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ANL/ESD/08-3

Full Fuel-Cycle Comparison of Forklift Propulsion Systems

Energy Systems Division

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Full Fuel-Cycle Comparison of Forklift Propulsion Systems

by
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NOTATION

The following is a list of the abbreviations, acronyms, and units of measure used in this document.

GENERAL ACRONYMS AND ABBREVIATIONS

AC	Alternating current
C2	Specific test cycle used for forklifts (see Table 7)
CI	Compression ignition (a synonym for diesel)
CO	Carbon monoxide
COG	Coke oven gas
DC	Direct current
DOE	U.S. Department of Energy
EERE	U.S. Department of Energy, Energy Efficiency and Renewable Energy Office
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
GHG	Greenhouse gas
GM	General Motors
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GTI	Gas Technology Institute
H_2	Hydrogen
HC	Hydrocarbon
ICE	Internal combustion engine (i.e., CI or SI)
LHV	Lower heating value
LPG	Liquefied petroleum gas (i.e., propane)
LSI	Large spark ignition (engine) (defined as >25 hp for forklifts)
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxide
PM	Particulate matter

SI	Spark ignition (describes a type of engine used in automobiles and forklifts)
SWRI	Southwest Research Institute
ULSD	ultra-low sulfur diesel

UNITS OF MEASURE

Btu	British thermal unit(s)
g	gram(s)
gal	gallon(s)
h	hour(s)
hp	horsepower
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt hour
lb	pound(s)
psi	pound(s) per square inch
psia	pound(s) per square inch absolute

FULL FUEL-CYCLE COMPARISON OF FORKLIFT PROPULSION SYSTEMS

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Center for Transportation Research

ABSTRACT

Hydrogen has received considerable attention as an alternative to fossil fuels. The U.S. Department of Energy (DOE) investigates the technical and economic feasibility of promising new technologies, such as hydrogen fuel cells. A recent report for DOE identified three near-term markets for fuel cells:

1. Emergency power for state and local emergency response agencies,

2. Forklifts in warehousing and distribution centers, and

3. Airport ground support equipment markets.

This report examines forklift propulsion systems and addresses the potential energy and environmental implications of substituting fuel-cell propulsion for existing technologies based on batteries and fossil fuels. Industry data and the Argonne Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model are used to estimate full fuel-cycle emissions and use of primary energy sources, back to the primary feedstocks for fuel production. Also considered are other environmental concerns at work locations. The benefits derived from using fuel-cell propulsion are determined by the sources of electricity and hydrogen. In particular, fuel-cell forklifts using hydrogen made from the reforming of natural gas had lower impacts than those using hydrogen from electrolysis.

1 INTRODUCTION

1.1 OVERVIEW

As a follow-on to the report for the U.S. Department of Energy (DOE) by Battelle, titled *Identification and Characterization of Near-Term Hydrogen Proton Exchange Membrane Fuel Cell Markets* (Mahadevan et al. 2007), Argonne National Laboratory was asked to focus in on one of the early markets for fuel cells that had been identified — namely, fuel-cell-powered forklifts (Figure 1). That report emphasized economic aspects. Argonne's task was to determine the savings of energy and petroleum, as well as reductions in greenhouse gas (GHG) emissions, that could be accomplished by using hydrogen to power forklifts.

FIGURE 1 Fuel-Cell Forklift (Toyota 2008)

First, it was necessary to identify the various types of forklifts in service and to characterize their operation. Much of this information had already been assembled by other authors. Rather than attempting to rewrite previous works, this report includes excerpts from such work, together with additional insights and data obtained from industrial sources and associated literature. Next, it was important to understand how actual users operated their forklifts (also referred to as trucks) and to determine the issues faced by the users. These issues turned out to be extremely important. Finally, we obtained data on the energy consumption of various types of forklifts, as well as emissions data on fossil-fueled forklifts, from industry literature and cooperative industry sources. These data were used, along with upstream fuel-cycle data from the Argonne Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, to estimate full fuel-cycle impacts from the operation of forklifts with different power trains. An analysis of these results enabled the identification of the forklift markets with the greatest potential for energy savings and GHG emission reductions.

1.2 USES, STATISTICS, SIZES, AND TYPES OF FORKLIFTS

Forklifts are used in a wide variety of commercial and industrial applications to move all types of goods and materials around, to, or from trucks; to or from storage areas; or from one work station to another. Some uses involve transport at ground level, while others involve lifting or lowering. The operator can either walk behind or ride on or within the forklift. The load can range from less than 1,000 lb to 20 tons. Forklifts can be used from a few hours per day to 24 hours per day, 7 days per week. Some forklifts are used indoors, while others serve outdoor purposes. Current designs are powered by lead-acid batteries or by fossil fuels (generally, the larger types). The fuel-cell forklifts that have been demonstrated so far have mostly been in the smaller size ranges, substituting for battery-powered forklifts. This section will describe the U.S. forklift population. Although a wide variety of devices is available, the relevant common characteristic is that power is required to move materials around.

Table 1 shows most of the classes and sub-classes (called lift codes) of forklifts. Figure 2 presents the latest U.S. sales of forklifts, by type, for the past 20 years, as reported by the Industrial Truck Association. Overall growth has occurred, with intermittent peaks and valleys. If these forklifts are kept in service for an average of 6 years (Ryan 2007), the total forklift population in the United States would be about 980,000; if they are kept for 10 years, the total population would reach approximately 1.6 million. The electric rider category includes Classes I and II; motorized hand Class III; and internal combustion engine Classes IV and V. The largest forklifts are not included in these statistics because of disclosure issues (Buddington 2008). To a first approximation, Class I, II, and III forklifts are electric and Classes IV through VII are fossil fueled; however, some Class VI forklifts are electric. The capacity of the fossil-fueled forklifts rises with the higher class number, but this is not true for the electric types. One trade publication compared forklifts in Classes I through V (ForkliftBiz 2008):

- *Class I.* This Class consists of a three-wheeled unit powered by an electric motor. The operator can be in the seated or standing position (sit-down units are counterbalanced.) Class I lift trucks can be fitted with cushions or pneumatic tires.

- *Class II.* This Class is powered by an electric motor. The truck is suited to the narrow isle work typical in inventory shuffling. There is the option of installing extra reach/swing mast applications.

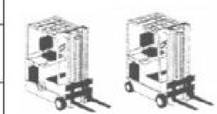
- *Class III.* This Class also is powered by an electric motor. This Class of truck usually has the operator "walk behind" it or, alternatively, is operated while in the standing position. Both the high lift and automated pallet models are counterbalanced.

- *Class IV.* This counterbalanced Class of forklift has a cab with controls and runs on an internal combustion engine. The tires are most often cushioned or solid.

- *Class V.* This counterbalanced Class of lift truck has a cab built to sit a driver and is powered by an internal combustion engine. The whole vehicle is mounted on pneumatic tires.

TABLE 1 Definition of Forklift Classes (Wikipedia 2008)

Forklift Classes and Lift Codes

Class #	Type of Propulsion and Operation	Lift Code	Description	Picture
I	Electric Motor Rider	4	Counterbalanced, sit-down, 3-wheel	
		5	Counterbalanced, sit-down, cushion (solid) tire	
		6	Counterbalanced, sit-down, pneumatic tire	
III	Electric Motor Walkie	2	Low-lift pallet	
		5	High lift reach type	
		7	High lift counterbalanced	
IV	Internal Combustion Engine Rider	3	Counterbalanced, sit-down, cushion (solid) tire	
V	Internal Combustion Engine Rider	4	Counterbalanced, sit-down, pneumatic tire	
VII	Rough Terrain	1	All types	

