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Vessel Cold-Ironing Using a Barge Mounted PEM Fuel Cell: Project Scoping and Feasibility

Joseph W. Pratt and Aaron P. Harris

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Vessel Cold-Ironing Using a Barge Mounted PEM Fuel Cell: Project Scoping and Feasibility

Joseph W. Pratt[1] and Aaron P. Harris[2]
[1]Energy Systems Engineering & Analysis (8366)
[2]Hydrogen and Combustion Technology (8367)
Sandia National Laboratories
P.O. Box 969
Livermore, California, 94551

Abstract

A barge-mounted hydrogen-fueled proton exchange membrane (PEM) fuel cell system has the potential to reduce emissions and fossil fuel use of maritime vessels in and around ports. This study determines the technical feasibility of this concept and examines specific options on the U.S. West Coast for deployment practicality and potential for commercialization.

The conceptual design of the system is found to be straightforward and technically feasible in several configurations corresponding to various power levels and run times.

The most technically viable and commercially attractive deployment options were found to be powering container ships at berth at the Port of Tacoma and/or Seattle, powering tugs at anchorage near the Port of Oakland, and powering refrigerated containers on-board Hawaiian inter-island transport barges. Other attractive demonstration options were found at the Port of Seattle, the Suisun Bay Reserve Fleet, the California Maritime Academy, and an excursion vessel on the Ohio River.

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SUMMARY

The Department of Energy is interested in reducing air pollution and greenhouse gas emissions, and reducing dependence on foreign energy sources. The fuel use of and emissions from maritime port sources can be significant. For example, a 2004 study showed the Port of Los Angeles (POLA) had average daily emissions exceeding that of 500,000 vehicles. Efforts have been underway to reduce these emissions from all sources, but ocean-going vessels (OGVs) and harbor craft are still major contributors to air pollution and greenhouse gas emissions in and around ports. Approximately one-third to one-half of emissions attributed to OGVs comes from their auxiliary diesel engines which are run while the vessel is at berth (docked) and requires electrical power for everything from lighting to loading/discharging equipment.

One recent effort to reduce vessel port emissions involves the practice referred to as cold-ironing, where a vessel at berth connects to a source of electricity on the shore. It has been proposed that a cold-ironing power supply be based on a hydrogen-fueled proton exchange membrane (PEM) fuel cell that is mounted on a floating barge. The PEM fuel cell produces zero emission and the barge provides flexibility and an alternative to installation of electrical infrastructure. The DOE has asked Sandia National Laboratories to examine the feasibility of a hydrogen-fueled PEM fuel cell barge to provide electrical power to vessels at anchorage or at berth. This study includes both a determination of the technical feasibility of the idea as well as an analysis of potential deployment options. To gain this information, interviews were conducted with the major West Coast ports, barge and tug owners and operators, and shipping fleets to understand the issues within the maritime environment that relate to this system and to the use of cold-ironing in general. We also consulted the literature to provide the necessary background and details.

Deployment of fuel cells at or around ports is affected by issues that are unique to the maritime setting. They include vessel types and frequency, environmental regulations, infrastructure requirements, safety rules, operator needs, and requirements imposed by surrounding operators and equipment owners. In general, the important aspects of vessel types are the electrical power required while in port, the duration of the port visit, and the frequency of an individual vessel's visit, which dictate the technical and commercial feasibility of a barge-mounted PEM fuel cell system. Of the vessel types examined, container ships are the most likely large-vessel application while smaller vessels such as tugs, fishing trawlers, and others also have high potential.

There are several regulations that affect the use of cold-ironing in the locales that are target of this study, the U.S. West Coast and Hawaii. These regulations have just taken effect (in 2012) or will in the coming two years. Fleets are currently looking at cost-effective compliance methods and if a fuel cell solution is not presented soon it may not be adopted. Instead fleets may turn to other solutions, such as diesel-electric hybrids or CNG/LNG. Therefore, there currently exists a window of opportunity for PEM fuel cell cold-ironing that may not exist in a year or two.

The conceptual design of a barge-mounted hydrogen-fueled PEM fuel cell system is straightforward and it is shown to be technically feasible in several configurations corresponding to various power levels and run times. For example, to supply a container ship at average power

level (1.4 MW) and run times (48 hrs) would require four 40-ft containers, two for the fuel cell and two for the hydrogen storage, which could readily fit on a typical flat-top barge. To supply power (200 kW) for a tug at berth for a day would likely require just a single 20-ft container housing both the fuel cell and the hydrogen.

Through the course of this study more than ten specific applications were analyzed in terms of technical feasibility and potential to result in a successful commercial product. The most feasible and commercially-attractive options for a fuel cell barge powering large ships at berth was found to be powering container ships at the Ports of Tacoma and Seattle. For smaller craft, powering tugs at anchorage in the Port of Oakland, and powering refrigerated containers on transport barges in Hawaii are also feasible and likely to be commercially-viable options. Other options are attractive for demonstration potential but their commercial viability is less understood. These include powering (1) the various smaller vessels that berth at Pier 91 at the Port of Seattle, (2) the reserve fleet and/or auxiliary personnel lighter at the Suisun Bay Reserve Fleet facility, (3) the training ship Golden Bear when at berth at the California Maritime Academy, and (4) providing propulsive power for RiverQuest's Explorer diesel-battery electric hybrid excursion vessel in Pittsburg, PA.

In general, with a design suited for the application, this study has found that a barge-mounted hydrogen-fueled PEM fuel cell can be a technically feasible and commercially viable option to reduce maritime vessel emissions and dependence on fossil fuels.

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NOMENCLATURE

AMP	Alternative Marine Power
APL	Auxiliary Personnel Lighter
AT/B	Articulated Tug-Barge
BP	British Petroleum
CAAP	Clean Air Action Plan
CARB	California Air Resources Board
CNG	Compressed Natural Gas
DOE	[U.S.] Department of Energy
DOT	[U.S.] Department of Transportation
DWT	Dead Weight Tons
ECA	Environmental Control Area
EPA	[U.S.] Environmental Protection Agency
IBEW	International Brotherhood of Electrical Workers
IBU	Inlandboatmen’s Union
IFO	Intermediate Fuel Oil
ILWU	International Longshore and Warehouse Union
IMO	International Maritime Organization
ITB	Integrated Tug-Barge
LEED	Leadership in Energy and Environmental Design
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MARAD	[DOT] Maritime Administration
MDO	Marine Distillate Oil
MGO	Marine Gas Oil
OGV	Ocean-going Vessel
PEM	Proton Exchange Membrane
POLA	Port of Los Angeles [CA]
POLB	Port of Long Beach [CA]
PM	Particulate Matter
RoRo	Roll-on/Roll-off
SBRF	Suisun Bay Reserve Fleet
SCF	Standard Cubic Feet
SCR	Selective Catalytic Reduction
TEU	Twenty-foot Equivalent Unit
TOTE	Totem Ocean Trailer Express
TS	Training Ship
TSGB	Training Ship Golden Bear
ULSD	Ultra Low Sulfur Diesel
USCG	United States Coast Guard

1 INTRODUCTION

The Department of Energy is interested in reducing air pollution and greenhouse gas emissions, and reducing dependence on foreign energy sources. Hydrogen and fuel cell technology has the potential to meet these demands and DOE has supported their development in many applications including light duty vehicles, buses and trucks, material handling equipment, construction equipment, aviation, backup power, portable power, and others. Although the maritime environment has been considered previously with niche applications, until now there has not been a concentrated effort to determine the role that hydrogen and fuel cells could play to reduce emissions of vessels in or around ports.

