An Evaluation of the Total Cost of Ownership of Fuel Cell-Powered Material Handling Equipment

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National Renewable Energy Laboratory

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Finally, facilities managers and representatives from commercially operated warehouses participating in the government-sponsored deployments of fuel cell material handling equipment provided detailed information on their fuel cell fleets that was used as a basis of the cost of ownership analysis. These commercial warehouse operators and representatives from Plug Power, Nuvera Fuel Cells, and Hydrogenics Corporation provided ongoing fuel cell system operational data and reviewed NREL's composite data products, many of which were instrumental in this report's cost of ownership evaluation.

Executive Summary

Although fuel cell electric vehicles are still are in a pre-commercialization phase, hydrogen fuel cells currently are being used commercially in early market applications such as material handling and backup power. These early commercialization fuel cell deployments are helping improve hydrogen and fuel cell technologies and expanding their market potential.

Fuel cell systems look particularly promising as replacements for batteries in material handling equipment (MHE, or more typically "forklifts") in warehouse applications where operations extend for two or three shifts each day. In such applications, batteries generally need to be charged and replaced one or more times each day, which complicates logistics and increases overall labor costs. Fuel cell MHE have zero emissions, can operate for more than 12 hours without performance degradation, and can be fueled in minutes, making fuel cells an attractive alternative to conventional battery systems.

The Fuel Cell Technologies Office within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy has helped fund deployments of fuel cell-powered material handling equipment in commercial warehouse facilities to better understand the real-world performance of fuel cells in these applications.[1] Additionally, the Department of Defense's Defense Logistics Agency (DLA), with support from DOE, funded deployments of fuel cell material handling equipment in DLA warehouses as part of its fuel cell research and development program. To date, DOE has helped fund the deployment of more than 500 fuel cell-powered material handling units in commercial facilities. Additionally, DLA deployed more than 100 fuel cell material handling units in its distribution warehouses as part of its research and development activities. Using data from these government co-funded deployments, DOE's National Renewable Energy Laboratory (NREL) has been evaluating the performance of fuel cells in material handling applications. As part of this evaluation, NREL has assessed the total cost of ownership of fuel cell MHE and compared it to the cost of ownership of traditional battery-powered MHE.

[1] DOE has funded deployments of both hydrogen-fueled polymer electrolyte membrane (PEM) fuel cells and methanol-fueled direct methanol fuel cells (DMFCs). This report limits its analysis to hydrogen-fueled PEM fuel cells.

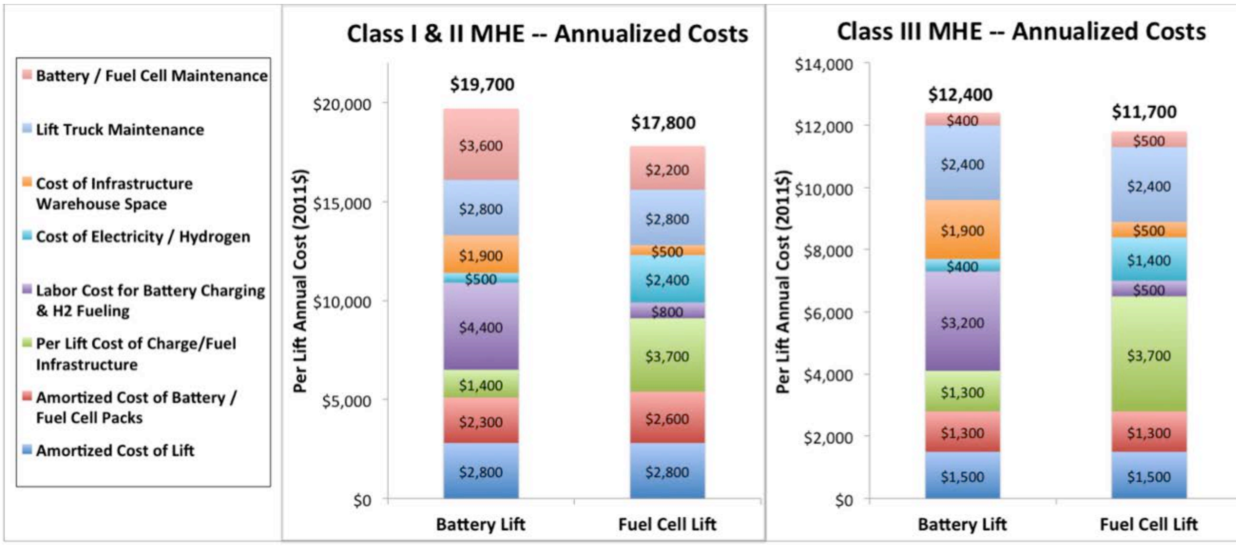

Figure ES-1. Total annual cost of ownership of battery and fuel cell MHE

As part of its cost of ownership assessment, NREL looked at a range of costs associated with MHE operation, including the capital costs of battery and fuel cell systems, the cost of supporting infrastructure, maintenance costs, warehouse space costs, and labor costs. Considering all these costs, NREL found that fuel cell MHE can have a lower overall cost of ownership than comparable battery-powered MHE (see Figure ES-1). The total cost assessment represents an analysis of the average of the deployment sites evaluated, which in turn reflects a fairly intensive warehouse and distribution application—a deployment of about 60 fuel cell lifts for 2–3 shifts per day, 6–7 days per week. NREL found that for Class I and II forklifts (three- and four-wheel, sit-down, counter-balanced forklifts) used in multi-shift operations, fuel cells could reduce the overall cost of ownership by 10%, from $19,700 per year per lift truck to $17,800 per year per lift truck. The cost of ownership of Class III forklifts (also known as pallet jacks) can be reduced by 5%, from $12,400 per year to $11,700 per year for each lift truck.[2]

NREL's evaluation limits itself to considering the cost of ownership and operation of battery and fuel cell MHE. Potential benefits of fuel cell MHE such as improved productivity, and more broadly the potential for increased sales and profits, were not evaluated. The cost analysis assumes that the currently-available federal tax credit for fuel cell purchases is available to help effectively lower the purchased cost of fuel cell systems.[3] As discussed in the report, total cost of

[2] These cost of ownership results have previously been published by NREL as part of its technology validation of early market fuel cell applications. As part of the publication process of the assessment results (known as "composite data products"), the fuel cell MHE cost of ownership results have been reviewed and approved by participants in the government-sponsored deployments, including representatives from Plug Power, Nuvera Fuel Cells, and Hydrogenics Corporation (the companies that provided fuel cell systems for the material handling equipment), as well as representatives from the deployment sites themselves. For more information on these deployments, see NREL's evaluations of early fuel cell market demonstrations available on the NREL Fuel Cell and Hydrogen Technology Validation website: http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

[3] The total cost of ownership assessment is based on data from deployments of fuel cell MHE that received funding support from DOE and DLA, as noted. The cost of ownership assessment does not include this funding support as part of the evaluation, and the results reflect ownership costs that would be seen by any commercial site deploying fuel cell MHE.

ownership of fuel cell MHE is lower than the ownership costs of comparable battery-powered MHE even without the federal tax credit, though the cost savings for fuel cell MHE are reduced.

Breaking down the total cost of ownership results into separate components provides an understanding of the benefits of using fuel cells for MHE and also shows some of the challenges hydrogen and fuel cell technologies face. In terms of equipment costs, fuel cell systems are more expensive than battery systems. When used in multi-shift warehousing operations, considering the longer predicted life of fuel cell systems and the need for multiple battery packs per lift, the total annualized equipment costs of fuel cell systems are comparable to that of batteries for Class I, II, and III MHE. The costs of hydrogen fuel and especially hydrogen fueling infrastructure are both higher than the comparable electricity and battery changing/charging infrastructure costs. For the deployments characterized in this study, these higher costs are more than offset by lower labor costs for hydrogen fueling compared to battery changing and charging and by lower facility space costs for hydrogen infrastructure compared to battery changing and charging infrastructure. For Class I and II MHE, fuel cells can lower annual per-lift truck labor costs from $4,400 for battery changing and charging to only $800 for hydrogen fueling and can lower annual facility space costs from $1,900 to $500 (Class III MHE annual labor costs can be reduced from $3,200 to $500).

As part of its total cost evaluation, NREL also conducted sensitivity analyses to better understand the driving factors associated with the cost of ownership. These analyses indicate that the intensity of the MHE deployment is the largest driving factor in whether fuel cell MHE will have a lower cost of ownership compared to battery MHE. Hydrogen-fueled fuel cell MHE offer significant labor savings over battery systems in intensive, multi-shift operations that require frequent battery changes. The number of operation days per year and particularly the number of MHE units deployed in a facility can also greatly affect whether using fuel cell MHE instead of battery MHE is a cost-effective choice. More operating days and operating hours further extends the labor saving aspects of fuel cell MHE compared to battery MHE, and a greater number of onsite fuel cell systems helps lower the per-lift truck cost of hydrogen fueling infrastructure.

Overall, NREL's cost of ownership evaluation finds that when deployed in larger-scale, multi-shift warehouse applications, fuel cell MHE can provide cost savings compared to traditional, battery-powered MHE. The case studied in this paper considers a fleet of almost 60 fuel cell material handling units. Although the study does not predict the minimum break-even number of fuel cell forklifts, as long as fuel cell MHE fleets are large enough to help minimize the per-lift truck cost of hydrogen infrastructure, and as long as the warehouse facility operates multiple shifts with the need for multiple battery changes, total fuel cell MHE costs appear to stay below the total cost of deploying battery lifts. NREL's findings suggest fairly modest cost of ownership reductions seen by deploying fuel cell MHE rather than traditional battery-powered MHE. As potential productivity assessments associated with fuel cell MHE were not evaluated, NREL's findings may be considered to be conservative.

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1 Introduction

1.1 Overview

Fuel cell electric vehicles are expected to provide significant positive environmental and energy security benefits, yet at this time they are still in a pre-commercialization state of development. However, hydrogen fuel cells are being used today to satisfy a commercial need in early market applications such as material handling and backup power, and these uses are furthering the development of fuel cells and related hydrogen fueling infrastructure and helping expand the market for these promising technologies.

A 2007 study by Battelle indicated that hydrogen-fueled polymer electrolyte membrane (PEM) fuel cells have the potential to provide material handling services at a lower cost than lead acid battery and combustion engine systems can under certain types of operating conditions.[4] Large warehouses can deploy several hundred forklifts per site for handling materials, with operations occurring during two or three shifts each day. Such material handling equipment (MHE) must be low- or zero-emission to meet safety requirements for indoor use. Current technologies meeting these requirements include battery-electric and propane-engine (LPG) MHE. Electric models generally can only operate for about 5–6 hours continuously before they need to be charged or have the drained battery pack replaced with a freshly charged battery pack. A battery can require as much as 8 hours for charging and freshly-charged batteries may need several additional hours of cooling time prior to reuse. This lowers productivity for the forklift unit as well as for the workers responsible for charging or replacing spent battery packs, and it increases equipment costs as multiple battery packs are needed for each lift. Electric forklifts also require additional warehouse space for charging equipment and up to three batteries per unit. LPG forklifts are appropriate for indoor or outdoor use; however, they are not zero-emission. Extra ventilation and safety equipment are necessary for indoor use, and widespread use of LPG MHE in indoor facilities is not generally preferred, particularly in food warehousing and distribution facilities.

Forklifts powered by hydrogen-fueled PEM fuel cells have zero emissions at their point of use, can operate for more than 12 hours without performance degradation, and can be fueled in minutes. Fuel cell MHE can be fueled rapidly, provide constant power without voltage drop during use, and eliminate the need for battery storage and charging infrastructure. Fuel cell MHE require new hydrogen fueling infrastructure, but much of the required infrastructure can be sited outdoors and optimal designs could take up less space than what is currently needed for electric forklifts. As such, fuel cell forklifts offer an alternative to conventional technology and potentially can provide substantial cost savings over comparable battery- and LPG-powered forklifts.