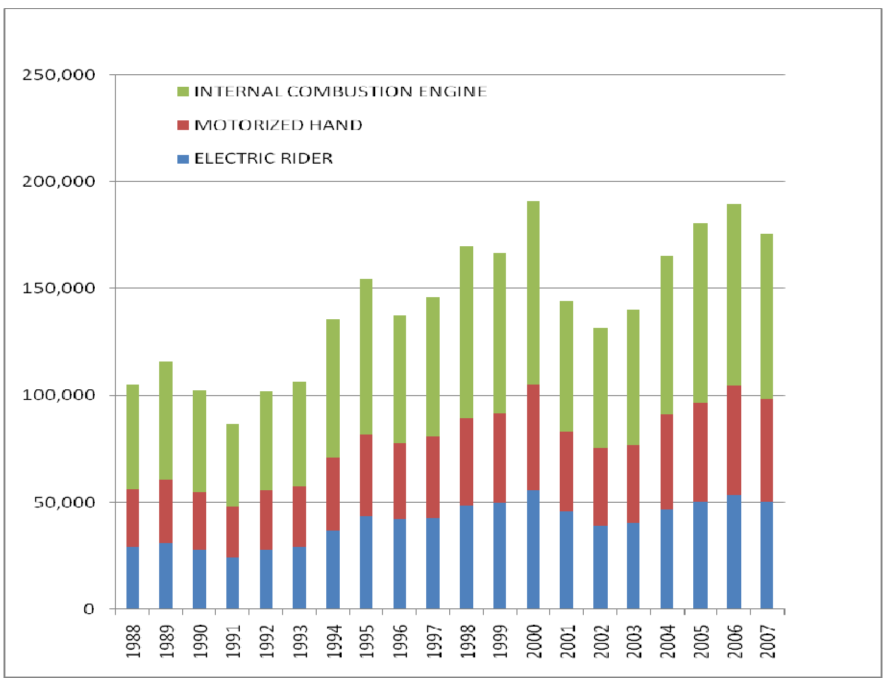


FIGURE 2 U.S. Forklift Shipments (ITA 2008)

2 PROPULSION SYSTEMS

2.1 BATTERY-POWERED FORKLIFTS

The battery serves several functions in a forklift. First and foremost, it supplies the *energy* to drive the forklift and lift loads. In addition, it accepts *regenerative* energy recovered from braking. In theory, energy also could be recovered when loads are lowered. This is an area where research and development could yield further energy savings. Finally, the massive lead-acid battery provides critical *counterweight* for stability (Medwin 2007). However, two concept forklifts shown at the CeMAT 08 show used lithium-ion batteries (De Smet 2008), which would be unable to serve as counterweights, but would have other significant advantages. It will be interesting to examine this improvement when additional information becomes available.

Electric forklifts (Classes I, II, and III) come in a variety of lift capacities, from 3,000 lb to 20,000 lb, although most electric forklifts are in the 3,000- to 6,000-lb range. Electric forklifts typically are used in indoor materials handling applications that do not require large lift capacities (i.e., warehouse and retail operations). For some applications, such as confined spaces, cold storage, and food retail (primarily grocery stores), worker safety mandates the use of electric forklifts. However, battery efficiency is compromised during low-temperature operation. This gives fuel-cell forklifts an advantage for use in refrigerated areas. Class I, II, and III forklifts are used in multi-shift operations at warehouses and distribution centers, at third-party logistics suppliers, at shipping and receiving locations, and for manufacturing. Class II and Class III forklifts are used in those applications where ICE-powered forklifts are not practical, such as indoor environments and narrow aisles.

Class IV, V, and VI forklifts are used in construction, agriculture, manufacturing, large warehousing, recycling, beverage and bottling, trucking, and garden supply operations. These forklifts also are used in the manufacturing and processing of paper and allied products; lumber and wood products; building supplies; stone, clay, and glass products; and primary metal products. Class I, IV, and V forklifts can be used in similar applications.

Although forklifts are primarily designed for indoor use, several features can enable electric models to be used outdoors. These features include using pneumatic tires (air filled) to enable use on unimproved surfaces, waterproofing the forklifts, and sealing the electronic compartment for more water resistance. Additionally, the use of alternating current (AC) motors provides greater lift and travel speeds (Mahadevan et al. 2007).

The key disadvantage of electric forklift operation is battery charging. Battery-powered forklifts use lead-acid batteries that provide enough power for one 8-hour shift, or 5 to 6 hours of constant use. Because there are no tailpipe emissions, they can safely be used indoors. However, it takes from 5 to15 minutes for an automatic battery change-out, and up to 45 minutes or more if it is done manually and there is a queue (Medwin 2008). The battery is charged for 8 hours, during which time it heats up, so it must then be allowed to cool for 8 hours. Therefore, an operation that runs 24/7 requires three batteries for each forklift. The battery chargers typically are located in a dry, ventilated, and temperature-controlled location, since batteries release oxygen and hydrogen during charging. Furthermore, testing and overcharging of the battery can result in acid spills, so charging operations are separated from other operations, thus increasing the cost if space is at a premium. Acid must be washed off the batteries regularly to prevent development of conductive paths that would reduce battery efficiency. The U.S. Environmental Protection Agency (EPA) requires that acid runoff be saved in a holding tank. One company is known to ship its batteries out weekly for a baking soda bath.

Fast charging of some battery types is possible. In such cases, the company must regulate charging to prevent demand spikes to the local utility during driver coffee breaks (McCabe 2008). Utilities in California offer incentives to users that avoid charging their forklifts during periods of peak demand (Cromie 2007).

Another disadvantage of battery-powered forklifts is that power declines as the battery discharges. This causes a decline in productivity, estimated by PlugPower to be about 7.5% (Schell 2008). This problem is reported to be alleviated by use of AC instead of direct current (DC) motors (EPRI 2004).

2.2 FOSSIL-FUELED FORKLIFTS

Internal combustion engine (ICE) forklifts consist of two types: those with spark ignition (SI) engines powered by gasoline, propane or compressed natural gas, with a lift capacity of up to 16,000 lb; and compression ignition (CI) forklifts, powered by diesel fuel, with lift capacities from 6,000 to 40,000 lb. Forklifts with SI engines powered by propane can be used indoors, while large diesels are generally used outdoors on rough terrain. Hydrogen also could be used to power ICE forklifts for indoor or outdoor use. Linde displayed the first such forklift at the CeMAT fair in Hanover, Germany, in May 2008. It could be an economical alternative by 2015 (Deutschen Wasserstoff–Verband 2008).

As shown in Table 2, forklifts powered by gasoline and LPG can range in size from 25 to 300 hp. These would have lift capacities up to approximately 8 tons. Diesel power is often used for the largest forklifts, but it can be used in smaller types as well. Forklift manufacturers purchase engines that range from 25-hp Kubota engines to 115-hp and larger General Motors (GM) engines. Lift capacities as large as 40,000 lb (20 tons) are advertised — which would imply an engine with up to 700 hp — so these forklifts can be extremely large. Several diesel hybrids have recently been reported, with both lithium-ion batteries and super-capacitors. These are claimed to reduce forklift fuel use by as much as 50% (De Smet 2008; Warehouse and Logistics News 2008).

Although recent data were not available, and diesels are not shown, Table 2 is of interest because it shows the large numbers of forklifts in service with ICEs. The main benefit of the ICE engine over batteries is the ease of refueling (<30 seconds). While ICE-powered forklifts are cheaper to purchase, the cost of maintenance is high. In addition, refueling equipment and

TABLE 2 Engine Size and Type Distribution for ICE Forklifts in 1996 (Mahadevan et al. 2007[1])

Equipment Description	Minimum Horsepower	Maximum Horsepower	Average Horsepower	Total Population
Gasoline 4 Stroke Forklifts	25	40	36.12	1,645
Gasoline 4 Stroke Forklifts	40	50	45.16	5,876
Gasoline 4 Stroke Forklifts	50	75	62.77	9,466
Gasoline 4 Stroke Forklifts	75	100	89.03	691
Gasoline 4 Stroke Forklifts	100	175	144.7	4,399
Gasoline 4 Stroke Forklifts	175	300	215.8	22
LPG-Forklifts	25	40	33.44	31,264
LPG-Forklifts	40	50	45.43	68,337
LPG-Forklifts	50	75	58.18	179,857
LPG-Forklifts	75	100	79.83	13,136
LPG-Forklifts	100	175	131.5	83,590
LPG-Forklifts	175	300	215.8	409
CNG-Forklifts	40	50	48	43,307
Total Population				**441,999**

storage equipment are an added cost. In many cases, dual-fuel equipment is available that allows a switch between liquefied petroleum gas (LPG) and diesel (Mahadevan et al. 2007).

