results show that fuel cell forklifts are more expensive to purchase and operate that battery powered forklifts for the types of facilities considered in this analysis. Fast charge forklifts are shown to be economically advantaged at high workloads relative to conventional battery-swapping forklifts.

1. Introduction

The introduction of polymer electrolyte membrane (PEM) fuel cell powerplants for materials handling equipment (including forklifts, pallet handlers) has been motivated by the potential for operating costs savings [1,2], improved environmental performance relative to conventional technologies [2,3], the strategic promise of forklifts being an early adoption market for PEM powerplants [1], and government subsidies to defray upfront costs [4].

To date, a few studies have concluded that PEM fuel cell forklifts may exhibit economic and operational benefits over conventional internal combustion and electric forklifts. These studies have proposed that the benefits of PEM fuel cell forklift powerplants over compressed natural gas internal combustion engines and conventional battery technologies are particularly relevant in large-scale, high-workload, and industrial environments with high operating costs [1]. Under these conditions, the intrinsic characteristics of fuel cell powerplants (longer maintenance intervals, short refueling time, and no need for battery rooms) have been documented to justify the increased upfront costs associated with the fuel cell powerplant and support systems. These studies have modeled the economic costs of fuel cell powered forklifts and support systems in comparison with conventional technologies to show an approximate payback period of less than 15 years relative to a business as usual scenario [1].

This previous work has left several outstanding questions open that have been brought to the attention of the authors through interviews with industrial partners. First, for high-workload environments, fuel cell forklifts are more typically in competition with fast-charge battery-powered forklifts than with the conventionally-charged battery-powered forklifts that have been the focus of previous comparisons [5]. A comparison of the fuel cell powerplants to fast-charge forklifts has not been performed. Second, previous studies have not addressed the costs of on-site hydrogen infrastructure. In other fuel cell powerplant applications (including automotive), the cost of hydrogen

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infrastructure is understood to be a significant near-term cost [6]. Finally, this previous work has compared the economic costs and benefits of fuel cell forklifts for only a single hypothetical facility [1–3]. Instead, managers in the materials handling industry would like to understand the applicability of the fuel cell forklift technology to their particular facility, which generally includes consideration of a facility's particular workload.

To expand the scope and address the shortcomings of these previous studies, this research effort quantifies the comprehensive lifetime economic costs of fuel cell forklifts. The lifetime costs of fuel cell forklifts are then compared to those of conventional battery-powered and fast-charge forklift technologies. This comparison is performed at a variety of workloads so as to provide an economic basis for discussion of which applications and workloads are economically-favored for any particular forklift technology.

2. Economic comparison of technologies

This study proposes an economic comparison of forklift powerplants for a set of theoretical workloads. The four powerplants considered are a conventionally-charged battery powerplant, a 15-kW fast-charged battery powerplant, a 30-kW fast-charge battery powerplant, and a PEM fuel cell powerplant. The discounted net present costs (NPC) of the four powerplants are analyzed including capital, infrastructure, operations and maintenance (O&M), and fueling or charging costs. This analysis will focus on the comparison of these technologies for a manufacturing plant in urban California using figures applicable to a fleet of 50 forklifts. The analysis models costs and capabilities for the year 2010.

2.1. *Model parameters*

The economic costs of forklift usage can be difficult to determine because of the lack of public information regarding forklift usage, how facilities value space and time required for materials handling, and accurate price points for the powerplants and support equipment. This report synthesizes information based on previous studies of forklifts, informal surveys of industrial forklift users, interviews with experts in forklift powerplant technology, and cost data from forklift manufacturers. A summary of the economic modeling parameters is presented in Table 1.

2.2. *Economic scenario definition*

This study uses a yearly discount rate of 8.0% and an inflation rate of 1.9%. A fleet size of 50 forklifts is used to model a facility of large enough scale to be targeted for fuel cell forklift introduction [7]. The project's economic life is assumed to be 5 years, the period of a typical hydrogen infrastructure contract. No economic incentives, such as state or federal tax breaks, are included in this study.

The cost of capital is based on the finance rates of large companies with AAA credit rating. The yearly finance rate used is 6.0%. All vehicles, infrastructure and facilities are assumed to be purchased on credit.

2.3. *Powerplant*

The cost and lifetime of the fuel cell forklifts and powerplants were determined through consultation with the fuel cell powerplant manufacturers Raymond Corporation and Plug Power, Inc. The costs and lifetime of battery-powered forklifts and powerplants were determined through consultation with the battery forklift manufacturers Toyota Materials Handling and Raymond Corporation.