This paper discusses an analysis of the total cost of ownership of PEM fuel cell and traditional battery-powered MHE. The analysis was conducted to better understand the market potential of fuel cells in material handling applications and to validate the business case for fuel cell MHE. The paper begins with a discussion of a number of fuel cell MHE deployments that received funding support from the federal government. These deployments are providing valuable data

[4] K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, “Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets,” Battelle, April 2007.

that form the basis of the cost of ownership assessment. The paper then discusses the role the National Renewable Energy Laboratory (NREL) is playing to compile and analyze these data. After that introduction to the project, the approach to the cost of ownership analysis is discussed. The major inputs driving the analysis are then described, first for Class I and II MHE and then again for Class III MHE. The paper concludes with a discussion of the analysis results, along with the results of sensitivity analyses.

1.2 Deployments of Hydrogen Fuel Cell Material Handling Equipment

The Fuel Cell Technologies Office at the U.S. Department of Energy (DOE) has been funding deployments of fuel cell MHE in order to evaluate their performance, help further fuel cell technology- and manufacturing-readiness levels, and help build and expand early markets for fuel cell technologies.[5] Leveraging funding from the American Recovery and Reinvestment Act of 2009, DOE helped fund deployments of PEM fuel cell MHE at eight commercial warehousing and distribution centers, including facilities operated by Sysco Houston, Sysco Philadelphia, HEB Grocers, Coca-Cola, FedEx, Wegman's Grocers, Whole Foods, and Kimberly Clark. Additionally, the Department of Defense's Defense Logistics Agency (DLA) recently concluded fuel cell research and development projects that have included multi-year demonstrations of the use of hydrogen fuel cell-powered forklifts in material handling operations at four of its warehousing and distribution centers.[6]

Building on its experience with the technology validation of hydrogen fuel cell vehicles and fueling infrastructure, NREL has been performing technical analyses of fuel cell MHE for DOE's Fuel Cell Technologies Office to assess the performance and market potential of fuel cell technologies in material handling applications. NREL is analyzing data from these deployment projects to evaluate the durability and performance of fuel cell forklifts and related hydrogen infrastructure using such metrics as operating hours between fills and operating hours per kilogram, maintenance events, availability, reliability, durability, and safety. While individual company data is kept confidential, NREL publishes aggregated performance analysis results called "composite data products" (CDPs) that show the status and performance of hydrogen and fuel cell technologies without identifying individual companies or their performance (see Appendix for more details on NREL's data analyses).

The DOE- and DOD-sponsored deployments of fuel cell MHE are providing a rich source of data to understand the performance of fuel cells and related hydrogen infrastructure in material handling applications. As part of a research and development project conducted over the course of three years, DLA operated 75 Class I MHE units from three different manufacturers in two DLA-operated warehouses.[7] Within these deployments, fuel cell-powered Class I forklifts have

[5] DOE has funded deployments of both hydrogen-fueled polymer electrolyte membrane (PEM) fuel cells and methanol-fueled direct methanol fuel cells (DMFCs). This report limits its analysis to hydrogen-fueled PEM fuel cells.

[6] For more information on DLA's fuel cell research and development activities, see T.J. Gross, A.J. Poche, and K. C. Ennis, "Beyond Demonstration: The Role of Fuel Cells in DoD's Energy Strategy," LMI, 2011.

[7] The DLA-funded demonstrations characterized in this analysis are now completed. Two additional DLA-funded fuel cell MHE deployments were conducted at the Joint Base Lewis-McChord and DLA's distribution center in Tracy, California. These more recent DLA deployments were not included in this analysis, as NREL did not participate in the data analysis from these projects.

logged more than 180,000 hours of operation, and more than 25,000 kilograms of hydrogen has been dispensed over nearly 50,000 fueling events.

The DOE-sponsored deployments are providing even more data to increase our understanding of the performance of fuel cell MHE under real-world operating conditions. As of June 2012, DOE-sponsored warehouse facilities have deployed more than 500 Class I, II, and III material handling units powered with fuel cells. Over more than three years of operation, these fuel cell forklifts have logged 1.25 million hours of operation using 140,000 kg of hydrogen dispensed over almost 200,000 fueling events.[8]

1.3 Total MHE Cost Analysis Overview

The CDPs from the government-sponsored deployments of fuel cell MHE continue to be updated and made available to the public.[9] As part of the set of CDPs characterizing fuel cell MHE operation, several CDPs have been developed to compare the total cost of ownership of fuel cell-powered MHE to the cost of ownership of traditional battery-powered MHE. This paper describes the analysis underlying the cost of ownership CDPs and discusses the results of those cost analyses. As with all CDPs, the cost of ownership CDPs and their results have been reviewed and approved by representatives of the participating deployments, including representatives from Plug Power, Nuvera Fuel Cells, and Hydrogenics Corporation (the companies that provided fuel cell systems for the material handling equipment), as well as representatives of DLA, FedEx, Wegman's Grocers, Sysco Foods, Coca-Cola, HEB, Whole Foods, and Kimberly Clark.

For the total cost of ownership assessment, separate analyses were conducted for Class I and II lifts (analyzed as a single class for the purposes of this assessment) and Class III lifts. The cost of ownership assessment considers a wide array of costs: capital and replacement costs, maintenance costs, and operational costs including labor costs, energy and fuel costs, and cost of warehouse space dedicated to MHE-related equipment.

The total cost of ownership analysis is based on two primary sources of data. Much of the data on MHE costs and usage come from a questionnaire provided to operations managers of the warehouses deploying fuel cell MHE, listed above. NREL sent questionnaires to facilities managers at 10 deployment sites and received responses from seven sites; five of the responses were from commercial warehouse facilities and two responses came from government-operated facilities. Data on usage patterns are also drawn from NREL's fuel cell MHE CDPs, which characterize fuel cell MHE performance and operations. In addition to these primary sources of data, some literature data are referenced.

For the cost of ownership analysis, all costs are presented as annualized costs on a per-lift truck basis (in present value terms). Costs of ownership are not analyzed over a specific time period. Rather, the use of material handling equipment and their associated infrastructure in the warehouse facility is presumed to be an ongoing enterprise, with operating costs expected to

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[8] For more information on these deployments, see NREL's evaluations of early fuel cell market demonstrations available on the NREL Fuel Cell and Hydrogen Technology Validation website: http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

[9] Current versions of early fuel cell market demonstration CDPs are available on the NREL Fuel Cell and Hydrogen Technology Validation website: http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

remain constant in real terms and capital equipment expected to be maintained and replaced as needed. Capital costs are amortized over the expected life (reported in years) of the specific equipment in question. Equipment is maintained and replaced as necessary, with equipment replacement costs assumed to remain constant in real dollar terms. With this analysis approach, the costs presented are essentially for development of a "greenfield" site without any existing infrastructure and no need for any demolition or remodeling of the existing facility. For the purposes of this analysis, material handling equipment is presumed to be deployed in commercial facilities (not government owned), and thus federal tax credits for fuel cell purchases would be available. (The federal tax credit for fuel cell system purchases is considered to be available in this evaluation, but no other government support is considered, even though the deployments analyzed in this evaluation did receive additional cost-sharing support.)

As costs are considered in present-value terms, a discount rate is applied to capital purchases. For this analysis, the discount rate of 1.5% has been used, based on U.S. Treasury bond rates as reported by the U.S. Treasury. In particular, the 1.5% real rate is the one-year average (from September 2010 to September 2011 when the cost of ownership analysis was initially conducted) of daily U.S. Treasury Long-Term Real Rates reported for U.S. Treasury Inflation Protected Securities (TIPS). The Treasury Department[10] notes that the "Long-Term Real Rate Average is the unweighted average of bid real yields on all outstanding TIPS with remaining maturities of more than 10 years and is intended as a proxy for long-term real rates."

This evaluation limits itself to considering the cost of ownership and operation of battery and fuel cell MHE. Potential benefits of fuel cell MHE such as improved productivity, and more broadly the potential for increased sales and profits, are not evaluated. The discussion around increased productivity attained by using fuel cell power modules is a contentious one in industry, often with differing opinions presented by material handling equipment manufacturers and fuel cell suppliers. Without detailed, controlled experiments of the two technologies, it is not possible for NREL to make any judgments about the specific potential productivity effects of using fuel cells instead of batteries for MHE power. There are far too many variables that affect operator productivity beyond the type of power module used in the vehicle. These include, but are not limited to, the following: the type of drive system in the vehicle (AC or DC), age, condition and state of charge of the battery in use, workload, equipment capacity factor, seasonality, operator fatigue, and operator experience.

2 Cost Analysis for Class I and II Material Handling Equipment

A summary of the cost elements contributing to the total cost of ownership of Class I and II forklifts is shown in Figure 1. These cost elements include:

- Cost of the bare forklift
- Cost of the required battery or fuel cell systems
- Cost of battery changing and charging or hydrogen fueling infrastructure

[10] U.S. Department of the Treasury, Resource Center: Daily Treasury Real Long-Term Rates, www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=reallongtermrate.

- Labor costs of battery changing or hydrogen fueling
- Cost of energy required by the forklifts
- Cost of facility space for infrastructure (indoor and outdoor)
- Cost of lift truck maintenance
- Cost of battery or fuel cell system maintenance.

The per-lift truck annualized cost calculations for these cost elements and the key input parameters affecting these costs are discussed in the sections below. There are a number of key parameters that drive these cost elements, which are shown in Figure 2 and Figure 3.

Total Annualized Costs Per Lift Truck		
Cost Element	**Battery MHE**	**Fuel Cell MHE**
Amortized Cost of Lift Truck	$2,800	$2,800
Amortized Cost of Battery / Fuel Cell Packs	$2,300	$2,600
Per-Lift Truck Cost of Charge/Fuel Infrastructure	$1,400	$3,700
Labor Cost for Charging and Fueling	$4,400	$800
Cost of Electricity / Hydrogen	$500	$2,400
Cost of Infrastructure Warehouse Space	$1,900	$500
Lift Truck Maintenance	$2,800	$2,800
Battery / Fuel Cell Maintenance	$3,600	$2,200
Total Annual Cost of Forklift	$19,700	$17,800

Figure 1. Contributing costs to total cost of ownership of Class I and II MHE

2.1 Cost of Bare Lift Truck, Battery Packs, and Fuel Cell Systems

Based on feedback from the questionnaire, warehouse operators reported that the cost of a bare lift truck ranged from $17,000 to $35,000 each, with an average cost of $25,000. Similarly, users reported lift truck lifetimes ranging from 5 to 15 years, with an average lifetime of 10 years. Using these data, the annualized, present value cost of a bare Class I lift truck is $2,800. (Note: though the cost of ownership analysis was generalized for Class I and II lift trucks, the cost presented for the bare lift truck only includes Class I lifts.)

Facility operators reported an average cost for a single battery pack of $4,800, with costs ranging from $2,900 to $8,000. They further reported a 4.4-year average lifetime for a battery pack (ranging from 4 to 5 years). The facilities operate for 2 to 3 shifts per day, with an average of 2.25 shifts per day. MHE batteries generally cannot remain charged for two full shifts, so users typically own more than one battery pack per lift truck if batteries are not charged in the lift. Facility operators reported an average of two battery packs per lift. Considering the cost of two battery packs with an average lifetime of 4.4 years, the annualized, present value of battery packs on a per-lift truck basis is $2,300.

In contrast to these battery costs, operators reported an average cost of $33,000 for a fuel cell system for Class I and II lifts (typically 8–10 kW in size), with costs ranging from $32,000 to $34,000. These equipment costs were generally offset by a federal tax credit available for fuel cell systems, set at the lesser of $3,000/kW or 30% of the cost. For an average system costing $33,000, this tax credit reduces the effective cost of the fuel cell system by about $10,000. This tax credit is assumed to be available and applicable for the purposes of this analysis, though all purchasers may not be able to take advantage of it (for example, as federal facilities, the DLA-sponsored deployments could not make use of this tax credit).