The emissions from all ports sources can be significant. As seen in Figure 1-1, a 2004 study showed the Port of Los Angeles (POLA) had average daily emissions exceeding that of 500,000 vehicles. Efforts have been underway to reduce these emissions from all sources, with particular emphasis and success in the trucking industry through old-engine retirement, use of ultra-low sulfur diesel, and exploration of electric and fuel cell-hybrid trucks. Vessel pollution has been addressed primarily through reduction of fuel sulfur content over the last 15 years. In spite of these efforts, vessels, including ocean-going vessels (OGVs) and harbor craft, are still major contributors to air pollution and greenhouse gas emissions at ports as shown in Figure 1-2 for the POLA, but can be taken as representative of other major ports. The POLA study also identified that one-third to one-half of emissions attributed to OGVs comes from their auxiliary diesel engines which are run while the vessel is at berth (docked) and requires electrical power for everything from lighting to loading/discharging equipment.

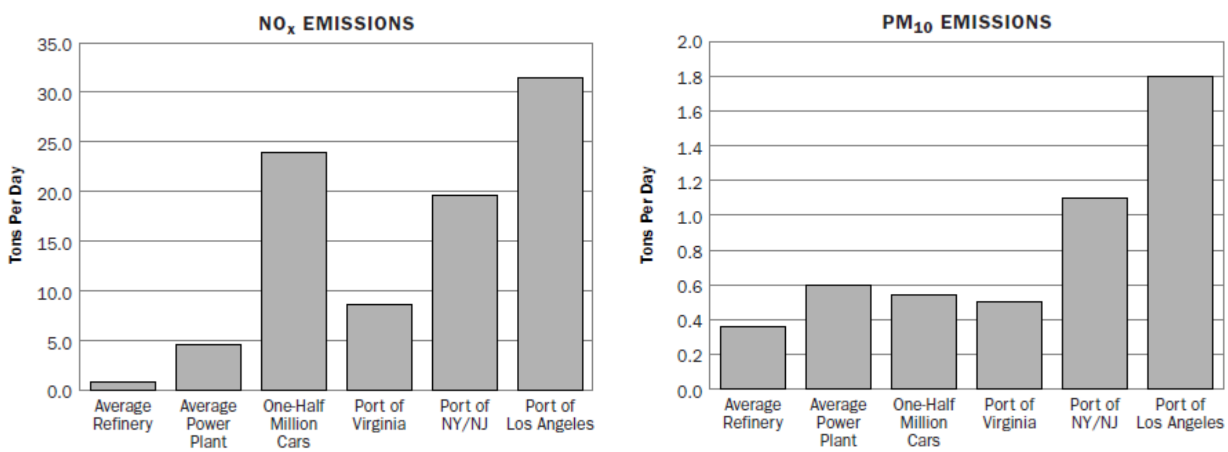


Figure 1-1: NOx and particulate matter (PM_{10}) emissions from ports compared to refineries, power plants, and cars [1].

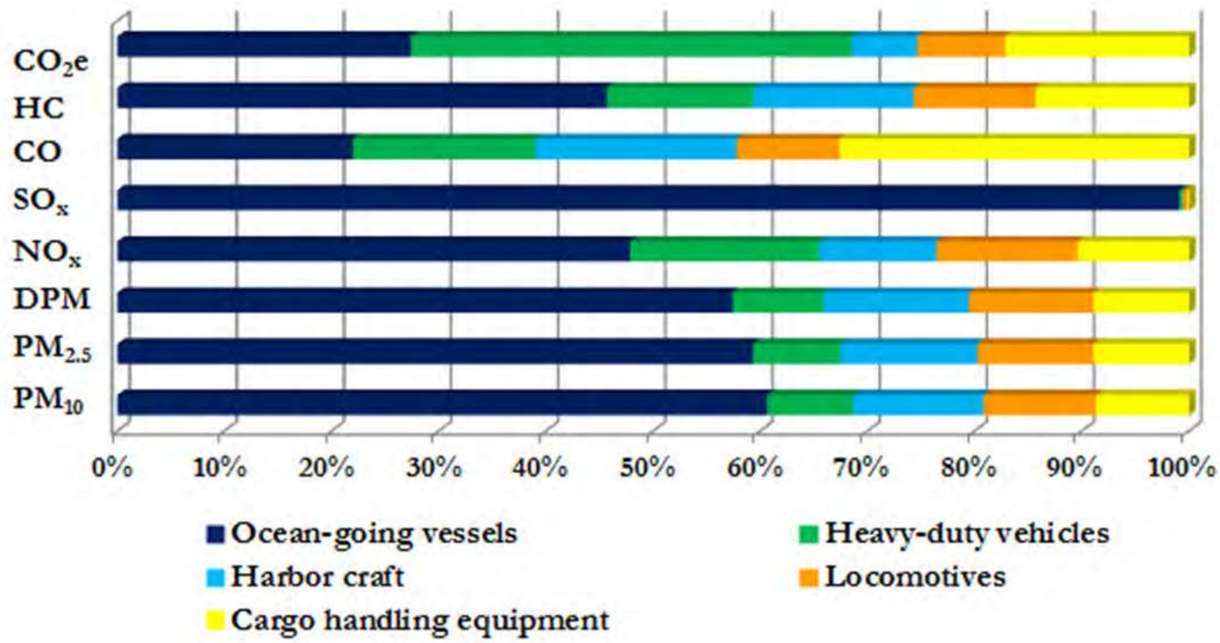


Figure 1-2: A source-by-source categorization of air emissions at the Port of Los Angeles from their 2011 Inventory of Air Emissions [2]. Note: Approximately one-third to one-half of the emissions from ocean-going vessels is due to running auxiliary engines for electrical power at berth [2].

One recent effort to reduce vessel port emissions involves the practice referred to as cold-ironing. In cold-ironing, a vessel at berth electrically connects to a source of electricity on the shore such as the grid, and shuts down its auxiliary engines. (The engine, made of steel/iron, will literally become cold, hence use of the term *cold-ironing*. The practice is also referred to as *shore power* and POLA uses the term *Alternative Maritime Power* (AMP). In this report these terms are used interchangeably.) The practice is common in the U.S. Navy but barely utilized in for large commercial vessels. Until recently, only a handful of ports in the world have provided cold-ironing capability to shipping vessels or cruise ships. However, the practice is becoming much more prevalent in California due to a California Air Resources Board regulation that requires shore power in many instances beginning in 2014 (the details of which are included in this report).

A disadvantage of grid-supplied cold-ironing is the complexity and cost of the shore-based infrastructure required to supply the megawatts of power that vessels need. These costs, which are detailed within the report, can be $5M-$10M or more per berth. In addition, while port emissions are reduced, it is displaced by emissions at the power plant and depending on the source of electricity can result in just minor overall emissions reductions.

To circumvent both of these potential disadvantages, it has been proposed that a cold-ironing power supply be based on a hydrogen-fueled proton exchange membrane (PEM) fuel cell that is mounted on a floating barge. The PEM fuel cell produces zero emissions, although the emissions required to generate the hydrogen must be considered. The barge provides an alternative to installation of electrical infrastructure and has the potential to be utilized more often because it can be moved from berth to berth as dictated by vessel schedules. It could also be moved to anchorage points to power vessels waiting for berths.

1.1 The Present Study

The DOE has asked Sandia National Laboratories to examine the feasibility of a hydrogen-fueled PEM fuel cell barge to provide electrical power to vessels at anchorage or at berth. The study includes both a determination of the technical feasibility of the idea as well as an analysis of potential deployment options. Sandia has previously examined the potential for hydrogen and fuel cells in aircraft [3-6]; construction equipment, electrical generators, and telecom backup [7]; man-portable power [8], and mobile lighting systems [9].