2.3 FUEL-CELL FORKLIFTS

If a fuel cell stack is to replace an existing power train, it must perform at least as well and not require changes in functionality. In order to replace a battery system, it must retain the same size and achieve a minimum weight (the battery counterbalances the forklift load); have the same performance (speed, braking, and lifting), productivity (pallet moves per hour), and center of gravity; perform the same electrical functions; and at least match the life, refueling frequency, maintenance, reliability, and repairability of the system it replaces.

A fuel-cell forklift is designed as hybrid system, with a fuel-cell stack as the power source, plus a battery or super-capacitor to handle peak demand using stored energy. Some of this energy is supplied directly by the fuel cell, and some is recovered from braking. Without this feature, a much larger and more expensive fuel cell stack would be required. The optimum size of the required energy storage device depends on how the forklift is expected to be operated. One manufacturer wrote, “The fuel-cell manufacturers are each struggling with their own best combinations of fuel cell plus battery or capacitor. We are looking for enough short-term storage to provide 15–20 seconds of high-current for lifting a heavy load, plus enough fuel-cell current delivery to allow the truck to continue driving after the lift *and* charge the storage medium for the next lift” (McCabe 2008). Another manufacturer confirms that no simple relationship exists. “There is a strong interdependence between the amount of energy storage capacity available and the amount of fuel-cell power required to balance the duty cycle power/energy requirements. We

[1] No more recent data were found. Note that Battelle compiled this table from a lengthy appendix in a December 2005 report by the EPA: *Nonroad Engine Population Estimates* (EPA 2005).

have utilized energy storage devices that range from 1% to 10% of the energy storage capacity of the battery they are replacing" (Corless 2008).

Figure 3 (Veenhuizen et al. 2007) shows that demand peaks (top solid line) can readily be handled by short bursts of peak power from a battery or ultra-capacitor. This allows for use of a smaller fuel cell stack than would have been required without the storage device as a buffer. A computer controls power management, supervises the balance of the plant, and monitors usage and error conditions. In this way, the fuel-cell forklift can emulate the performance of a battery forklift.

Fuel-cell forklifts have several important advantages over the battery-powered types they replace. These forklifts lead to higher productivity by eliminating time-consuming battery changing. They can be refueled in less than 5 minutes, and there can be multiple fuel stations, with hydrogen distributed around the site from a central tank. The space required for fueling is much smaller than that required for a battery room. Fuel cells maintain a constant voltage, without the voltage drop towards end of shift or in cold locations, as observed for batteries. There are no environmental concerns from acid runoff or lead, or from tailpipe emissions (Medwin 2007), though handling and storage of hydrogen may have safety concerns. Individual plants can establish their own hydrogen fueling stations, based either on hydrogen produced onsite or at a central location. In either case, the hydrogen can be produced by steam reforming of natural gas, as shown schematically in Figure 4, or by the electrolysis of water. The adoption of fuel-cell-powered forklifts will result in lower total logistics costs, but higher initial costs.

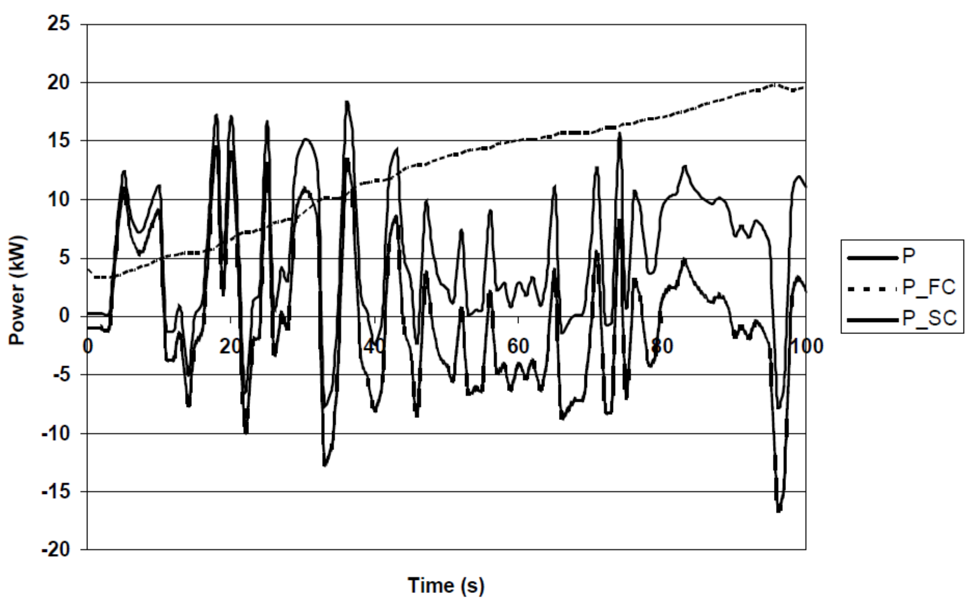


FIGURE 3 Comparison of Input Power of the Fuel Cell System (P_FC), the Input Power of the Super Capacitor Set (P_SC), and Power Demand (P) of the Fork Lift Truck

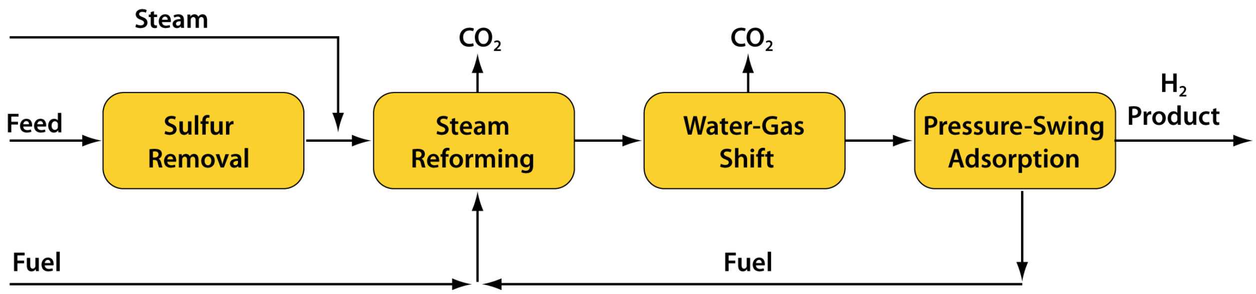


FIGURE 4 Schematic of Steam Methane Reforming to Produce Hydrogen

3 ENERGY USE AND EMISSIONS DATA

3.1 ENERGY USE

Total energy use by a forklift depends on the number of hours it is used, which can vary from continual use to less than 4 hours per shift. In 1995, the Gas Technology Institute (GTI) reported a range of annual runtimes from 500 to 3,500 hours for battery-powered forklifts, and 1,800 to 1,900 hours for ICE forklifts. For Class I and II forklifts, they reported that 69% operate during one shift a day, 16% during two shifts, and 15% during three shifts. Further, while 59% of ICE forklifts operate during one shift and almost 40% during two shifts, both types averaged 1.5 shifts for 5 days a week. On average, battery-powered forklifts recharged after 11 clock (not meter) hours, and propane tanks were replaced or refilled after 15 hours (Fulghum 1995). In this report, we examine impacts on a per-kWh to the wheels/fork basis.

Data related to energy consumption by forklifts are scarce, and the reported information is often incomplete or inaccurate, thus making comparison among types difficult. For instance, a typical report about a fuel-cell forklift would state that it had a storage capacity of 2 kg of hydrogen, but not specify how many hours of service that would provide. However, industry contacts were extremely helpful, and their input enabled analysis to proceed.

The large number of device types and operating schedules posed further difficulty in gathering data for comparison. Therefore, sources that could provide direct comparisons between two (or more) comparable forklifts were invaluable. In addition, it was determined that the equivalency among power sources did not change with unit size. That is, the number of kg of hydrogen that substituted for 1 kWh of electricity was the same for large and small forklifts (Rubright 2007). Care was required to distinguish between reports of kWh equivalences in terms of power delivered to the device vs. kWh purchased from the utility. These differ from each other because a typical charger is only 84% efficient, and a forklift battery 76% efficient (Marwell et al. 1981), leading to only 64% of the electricity from the grid actually providing useful work. Furthermore, battery energy was often cited in kWh capacity (or worse, amp-hours, with no voltage specified), not taking into account that only 80% of the battery charge can be used without damage to the battery.