Key Parameters for General And Capital Costs		Class I/II MHE Battery	Class I/II MHE Fuel Cell
General	Discount Rate for Capital Purchases	1.5%	1.5%
	Operation Days Per Year	340	340
	Operation Hours Per Year	2,400	2,400
	Average Shifts Per Day	2.25	2.25
	Size of Combined Class I, II & III Fleet	97	58
	Cost of Hydrogen ($/kg)	–	$8/kg
Lift Truck Capital	Capital Cost of Bare Lift Truck	$25,000	$25,000
	Average Life of Lift Truck (years)	10	10
Battery & Fuel Cell Capital	Cost of Batteries (2) / Fuel Cell System	$9,600	$33,000
	Federal Tax Credits Available	–	$9,800
	Battery / Fuel Cell Systems Per Lift	2	1
	Battery / Fuel Cell System Life (years)	4.4	10

Figure 2. General facility and capital cost inputs for Class I and II MHE[11]

Users reported an expected fuel cell lifetime of 10 years (ranging from 5 to 15 years). (This cost analysis does include costs for ongoing maintenance of fuel cell MHE as discussed below, but no specific capital costs are included for the potential need for a fuel cell stack replacement during the 10-year fuel cell system lifetime.) Because hydrogen-based fuel cell systems can be filled quickly compared to the time needed for battery charging, users reported an average of one fuel cell system per lift truck. Considering the cost less the available tax credit and a lifetime of 10 years, the annualized, present value of fuel cell systems per lift truck is $2,600. If the tax credit is not available, the annualized cost of a fuel cell system rises by $1,100 to a total of $3,700 per year per lift truck.

2.2 Cost of Battery-Charging and Hydrogen Infrastructure

Batteries used in material handling applications can typically only provide adequate power for one 8-hour shift, or about 5–6 hours of actual "pedal time" (time the lift is in use during the shift), after which they must be charged and allowed to cool down before use. In multi-shift

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[11] Figure 2 is taken from NREL CDP MHE 64a, General & Capital Cost Inputs for Class I/II MHE, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

operations, batteries are generally changed out each shift. Battery charging infrastructure includes the actual battery chargers but also includes a battery charge and change-out area or room, charging stations with charging/cooling racks, hoists and cranes used to change batteries, and battery wash and fill stations.

Facility operators reported keeping an average of 1.1 chargers for every battery lift truck deployed, with an average charger cost of $2,800 (ranging from $2,200 to $3,500 per charger). On average, users reported battery chargers lasting 7.5 years, with lifetimes ranging from 5 to 10 years. Based on these data, the present value, annualized cost of chargers reported on a per-lift truck basis is $500.

In addition to these equipment costs for battery chargers, battery infrastructure costs include the equipment costs for the racks, hoists, and cranes; periodic refurbishment of changing equipment; amortized construction costs for the battery changing and charging room; and maintenance of both the chargers and the battery changing equipment. Respondents to the questionnaire did not provide enough depth of detail on these battery infrastructure items to estimate annualized costs. Based on feedback on the deployment experience at DLA's Defense Depot in Susquehanna, Pennsylvania, together with data from available literature,[12] these costs were estimated to be $900 per lift truck per year. Together with the equipment costs of the chargers, the total present value, annualized cost of battery infrastructure capital and operating and maintenance costs is $1,400 per lift truck.

For the fuel cell MHE deployments analyzed, most facilities operated leased hydrogen fueling infrastructure although some facilities purchased the hydrogen infrastructure. Leased equipment costs were based on monthly service charges, which include both depreciation on installed capital equipment and a service fee to cover maintenance. Respondents using purchased equipment provided information on the cost of the installed infrastructure and the cost of maintaining and operating that equipment. The total monthly cost of hydrogen infrastructure—either the amortized purchase cost of infrastructure plus maintenance costs or the service charge for leased infrastructure—ranged from $12,000 to $22,000 per site. Taking into account the number of fuel cell MHE served, the present value, annualized cost of hydrogen infrastructure (including capital, operating, and maintenance costs) is $3,700 per lift truck. This average infrastructure cost assessment is estimated on a per-lift truck basis, not on the amount of hydrogen consumed, and considers all fuel cell lifts deployed, including Class I, II, and III MHE. It is important to note that this per-lift truck cost of hydrogen infrastructure is for an average fuel cell MHE fleet size of 58 units. Per-lift truck hydrogen infrastructure costs vary inversely to the

[12] For more information, please see the following: K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, "Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets," Battelle, April 2007; M. Canes, "Economic Aspects of Fuel Cell Forklifts: What Have We Learned from Two Defense Logistics Agency Pilot Projects," USAEE Conference, October 2011; A. Schneider, "Vistavia Warehousing, Inc.," *Global Perspectives on Accounting Education*, Vol. 1, 2004; J. Bowles, "The Case for Choosing 3-Phase AC Electric Trucks Over Vehicles Based on DC Electric, Internal Combustion, or Diesel Technologies," Jungheinrich Lift Truck Corporation; "The Truth About Electric Lift Trucks," Hyster Company, 2010.

number of fuel cell units deployed, and thus would be higher for smaller fleets and lower for larger fleets.[13]

2.3 Labor Costs for Battery Changing and Hydrogen Fueling

For MHE operated in multiple shifts per day, the short hydrogen fueling times for fuel cells compared to the more lengthy time required to change out and charge batteries give fuel cell lifts an advantage over battery lifts under these operating conditions. (Because these labor savings are one of the primary advantages of fuel cell MHE over battery-powered lifts, this analysis only considers multi-shift operations.) This analysis estimates the cost of warehouse labor spent changing and charging batteries or spent fueling fuel cell MHE with hydrogen. Fuel cell MHE provide a consistent level of power throughout their operation, whereas battery-powered MHE can sometimes exhibit a sag in their available voltage at the end of the discharge cycle, reducing available performance. As such, fuel cell MHE might be able to provide improved performance compared to battery lifts towards the end of the shift or discharge cycle. However, this analysis does not attempt to quantify any differences in labor productivity between fuel cell MHE and battery MHE.

Key Parameters for Infrastructure and Operations & Maintenance Costs		Class I/II MHE	
		Battery	Fuel Cell
Battery & Hydrogen Infrastructure	Capital Cost of Battery Charger	$2,800	–
	Average Life of Charger (years)	7.5	–
	Average Number of Chargers/Lift	1.1	–
	Infrastructure Capital + Maintenance	$75/lift/mo.	$17,000/mo.
Labor Cost for Battery Changes & H2 Fueling	Battery Change / H2 Fill Time (min.)	10.5	3.0
	Lift Travel + Queue Time (min.)	3.8	3.3
	Battery Changes / H2 Fills Per Day	2.25	1.0
	Operator Loaded Labor Rate ($/hr.)	$24	$24
Warehouse Space Cost	Indoor Space for Infrastructure (ft^2)	5,100 ft^2	500 ft^2
	Outdoor Space for Infrastructure (ft^2)	–	2,500 ft^2
	Indoor Warehouse Space Cost ($/$ft^2$)	$3/$ft^2$	$3/$ft^2$
	Outdoor Land Space Cost ($/$ft^2$)	–	$0.34/$ft^2$
Maintenance	Monthly Lift Truck Maintenance	$230	$230
	Monthly Battery / FC Maintenance	$150	$180

Figure 3. Infrastructure and operational cost inputs for Class I and II MHE[14]

[13] As some of the infrastructure costs associated with MHE operation may not scale linearly with fleet size, the sizes of the analyzed MHE fleets are shown in Figure 2. The costs analyzed come from responses from facility managers who may operate both battery-powered and fuel cell MHE. The difference in fleet sizes shown in Figure 2 (97 battery-powered MHE vs. 58 fuel cell MHE) represent the average fleet sizes of battery-powered and fuel cell MHE at these warehouses, indicating that the facilities analyzed deploy more battery-powered lifts on average.

The labor cost analysis considers both the labor time for battery change and charge compared to hydrogen fueling time and the travel time and queuing time for the lift operator. The cost and space required for battery changes generally mean that only one battery changing area is available in the warehouse facility. Conversely, the low cost and footprint requirements for hydrogen fueling dispensers often enable warehouses to provide more than one hydrogen dispenser, potentially in multiple warehouse locations. At the same time, because hydrogen fueling time is shorter than the time required to change out batteries, queuing time can be reduced. As a result, travel and queue times for battery lifts can be longer than those for fuel cell lifts.

Based on data collected from the analyzed deployments, warehouse facilities operate an average of 340 days each year, with 2,400 hours of operation each year per lift. This level of operation, which is used in the cost analysis, tracks feedback received from facility operators. Based on the questionnaire, warehouse facilities operated an average of 333 days per year (ranging from 280 to 360 days per year) with material handling units averaging 2,100 hours of operation per year. Facilities operated 2 or 3 shifts each day, with an average of 2.25 shifts per day. Facility managers reported an average loaded labor rate for battery change-out labor of $24/hour (ranging from $19 to $28 per hour). Hydrogen fueling labor also averaged $24/hour, with a range of $18 to $32 per hour.

Respondents reported an average of 2.25 battery changes per day, which corresponds to one battery change for each shift. Travel and queuing time for battery lifts averaged 3.8 minutes, and battery changes required an average of 10.5 minutes. Based on this, the annual per-lift truck labor cost for battery changing and charging is $4,400 (about $13 per day per lift truck).

The labor cost analysis for fuel cell MHE used data from questionnaire respondents together with data on filling time and frequency collected from the analyzed deployments and analyzed by NREL (particularly data from MHE CDPs 6, 8, and 22). Respondents reported an average travel and queuing time of 3.3 minutes for filling fuel cell MHE with hydrogen. Based on data from the deployments, actual hydrogen fueling time for Class I and II lifts is 3 minutes per fill (compared to an average hydrogen filling time of 3.4 minutes as reported from facilities managers based on the questionnaire). Analyzing the data from the questionnaire and from the fuel cell MHE deployments, the annual per-lift truck labor cost for hydrogen fueling is $800 (about $2.50 per day per lift).

2.4 Cost of Electricity and Hydrogen

The cost of energy to operate MHE can be a significant annual expense, particularly for fuel cell lifts as hydrogen is more expensive than electricity on a per-unit-energy basis. Based on feedback from warehouse operators, battery-powered lifts require $500 per year on average in electricity costs, per lift. Respondents provided electricity costs as a total per lift truck or per fleet, not in terms of usage and cost per kilowatt-hour of electricity. As a reference, average commercial electricity rates in the United States are about 7.5 cents/kWh.

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[14] Figure 3 is taken from NREL CDP MHE 64b, Infrastructure & Operation Costs for Class I/II MHE, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

Facility operators reported an average hydrogen cost of $8/kg (ranging from $5 to $22 per kilogram). Using fuel cell MHE deployment data on per-lift truck hydrogen usage together with this average $8/kg hydrogen cost, fuel cell MHE incur annual hydrogen expenses of $2,400 per lift. In addition to the per-kilogram hydrogen cost, respondents also provided total fuel cell MHE fleet costs for hydrogen. These costs ranged from $100 to $300 per month per lift, or an average of $2,300 per year, closely tracking the $2,400 cost developed using actual deployment data on hydrogen usage.