The forklift battery has a nameplate capacity of 50 kWh and is usable between 90% and 20% state of charge, resulting in a 35 kWh usable capacity. The battery is assumed to require complete replacement at end of life, which is assumed to be 5 years for conventionally-charged forklifts and is 3 years for the fast-charge forklifts.

2.4. *Infrastructure*

Each powerplant technology requires infrastructure to support the operation of the forklift in the form of fueling

Table 1 – Economic modeling parameters associated with the four powerplant technology options.

	Cost Item	Fuel cell forklift	Fast charge forklift (15 kW)	Fast charge forklift (30 kW)	Conventionally charged forklift
Powerplant	Forklift and powerplant	$35,000 per unit [8]	$27,500 per unit [9]	$27,500 per unit [9]	$27,000 per unit [9]
	Replacement powerplant	$11,000 per unit [8]	$4500 per unit	$4500 per unit [9]	$4000 per unit [9]
	Powerplant lifetime	5 years [8]	3 years [9]	3 years [9]	5 years [9]
Infrastructure	Refueling time/battery change time	5 min.	N/A	N/A	15 min.
	Charger purchase	0	$15,000 per [9]	$30,000 per [9]	$3000 per [9]
	Hydrogen storage unit maintenance	$13,186 per year [7]	N/A	N/A	N/A
	Hydrogen storage equipment	$220,101 [7]	N/A	N/A	N/A
	Siting for hydrogen storage unit	$33,807 [7]	N/A	N/A	N/A
	Hydrogen storage installation	$85,839 [7]	N/A	N/A	N/A
	Battery room or forklift charging warehouse space	N/A	$75,000 for 2000 ft^2 [10]	$75,000 for 2000 ft^2 [10]	$150,000 for 2000 ft^2 [10]
Operations and maintenance	Battery room operator wages	N/A	N/A	N/A	$240 per shift
	Powerplant maintenance	$500 per year	15 min per week	15 min per week	15 min per week

space and equipment, and charging space and equipment. Electricity and hydrogen delivery costs are.

The infrastructure cost for the hydrogen fueling system was modeled using the USDOE H2A delivery analysis model [8]. All hydrogen is assumed to be delivered by truck, and stored on site as compressed gaseous hydrogen. Liquid hydrogen delivery and storage is lower cost per unit of delivered hydrogen, but has higher infrastructure costs. For the liquid hydrogen system to be less costly than the compressed hydrogen system requires more hydrogen consumption that was required by the modeled 50 forklift fleet.

In general, the materials handling facility does not actually purchase the hydrogen infrastructure. Instead, the hydrogen provider and materials handling facility will develop an operating lease of the hydrogen equipment. The hydrogen infrastructure and delivery lease is generally of minimum five-year duration. For this study we assume that the capital cost of the hydrogen infrastructure is represented by its cost at purchase. Due to a lack of information, no financing costs or profit for the hydrogen provider are included in the modeled operating lease.

A battery room is required to allow space and equipment for charging the batteries of large fleets of conventionally-charged forklifts. The size of the battery room is modeled by arranging the footprint of the forklift, batteries, charger, water station, and battery change-out machinery in a rectangular room. Based on this method, a battery room for 50 forklifts would require approximately 2000 ft^2 of additional facility space. The cost of industrial space per square foot is highly variable; each facility will value the marginal costs of space differently. This study uses RSMeans CostWorks [10] to calculate the cost of constructing a large warehouse at $75 per ft^2. Because batteries only need be changed once per shift, a full-time operator would not be required for the battery room for the workloads considered here. Instead, labor costs are allocated to the battery room based on the number of times that batteries must be changed out.

As with conventionally-charged forklifts, the fast-charged forklifts will also need additional space within the facility, in this case to house the chargers and forklift parking spots. The space requirements for fast-charge forklifts are 1000 ft^2 at a cost of $75 per ft^2 [10]. There is no need for a battery room operator in fast-charging scenarios because opportunity charging is performed during down-time such as breaks and shift changes. Should the SOC of the fast-charge forklift consistently reach its lower limit (SOC $<20\%$), the facility will need additional fast-charged forklifts to maintain a given workload.

2.5. *Operations and maintenance*

The maintenance costs for the fuel cell forklift are derived from consultation with the forklift manufacturer Raymond Corporation and the employees who perform forklift maintenance in an industrial setting [7]. These costs include the time for a technician to travel to the plant, the time to run diagnostic tests on the fuel cell to ensure correct performance, the time for scheduled maintenance, and the time for unscheduled maintenance to be performed at the materials handling facility. An example of this unscheduled maintenance that could be performed at the facility includes clearing out obstructed fuel cell blowers.