Several sources provided equivalences between electricity and hydrogen, and these were relatively consistent, especially since no fuel-cell efficiencies were specified. Additional definitive data will be available at the conclusion of a 2-year demonstration project being funded by the New York State Energy Research and Development Authority (Medwin 2008). One source told us that 1 kg of H_2 delivered 15 kWh to the wheels, and other sources confirmed this as a reasonable estimate (Bosio 2007; Schell 2008). This would require 24 kWh from the wall for an equivalent battery-powered forklift. Another source included costs for electricity, in a table of costs, for two different sizes of forklift. There was some ambiguity and inconsistency in this table, but the entries implied an equivalence of 20–28 kWh purchased from the grid per kg of H_2 used (Mahadevan et al. 2008). Still another source maintained that 1 kg of H_2 was equivalent to the range of a 36-V forklift (Medwin 2008). This, in turn, would have a 30–38 kWh battery capacity, of which only 80%, or 24–30 kWh, could be used, at 76% efficiency, for a net of 18–23 kWh available for use. There obviously is some uncertainty and variation in these estimates; for a preliminary calculation, we used 15 kWh at the wheels = 1 kg H_2. This implies a fuel-cell power-train efficiency of 45% (the lower heating value [LHV] of H_2 is 33.3 kWh/kg). The projected fuel-cell efficiency would be 56%, if 80% is assumed for the efficiency of the remainder of the power train (motor, inverter, etc.). This is consistent with the reported 59% part load and 50% full load efficiency for proton exchange membrane fuel cells (EERE 2007).

A number of data sources were identified that could provide information on energy use by ICE forklifts. Recent tests done at the Southwest Research Institute (SWRI) included fuel consumption for propane-powered forklifts, as well as emissions (SWRI 2006). A considerable range occurred in their measurements, which averaged 0.35 kg/kWh or 0.19 gal per kWh delivered to the wheels. Other estimates are inferred from cost reports. An Electric Power Research Institute (EPRI) report for Alabama Power (EPRI 2001) compared the costs of a battery-powered forklift with those for one fueled by propane. The report included a side-by-side cost table for electric and propane forklifts, each with a capacity of 5,000 lb. The electric forklift is reported to incur a cost \$0.58/h for electricity, at \$0.077/kWh (7.5 kWh/h), and the ICE a propane cost of \$1.50/h for fuel, at \$1.09/gal (1.38 gal/h). This implies the equivalence of 5.4 kWh of electricity purchased = 1 gal of propane, or 0.185 gal/kWh purchased. Because of charger and battery inefficiencies, 1.56 kWh must be purchased to deliver 1 kWh to the wheels, so this number differs by about 35% from the SWRI number. A cost estimate recently received from Toyota (Vasta 2008) implies even lower propane consumption and more than 40% conversion efficiency of propane energy to energy at the wheels. This is implausibly high, especially considering that forklifts run on transient cycles, where the average load is relatively low and efficiency is poor. One colleague (McConnell 2008), who is an expert on engine operation, made a rough estimate of 15–20% efficiency expected in such a case, consistent with the SWRI fuel-use estimate. We used the data from SWRI, which were measured under careful scientific conditions, and are therefore considered the most credible.

No reliable sources have yet been found to provide fuel consumption data for forklifts fueled by gasoline or diesel fuel. However, one company provides a web-based worksheet for estimating the total costs of different types of forklifts (Agroplastics 2008). The worksheet provides the average cost of fuel per hour (and gives the assumed unit fuel cost) for gasoline, LPG (propane), diesel, and electricity, allowing for calculation of fuel consumption. When their assumed worst-case battery and charger efficiencies are corrected, one can obtain equivalences per delivered kWh of 0.26, 0.24, and 0.16 gal for gasoline, LPG, and diesel, respectively. Although the per-kWh fuel consumption for propane is consistent with the SWRI report (once the adjustment from kWh at the wheels to kWh purchased is made), this source cannot be used to estimate consumption of diesel and gasoline forklifts, because consideration of the Btu content of these fuels and the relative efficiencies expected for their combustion casts serious doubt on the validity of the number for gasoline. The energy densities of gasoline and diesel are 1.37 and 1.5 times, respectively, that of propane. Therefore, for a given engine efficiency, 73% as many gallons of gasoline, or 66% as many gallons of diesel, would be used. (In addition, diesel combustion is more efficient, so even less diesel would be expected to be required than is implied by this source.) Additional help will be requested from the manufacturers of the forklifts and engines, which might be more fruitful. Full fuel-cycle calculations in this report are performed with the assumption that equal numbers of Btus are needed for all SI engines. This may result in an over-estimate of diesel impacts by as much as 20%.

3.2 EMISSIONS

Actual tailpipe emissions from ICE forklifts have been reported, and emission standards are in place for hydrocarbon (HC) + nitrogen oxide (NO_x) and carbon monoxide (CO). Emissions of carbon dioxide can be calculated from fuel consumption data.

Conventional diesel fuel is used for forklifts, and it is not subject to road taxes. Biodiesel has been tested recently, but found to produce a slight increase in CO emissions (20% for B20-soy fuel). Emission results for the 55-hp forklift run on conventional ultra-low sulfur diesel (ULSD) and 20% soy diesel are compared in Figure 5. It can be seen that the emissions from the combustion of biodiesel are very similar to those from conventional ULSD.

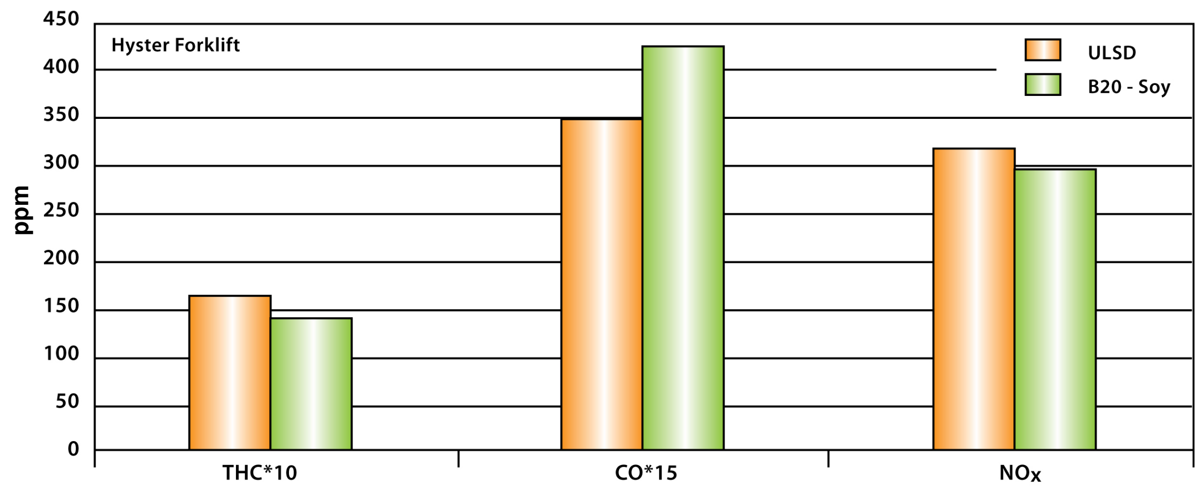


FIGURE 5 Emissions from ULSD and Soy Diesel (in parts per million) (Durbin et al. 2007)

3.3 DIESEL ENGINE STANDARDS

Non-road emission standards that apply to diesel forklifts are shown in Table 3. They vary as a function of engine size, with the smallest engines being subject to the least stringent regulation. Voluntary standards are shown in Table 4 (Dieselnet 2008).

The Tier 4 emission standards — to be phased-in from 2008–2015 — are listed in Table 5 for engines below 560 kW. These standards introduce substantial reductions of NO_x (for engines above 56 kW) and particulate matter (PM) (above 19 kW), as well as the more stringent HC limits. The CO emission limits remain unchanged from the Tier 2–3 stage.