Though questionnaire respondents did not provide a lot of depth on electricity costs for battery lifts, the reported costs were compared with reported hydrogen usage for comparable fuel cell MHE at the deployment site using available literature data on fuel cell and battery efficiency. Argonne National Laboratory has reported that a Class I fuel cell MHE unit typically provides 15 kWh of useable energy or work per kilogram of hydrogen.[15] At the same time, Argonne reports that the typical charging efficiency of a battery charger is 84% and the typical discharge efficiency of batteries used in MHE is 76%. Combining these efficiency figures with the reported hydrogen use for fuel cell MHE at the deployment sites implies that comparable battery lifts would require an average of 550 kWh of electricity per month (ranging from 350 kWh to 1,000 kWh). At an average electricity rate of 7.5 cents/kWh, this means comparable battery lifts would have average annual electricity expenses of $500 per lift truck, which matches the average $500 per year electricity costs reported in the questionnaire.

2.5 Cost of Infrastructure Warehouse Space

The total cost of ownership analysis also considers the cost of warehouse space and outdoor space dedicated to hydrogen infrastructure and battery changing and charging infrastructure. Based on responses to the questionnaire, the average cost of indoor warehouse space is $\$3/ft^2$/month, with a reported range of $0.50 to $4.80 per square foot per month. Respondents did not address the cost of outdoor space, so the cost analysis uses a value of $\$0.34/ft^2$/month, which is the cost of leased land at fueling stations used by NREL's Hydrogen Analysis (H2A) model.[16]

Respondents reported an average of 5,100 square feet of warehouse space dedicated to battery changing and charging, in support of an average fleet size of 97 battery lifts (with warehouse space requirements ranging from 2,300 to 8,400 square feet). At an average warehouse cost of $\$3/ft^2$/month, this results in an average annual warehouse space cost of $1,900 per battery lift.

Respondents reported an average of 500 square feet of warehouse space dedicated to hydrogen infrastructure, in support of an average fleet size of 58 fuel cell lifts (with warehouse space requirements ranging from 200 to 700 square feet). Users also reported an average of 2,500 square feet of outdoor space dedicated to hydrogen infrastructure, with a range of 500 to 5,000 square feet. Applying the average costs of warehouse and outdoor space reported above results in an average annual infrastructure space cost of $500 per fuel cell lift truck.

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[15] L.L. Gaines, A. Elgowainy, and M.Q. Wang, "Full Fuel-Cycle Comparison of Forklift Propulsion Systems," Argonne National Laboratory Center for Transportation Research, ANL/ESD/08-3, October 2008.

[16] NREL's H2A Production model is a widely used and transparent techno-economic analysis tool that calculates the dispensed cost of hydrogen based on operating and capital inputs. It is available for download at http://www.hydrogen.energy.gov/h2a_production.html.

2.6 Cost of Maintenance for Lift Trucks, Battery Packs, and Fuel Cell Systems

Warehouse operators reported an average of $230 per month spent on lift truck maintenance, or $2,800 per lift truck each year. This maintenance cost is assumed to be the same for battery lift trucks and fuel cell lift trucks. Operators reported an average of $150 per month in maintenance costs per battery system. With an average of two battery packs per lift, this results in an annual battery pack maintenance cost of $3,600 per lift truck.

Based on data provided for the fuel cell MHE deployments (particularly from MHE CDP 14), fuel cell systems average about 1.5 hours of maintenance per month. To determine labor costs, the analysis assumes a labor rate of $80/hour fully burdened, which is the upper end reported labor rate for fuel cell system maintenance labor. Available data for parts costs are more limited, but based on available data, the analysis assumes that the total parts cost averages half the maintenance labor cost. Based on this, the total annual maintenance cost for fuel cell systems is $2,200 per lift truck. This calculated maintenance cost using deployment data matches the average $2,200 annual per-lift truck maintenance cost reported in the questionnaire.

3 Cost Analysis for Class III Material Handling Equipment

A summary of the cost elements contributing to the total cost of ownership of Class III forklifts is shown in Figure 4. These cost elements include:

- Cost of the bare forklift
- Cost of the required battery or fuel cell systems
- Cost of battery changing and charging or hydrogen fueling infrastructure
- Labor costs of battery changing or hydrogen fueling
- Cost of energy required by the forklifts
- Cost of facility space for infrastructure (indoor and outdoor)
- Cost of lift truck maintenance
- Cost of battery or fuel cell system maintenance.

The per-lift truck annualized cost calculations for these cost elements and the key input parameters affecting these costs are discussed in the sections below. There are a number of key parameters that drive these cost elements, which are shown in Figure 5 and Figure 6.

As noted above, this cost analysis does not attempt to address any changes in productivity between facilities operating fuel cell MHE and facilities operating battery MHE. The analysis focuses explicitly on costs of operation. As such, the cost of labor to fuel or change batteries for MHE are considered, as are the facility space costs of necessary infrastructure, but potential productivity gains associated with re-assigning personnel to other tasks or re-purposing warehouse space due to smaller infrastructure footprints are not considered.

Total Annualized Costs Per Lift Truck		
Cost Element	**Battery MHE**	**Fuel Cell MHE**
Amortized Cost of Lift Truck	$1,500	$1,500
Amortized Cost of Battery / Fuel Cell Packs	$1,300	$1,300
Per Lift Truck Cost of Charge/Fuel Infrastructure	$1,300	$3,700
Labor Cost for Charging and Fueling	$3,200	$500
Cost of Electricity / Hydrogen	$400	$1,400
Cost of Infrastructure Warehouse Space	$1,900	$500
Lift Truck Maintenance	$2,400	$2,400
Battery / Fuel Cell Maintenance	$400	$500
Total Annual Cost of Forklift	$12,400	$11,700

Figure 4. Contributing costs to total cost of ownership of Class III MHE

3.1 Cost of Bare Lift Truck, Battery Packs, and Fuel Cell Systems

Based on feedback from the questionnaire, warehouse operators reported that the cost of a bare Class III pallet jack ranged from $6,500 to $9,900 each, with an average cost of $7,800. Users reported lift truck lifetimes ranging from 5 to 7 years, with an average lifetime of 5.7 years. Using these data, the annualized, present value cost of a bare Class III lift truck is $1,500.

Warehouse operators reported an average cost for a single battery pack of $2,800, with costs ranging from $2,200 to $3,500. They further reported a 4.5-year average lifetime for a battery pack (ranging from 4 to 5 years). The facilities analyzed operate for 2 shifts per day. To support multi-shift operations, an average of two battery packs per lift truck is assumed. Considering the cost of two battery packs with an average lifetime of 4.5 years, the annualized, present value of battery packs on a per-lift truck basis is $1,300.

For Class III lifts, operators reported an average cost of $15,000 for a fuel cell system (typically <3 kW in size). The federal tax credit available for fuel cell systems, set at the lesser of $3,000/kW or 30% of the cost, can offset this average fuel cell system cost by about $4,600. This tax credit is assumed to be available and applicable for the purposes of this analysis, though all purchasers may not be able to take advantage of it.

Users reported an expected fuel cell lifetime of 9 years (ranging from 8 to 10 years). Because hydrogen-based fuel cell systems can be filled quickly compared to the time needed for battery charging, users reported an average of one fuel cell system per material handling unit. Similar to the analysis of Class I and II MHE, the cost analysis of Class III MHE considers ongoing maintenance of the fuel cell system but does not specifically allocate a capital cost for potential fuel cell stack replacements during the 9-year lifetime. Considering the cost less the available tax credit and a lifetime of 9 years, the annualized, present value of fuel cell systems per lift truck is $1,300. If the tax credit is not available, the annualized cost of a fuel cell system rises by $500 to a total of $1,800 per year per lift truck.

Key Parameters for General And Capital Costs		Class III MHE Battery	Class III MHE Fuel Cell
General	Discount Rate for Capital Purchases	1.5%	1.5%
	Operation Days Per Year	340	340
	Operation Hours Per Year	3,000	3,000
	Average Shifts Per Day	2	2
	Size of Combined Class I, II & III Fleet	97	58
	Cost of Hydrogen ($/kg)	–	$8/kg
Lift Truck Capital	Capital Cost of Bare Lift Truck	$7,800	$7,800
	Average Life of Lift Truck (years)	5.7	5.7
Battery & Fuel Cell Capital	Cost of Batteries (2) / Fuel Cell System	$5,600	$15,000
	Federal Tax Credits Available	–	$4,600
	Battery / Fuel Cell Systems Per Lift	2	1
	Battery / Fuel Cell System Life (years)	4.5	9

Figure 5. General facility and capital cost inputs for Class III MHE[17]

3.2 Cost of Battery-Charging and Hydrogen Infrastructure

Batteries used in material handling applications can typically only provide adequate power for one 8-hour shift, or about 5–6 hours of actual "pedal time," after which they must be charged and allowed to cool down before use. In multi-shift operations, batteries are generally changed out each shift. Battery charging infrastructure includes the actual battery chargers but also includes a battery charge and change-out area or room, charging stations with charging/cooling racks, hoists and cranes used to change batteries, and battery wash and fill stations.

Facility operators reported keeping an average of 1.1 chargers for every battery lift truck deployed, with an average charger cost of $1,600. Users reported battery chargers lasting 5 years. Based on these data, the present value, annualized cost of chargers reported on a per-lift truck basis is $400.

As in the case for Class I lifts, total infrastructure costs also include the equipment costs for the racks, hoists, and cranes; periodic refurbishment of changing equipment; amortized construction costs for the battery changing and charging room; and maintenance of both the chargers and the battery changing equipment. Respondents to the questionnaire did not provide enough depth of detail on these battery infrastructure items to estimate annualized costs. These costs were estimated to be $900 per lift truck each year, consistent with the estimate for these costs for Class I and II battery infrastructure. Together with the equipment costs of the chargers, the total present value, annualized cost of battery infrastructure capital and operating and maintenance costs is $1,300 per lift truck.

As described above, the total monthly cost of hydrogen infrastructure ranged from $12,000 to $22,000 per site. On an annualized, present value basis, the cost of hydrogen infrastructure (including capital, operating, and maintenance costs) is estimated to be $3,700 per lift truck for

[17] Figure 5 is taken from NREL CDP MHE 64c, General & Capital Cost Inputs for Class III MHE, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

Class I, II, and III fuel cell MHE. Once again, this cost estimate is based on an average fleet size of 58 fuel cell material handling units.

3.3 Labor Costs for Battery Changing and Hydrogen Fueling

The cost of ownership analysis includes an estimate of the cost of warehouse labor spent changing and charging batteries or spent fueling fuel cell MHE with hydrogen. The labor cost analysis considers both the labor time for battery change and charge compared to hydrogen fueling time and the travel time and queuing time for the lift truck operator.

Based on data from the deployments, the Class III MHE are operated 340 days a year, averaging 3,000 hours of operation per year. (As part of the questionnaire, warehouse facility operators also reported an average of 340 days of operation, ranging from 300 to 360 days per year.) Facilities operate two shifts each day, and facility managers reported an average loaded labor rate of $24/hour for both battery change-out labor and hydrogen fueling labor.

Respondents reported an average of two battery changes per day for Class III MHE. Travel and queuing time for battery lifts averaged 2.8 minutes, and battery changes required an average of 9 minutes. Based on these data, the annual per-lift truck labor cost for battery changing and charging is $3,200, or about $9 per day per lift truck.

The labor cost analysis for fuel cell MHE used data from questionnaire respondents together with data on filling time and frequency collected from the analyzed deployments and analyzed by NREL (particularly data from MHE CDPs 6, 8, and 22). Respondents reported an average travel and queuing time of 2.8 minutes for filling fuel cell MHE. Based on data from the deployments, actual hydrogen fueling time for Class III lifts is 1.6 minutes per fill (compared to a reported average hydrogen filling time of 1.1 minutes based on facilities managers' responses to the questionnaire). Analyzing the data from the questionnaire and from the fuel cell MHE deployments, the annual per-lift truck labor cost for hydrogen fueling is $500, or about $1.50 per day per lift truck.

3.4 Cost of Electricity and Hydrogen

The cost of ownership analysis includes the cost of electric or hydrogen energy needed to operate the lifts. Based on feedback from warehouse operators, battery-powered lifts require $400 per year on average in electricity costs, per lift truck. Fuel cell MHE fleet operators reported an average hydrogen cost of $8/kg (ranging from $5 to $22 per kilogram). Respondents provided an average annual cost for hydrogen of $1,400 per lift truck.