Other studies have examined cold-ironing for vessels. Theodoros examines the current state of cold-ironing (2012) and presents a calculation tool for evaluating cost-effectiveness [10]. Ericsson and Fazlagic looks at the feasibility and outlines a design for effective cold-ironing, focusing primarily on the electrical aspects [11]. Studies by Yorke Engineering [12] and Doves [13] examine the feasibility of cold-ironing at specific ports, the Port of San Diego and Port of Rotterdam, respectively. Unfortunately, none of these studies examine a hydrogen-fueled PEM fuel cell system or a barge-mounted system, and none of them examine the multitude of potential site deployments that is contained in the present study.

The ultimate goal of the DOE is industry-led commercialization of such a fuel cell system. Therefore it is imperative to understand the perspective of those that would build, deploy, and operate such systems, including current practices and needed areas of improvement, to determine if such a product could be commercially successful. To this end, we interviewed ports, barge and tug owners and operators, and shipping fleets to understand the issues within the maritime environment that relate to this system and to the use of cold-ironing in general. We also consulted the literature to provide the necessary background and details.

1.2 Content of the Report

After this introductory section, the issues of the maritime environment are explored in the Background provided in Chapter 2. These include a description of vessel types, ship- and shore-side infrastructure requirements for cold-ironing, an up-to-date summary of pertinent environmental regulations, and a synopsis of the stakeholders in the maritime environment. An understanding of these topics is necessary to determine the feasibility and suitability of a barge-mounted PEM fuel cell system. However, those already familiar with the port environment and cold-ironing for commercial vessels will likely be able to skip this chapter without detriment.

Chapter 3 describes the concept of the PEM fuel cell barge and evaluates several design and deployment options. Chapter 4 presents an assessment of various sites including some that do not require a barge solution but may still benefit from a hydrogen-fueled PEM system for vessel power. The conclusions of the study are given in Chapter 5.

2 BACKGROUND: ISSUES IN THE MARITIME SETTING

Deployment of fuel cells at or around ports is affected by issues that are unique to the maritime setting. They include vessel types and frequency, environmental regulations, infrastructure requirements, safety rules, operator needs, and requirements imposed by surrounding operators and equipment owners. In principal these are the same issues that would be encountered in deploying a fuel cell at a truck stop to supply diesel trucks with electrical power for hotel loads when parked, but the details can be vastly different. In this chapter we examine the details of each of these issues that are particular to the maritime setting. To provide the widest usefulness of this report, it is assumed the reader has little familiarity with the maritime shipping environment.

2.1 Vessel and Fleets

Most of the information in this section comes from the *2011 Puget Sound Maritime Air Emissions Inventory* [14] unless otherwise noted. There are multiple numbers given for auxiliary engine power in this report, and the author has stated that the numbers given for “Hotelling” load in Table 3.20 (for OGVs) are based on data from boarding actual vessels, and the numbers in Table 4.2 for harbor craft, are the best numbers to use for the purposes of this study [15]. The Puget Sound data is considered widely applicable to other ports because that geographic area contains a wide variety of port sizes and facilities.

A port hosts many types of vessels that could be candidates for cold ironing. Broadly, they can be divided into Ocean Going Vessels (OGV) and Harbor Craft. Understandably, OGVs are usually larger vessels with higher shore-power requirements than harbor craft.

OGVs are typically those that carry goods or people between different ports. The most common ones include:

- Roll-on/Roll-off (“RoRo”) carrier, including auto carrier
- Containership
- Refrigerated vessel (“Reefer”)
- Tanker
- Bulk carrier
- Cruise
- Tug-barge

Harbor craft are those that spend the majority of their time within the port and include:

- Tug
- Commercial fishing vessel
- Crew boat
- Ferry vessel
- Excursion vessel
- Government vessel
- Work boat

In this section we describe the attributes relevant to shore power of the OGV types and the harbor craft. In general, the important aspects to be focused upon are the electrical power required while in port, the duration of the port visit, and the frequency of an individual vessel's visit. The electrical power will determine the size of the shore power generator, the duration of stay will determine the amount of energy required for a stand-alone shore power system, and the frequency of visits will determine the economic feasibility of a vessel retrofit. Therefore, these are the three most important factors in determining the technical and economic feasibility of shore power for each vessel type.

In the sections that follow the three important characteristics for each vessel type are summarized, followed by a brief description. The first numbers given for "Auxiliary Engine Power – Hotel Load" are taken from the Puget Sound report, with data from other sources following. The "Visit Duration" is taken from various referenced sources. The first number given for "Single Vessel Visits Frequency" is an average calculated from the Puget Sound data, with data from other sources following.

2.1.1 Auto Carrier and RoRo Carrier

Figure 2-1: The auto carrier *Liberty Ace* (IMO 9293650), 19,106 DWT, 656 ft. long [16], with a capacity of approximately 6,400 average-sized cars. The asymmetric stern and ramp for loading/discharging vehicles is a typical feature of vehicle carriers.

Figure 2-2: The *Medcoa Lome* (IMO 8508369) RoRo carrier, 10,517 DWT and 486 ft. long [16].

Auxiliary Engine Power – Hotel Load: 890 kW (700 kW [17])
Visit Duration: About 1 day [18, 19]
Single Vessel Visit Frequency: 1.6/yr (auto), 11.9/yr (RoRo) (9/yr [18])

An auto carrier (example in Figure 2-1) is a type of RoRo carrier that can only handle automobiles, while the RoRo carrier (example in Figure 2-2) can handle large wheeled vehicles such as heavy construction equipment, buses, tractor trailers, and military equipment. Both types of vessels require forced air ventilation of auto exhaust and potential fuel fumes during loading and discharging which is the reason for the moderate power demand while at berth. In many cases, open decks on RoRo carriers allow for handling containers in addition to the vehicular cargo. Some RoRo ships are on regular rotations, meaning the same ship may visit a port frequently over the course of the year, but those are the exception. Most are dispatched according to commodity needs and thus may be infrequent callers.

2.1.2 Container

Figure 2-3: The container ship *Ever Elite* (IMO 9241281), 75,898 DWT, 981 ft. long, about 6,000 TEU [16].

Auxiliary Engine Power: 0.5 – 1.5 MW (1.5 – 2 MW [20-22], up to 6 MW for 8,000 TEU [19], 600 kW – 8.4 MW [18])
Visit Duration: 1-3 days (correlates with size) [19-21, 23]
Single Vessel Visit Frequency: 4.6/yr (up to 8.6 [23], up to 10 [18])

Container ships (example in Figure 2-3) carry most of the world's goods packaged in 20- or 40-foot steel containers. The ships vary widely in size with carrying capacity from 1,000 TEU (Twenty-foot Equivalent Unit) to over 15,000 TEUs. The main advantage of carrying goods in containers as opposed to bulk cargo is that the same amount of goods that could take more than a week to load/discharge as bulk can be loaded/discharged in a day or less when packed in containers [24]. Container ships also have the ability to supply electricity for refrigerated containers, with some predicting the eventual demise of the reefer ship as a result [17]. As can be seen in the data above, hotel load at berth can vary dramatically due to the number of refrigerated containers on-board [20, 21]. Most container ships are on regular, predictable schedules and it is not uncommon for the same ship to visit a port 8 – 10 times per year.

2.1.3 Reefer

Figure 2-4: The *Southern Harvest* (IMO 8916748) reefer, 8,946 DWT and 459 ft. long [16].

Auxiliary Engine Power: 900 kW (> 3 MW [17], 3.5 – 5.6 MW [18])
Visit Duration: 2-3 days [18]
Single Vessel Visit Frequency: 3.0/yr (up to 25 [18])

Refrigerated vessels (reefers) carry cargo that must be refrigerated to avoid spoilage, such as fruit and meat. They are usually on the small side, smaller than 1,000 TEU container ships. An example is shown in Figure 2-4. Some ports, such as San Diego (CA) have reefers that make regular visits, but at most ports the service is intermittent.

2.1.4 Tanker

Figure 2-5: The crude oil tanker *Alaskan Navigator* (IMO 9244673), 193,048 DWT, 945 ft. long.