TABLE 3 EPA Tiers 1–3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·h) (Dieselnet 2008)

Engine Power	Tier	Year	CO	HC	NMHC+NO_x	NO_x	PM
kW < 8	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
(hp < 11)	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.8 (0.6)
8 ≤ kW < 19	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.8 (0.6)
(11 ≤ hp < 25)	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.8 (0.6)
19 ≤ kW < 37	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.8 (0.6)
(25 ≤ hp < 50)	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.6 (0.45)
37 ≤ kW < 75	Tier 1	1998	-	-	-	9.2 (6.9)	-
(50 ≤ hp < 100)	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.4 (.3)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ≤ kW < 130	Tier 1	1997	-	-	-	9.2 (6.9)	-
(100 ≤ hp < 175)	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.3 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ≤ kW < 225	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(175 ≤ hp < 300)	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ≤ kW < 450	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(300 ≤ hp < 600)	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ≤ kW < 560	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(600 ≤ hp < 750)	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ≥ 560	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(hp ≥ 750)	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

† Not adopted; engines must meet Tier 2 PM standard.

TABLE 4 EPA Voluntary Emission Standards for Nonroad Diesel Engines, g/kWh (g/bhp·h) (Dieselnet 2008)

Rated Power (kW)	NMHC+NO_x	PM
kW < 8	4.6 (3.4)	0.48 (0.36)
8 ≤ kW <19	4.5 (3.4)	0.48 (0.36)
19 ≤ kW <37	4.5 (3.4)	0.36 (0.27)
37 ≤ kW < 75	4.7 (3.5)	0.24 (0.18)
75 ≤ kW <130	4.0 (3.0)	0.18 (0.13)
130 ≤ kW < 560	4.0 (3.0)	0.12 (0.09)
kW ≥ 560	3.8 (2.8)	0.12 (0.09)

TABLE 5 Tier 4 Emission Standards — Engines up to 560 kW, g/kWh (g/bhp-h) (Dieselnet 2008)

Engine Power	Year	CO	NMHC	$NMHC+NO_x$	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008 2013	5.5 (4.1) 5.5 (4.1)	- -	7.5 (5.6) 4.7 (3.5)	- -	0.3 (0.22) 0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008 2013	5.0 (3.7) 5.0 (3.7)	- -	4.7 (3.5) 4.7 (3.5)	- -	0.3[b] (0.22) 0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012–2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011–2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

[a] Hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010.

[b] 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012.

[c] PM/CO: full compliance from 2012; NO_x/HC: Option 1 (if banked Tier 2 credits used) — 50% engines must comply in 2012–2013; Option 2 (if no Tier 2 credits claimed) — 25% engines must comply in 2012–2014, with full compliance from 2014.12.31.

[d] PM/CO: full compliance from 2011; NO_x/HC: 50% engines must comply in 2011–2013.

3.4 STANDARDS FOR SI FORKLIFTS

The EPA promulgated emission standards that apply to SI engines in forklifts (i.e., those burning propane, natural gas, or gasoline). These are shown in Table 6. Note that the PM emissions are not regulated, presumably because they are negligible, and the HC + NO_X limit is considerably lower for SI engines than it is for diesels. The CO limit is lower for SI engines than for small diesels but higher than that for large diesels. We assume that any new SI forklifts that might be purchased will at least meet the applicable standards over both standard test (C2) and transient cycles, as required by the EPA and defined below in Table 7 and Figure 6. Actual emissions from current forklifts will be seen to be considerably below these standards for propane and, by inference, for natural gas as well. Emissions could, of course, increase over the useful life of the machines. That issue has been addressed in a report about propane-fueled forklift testing performed by Southwest Research Institute for the Propane Education and Research Council. The report concluded that the forklifts that were tested would still meet the 2007 standards after 5,000 hours of operation, as required (SWRI 2006). It should be noted that the more recent emissions measured and shown in Table 8 are significantly lower than those measured by SWRI and reported in 2002, as shown in Table 9. The emissions from gasoline-powered forklifts, reviewed in the same SWRI work, also are assumed to be higher than those of current forklift models, for which fuel cells might substitute.

TABLE 6 Large Spark Ignition Engine Standards

Tier/Year	HC+NO_x (g/kWh)	CO (g/kWh)	Useful Life Hours
Tier 1, 2004	4.0	50	3,500
Tier 2, 2007	2.7	4.4	5,000

TABLE 7 Definition of C2 Test Cycle

Mode	1	2	3	4	5	6	7
Speed	Rated	Intermediate					Idle
Torque %	25	100	75	50	25	10	0
Weight Factor	0.06	0.02	0.05	0.32	0.30	0.10	0.15

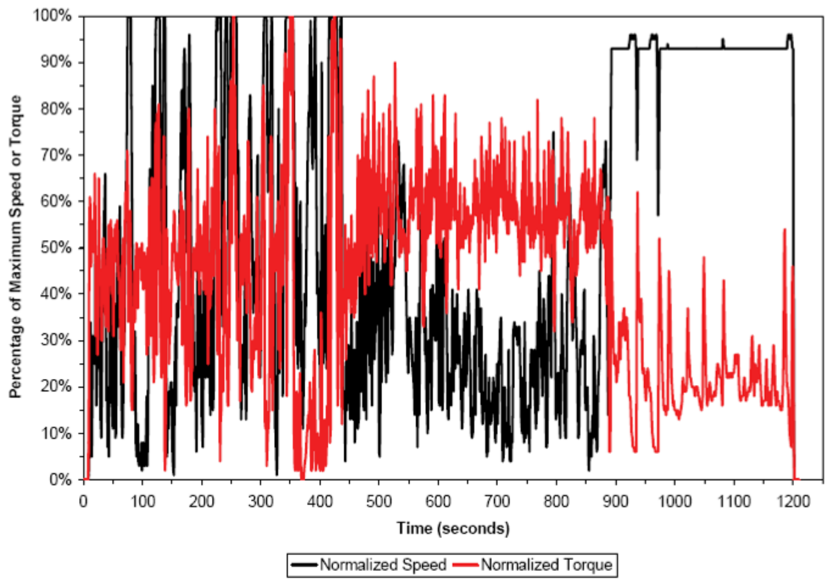


FIGURE 6 Transient Cycle (SWRI 2006)

TABLE 8 Transient and C2 Cycle Emission Results (SWRI 2006)

Configuration	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	HC+NO_x (g/kWh)	BSFC (kg/kWh)
Transient Cycle Results					
2007 EPA Std.	4.40			2.70	
Older ICCS Controller	1.07	0.17	0.07	0.25	0.340
Newer ICCS Controller	1.67	0.22	0.12	0.34	0.343
Econtrols System	1.60	0.08	0.39	0.47	0.386
Safe Controls System	1.95	0.19	0.02	0.21	0.361
System J	6.52	0.09	0.95	1.04	0.318
C2 Cycle Results					
2007 EPA Std.	4.40			2.70	
Older ICCS Controller	0.65	0.22	0.02	0.24	0.357
Newer ICCS Controller	1.22	0.33	0.13	0.45	0.356
Econtrols System	0.11	0.07	0.10	0.17	0.378
Safe Controls System	2.75	0.36	0.02	0.38	0.361
System J	2.96	0.34	0.07	0.41	0.306

For all but one emission control system tested by SWRI (and for only CO), emissions from a propane-fueled forklift were well below the EPA standard for 2007. The associated literature includes some discussion of the possible emission benefits of natural gas over propane as a forklift fuel (Checkel and Dhaliwal 2000).

TABLE 9 Gasoline and LPG Engine Emissions (g/kWh) (McGlinchey and Jaques 2008)

Parameter	HC	NO_x	HC+NO_x	CO
Gasoline Avg.	3.6	10.8	14.4	45.0
LPG Avg.	1.8	15.6	17.3	10.9

Table 10 summarizes the direct impacts of fossil-fueled forklifts. Until actual data are available, fuel use for gasoline and diesel forklifts is simply approximated to be the same, on a Btu basis, as that measured for propane, and then converted to gallons using the relative energy densities of the fuels. The propane emissions are simply the averages of those measured by SWRI, in the absence of information regarding which control system is most representative of the class. Emissions are assumed to be compliant with the EPA standards shown in the table.