Key Parameters for Infrastructure and Operations & Maintenance Costs		Class III MHE Battery	Class III MHE Fuel Cell
Battery & Hydrogen Infrastructure	Capital Cost of Battery Charger	$1,600	–
	Average Life of Charger (years)	5	–
	Average Number of Chargers/Lift	1.1	–
	Infrastructure Capital + Maintenance	$75/lift/mo.	$17,000/mo.
Labor Cost for Battery Changes & H2 Fueling	Battery Change / H2 Fill Time (min.)	9	1.6
	Lift Travel + Queue Time (min.)	2.8	2.8
	Battery Changes / H2 Fills Per Day	2	0.8
	Operator Loaded Labor Rate ($/hr.)	$24	$24
Warehouse Space Cost	Indoor Space for Infrastructure (ft^2)	5,100 ft^2	500 ft^2
	Outdoor Space for Infrastructure (ft^2)	–	2,500 ft^2
	Indoor Warehouse Space Cost ($/$ft^2$)	$3/$ft^2$	$3/$ft^2$
	Outdoor Land Space Cost ($/$ft^2$)	–	$0.34/$ft^2$
Maintenance	Monthly Lift Truck Maintenance	$200	$200
	Monthly Battery / FC Maintenance	$18	$45

Figure 6. Infrastructure and operational cost inputs for Class III MHE[18]

As in the case for Class I and II lifts, reported electricity costs were compared against reported hydrogen usage for comparable fuel cell MHE at the deployment sites using available literature data on fuel cell and battery efficiency. Based on the efficiency figures for battery and fuel cell MHE discussed above and using reported data on hydrogen usage for comparable Class III fuel cell MHE, battery lifts are expected to have annual electricity expenses of $300 per lift truck.

3.5 Cost of Infrastructure Warehouse Space

Cost of ownership calculations for the cost of warehouse space discussed above do not differentiate between the infrastructure needs of Class I/II MHE and the infrastructure needs of Class III MHE. Thus, the cost of warehouse space for Class III lifts is assumed to be the same as reported for Class I/II lifts. That is, battery lifts incur warehouse space costs for battery changing and charging infrastructure of $1,900 per lift truck per year. Fuel cell lifts incur warehouse space costs for hydrogen infrastructure of $500 per lift truck per year.

3.6 Cost of Maintenance for Lift Trucks, Battery Packs, and Fuel Cell Systems

An average of $200 per month is assumed to be spent on lift truck maintenance (not including maintenance of the battery and fuel cell systems), based on responses to the questionnaire and

[18] Figure 6 is taken from NREL CDP MHE 64d, Infrastructure & Operation Costs for Class III MHE, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

available literature. This equates to an annual lift truck maintenance cost of $2,400 per lift truck. This maintenance cost is assumed to be the same for battery lift trucks and fuel cell lift trucks. Operators reported an average $200 per year in maintenance costs per battery system. With an average of two battery packs per lift, this results in an annual battery pack maintenance cost of $400 per lift truck.

Based on data provided for the fuel cell MHE deployments (particularly from MHE CDP 14), fuel cell systems averaged about 4.5 hours of maintenance per year. Using an assumed labor rate of $80/hour fully burdened and accounting for parts costs as described above, the total annual maintenance cost for Class III fuel cell systems is $500 per lift truck. This calculated maintenance cost using deployment data tracks the average $440 annual per-lift truck maintenance cost reported in the questionnaire.

4 Total Cost of Ownership Results

The deployments of fuel cell MHE analyzed in this study have supplied a rich source of data for NREL to analyze to better understand the operation and performance of fuel cells used in material handling applications. In total, more than 600 fuel cell MHE units were deployed in eight commercial facilities and two government-operated warehouses. These fuel cell MHE accumulated more than 1.4 million hours of operation and used 160,000 kg of hydrogen dispensed over 245,000 filling events. Using this detailed set of data combined with responses from facility managers of seven of the deployment sites, NREL developed cost of ownership estimates for fuel cell MHE and compared them to the cost of battery-operated MHE.

Figure 7 shows the results of the total cost of ownership assessment of Class I and II MHE for both battery lifts and fuel cell lifts. The fuel cell MHE deployments characterized in this cost analysis included an average of nearly 60 fuel cell material handling units per site, with facilities operating two to three shifts per day. Under these conditions, fuel cell MHE are predicted to have a lower total cost of ownership than their comparable battery-powered counterparts. Overall, NREL found that for Class I and II forklifts used in multi-shift operations, fuel cells could reduce the overall cost of ownership by 10%, from $19,700 per year per lift truck to $17,800 per year per lift truck.

Breaking down the total cost of ownership provides insight into the relative advantages and disadvantages of fuel cell MHE. The costs of hydrogen infrastructure and hydrogen fuel are far greater than the comparable costs for electricity and battery infrastructure, with annual per-lift truck infrastructure costs of $3,700 for fuel cell MHE compared to $1,400 for battery MHE and annual energy costs of $2,400 for hydrogen compared to only $500 for electricity. However, these higher fuel and infrastructure costs are more than offset by the lower labor costs for hydrogen fueling compared to battery changing and charging and by the lower cost of warehouse space dedicated to infrastructure. Labor costs for hydrogen fueling of fuel cell MHE are only $800 per year, compared to $4,400 for labor for changing out batteries on battery MHE. Battery MHE incur $1,900 in facility space costs compared to only $500 for fuel cell MHE, in part because hydrogen infrastructure can be located outside instead of taking up more valuable indoor warehouse space as is the case for battery charging infrastructure. As noted previously, hydrogen infrastructure costs (reported here based on the average fleet size of 58 fuel cell lifts) vary inversely based on fleet size, while battery infrastructure costs vary in proportion to battery fleet size. As such, the cost differential for infrastructure for fuel cell and battery MHE narrows as fleet sizes increase.

Based on data collected from the deployments and feedback from the distributed questionnaire, it also appears that fuel cell systems used in Class I and II MHE incur lower maintenance costs relative to battery systems, mainly due to the fact that only one fuel cell system per lift truck is needed for multi-shift material handling operations while two or three battery packs are required per lift truck to support multi-shift operations. The annualized equipment costs of fuel cell systems are slightly greater than the annualized costs for batteries, even accounting for fewer systems per lift truck and a longer expected lifetime, but the expected maintenance savings more than offset the higher annualized purchase cost. As noted previously, the annualized cost of fuel cell systems reflects the availability of a federal tax credit for fuel cells. Without this tax credit, the annual cost of the fuel cell system increases by $1,100 per lift.

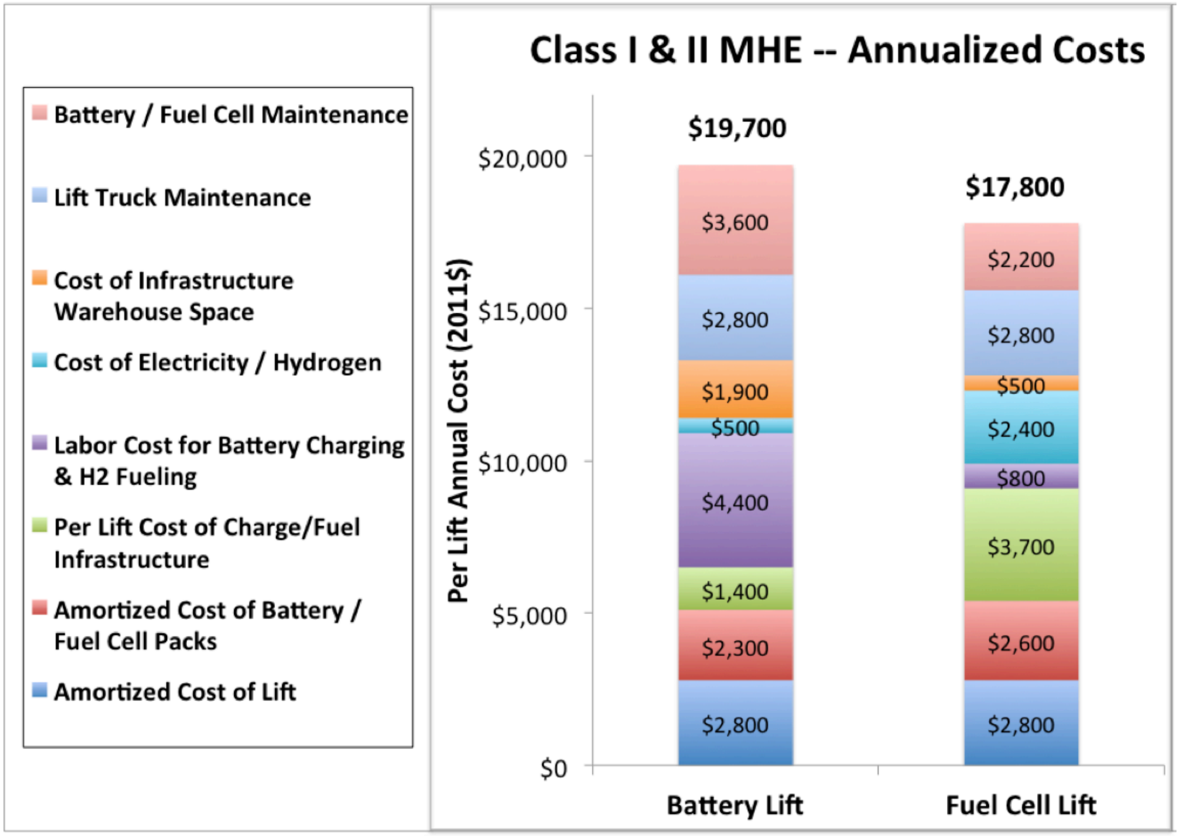

Figure 7. Total annual cost of ownership of Class I and II battery and fuel cell MHE

Figure 8 shows the comparable total cost of ownership results for Class III MHE. Overall, Class III lifts have lower cost of ownership than Class I and II lifts, reflecting both lower capital costs for the lift truck and power pack (battery or fuel cell) and lower operating and maintenance costs.

Similar to Class I and II forklifts, fuel cell-powered Class III lifts are expected to have a lower total cost of ownership compared to battery-powered units in multiple-shift warehouse facilities that deploy a large number of lifts. NREL's analysis found that the cost of ownership of Class III pallet jacks can be reduced by 5%, from $12,400 per year to $11,700 per year for each lift. Once again, higher hydrogen infrastructure and hydrogen fuel costs are more than offset by labor cost savings and warehouse space cost savings for infrastructure (though battery pack maintenance and fuel cell maintenance costs are expected to be more comparable for Class III lifts than they were for Class I and II lifts). The cost of ownership results for Class III MHE show similar differential costs for hydrogen infrastructure compared to battery infrastructure, but fuel cell MHE require only $500 in labor costs for hydrogen fueling compared to $3,200 for battery changes, and Class III fuel cell MHE again show significant savings for facility space costs for infrastructure ($500 per year for fuel cell MHE compared to $1,900 for battery MHE).