The maintenance costs of the battery powered forklifts were determined through surveys of industrial forklift owners. The weekly maintenance associated with the conventionally-charged and fast-charged forklifts includes the time to wipe down the batteries, and the time to check water levels. It should be noted that the maintenance costs for this study are significantly lower than those cited in previous studies [1].

The operation costs for each technology includes the costs of labor for charging (or fueling) the forklift. The refueling time and battery charge time was determined through surveys of industrial forklift users. For the fast-charge forklifts, opportunity charging is assumed to occur during breaks and shift changes for a total of 1 h per shift. Opportunity charging does incur a labor cost since it occurs during allocated break periods or shift changes.

2.6. *Electricity and hydrogen consumption and fuel costs*

The electric rate and demand charge were calculated using the Pacific Gas and Electric (PG&E) tariff rates for tariff E-20, service to customers with maximum demand of 1000 kW or more [14]. This rate structure uses an off-peak, partial-peak, and on-peak energy (kWh) and demand (kW) rate for both summer and winter months. The rates used in calculation and presented in Table 2 are the time-weighted averages of tariff E-20, and assumes that forklift peak loads add directly to the facility peak loads. The total energy consumption for the fast charge and conventional charge batteries was calculated including AC to DC charger efficiency.

The hydrogen use per shift was determined by converting the usable energy content of the battery, 35 kWh DC, into kilograms of hydrogen by using the lower heating value of hydrogen divided by typical fuel cell efficiency. The efficiency of the fuel cell system was calculated from measurements of the fuel cell output voltage of a fleet of fuel cell forklifts [11]. The fleet average efficiency was calculated assuming that maximum fuel cell current corresponds to a cell voltage of 0.6 V and that the minimum fuel cell current corresponds to an open circuit voltage of 1.0 V. Fuel cell

Table 2 – Energy usage and efficiency scenario definitions.

Scenario parameter	Value
Electricity cost	$0.09 per kWh [14]
Demand charge	$6.89 per kW [14]
Battery forklift energy consumption	35 DC kWh battery energy content per shift 50.0 AC kWh energy consumption for conventionally-charged forklifts per shift 61.5 AC kWh energy consumption for fast-charge forklifts per shift
Hydrogen (molecular) cost	$16.25 per kg [13]
Hydrogen consumption	1.75 kg per shift per forklift
AC to DC charging and battery efficiencies	0.65 for fast charge 0.80 for conventional charge
H_2 to DC fuel cell efficiency	0.69

efficiency is then calculated from the weighted sum of the measurements considering the standard potential of the oxygen reduction reaction of 1.229 V [12]. This calculation resulted in a hydrogen consumption of 1.75 kg per shift per forklift. Hydrogen delivery costs are modeled as per the recommendations of a hydrogen supplier for this size and type of installation at $16.25 per kg for gaseous hydrogen [13]. This value is significantly higher than the US Department of Energy goals for a automotive-scale hydrogen production ($3 kg^{-1} at 1500 kg day^{-1}) and is 50% higher than early market median projections for automotive scale hydrogen production. According to industrial interviews, a large fraction of this difference is ascribable to the difference is scale between automotive and forklift-scales of hydrogen storage and distribution systems [13].

Modeled energy usage parameters are summarized in Table 2.

3. State of charge modeling

3.1. Characterizing forklift workload

To allow for a direct comparison of vehicle operation for various powerplant technologies, this report adopts a metric of forklift workload called the equivalent battery unit (EBU). The EBU uses the conventional battery powered forklift as the baseline for measuring the workload of a forklift operation. One EBU is the direct current (DC) electrical energy required to discharge a conventionally-charged battery-powered forklift from 90% to a 20% state of charge (SOC). For this study, one EBU is equivalent to 35 kWh of DC output electrical energy, which is extracted at a rate so that 1 EBU occurs over the 7 working hours of a shift (for this study, the workload is assumed to be a constant 5 kW discharge).

3.2. Detailed state of energy modeling for battery forklifts

To understand the effect of fast charge scenarios and opportunity charging on workload capabilities, a quantitative analysis of the relationship between workload and SOC was performed. The SOC model was created by modeling opportunity charging at every work break: two 15-min breaks, and a 30-min lunch break. Fig. 1 compares the state of energy (SOE) for the baseline conventional charging scenario, to the SOE of the two fast charge scenarios which used 15 kW and 30 kW chargers, respectively.