TABLE 10 Summary of Fossil-Fueled Forklift Tailpipe Impacts

Fuel	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	HC+NO_x (g/kWh)	PM (g/kWh)	Fuel Use (gal/kWh)
Tier 2 standard for SI engines	4.40	--	--	2.70	--	--
Propane (measured by SWRI)	2.0	0.21	0.19	0.40		0.19
Gasoline						0.14
Tier 3 standards for diesels (100–175 hp)	5.0	--	--	4.0	0.3	--
Tier 3 standards for diesels > 175 hp	3.5	1.3		4.0	0.2	--
Diesel						0.12

4 COMPARISON ON FULL FUEL-CYCLE BASIS

Only ICE forklifts produce emissions at their point of use, but all types have upstream emissions from converting primary energy sources into the forms that power the forklifts. These are added to the direct impacts, via the GREET model, to calculate the full fuel-cycle impacts. In addition, emissions to air and water result from battery testing and charging. Although no measured quantities have been reported for the latter, a calculator tool is available on the web to enable estimation of the hydrogen concentration in a charging area (Raymond Handling Solutions 2008). The impacts from electricity production depend on the mix of sources used to generate the power. The U.S. and California mixes, and the efficiencies of the various types of plants utilized, are shown in Tables 11 (U.S.) and 12 (California). The California mix relies much less heavily on coal than the U.S. mix, and it uses higher percentages of natural gas and renewable energy sources.

TABLE 11 Projected Electricity Generation Mix and Generation Efficiencies in the United States for 2010 (from GREET 1.8a 2008)

Grid Generation Technology	Share (%)	Efficiency (%)
Residual oil-fired power plants	2.7	34.8
Natural gas-fired boiler, steam cycle power plant	3.8	34.8
Natural gas turbine, simple cycle power plants	6.8	33.1
Natural gas turbine, combined cycle power plants	8.3	46.0
Coal-fired boiler, steam cycle power plant	50.7	34.1
Biomass-fired boiler, steam cycle power plant	1.3	32.1
Other power plants (renewable; e.g., wind)	7.7	Not applicable
Nuclear power plant	18.7	Not applicable

TABLE 12 Projected Electricity Generation Mix and Generation Efficiencies in California for 2010 (from GREET 1.8a 2008)

Grid Generation Technology	Share (%)	Efficiency (%)
Residual oil-fired power plants	0.7	34.8
Natural gas-fired boiler, steam cycle power plant	8.3	34.8
Natural gas turbine, simple cycle power plants	14.9	33.1
Natural gas turbine, combined cycle power plants	18.3	46.0
Coal-fired boiler, steam cycle power plant	14.6	34.1
Biomass-fired boiler, steam cycle power plant	1.7	32.1
Other power plants (renewable; e.g., wind)	22.6	Not applicable
Nuclear power plant	18.9	Not applicable

For this analysis, it is assumed that hydrogen will be supplied either by steam reforming of methane or from coke oven gas (COG). The hydrogen also could be supplied by electrolysis, but that uses a larger quantity of fossil energy than does reforming, as shown in Figure 7 for both the U.S. generation mix and the most efficient power from natural gas (NGCC). Therefore, we will not further consider electrolysis. Of course, if renewable energy is used to generate either electricity or hydrogen, both fossil fuel use and GHG emissions are negligible, and the decision regarding the use of electrolysis would be made on other grounds, such as the local availability of natural gas. The figure also indicates that producing 1 million Btu of hydrogen from natural gas via steam methane reforming requires a total of 1.7 million Btu of primary energy use. The upstream energy includes the energy use associated with natural gas recovery, processing, and transportation to the hydrogen production plant; the energy associated with the compression and delivery of hydrogen to the point of use; and the heat of combustion of the primary feedstock and process fuels. The GREET model assumes a reformer efficiency of 70% (GREET 1.8a 2008).

Hydrogen compression is necessary to increase its energy density during transportation (if produced at a location other than where it is to be used), as well as for storage onboard the forklift. Energy is required to compress the hydrogen from a production supply pressure of 300 (psia) to the forklift onboard pressure. For Class III forklifts, that typically is 3,000 psi (used for figures shown) or 3,600 (psia). However, for Classes I and II it is 5,000 (psia) or higher to enable longer operation without refueling (McKinnon 2008; Medwin 2008). It should be noted that increasing the onboard storage pressure from 3,000 psi to 5,000 psi would result in a corresponding increase of 30% in compression energy (2 kWh/kg for 5,000 psi vs. 1.5kWh/kg

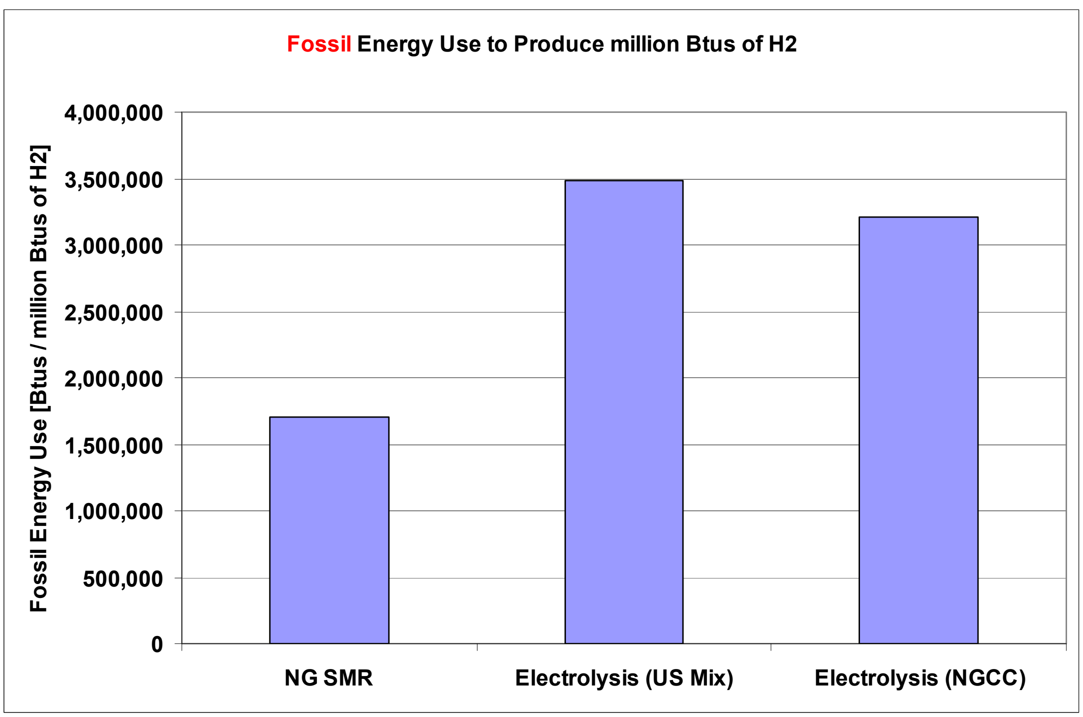


FIGURE 7 Fossil Energy Use to Produce Hydrogen from Primary Energy Extraction to Point of Use

for 3,000 psi), which amounts to only a 2% increase in the fuel cycle total energy use. Compression energy represents only 7% and 9% of the fuel cycle total energy use for the 3,000 psi and 5,000 psi pressures, respectively. We assume pipeline delivery of hydrogen to the point of use for the hydrogen central production cases (i.e., the COG-to-H_2). The entire H_2 compression energy in this analysis is assumed to be drawn from the U.S. mix of electricity.

Figures 8 through 11 summarize our results on a per-kWh-to-the-wheels basis. Full fuel-cycle impacts, as calculated by the Argonne GREET model, are shown, including initial recovery of the primary energy, conversion to the form used by the forklift (including compression and any required transport), and use at the forklift. Comparative results are independent of forklift size. Figure 8 compares total energy use per kWh supplied to the forklift. A striking feature is the high total energy use by the ICE forklifts, indicating significant engine inefficiency. This is similar to results for other vehicle types (Gaines et al. 2007). The fuel-cell forklift with hydrogen from natural gas or COG uses slightly less energy than the battery type powered by U.S. average electricity, and slightly more than a battery type powered by the California mix, which reflects the use of non-fossil sources in that generation mix. Use of wind to generate the H_2 has a similar effect.