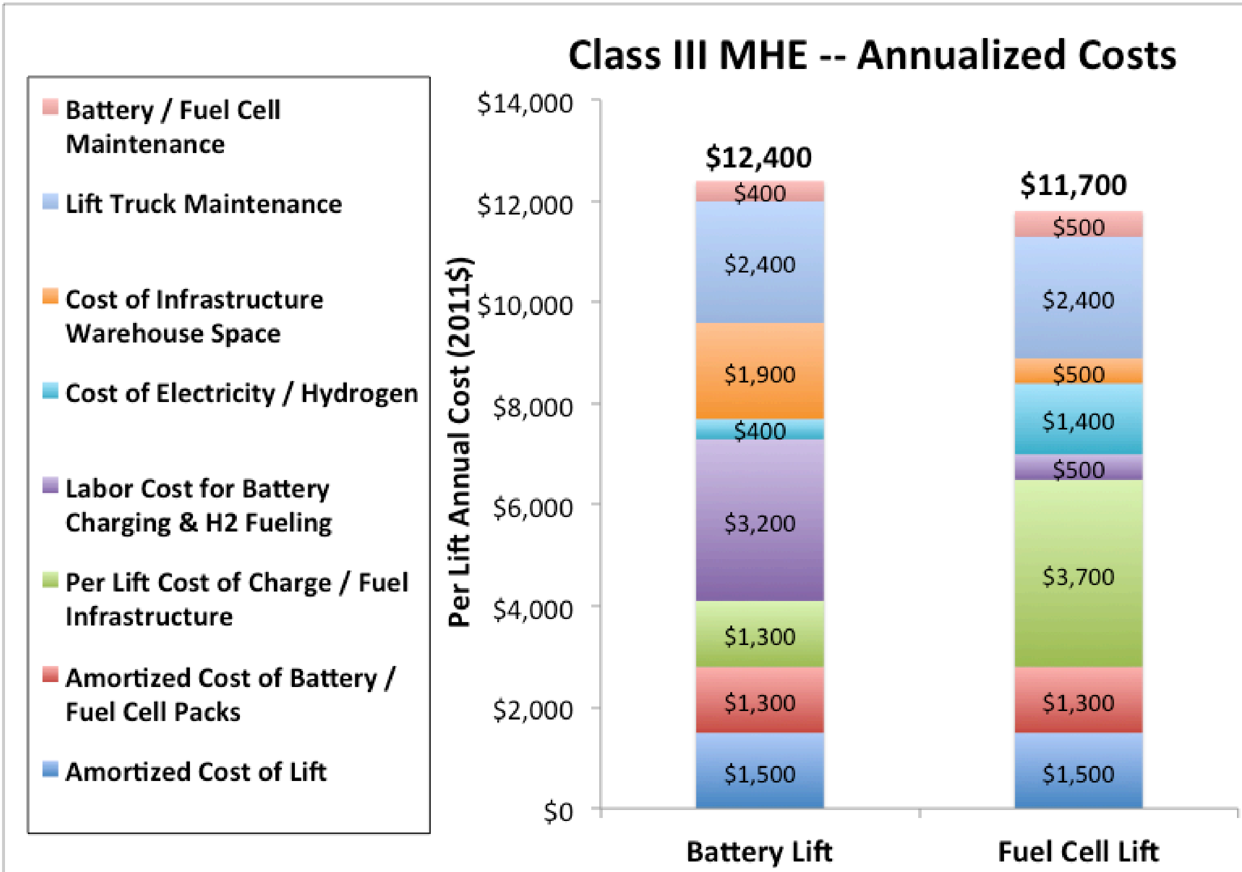

Figure 8. Total annual cost of ownership of Class III battery and fuel cell MHE

Based on the extent of data available for this cost assessment and to limit the scope of the analysis to reflect the mandate of this research project, this cost evaluation considers the costs of operating fuel cell MHE compared to the costs of operating comparable battery MHE. The evaluation does not attempt to assess potential changes in the productivity of the warehouse distribution center deploying fuel cell or battery MHE, and more broadly does not attempt to consider additional sales or profits that might be seen by the company operating the warehouse facilities. As such, it is not possible to evaluate fuel cell MHE on a net present value basis. This would require an evaluation of incoming revenues or cash flows and outgoing expenditures, which the partner companies hold very closely and would likely not be able to share with NREL.

For this analysis, costs of operation are discussed in present value terms, based on the average costs on an annualized basis considering both capital and operating costs. An additional metric would be to consider a payback period. In the case of fuel cell MHE, a payback period assessment is not based on incoming revenues offsetting initial capital expenditures, but rather it describes the time it would take for an investment in fuel cell MHE to lead to reduced costs compared to a decision to instead deploy comparable battery MHE. Using the data on the costs of operating and maintaining fuel cell and battery propulsion systems together with the costs and timing for necessary equipment replacements, a payback period for fuel cell MHE purchases can be estimated relative to battery MHE ownership.

Using the findings of this cost analysis, for Class I, II and III MHE, deploying fuel cell MHE instead of battery MHE would lead to lower overall expenditures in the fifth year of operation, when battery MHE would require a replacement of battery systems at the end of their useful life (estimated at 4.4 years for Class I and II and 4.5 years for Class III batteries). As discussed above, this payback analysis only considers the relative costs of operation of fuel cell and battery MHE; it does not take into account any potential benefits such as improved warehouse productivity.

5 Total Cost of Ownership Sensitivity Analysis

In conjunction with the MHE cost of ownership analysis, sensitivity analyses were conducted to better understand the effect of various input parameters on the total cost of ownership and to account for data uncertainty. The sensitivity analyses show the ranges in annual per-lift truck cost of ownership for both battery and fuel cell MHE resulting from varying key parameters that affect cost.

To conduct the sensitivity analyses, one input parameter is varied while all others remain at their nominal value. Figure 9 shows the nominal values and the lower value and upper value sensitivity ranges of key input parameters affecting total cost of ownership of Class I/II and Class III MHE.

MHE Total Cost of Ownership Sensitivity Ranges		Battery MHE			Fuel Cell MHE		
		Nominal	Lower	Upper	Nominal	Lower	Upper
Class I and II MHE	Range						
Battery / Fuel Cell Maintenance	+/- 50%	$3,600	$1,800	$5,400	$2,800	$1,400	$4,200
Discount Rate	0% – 10%	1.5%	0%	10%	1.5%	0%	10%
Life of Battery / Fuel Cell System	+25%, -50%	4.4 yrs.	2.2 yrs.	6.6 yrs.	10 yrs.	5 yrs.	15 yrs.
Size of Fuel Cell Forklift Fleet	30 – 100	–	–	–	58	30	100
Cost of Charge / Fuel Infrastructure	-30%, +10%	$1,400	$1,100	$1,600	$3,700	$2,600	$4,100
Cost of Electricity / Hydrogen	5-10 (¢/kWh, $/kg)	$500	$350	$700	$2,100	$1,300	$2,500
Cost of Battery / Fuel Cell System	Reported Data	$4,800	$3,000	$8,000	$33,000	$24,000	$36,000
Battery Changes / H2 Fills Per Day	1 – 3	2.5	1	3	1.4	1	3
Battery Change / H2 Fueling Time	+/- 50%	10.5 min	5 min	16 min	2.9 min	1.5 min	4.5 min
Operation Days Per Year	250 – 365	333	250	365	333	250	365
Warehouse Space for Charge / Fuel	+/- 50%	5100 ft^2	2500 ft^2	7500 ft^2	500 ft^2	250 ft^2	750 ft^2
Battery / Fuel Cell Systems Per Lift	1 – 3; 1 – 1.2	2	1	3	1	1	1.2
Class III MHE	Range						
Battery / Fuel Cell Maintenance	+/- 50%	$400	$200	$600	$500	$250	$750
Discount Rate	0% – 10%	1.5%	0%	10%	1.5%	0%	10%
Life of Battery / Fuel Cell System	+25%, -50%	4.5 yrs.	2 yrs.	6 yrs.	9 yrs.	5 yrs.	11 yrs.
Size of Forklift Fleet	30 – 100	–	–	–	58	30	100
Cost of Charge / Fuel Infrastructure	-30%, +10%	$1,400	$1,100	$1,600	$3,700	$2,600	$4,100
Annual Cost of Electricity / H2	5-10 (¢/kWh, $/kg)	$400	$300	$600	$1,300	$800	$1,600
Cost of Battery / Fuel Cell System	Reported Data	$2,800	$2,000	$4,000	$15,000	$10,000	$18,000
Battery Changes / H2 Fills Per Day	1 – 3; 0.5 – 2	2	1	3	1	0.5	2
Battery Change / H2 Fueling Time	+/- 50%	9 min	4.5 min	14 min	1.1 min	0.5 min	1.7 min
Operation Days Per Year	250 – 365	340	250	365	340	250	365
Warehouse Space for Charge / Fuel	+/- 50%	5100 ft^2	2500 ft^2	7500 ft^2	500 ft^2	250 ft^2	750 ft^2
Battery / Fuel Cell Systems Per Lift	1 – 3; 1 – 1.1	2	1	3	1	1	1.1

Figure 9. Total cost sensitivity analysis data ranges

5.1 Sensitivity Analysis for Class I and II Material Handling Equipment

Figure 10 shows the total cost sensitivity for Class I and II MHE. For fuel cell MHE, the discount range applied, the cost of fuel cell system maintenance, the life of the fuel cell system, and the size of the fuel cell MHE fleet have the largest effect on the resulting total cost of ownership. For battery MHE, the maintenance costs, the number of battery changes and charges per day, and the battery change time have the largest effect on the resulting cost of ownership.

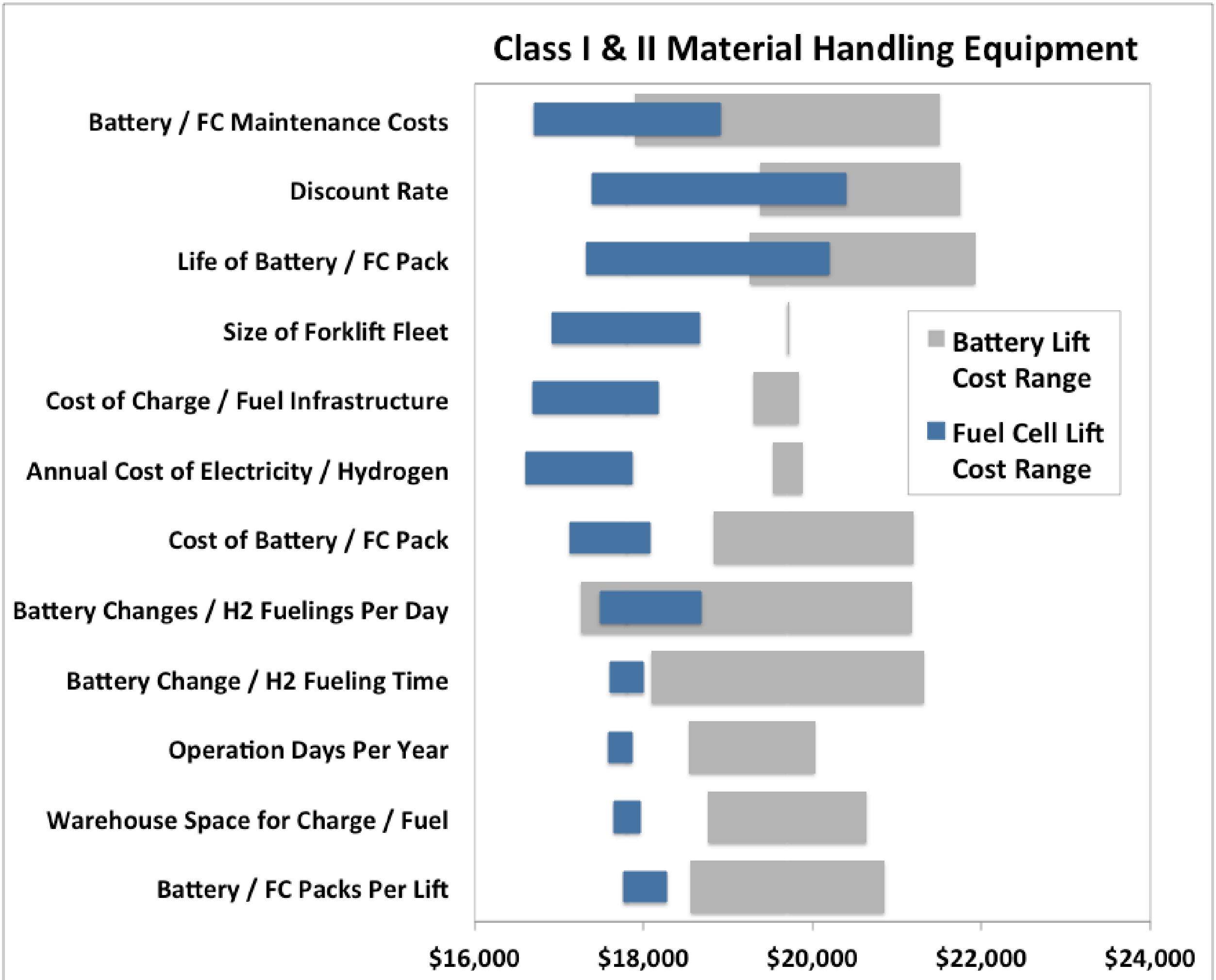

Figure 10. Total cost of ownership sensitivity analysis results for Class I & II MHE[19]

[19] Figure 10 is taken from NREL CDP MHE 59, Total Cost Sensitivity, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

The input parameter sensitivity analysis indicates that total fuel cell MHE cost of ownership generally is expected to be less than the total battery MHE cost of ownership. While fuel cell lifetime and maintenance costs are large drivers of total cost, unless fuel cell life and maintenance costs worsen relative to battery lifts (or costs are being over- or under-estimated), the total cost of fuel cell forklift ownership continues to track lower than the total cost of battery forklift ownership.