Fig. 1 shows a sample result of the SOE analysis. The 5-kW charger (conventional charger) reaches 0 kW of energy content (1 EBU) at the end of one shift (1700 h). It is then recharged to full energy content, and then allowed to cool until the start of the next day at 0900 h. The 15-kW charger stays above the 0 energy content condition until 1.75 shifts, which means that it has performed 1.75 EBUs of workload between 0900 and 2300. This suggests that the facility will need to purchase more forklifts to operate at a higher workload than 1.75 EBUs with 15 kW chargers. The 30-kW charger is able to keep the batteries at a positive SOE the entire day. The lowest SOE was 13.7 kWh at 0500. and the final SOE was 20 kWh. Because the final SOE was not as high as the starting

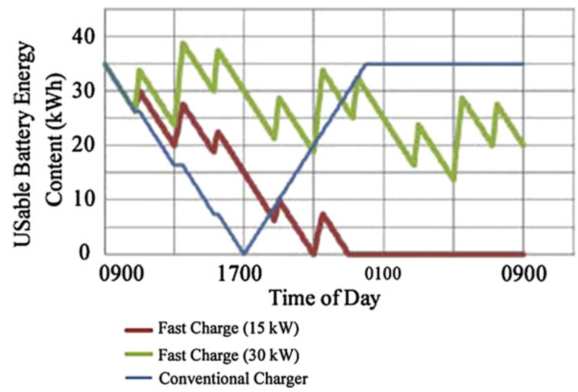

Fig. 1 – Battery energy content for a workday resulting from three different technologies/charging scenarios.

SOE, the forklifts would need to charge during the last ~30 min of each day to sustain continuous operation. This analysis suggests that using 30 kW fast chargers to operate with a workload of over 2.95 EBUs would require the purchase of additional forklifts to maintain full capabilities.

3.3. Workload scaling of conventionally charged battery forklift operation

The conventionally-charged battery forklift scenario is used as the baseline for this economic comparison. The battery takes 8 h to charge and another 8 h to cool, meaning each forklift would need one battery per shift of operation. The economic model therefore requires an extra battery be purchased for each battery change. Only a single charger is required for each forklift (with workloads up to 3 EBUs).

3.4. Workload scaling of fast charged battery forklift operation

The fast-charge battery forklift allows for opportunity charging when the conventional forklift is not in operation. This decreases the number of forklifts and chargers needed for high-workload operations. Two different fast-charge scenarios were considered, charging at 15 kW and 30 kW. The manufacturer of fast-charge batteries states that overheating will occur when batteries are charged more than twice a day. If a facility has a workload greater than 2 EBUs, the fast-charge forklifts would need higher current bus bars, more battery spacing, or active onboard cooling to ensure the battery does not overheat. These systems can be installed on any forklift at an additional cost. In this model, the cost of these cooling mechanisms is not included when analyzing operations over 2 EBUs as the means to cool the batteries are specific to the facility and fast-charger manufacturer, and are generally low cost.

3.5. Workload scaling of fuel cell forklift operation

The fuel cell powered forklifts are the most scalable forklift system. Charging is eliminated and refueling takes only ~5 min at a hydrogen filling station. Fuel cell forklifts have no thermal management problems at the workloads considered for this study. For workloads under 3 EBUs, the fuel cell

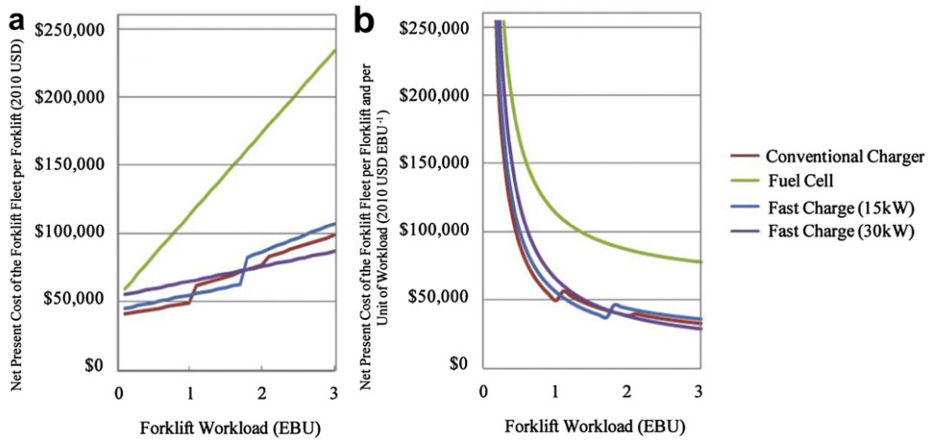

Fig. 2 – Comparison of project net present cost (NPC) among the technologies modeled for two metrics of comparison: NPC per forklift, and NPC per forklift per unit of workload, measured in equivalent battery units (EBU).

forklifts are assumed to require no additional floor space and no duplicated vehicles or powerplants.