Auxiliary Engine Power: 550 – 800 kW (steam-powered pumps) (7.78 MW (electrical pumps) [25])
Visit Duration: 1-3 days [18]
Single Vessel Visit Frequency: 3.2/yr (up to 24 [18])

Tankers (example in Figure 2-5) are used to transport liquid products such as crude oil, refined petroleum, and chemicals. While tankers must run large pumps while at berth for discharging product, on the vast majority of tankers the pumps are steam-powered [15]. A few newer tankers, such as the Alaska-class tanker shown in the figure, use electrical power for these pumps and as can be seen from the electrical use data shown above this can increase the power required at berth by a factor of 10. Typically, tankers are on intermittent service as dictated by local commodity prices. In some cases, such as the BP terminal (berth 121, Terminal T) at the Port of Long Beach, the tankers have a regular, predictable schedule and numerous visits per year.

2.1.5 Bulk Carrier

Figure 2-6: The self-discharging dry-bulk vessel *CSL Cabo* (IMO 7117278), 13,364 DWT, 594 ft. long, discharging gypsum onto a barge alongside [26].

Figure 2-7: The break-bulk carrier *Thor Friendship* (IMO 9424601), 54,123 DWT, 623 ft. long [16].

Auxiliary Engine Power: 150 – 300 kW
Visit Duration: 2 days [18]
Single Vessel Visit Frequency: 1.2/yr (up to 21 [18])

Bulk carriers include both dry bulk and break-bulk. Dry bulk refers to goods such as grains, granulated food, minerals, and coal and can be loaded/discharged with conveyer belts. Break-bulk refers to large, discrete items such as machinery, scrap metal, timber, and also to palletized goods – a kind of "catch-all" vessel when the cargo can't be transported by container, RoRo, or other means and does not need to be refrigerated. Bulk carriers are usually charter vessels that are only scheduled when needed; hence, it is rare for the same bulk vessel to visit a port more than a once per year [19]. It is also more common for bulk carriers to utilize anchorages since their unpredictable schedules make it more likely to arrive when the berth is occupied by another vessel, grain silos are not yet filled, and/or rain prevents loading/discharging [19, 22]. Most break-bulk vessels have on-board cranes or and some dry bulk vessels have conveyers to self-load/discharge. It is expected that the electrical load required during loading/discharging will be higher than indicated above.

2.1.6 Cruise

Figure 2-8: The *Carnival Inspiration* (IMO 9087489) cruise ship, 2,972 passengers and crew, 856 ft. long [16].

Auxiliary Engine Power: 3.5-11 MW (14 MW design [22], 5-11 MW [17])
Visit Duration: 10 hr [17], 12 hr [18]
Single Vessel Visit Frequency: 10.4/yr (up to 22 [27], up to 100 [28])

Cruise ships have the highest power demands of any vessel and are usually at berth for the shortest time. They are also usually frequent callers on precise schedules. Vessels that have short cruises, such as the Carnival Inspiration (Figure 2-8) which sails between Long Beach, CA and Ensenada, Mexico, every 3-4 days will visit the Port about 100 times per year. That would be about the upper limit on frequency of visits, but they are still overall the most frequent visitors of the ocean-going vessels. All of these factors make them prime targets for grid-based cold ironing.

2.1.7 Tug-Barge

Figure 2-9: The articulated tug-barge *Coastal Reliance* (IMO 9271119) [16]. The V-shaped notch where the tug joins with the barge can be seen just in front of the white wheelhouse at the stern.

Auxiliary Engine Power: 115 kW
Visit Duration: Not Available
Single Vessel Visit Frequency: 14.9/yr

Tug-barges are vessels where a barge is specially designed with a notch at the stern to accept a specially-designed tug to act as a pusher. This gives some flexibility to the owner/operators of such systems to utilize more of their tug investment, i.e., to use one tug to service multiple barges. Integrated tug-barges (ITB) are rigidly connected to the barge and the disadvantages of this design have led to them falling out of favor. Articulated tug-barges (AT/B) have a more flexible connection between the barge and the tug and are the preferred embodiment of tug-barges today. Tug-barges are typically used for shorter-haul transportation and thus have the potential to frequently visit the same port.

2.1.8 Harbor Craft

Figure 2-10: The tug *Mamo* (IMO 9145190), 3,400 hp, 78 ft. long [16, 29].

Figure 2-11: The U.S. Coast Guard *Swordfish*, 87 ft. patrol boat [30].

Figure 2-12: The commercial fishing trawler *Arctic Storm* (IMO 8720113), 2,638 DWT, 334 ft. long [16].

Figure 2-13: The Training Ship *Golden Bear* (IMO 8834407), 6,974 DWT, 500 ft. long [31].

Auxiliary Engine Power: 7.5 kW – 410 kW (tugs); 75 kW – 670 kW (fishing); (192 kW – 384 kW (fishing trawlers) [22], 700 kW – 1.2 MW (training ship) [32])
Visit Duration: hours to months [22, 33]
Single Vessel Visit Frequency: 1-2 times per year (trawlers) to several times a day (tugs, patrol boats).

Harbor vessels are typically smaller than OGVs and spend more time at the same port – either because of frequent visits (tugs, government vessels) or because of extended stays between voyages at sea (trawlers, research vessels, training ships). The power requirements are typically smaller than OGVs because they are smaller vessels, but still can reach more than a megawatt for the larger vessels. The power may be needed for a variety of uses, from lighting and communications equipment to refrigerated holds.

2.2 Infrastructure Requirements

As mentioned in the introduction, cold ironing is widespread in the U.S. Navy, used somewhat for smaller craft, sparingly for cruise ships, and only in sporadic instances for ocean going shipping. The practice requires two sets of infrastructure: the first is the ability for the ship to receive electrical power from an external source, and the second is the external source itself. Furthermore, the two sets of infrastructure must be compatible, both in physical connections and in capabilities: the source of power should be sized appropriately depending on the need of the vessel that will be using it. Both sets of infrastructure are examined in this section.

2.2.1 Vessel Infrastructure

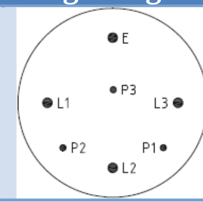
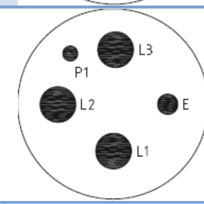
There are two main disadvantages to making a vessel ready to accept shore power. The first is the cost: retrofitting an existing ocean-going shipping vessel to accept shore power is estimated to cost between $300,000 and $750,000, with earlier retrofits being as much as $1.5M [17]. Some shipping lines are having new vessels built with the capability, and while this is assumed to be more cost effective, it will still add cost to the vessel.

The second disadvantage is fleet flexibility. To realize a return on their investment, shippers prefer that an equipped vessel be utilized often, and that any retrofits are done on newer vessels with longer useful lifetimes remaining [34]. The implications are that shippers will dedicate equipped vessels to the ports which are equipped to provide shore power and will relegate older vessels to routes which do not. Because of the limited availability of shore power at ports, this constrains the routes on which certain vessels can be used. Shipping companies would rather assign their varying vessels based on cargo need which is constantly in flux, depending on factors such as the local economy and the commodity being shipped [20, 21].

Until recently, a third disadvantage to making a vessel shore power ready was the lack of standard connection specifications. Various vessel voltages and frequencies, and vendor- and site-specific cable connector designs meant that a vessel was more likely to be tied to a single port than to be able to take advantage of other ports with shore power available. However, a recent standard has been developed, in large part due to the work at the Ports of Los Angeles and Long Beach and subsequently in the rest of California, which should resolve this issue. IEC/ISO/IEEE 80005-1 [35] outlines specific plug designs, voltages, power ratings, circuit designs, etc. of shore power installations for several vessel classes, with selected information summarized in Table 2-1 to demonstrate the level of detail included. While use of this standard is not yet mandated in most areas, it contains an ominous caution:

> *NOTE: If an alternative to the standard arrangement of cable and HV plug and socket-outlets is designed, it is likely that the installation will not be able to connect to a compliant shore supply/ship without significant additional equipment and modification.*

Table 2-1: Selected specification information from IEC/ISO/IEEE 80005-1 [35].