As long as fuel cell MHE fleets are large enough to help minimize the per-lift truck cost of hydrogen infrastructure, and as long as the facility operates multiple shifts with the need for multiple battery changes, total fuel cell MHE costs appear to stay below the total cost of deploying battery MHE. The sensitivity analysis shows that with only one battery change per day, the total cost of ownership of battery lifts is less than that of comparable fuel cell lifts. In fact, the total annual cost of ownership falls to nearly $16,000 per year for battery lifts if these lifts are deployed for only a single shift per day and the batteries are charged in the lift truck (thus requiring zero battery changes per day).

Unfortunately, not enough detailed data were available from these fuel cell MHE deployments to fully understand the impact of fuel cell fleet size on per-unit annualized costs, and particularly what might be considered the minimum fleet size needed to attain a positive cost differential compared to battery MHE. Fuel cell MHE require supporting hydrogen infrastructure. Though the extent of this hydrogen infrastructure can vary based on the number of units deployed and their intensity of use (e.g., number of shifts operated per day), the requirement for hydrogen infrastructure represents a significant investment. The sensitivity analysis only assessed a lower bound of 30 fuel cell forklifts deployed per site. Further investigation is required to understand how fleets of fuel cell MHE with fewer than 30 lifts per site compare to battery lifts on a cost basis, as high hydrogen infrastructure costs would be spread out over fewer fuel cell MHE units.

5.2 Sensitivity Analysis for Class III Material Handling Equipment

Figure 11 shows the results of the total cost of ownership sensitivity analysis conducted for Class III fuel cell MHE. As in the case with Class I and II MHE, the discount rate applied and the life of the fuel cell system have a large effect on the estimated annual cost of ownership of a fuel cell lift. However, for Class III MHE, fuel cell maintenance costs have a lesser effect on the total cost, and the size of the forklift fleet and the cost of hydrogen infrastructure have a greater effect. This is a result of the lower overall cost of maintenance for Class III fuel cell systems and the greater proportion of cost that hydrogen infrastructure represents in the total cost figure (since forklift and fuel cell system equipment and maintenance costs are less).

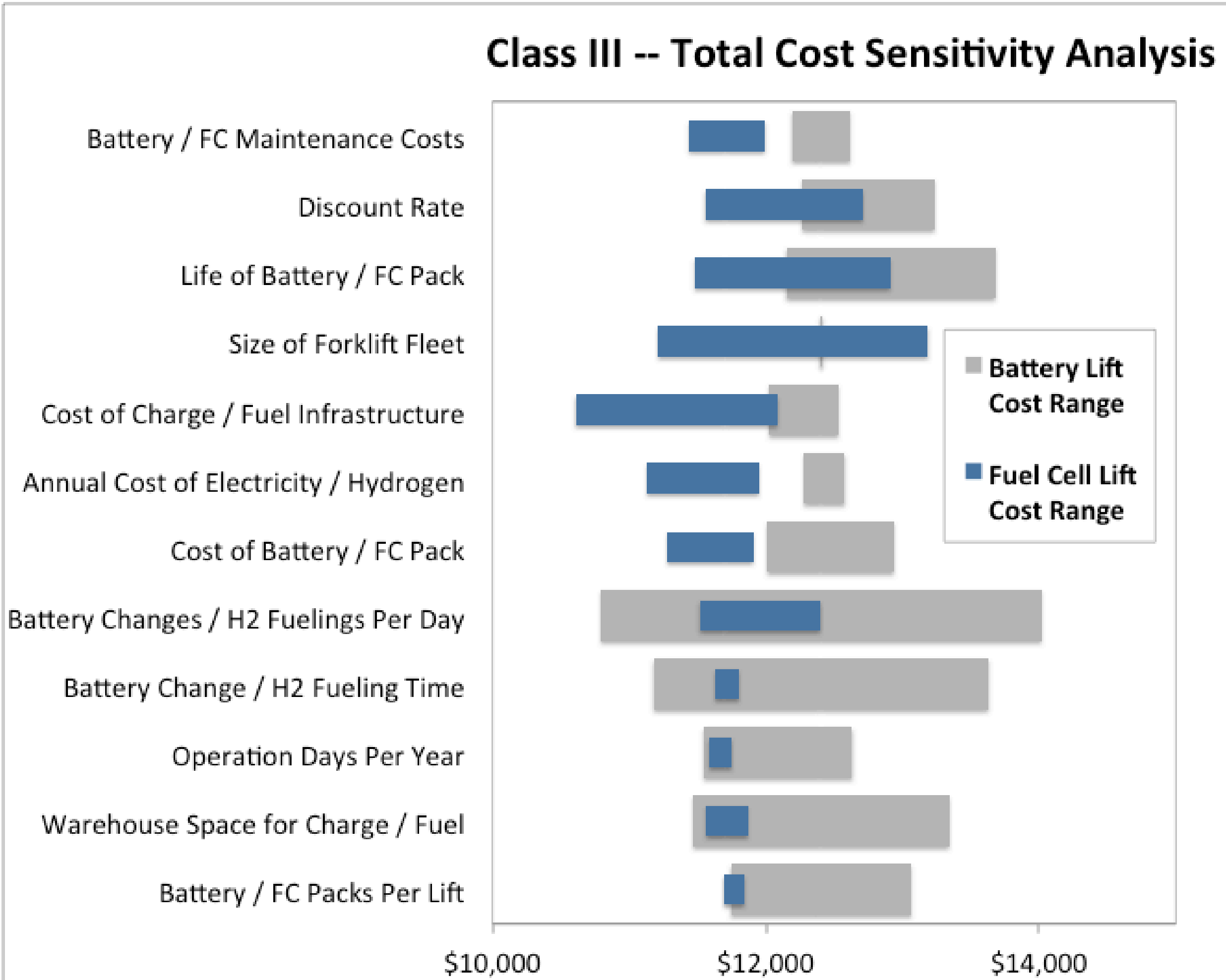

Figure 11. Total cost of ownership sensitivity analysis results for Class III MHE[20]

As in the case of Class I and II lifts, the total cost of ownership of Class III battery lifts is most sensitive to the number of battery changes per day and the time needed to complete a battery change. The sensitivity analysis for Class III MHE also shows that the intensity of the MHE deployment scenario is a defining factor in whether fuel cell MHE will have a lower total cost of ownership compared to battery lifts. As noted, the high and relatively static costs for hydrogen infrastructure play a more prominent role in the total cost of ownership of Class III MHE because the equipment costs and maintenance costs for both the bare Class III lift truck and the Class III power pack (battery vs. fuel cell) are less.

The sensitivity analysis for Class III MHE shows that total cost of ownership can swing in favor of batteries over fuel cell systems when fewer Class III lifts are deployed in the fleet (as there are fewer lifts to amortize the cost of hydrogen infrastructure), when there is only one battery change per day (or zero in the case of in-lift truck battery charging), and when there are fewer operation days per year.

[20] Figure 11 is taken from NREL CDP MHE 59, Total Cost Sensitivity, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

6 Intensive Deployment Scenario Cost Analysis

In addition to the cost sensitivity analysis, a scenario of an intensive MHE deployment was modeled to further evaluate the sensitivity of the total cost findings to changes to specific input parameters. The deployments that served as the basis for the total cost of ownership assessment represent a high utilization of material handling equipment. To better understand the effects of heavy usage on MHE cost of ownership, total costs were estimated for a more extreme material handling scenario.

The intensive deployment scenario modeled a material handling operation that:

- Deployed 100 forklifts
- Operated for 350 days each year
- Operated 3 shifts per day
- Logged 3,000 hours of operation per year on each lift.

The total cost assessment for the intensive deployment scenario uses the same methodology and data as the original total cost assessment, with a number of changes reflecting the more intensive usage patterns of this scenario. In particular:

- The average lifetimes in years of lift trucks, batteries, chargers, and fuel cell systems were lowered to reflect the greater number of annual operation hours.
- The average number of battery systems per lift truck was increased to three, reflecting the total number of shifts per day.
- The average number of daily battery changes and hydrogen fills and the average energy costs increased, reflecting the greater number of annual operation hours.
- Lift truck, battery, and fuel cell maintenance costs increased, reflecting more intensive usage.
- The cost of hydrogen infrastructure increased on a per-site basis, reflecting the greater number of fuel cell lifts deployed (though per-lift truck hydrogen infrastructure costs dropped, reflecting economies-of-scale cost improvements).

The results of the intensive scenario cost assessment are shown in Figure 12 (see Figure 7 for color key). Considering the lifetime costs of material handling equipment on an annualized, present value basis, fuel cell MHE provide even greater cost savings relative to battery MHE than was modeled in the original total cost assessment based on the analyzed deployments. Fuel cell MHE enjoy a greater cost advantage compared to battery MHE in intensive deployment scenarios due to lower fuel cell equipment costs compared to battery costs and lower labor costs for hydrogen fueling compared to labor for battery changes (which is higher due to the greater number of battery packs and battery changes required to meet intensive deployment demands). The relative cost advantages for fuel cell maintenance and lifetime compared to battery maintenance and lifetime further widen the gap in favor of fuel cell MHE in intensive deployments.