4. Results

The NPC for each power scenario was calculated by varying the workload from 0.1 EBU to 3.0 EBU in increments of 0.1 EBU. Fig. 2a shows the project NPC (normalized by the number of forklifts) versus forklift workload. Fig. 2a illustrates that fuel cell forklifts are significantly more expensive than battery powered forklifts at all workloads considered. The slopes of each line correspond to operational cost of the forklift, including refueling time, battery change time, and hydrogen fuel or electricity. The slope of the fuel cell forklift cost (indicative of the operational costs) is much higher than that of the battery powered forklifts. The largest contributor to the operational costs of the fuel cell forklift system is the cost of hydrogen.

For a low workload (less than 1 EBU), the conventional-forklift system is the least expensive technology option. The conventional system has the lowest capital costs and lowest operating costs due to its high charging efficiency, and the low cost of electricity relative to hydrogen. This result is relatively insensitive to assumptions regarding electricity costs. Under a worst-case scenario, where only on-peak electricity is consumed, would increase NPC per forklift at 1 EBU by 6.7% for the conventional forklift.

For higher workloads, between 1 EBU and 1.75 EBU, the least expensive technology option is the fast-charging battery forklift at 15 kW. At greater than 1 EBU, the conventional charge scenario requires additional batteries and a battery room operator to operate at full productivity. These changes are visible as a step increase in the cost and a slight increase in the operational costs of the conventional charge scenario. This additional cost makes the conventional charging scenario more expensive than the fast-charging scenario at 15 kW. The fast charging scenario at 15 kW is the least expensive technology option between 1 and 1.75 EBU.

At 1.75 EBUs, the 15-kW fast-charger can no longer keep up with the power demand of the forklift using only opportunity charging, as shown in Fig. 1. Without allowing for battery replacement the forklift operator would not be able to work while the battery was being recharged. Because the operators' time over the 5 year economic life of the project outweighs the capital costs of additional forklifts, and because batteries cannot be changed out in fast charge forklifts, the facility purchases an extra forklift to maintain full productivity. The purchase of additional forklifts creates a step in the NPC per forklift for the 15-kW fast-charge scenario at 1.75 EBUs.

For workloads greater than 1.75 EBU, the 30-kW fast-charge forklift system is the least expensive technology.

A second metric, the project NPC per forklift per unit workload, is shown in Fig. 2b. This metric can be a good criterion for determining the value of the four technology options because it shows that the cost per unit of operation time decreases the more the forklift is in use. As workload decreases and the EBUs drop to zero, the cost per unit of operation time approaches an infinite value. These results illustrate that the fuel cell forklift scenario is more costly than the battery powered scenarios, even at very high workloads.

Comparing the costs of the conventional and fast-charge technology options shows that there are regions where each technology is most economical. For lower workloads, the conventional charging scenario is least expensive. For more than 1 EBU, fast-charging at 15-kW becomes least expensive. The interaction between the workload requirements and the capital costs of addition forklifts, batteries and battery rooms determines which technology is least cost for any particular workload.

5. Conclusions

The project NPC was calculated using models of the capital and operational costs for four technologies of interest, conventionally charged batteries, fast charging of conventional batteries with 15 kW and 30 kW chargers and PEM fuel cells. Analysis of the project NPC and project NPC per unit of workload shows that fuel cell forklifts cannot compete with battery technologies on an economic basis for the workloads and facility types considered. For low workloads, conventional battery swapping forklifts allow for the lowest project NPC. At higher workloads, fast-charge forklifts have the lowest project NPC because they require less battery changing infrastructure and space.

These quantitative results agreed with the qualitative understanding of the fuel cell forklift industry based on interviews conducted for this research. In general, fuel cell forklifts were considered most commercially viable at materials handling facilities that had extraordinary costs of facility space, labor, and electricity. These outlier facilities might be physically unable to expand a battery room with increasing workload, located in geographic areas with high prevailing wages, and are subject to high electricity peak demand prices. These types of facilities should perform the type of economic analysis described in this report using their particular valuations of these key costs.

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