A comparison of options for powering a forklift with natural gas as the primary energy source shows that the fuel cell has a big total-energy advantage over battery power from natural gas burned in a simple steam cycle — which is very inefficient — and comes close to battery power supplied by the more efficient combined cycle. It should be noted that the losses due to

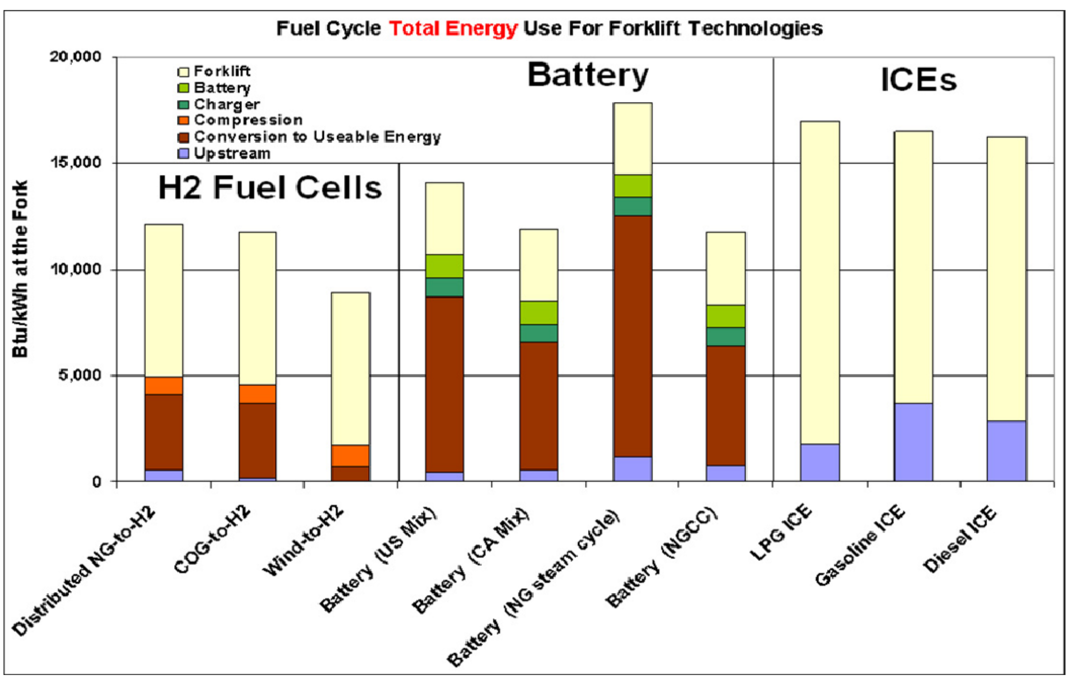


FIGURE 8 Comparison of Energy Use by Forklift Type (per kWh to the wheels)

battery charging and discharging contribute significantly to the total energy use for battery-powered forklifts. Therefore, improvements in charging and battery efficiency could reduce impacts from battery-powered forklifts. Similarly, improvements in reforming and fuel-cell efficiencies could reduce impacts from fuel-cell forklifts. The COG path resembles the steam-reforming path for total energy use, fossil fuel use, and petroleum use, but appears to have a GHG advantage. The allocation of energy use and emissions in the production of COG are discussed in a recent publication (Joseck et al. 2007).

Figure 9 compares fossil energy use for the same cases. A battery-powered forklift charged from a power plant with a natural gas simple cycle uses the most fossil fuel of all the pathways considered, followed closely by the ICE forklifts. In California, with its higher percentage of non-fossil sources in its electricity generation mix, forklifts powered by batteries show lower fossil use than battery-powered forklifts that use U.S. average power or fuel-cell forklifts that rely on natural gas or COG. Of course, the wind-to-H_2 pathway shows minimal fossil fuel use. The battery-powered forklift that uses the U.S. average electric mix consumes only slightly more fossil fuel than the natural gas-to-H_2 fuel-cell forklift because of the nuclear and hydropower contributions.