Vessel Type	Voltage	Design Power	Cables	Plug Design*
RoRo	11 kV (6.6 kV for regional waterborne transportation services (i.e., ferry))	6.5 MVA	1	
Cruise	11 kV or 6.6 kV	16 MVA, 20 MVA is recommended where practical.	As needed (4 typical)	
Container	6.6 kV	7.5 MVA	2	Same as RoRo
LNG Carrier	6.6 kV	10.7 MVA	"Generally 3"	Same as RoRo
Tanker	6.6 kV	3.6 MVA per cable	2 cable minimum, 3 may be required	Same as RoRo

*Only the plug (shore-side) is shown here. The socket (ship-side) is a mirror image.

The location of the sockets on the vessel is also an issue. IEC/ISO/IEEE 80005-1 specifies the location of the vessel connection only for the LNG Carrier vessel type, so for others it is at the discretion of the vessel owner/operator and only specified to be "as short as possible." If a vessel is retrofitted so that the connection is, for example, at midship on the starboard side, and it arrives at a berth where it would naturally be oriented with its port side against the dock (where the shore power supply is located), then if it cannot be turned around it may not be able to connect. While turning the vessel is usually possible, it would likely delay the vessel's arrival or departure potentially incurring extra cost. If the vessel connection were at the stern and the cables at midship (or vice-versa), the vessel could potentially orient either way as long as the cables were long enough. For reference, a Post Panamax container ship (the largest expected) is approximately 1,200 feet long, making a cable run between the stern and midship over 600 feet. This additional cable length compared to the matched location design would add capital cost and potentially increased connection complexity and time. In practice, shore power installations typically have several connection points along the dock (see Figure 2-17), thus placing the vessel connection at the bow or stern would allow for maximum flexibility with minimum cable length (see Figure 2-14 through Figure 2-16 for examples).

Figure 2-14: Hapag-Lloyd's Dallas Express using shore power at the Port of Oakland. The ship-side connectors and cables are housed in a special shipping container at the stern on the starboard side (white container at the bottom corner of the container stack). Left-side picture from [36], right side picture from [37].

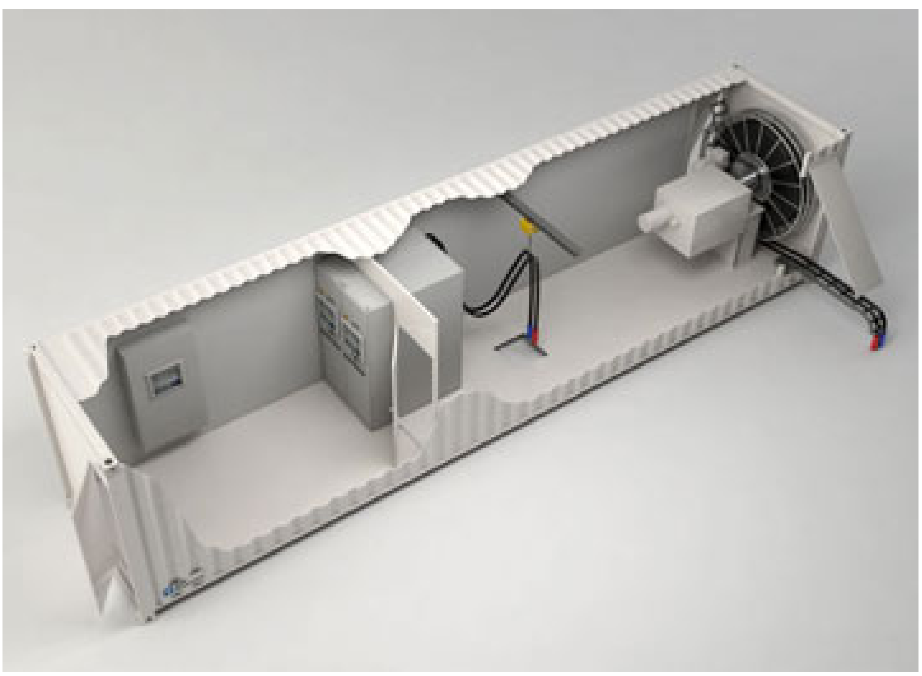


Figure 2-15: The custom shipping container housing the shore power connection on the Hapag-Lloyd's Dallas Express, developed jointly with SAM Electronics [36].

Figure 2-16: The ship-side shore power connection in a specialized shipping container mounted at the stern of one of "K" Line's five retrofitted container vessels [38].

2.2.2 Shore-side Infrastructure

Installation of shore power equipment for a berth is expensive. It requires high voltage distribution equipment to connect to the grid, dock modification for conduits and outlets, and cable and plug hardware and handling equipment. The design of the shore-side system is addressed in IEC/ISO/IEEE 80005-1. Figure 2-17 shows a schematic for shore power installation at berth 232 on Pier G at the Port of Long Beach, Figure 2-18 shows some installation work at the Port of Oakland, and Figure 2-19 and Figure 2-20 show some of the infrastructure at the Port of Seattle and Port of Los Angeles cruise terminals, respectively.

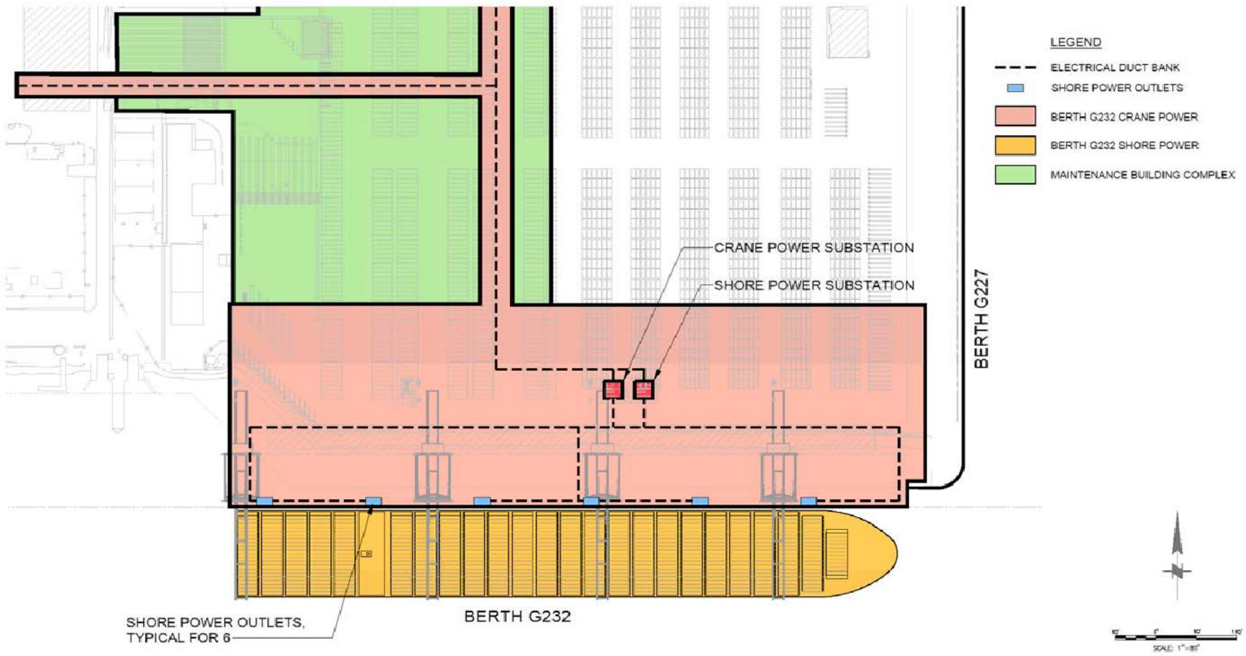


Figure 2-17: Installation schematic for shore power at berth 232 of pier G at the Port of Long Beach [38].