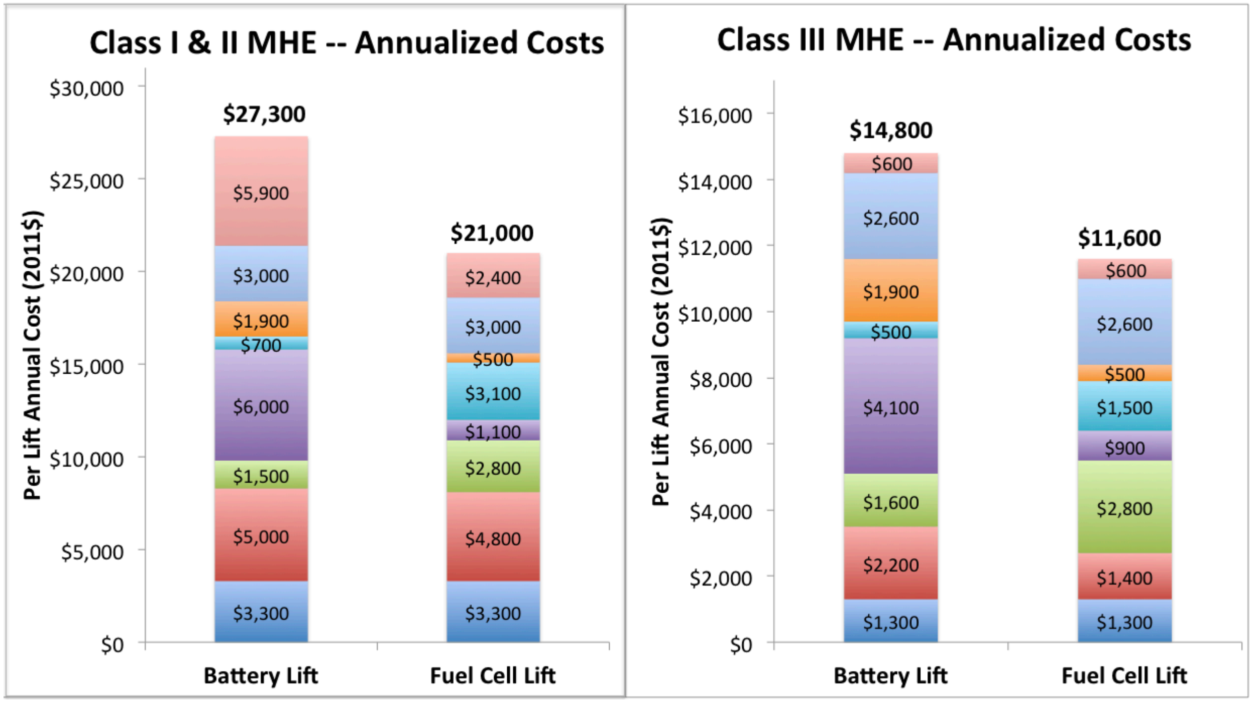

Figure 12. Total annual cost of ownership for MHE deployed in an intensive deployment scenario[21]

[21] Figure 12 is taken from NREL CDP MHE 60, MHE Intensive Deployment Total Cost, 3/29/2012, available at http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

7 Conclusions

This study leverages DOE's co-funding of fuel cell systems in the emerging market of fuel cell material handling equipment. With DOE's sponsorship, commercial warehousing and material handling facilities provided data on costs, operation, and performance of material handling equipment and NREL analyzed these data to develop an independent evaluation of the costs of operating fuel cell MHE. NREL's total cost assessment shows that for fairly intensive warehouse and distribution applications—in the case studied, a deployment of about 60 fuel cell lifts for 2–3 shifts per day, 6–7 days per week—fuel cell-powered MHE can have a lower total cost of ownership than comparable battery lifts. Fuel cells are predicted to have a lower cost of ownership compared to traditional battery lifts in both Class I/II and Class III material handling equipment.

NREL found that for Class I and II forklifts used in multi-shift operations, fuel cells could reduce the overall cost of ownership by 10%, from $19,700 per year per lift truck to $17,800 per year per lift truck. The cost of ownership of Class III forklifts can be reduced by 5%, from $12,400 per year to $11,700 per year for each lift truck. While fuel cell MHE have higher costs for hydrogen fuel and hydrogen infrastructure compared to the energy and infrastructure needs for battery MHE, fuel cell MHE can yield significant savings in labor costs and facility space costs. For Class I and II MHE, fuel cells can lower annual per-lift truck labor costs from $4,400 for battery change and charging to only $800 for hydrogen fueling and can lower annual facility space costs from $1,900 to $500 (Class III MHE annual labor costs can be reduced from $3,200 to $500).[22]

The sensitivity analyses and the cost analysis of a more intensive material handling scenario, with 100 forklifts deployed for three shifts per day, show that even larger cost savings can be realized by deploying fuel cell MHE instead of traditional battery-powered MHE in very intensive material handling applications. NREL's cost analysis of such an intensive material handling operation shows that costs can be reduced by almost 25% by choosing fuel cell MHE over battery MHE, with annual costs of Class I and II fuel cell MHE dropping to $21,000 per lift truck compared to $27,300 for battery MHE. Annual costs for Class III fuel cell MHE can drop over 20% in an intensive material handling operation, with annual fuel cell MHE costs of $11,600 compared to $14,800 for battery pallet jacks.

In terms of equipment costs, fuel cell systems are more expensive than battery systems, but considering the longer predicted life of the fuel cell systems and the need for multiple battery packs per lift truck in multi-shift warehousing operations, the total annualized equipment costs of fuel cell systems are comparable to those of batteries for Class I, II, and III MHE. The costs of hydrogen fuel and especially hydrogen fueling infrastructure are both higher than the comparable electricity and battery changing/charging infrastructure costs. For the deployments characterized in this study, these higher costs are more than offset by lower labor costs for hydrogen fueling compared to battery changing and charging and by lower warehouse space costs for hydrogen

[22] These cost of ownership results have previously been published by NREL as composite data products (CDPs). As part of the CDP publication process, the cost of ownership CDPs and their results have been reviewed and approved by participants in the government-sponsored deployments, including representatives from Plug Power, Nuvera Fuel Cells, and Hydrogenics Corporation, the companies that provided fuel cell systems for the material handling equipment.

infrastructure compared to battery changing infrastructure (mainly due to the fact that much of the hydrogen infrastructure can be sited outside where space costs are less).

The sensitivity analyses indicate that intensity of the MHE deployment is the largest driving factor in whether fuel cell MHE will have a lower cost of ownership compared to battery MHE. The significant labor savings of hydrogen fueling over battery changes is lost if facility operations only require one battery change per day (or no changes, in the case of in-lift truck battery charging). Based on this cost assessment and the accompanying sensitivity analysis, it appears unlikely that fuel cell MHE will have a total cost of ownership advantage over battery lifts in facilities that only operate for one shift per day.

Based on the sensitivity analysis, the number of operation days per year and particularly the number of MHE units deployed in a facility can also greatly affect whether the use of fuel cell MHE instead of battery MHE is a cost effective choice. Class III MHE especially do not appear to be good candidates for using fuel cells in place of batteries unless a sufficient number of forklifts are deployed. This results mainly from the higher proportional cost that hydrogen infrastructure represents in the total cost of ownership of Class III MHE. For example, a deployment at the studied forklift deployment level of 60 units favored fuel cell lifts over battery lifts, but deployments of only 30 Class III fuel cell lifts were not predicted to result in overall cost savings compared to battery lifts. For Class I and II MHE, deployments of as few as 30 fuel cell forklifts appear to provide cost savings over battery lifts as long as facilities operate for two or more shifts per day and six or seven days per week. Further analysis is required to determine the break-even point for fuel cell MHE over battery MHE in terms of the number of units deployed.

NREL's cost analysis assumes fuel cell MHE will receive a federal tax credit available for fuel cell systems. Even without the federal tax credit, the evaluation shows that fuel cell MHE have a lower cost of ownership compared to battery lifts, though cost savings are reduced.[23] It is also important to note that NREL's evaluation only considered costs of operation. Potential changes in facility productivity and any benefits in terms of higher throughput and increased profitability have not been addressed. The cost evaluation also assumed constant equipment costs in real-dollar terms. As fuel cells in material handling equipment are in the early stages of commercialization, the cost of fuel cell systems may be expected to decline over time. The assessment of the overall benefits of fuel cell MHE may show increased improvement over battery-powered MHE as potential productivity gains are evaluated and as the market for fuel cell MHE matures.

[23] Class I and II fuel cell forklifts will incur $1,100 per year in additional costs without the tax credit, reducing the annual per-lift truck savings to $800 compared to battery forklifts. Class III fuel cell forklifts will incur $500 in additional annual costs without the tax credit, reducing the annual per-lift truck savings to $200 compared to comparable battery forklifts.

Appendix

NREL's Technology Validation group has participated in a variety of projects to assess the real-world performance of fuel cell systems and the related hydrogen fueling infrastructure. Demonstration and validation projects have included assessments of fuel cell electric vehicles, fuel cell buses, fuel cell powered material handling equipment, and fuel cell backup power. Working in collaboration with industry project partners, NREL acts as the central data repository for the data collected from these fuel cell demonstration projects, including the DOD- and DOE-sponsored fuel cell MHE deployments. To protect proprietary and business-sensitive data that have been supplied by industry partners, NREL established a Hydrogen Secure Data Center (HSDC) to house sensitive data and enable data analysis (see Figure A-1).

While the raw data are protected by NREL in its HSDC, in-depth analyses allow the data to be aggregated into high-level, publicly available results called "composite data products" (CDPs) that show the status and performance of hydrogen and fuel cell technologies without identifying individual companies or their performance. These CDPs report on the progress of the technology and the deployment projects, focusing on the most significant results. In addition to these publicly available aggregated results, detailed data products (DDPs) that identify individual company contributions to CDPs are developed for and provided to each company based on their specific data. These DDPs identify individual contributions to CDPs and are intended to assist companies as they refine and improve fuel cell technologies but are not made available to the public.

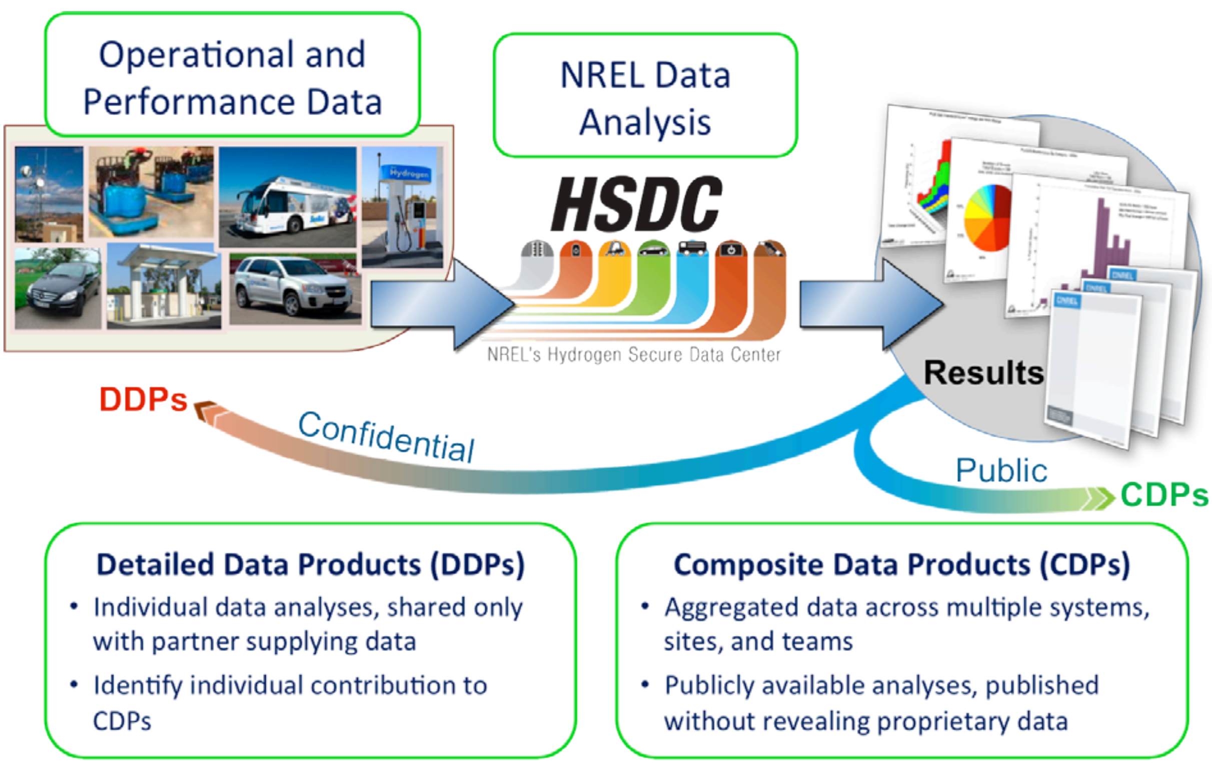

Figure A-1. NREL's aggregated data analysis using the HSDC