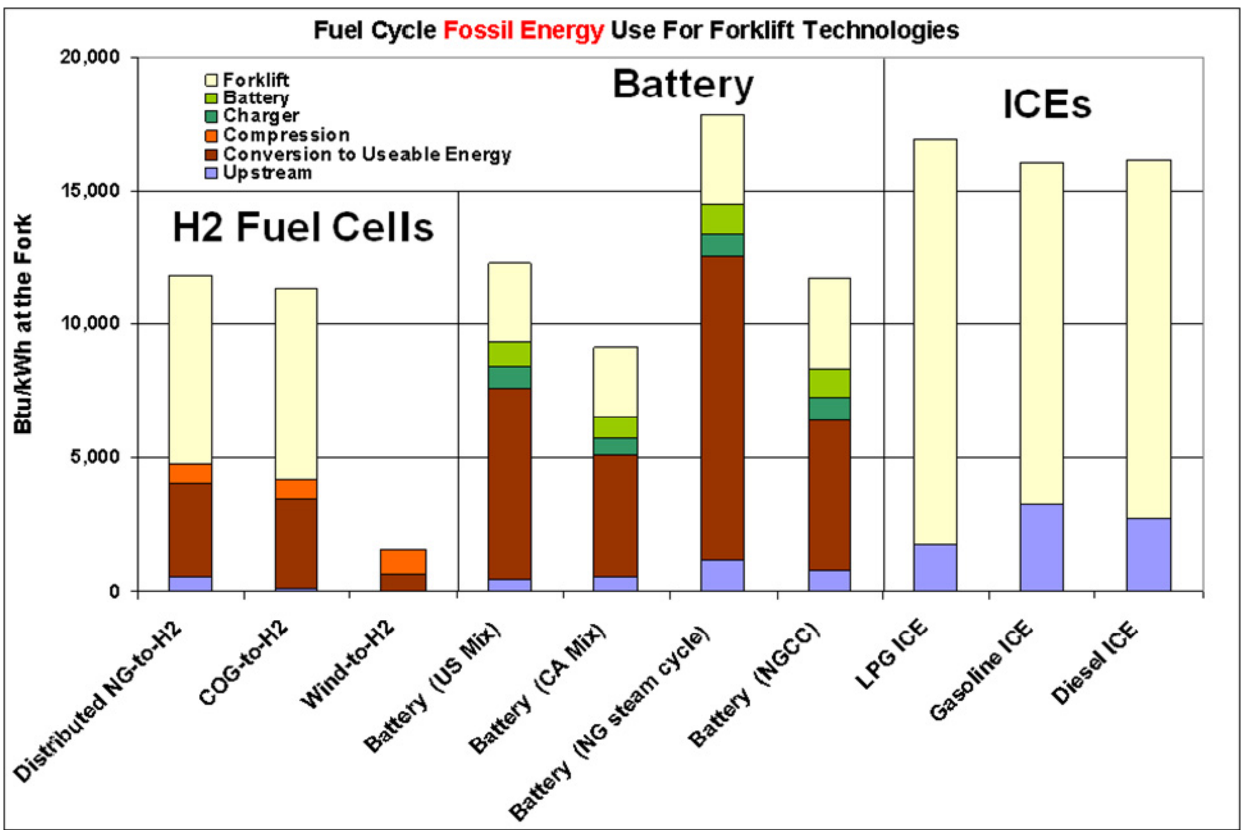


FIGURE 9 Comparison of Fossil Fuel Use by Forklifts

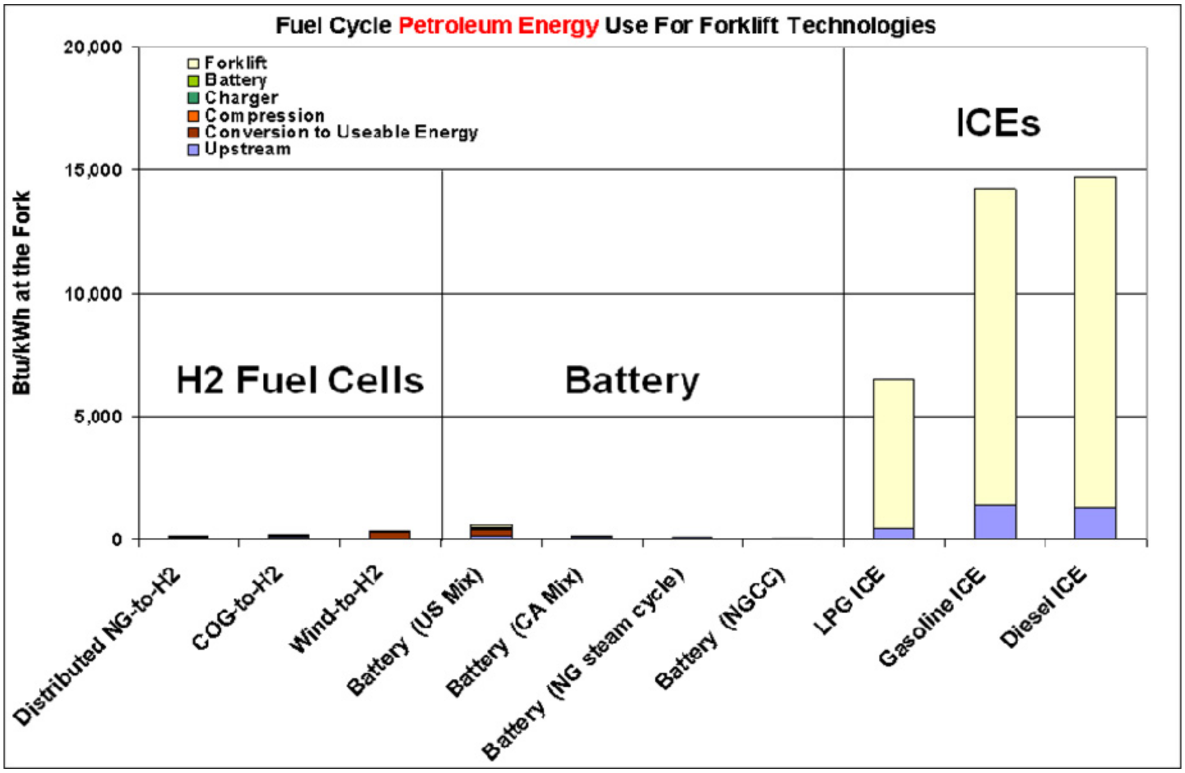


FIGURE 10 Comparison of Petroleum Use by Different Forklift Types

Petroleum use is shown in Figure 10. The ICE forklifts, with petroleum fuels, use significant quantities of petroleum products. Generally, these are not used to produce electricity. The internal-combustion engine forklift running on LPG shows less petroleum use than the other ICEs, because more than half the LPG is assumed to be recovered from natural gas processing. All the H_2 and battery-powered options minimize the use of petroleum products.

Figure 11 compares GHG impacts for the different forklift types. The ICE-powered forklifts produce the highest full fuel-cycle GHG emissions, but the battery-powered forklifts that rely on the average U.S. electricity mix produce almost as much. This is because of the grid's heavy reliance on coal, which results in more GHG per Btu. The use of wind to produce H_2 or electricity minimizes emissions of GHG. The GHG emissions from the use of COG are low, because COG is a by-product of coke production and typically contains 55% H_2 to begin with.

It is interesting to compare the pathways, starting with natural gas as the primary energy source. Of these, the path using the single-cycle power plants results in the highest GHG emissions, and the combined cycle the lowest. The path using steam reforming is only slightly higher, but still well below the path using batteries charged with the average U.S. generation mix.

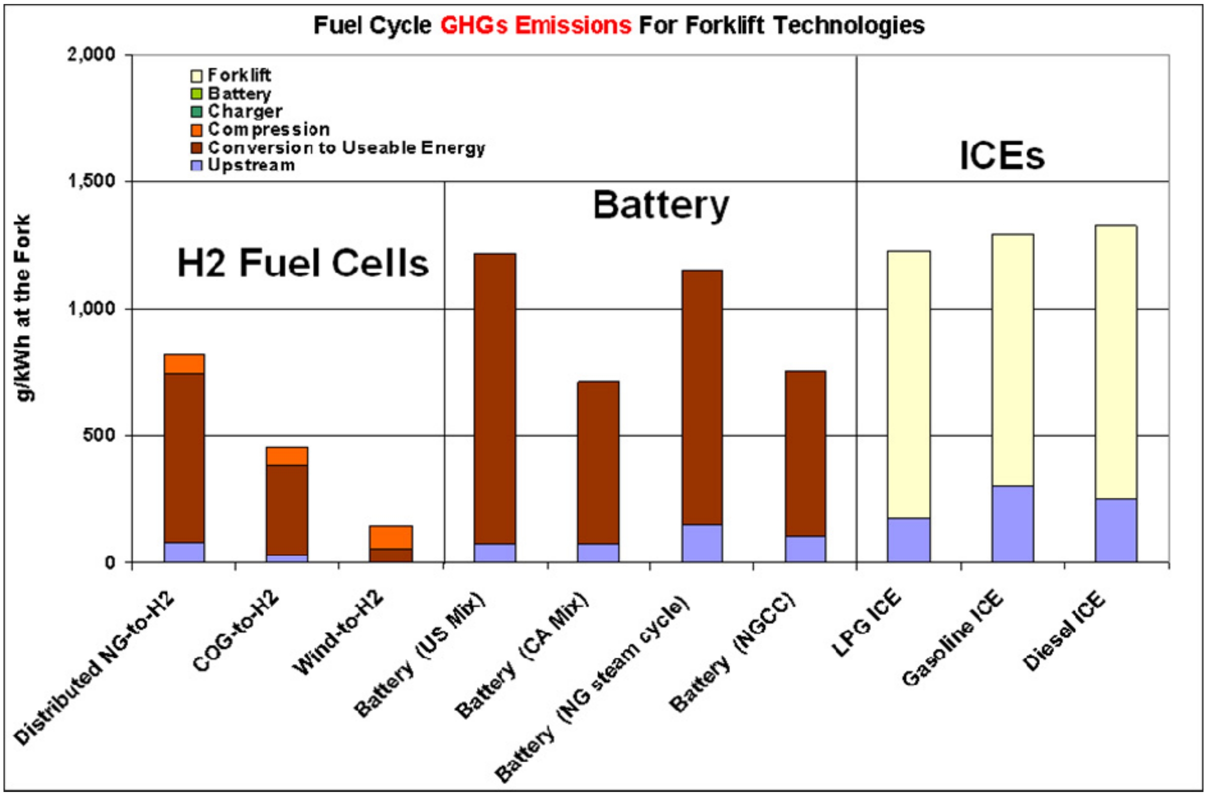


FIGURE 11 Greenhouse Gas Comparison for Forklift Types

5 SUMMARY AND CONCLUSIONS

The impacts of both fuel-cell and battery-powered forklifts are generally lower than those of forklifts powered by IC engines, and technical improvements could further decrease the impacts. Therefore, reductions in energy use and petroleum imports, as well as GHG reductions, can be accomplished by displacement of fossil fuels in forklifts. Further, a large number of ICE forklifts are in service, and many have high horsepower ratings and therefore use significant quantities of fuel (refer to Table 2). As such, replacement of these forklifts with either fuel-cell or battery-powered units offers the potential for a considerable reduction in the use of fossil fuels and petroleum imports in the United States. Reductions in GHG emissions could be accomplished by low-carbon production of the hydrogen for fuel-cell forklifts or the electricity for battery-powered forklifts.

The impacts of fuel-cell forklifts using hydrogen from natural gas are similar to those from battery-powered forklifts using electricity from the best natural-gas-fired power plants. However, they have considerably lower impacts than those using electricity from the average U.S. grid. Therefore, in many parts of the United States, significant and immediate benefits could be obtained by replacing battery-powered forklifts with those powered by fuel cells using H_2 from steam reforming of natural gas or from COG. In states like California, with lower-impact grids, the H_2 also must have a lower impact to compete on an energy/environmental basis.

Use of batteries to power large forklifts for outdoor use would require enclosure and waterproofing of the battery compartment, and this would make it harder to change the batteries. In terms of convenience and low labor requirements for fueling, such difficulty would increase the advantage of fuel-cell forklifts. For many applications, this lower labor cost may balance out the higher capital cost of fuel-cell forklifts (Mahadevan et al. 2007).

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