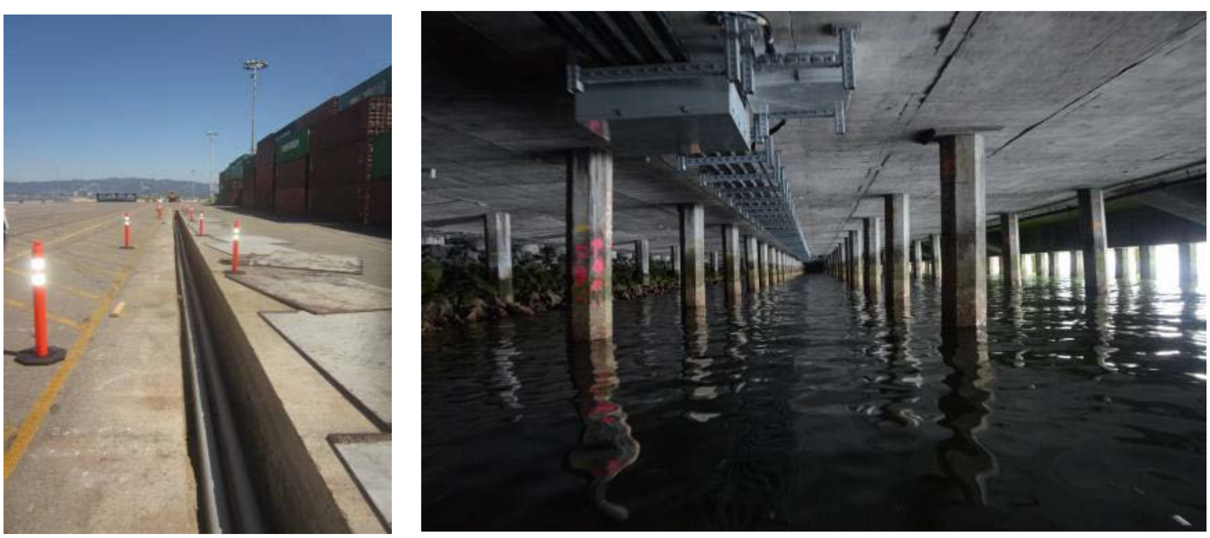


Figure 2-18: Pictures showing some shore power retrofit work at the Port of Oakland [39].

Figure 2-19: Shore power infrastructure for the cruise terminal at Pier 91, Port of Seattle. In this picture, the cable handling system is shown its storage position. During cruise season (May – September) it is moved to the edge of the dock.

Figure 2-20: An "AMP Mobile" unit at the Port of Los Angeles' World Cruise Center. The Port has three units and is capable of supplying shore power to two cruise ships simultaneously with up to 20 MW of power each [40].

Cost estimates for grid-supplied shore power range from $4M to $17.5M per berth on average. Construction time varies depending on the scope with the minimum time being just over a year, but longer when pre-construction planning and design is also considered. Thus, installing grid-supplied shore power infrastructure is a significant investment and commitment for a port. In California, the six ports affected by the upcoming shore power regulation (see Section 2.3.3) are spending most of their capital budgets on building the required infrastructure [34].

Some examples may be useful to understand the range of costs given above:

- The Port of Oakland (CA) is installing shore power at 11 berths on six terminals at an estimated cost to the Port of approximately $70M [37].
- At the Port of Hueneme (CA), the cost is estimated to be $11.4M to retrofit three adjacent berths at one wharf [41, 42]. The cost of the project is broken down into components: Design and Engineering ($510,000), Equipment Procurement ($5.38M), Construction Management ($754,000), Program Management ($130,000), and Construction ($4.67M) [41]. The cost is causing cash-flow problems for this smaller port and the California governor had to act to change the funding guidelines so the project could go forward [43].
- At the Port of Seattle (WA), the cost of retrofitting a single cruise berth at Pier 67 was estimated to be $15M, partially due to required upgrades of the local utility's infrastructure, and at their Harbor Island terminal shore power is not possible without a utility-side upgrade which the Port has been asked to fund [22].
- It cost the Port of Los Angeles (CA) $10M to retrofit the World Cruise Center for shore power on a moveable system that can supply two cruise ships at the same time at up to 20 MW per ship (see Figure 2-20) [40, 44]. POLA estimates that total infrastructure cost needed to outfit 24 berths will be over $85M [45].
- The Port of Long Beach (CA) spent $8M to retrofit berth 232 on Pier G [46], $17.5M for berth 121 on Pier T [47], and $10M for berths 60 and 62 on Pier C (of which $6.5M was for actual procurement and construction) [48]. POLB estimates that total infrastructure cost needed to outfit 22-24 berths will be nearly $214M [45]. The reason for the difference between this and the POLA estimate is that POLA already had the main electrical lines feeding into the port, while POLB needs to construct a new 6.6 kV transmission line from a grid point several miles away to feed into the port.

2.3 Regulations

This section describes the regulations that affect the use of cold-ironing in the locales that are target of this study, the U.S. West Coast and Hawaii. It is divided into four sections, the first describes the U.S. Environmental Protection Agency (EPA) regulation which affects all vessels visiting or transiting U.S. ports or its waters, the second describes the International Maritime Organization regulation which is adopted by the EPA regulation, the third the California Air Resources Board regulation which affects six California ports, and the fourth section describes regulations or guidelines established at individual ports.

Note: The summaries of regulations given here are generalizations that focus on the parts that affect the common users and do not capture the many nuances and exceptions contained in each regulation. In addition, because the predominant concern among all those interviewed was on the required fuel types that result from these regulations, which are governed by sulfur content, the other aspects of the regulations such as engine design and NOx emissions are not examined here in any detail. For all of these details it is recommended to consult the original sources.

2.3.1 U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency (EPA) regulates emissions from maritime sources through its non-road engines category. There are two main components to the EPA regulation and can be summarized as:

1. "Diesel Boats and Ships" [49]
   a. Applies to:
      i. Engines *not* for large ship propulsion (displacement < 30 L (1,831 in^3)/cylinder)
         1. Propulsion for small vessels such as tugs, fishing boats, towboats.
         2. Engines for auxiliary engines on nearly all vessel sizes.
      ii. U.S.-flagged vessels only
   b. Requires:
      i. Use of Ultra Low Sulfur Diesel (ULSD)
         1. 15 ppm sulfur content.
         2. Same as the "red-dye" ULSD diesel already used for off-road land-based vehicles and equipment in the U.S.
   c. Takes effect: July, 2012
2. "Ocean Vessels and Large Ships" [50]
   a. Applies to:
      i. Engines for large ship propulsion (displacement > 30 L (1,831 in^3)/cylinder) for both U.S.- and internationally-flagged vessels.
      ii. Smaller engines on internationally-flagged vessels.
   b. Requires:
      i. Refers to the International Maritime Organization regulation (see Section 2.3.2 for details).
   c. Takes effect: Staged - see Table 2-2.

The previous sulfur limit was 500 ppm starting in 2007, and prior to that was not regulated by the EPA and could have been a fuel oil or blend. As can be seen in Table 2-6 in Section 2.4, the cost difference between low and the high sulfur fuels can be significant and the clean fuel regulations have increased the operating costs for the maritime companies. For example, at Hawaiian Tug & Barge / Young Brothers Ltd., fuel is currently the single most expensive company cost [51]. Totem Ocean Trailer Express (TOTE) which operates between Tacoma (WA) and Anchorage (AK), is in the process of converting all of their ships to liquefied natural gas (LNG) [19].

2.3.2 International Maritime Organization

In 2010, the U.S. Environmental Protection Agency (EPA) adopted the International Maritime Organization (IMO) standards for fuels produced and distributed in the U.S., and designated specific portions of the U.S. waters as the North American Emissions Control Area (ECA) [52]. The regulation mandates the sulfur content of fuel burned and the allowed amounts of NOx emissions for a vessel operating within the ECA. Figure 2-21 shows the location of the North American ECA; it is approximately 200 nm within the shoreline. Table 2-2 shows the sulfur and

NOx requirements for ships operating within the ECA, with the sulfur requirements graphically depicted in Figure 2-22.

Figure 2-21: The boundary of the North American Emissions Control Area is shown by the green line. It is approximately the portion of the sea within 200 nm of shore. Within this area, ships must burn low sulfur fuel and limit NO_x emissions to comply with the limits shown in Table 2-2 [52].

Table 2-2: Sulfur and NOx limits within the IMO ECA [53]. A graphical depiction is shown in Figure 2-22.

Place	Year	Max Fuel Sulfur	NOx
Emission Control Area	Prior to July 2010	15,000 ppm (1.5%)	
	2010	10,000 ppm (1.0%)	
	2015	1,000 ppm (0.1%)	
	2016		Tier III (Aftertreatment-forcing)
Global	Prior to January 2011		Tier I (Engine-based controls)
	2011		Tier II (Engine-based controls)
	Prior to January 2012	45,000 ppm (4.5%)	
	2012	35,000 ppm (3.5%)	
	2020[a]	5,000 ppm (0.5%)	

[a] Subject to fuel availability study in 2018; may be extended to 2025.

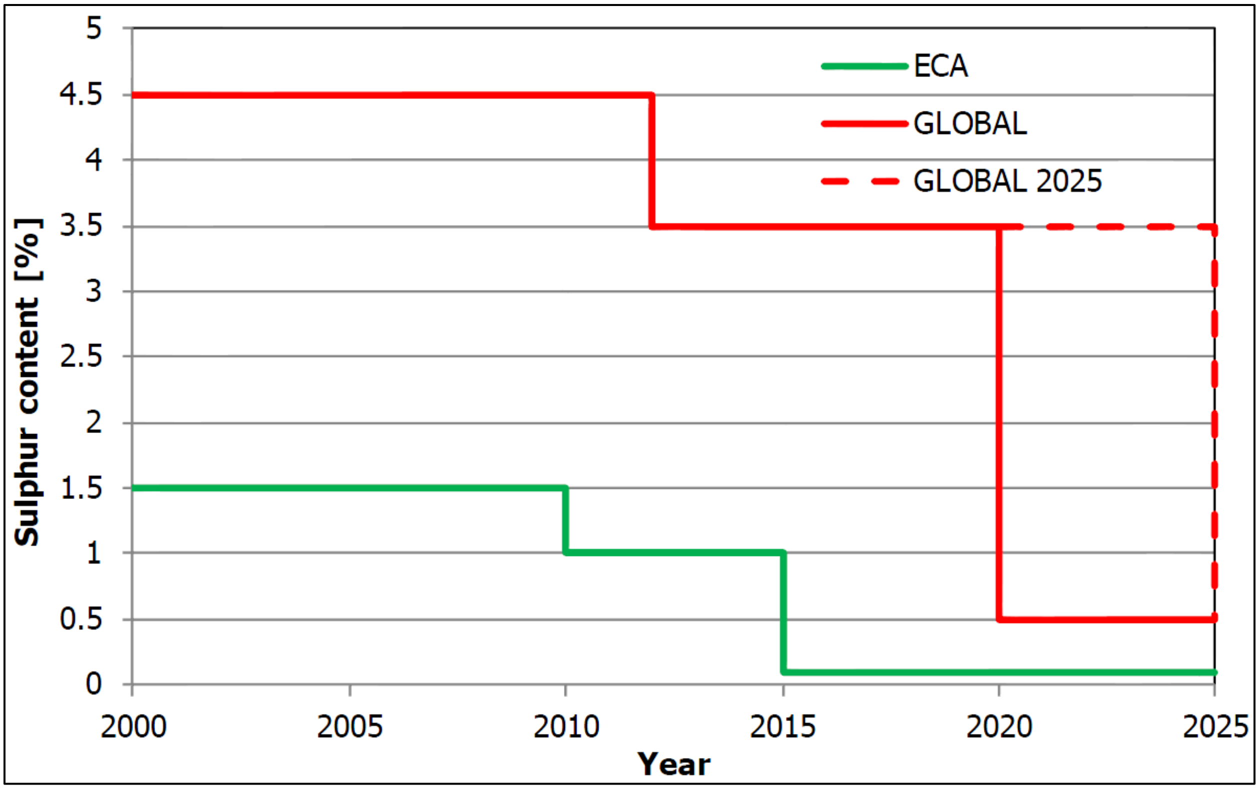


Figure 2-22: Graphical depiction of maximum sulfur content in marine fuels dictated by the IMO ECA [54].

The shipping industry is concerned more about the portion of the regulation about sulfur content. As sulfur is reduced, the cost of fuel increases. Table 2-6 of Section 2.4 shows the common maritime fuels with sulfur content and recent cost - it is clear that lower sulfur fuels cost more. There is an additional concern about a fuel cost spike for MGO when the ECA limit is lowered from 1.0% to 0.1% in 2015, because this will be the fuel needed to reach this level.

Vessels visiting ports within the Puget Sound (Tacoma, Seattle, and others) are additionally affected because of the additional distance needed to travel from the western entrance of the Strait of Juan de Fuca to the port – for Tacoma this adds an extra 120 nm to the 200 nm that the ECA already encompasses [53].

The new ECA rule also affects the attitude towards cold ironing while in port for two reasons. First, the economics of running auxiliary generators suddenly changes when vessels are required to use MGO instead of IFO (from Table 2-6 MGO can be seen to cost about 50% more than IFO). For vessels that are frequent visitors to ECA-covered ports, there can be a cost savings by plugging into the grid – this is explained more in Section 2.4. Second, the ECA rules apply on a fleet basis, not a ship-by-ship basis, so that a vessel that cold-irons while in port instead of burning MGO will receive additional “credit” that can be applied to that vessel’s fleet [22]. The importance of this second reason increases with the cleanliness of the source that provides the shore power. For example, with “clean” grids typical to the Pacific Northwest the credit received would be more than with “dirty” grids provided by some California utilities. Power provided by renewable energy would give the largest benefit possible.

A last implication of the ECA rule is the timing. Ships must begin to comply by Jan. 1, 2015, which means that they must have solutions decided upon well before this date. For a PEM fuel cell barge system or other alternative energy solution to be considered, there must be a be a working example ahead of this time. This means that the window of opportunity for alternatives is open now but may not stay open after another year or so.

2.3.3 California Air Resources Board Shore Power Regulation

(Unless otherwise noted, all information in this section is from Refs. [55-57]) In 2007, the California Air Resources Board (CARB) approved a regulation that requires container ships, reefers, and cruise ships to either connect to shore power while at berth in six California ports, or to use alternative emissions control strategies that achieve equivalent emissions reductions. The shore power requirement takes effect Jan. 1, 2014. The regulation was crafted to address the most impactful polluters – ships that have large power requirements and are frequent visitors to California [17]. It is written to regulate on a fleet-wide basis rather than a ship-by-ship basis, and exempts vessels that belong to fleets which have less than an aggregate of 25 total visits per year (container and reefers) or 5 total visits per year (cruise). The ports affected were chosen based on the ones that have vessel traffic which meets these requirements and are:

- Port of Long Beach and Port of Los Angeles (considered one port)
- Port of Oakland
- Port of Hueneme
- Port of San Diego
- Port of San Francisco

Table 2-3 shows the graduated compliance minimums for the fleet on a year-by-year basis. Initially, 50% of visits must be shore powered, and this will rise to 80% by 2020 and thereafter. California will provide funding for shore power projects through an application procedure using Proposition 1B funds; any port using these funds is subject to 10% higher compliance minimums [58]. The implication of the fleet-wide application is that not all vessels within a fleet are required to use shore power, as long as another ship can utilize shore power on additional visits to make up for it. There is an allowance for running auxiliary engines at berth in case of equipment breakdown or emergencies, and for a total of 3 hours to allow for connecting and disconnecting shore power.

Table 2-3: California Air Resources Board Shore Power Regulation Compliance Schedule.

	Visits using Shore Power	
Period	**Regulation**	**With Prop. 1B Funding[a]**
2014-2016	50%	60%
2017-2019	70%	80%
2020+	80%	90%

[a] Proposition 1B uses an averaging formula different than that in the regulation, but the effect is similar.

Auxiliary engines that use CNG or LNG are excluded from the regulation. Acceptable sources of electrical power are the grid and distributed generation, as long as the generation of that power meets the emissions standards shown in Table 2-4.

Table 2-4: Emissions standards for electrical power generation that will be used to meet the CARB shore power regulation.

Emission Type	Upper Limit
NO_x	0.03 g/kW-hr
Particulate Matter	That from combustion of natural gas with a fuel sulfur content of no more than 1 grain per 100 SCF.
CO_2	500 g/kW-hr
Ammonia	5 ppm_{dv}, if SCR is used

At the time of its adoption shore power for commercial OGVs was only available at a few berths in the state and few ships were outfitted to accept it. So at a minimum, it has forced the six California ports to install infrastructure needed to provide affected vessels with shore power, and it forces fleets to install the equipment on their vessels to accept shore power. It has also indirectly led to the adoption of the shore power standard, IEC/ISO/IEEE 80005-1, to make the developed infrastructure compatible between different vessels and ports. The details of both of these infrastructure requirements and in turn their impacts beyond the shores of California are described previously in Section 2.2. In particular, the commitment of the ports and fleets to have an electrical infrastructure installed in time to meet the 1/1/2014 deadline has, in absence of other viable options, committed ports to installing grid-based electrical infrastructure. Therefore, alternatives such as distributed generation at the dock or on the water is not likely to be needed at these six ports anymore except in special circumstances such as during construction [20, 21]. Economically, any solution other than grid-based power at these ports would have to compete with the grid-delivered electrical rate, as described in Section 2.4.

2.3.4 Port-by-Port Initiatives

Many ports have their own incentives to reduce emissions of ships that operate in their vicinity. This section describes some of them on a port-by-port basis.

2.3.4.1 Long Beach and Los Angeles

The ports of Long Beach and Los Angeles voluntarily created and approved the San Pedro Bay Ports Clean Air Action Plan (CAAP) [45]. Table 2-5 summarizes the emissions reduction goals. The measures the ports will utilize to meet these goals apply to many port activities including:

- Heavy-duty vehicles
- Ocean-going vessels
- Cargo handling equipment
- Harbor craft
- Railroad locomotives
- Construction
- Container handling
- Operational efficiencies

The control measure that affects shore power in particular is OGV2: Reduction of At-Berth OGV Emissions. Through this measure, the two ports are committed to providing shore power infrastructure to all container terminals, cruise terminal (POLA only), and selected liquid bulk terminals. The goal is for 100% of container calls to utilize shore power while at berth, in excess of that required by the CARB regulation. Part of the way they are implementing this is to incorporate into terminal operator leases as they are renewed the requirement to have 100% shore power capability at container terminals. Because both ports have received Proposition 1B funding, they are subject to the higher compliance minimums shown in Table 2-3 .

Table 2-5: Emissions reduction targets in the San Pedro Bay Ports Clean Air Action Plan [45].

	Emissions Reduction, Relative to 2005 Levels, By Target Year	
Pollutant	**2014**	**2023**
NOx	22%	59%
SOx	93%	93%
DPM[a]	72%	77%

[a] Diesel particulate matter

2.3.4.2 Oakland

The Port of Oakland does not have any additional requirements or incentives beyond the CARB regulation. Because they receive Proposition 1B funding for the shore power retrofits, they are subject to the 10% higher requirements for shore-powered visits as explained in Section 2.3.3. The combination of these factors means that, realistically, all regulated OGVs will be plugging in to shore power by 2020. The Port has already noticed a large decrease in emissions due to the low-sulfur fuel requirements and believe that this combined with CARB regulations will meet objectives to clean up OGV emissions. [34]

2.3.4.3 Portland

Regarding CO_2, the Port of Portland has the objective to reduce emissions by 15% by 2020, the state of Oregon has mandated that all state agencies account for 10% less emissions by 2020, and the state has also required that utilities reduce the CO_2 generated in producing grid power to decrease by 25% in 2025 (all compared to 1990 levels) [59]. The Port has an additional objective to reduce PM from port-controlled diesel engines by 25% by 2015 compared to 2000 levels [60]. However, none of these initiatives directly affect the use of shore power by visiting vessels. In fact, because the Port consists of both aviation and maritime operations, the port goals could conceivably be met without affecting any maritime activities. Thus any incentive to install or use shore power at Portland would have to be primarily based on economics [59].

2.3.4.4 Tacoma

The Port of Tacoma is part of the Northwest Ports Clean Air Strategy [61] along with the Port of Seattle and Port Metro Vancouver (B.C., Canada). Similar to CAAP at the Ports of Los Angeles and Long Beach, it is a multi-faceted strategy affecting many aspects of port operations. For OGVs it calls for, by 2010, to reach the equivalent PM reduction of using distillate fuels with a maximum sulfur content of 0.5% for all hotelling auxiliary engine operation, and to use a fuel with maximum 1.5% sulfur or use equivalent PM reduction measures for all hotelling with main or diesel electric engine operation. By 2015, the Strategy calls for compliance with all measures of the IMO regulation in terms of emissions reduction that would result from the use of 0.1% sulfur fuels and those related to NOx (see Section 2.3.2). To reach these voluntary goals, the three ports are (a) making available cleaner fuels at berth or at anchor and (b) using shore power where currently available. By 2015, the goals are to standardize fuels and technology identified by the IMO, to install alternative ship-side or shore-side power at berth for equipped vessels, to implement additional emissions reduction options while at-dock or during voyage, including electrification potentially with portable power units, and to support pilot projects that support early implementation of technologies that will help meet the goals.

Because the goals in the Northwest Ports Clean Air Strategy are voluntary, any solution addressing them would have to be economically viable. While the Port of Tacoma encourages its fleets and terminal operators to assist in compliance, it does not offer any tangible incentives [19].

2.3.4.5 Seattle

The Port of Seattle is a part of the Northwest Ports Clean Air Strategy, which is described in the previous section about the Port of Tacoma. It has implemented a cash-incentive program called At-Berth Clean (ABC) Fuels, which provides tiered incentives that average $2,250 to OGVs that use low-sulfur (< 0.5%) fuels in auxiliary engines for each call.

2.3.4.6 Hawaii

Port Hawaii does not have any additional incentives or regulations that affect the use of shore power or clean fuels while at berth in any of its 10 harbors throughout the state. However, with the exception of the Barbers Point harbor which is primarily petroleum imports, vessel traffic at Hawaiian ports is primarily domestic (87% at Honolulu according to [62]). As explained in Section 2.3.1, this means that vessels are using ULSD in their shore power auxiliary engines, greatly reducing air pollution, and the smaller inter-island transports are likely also to be using ULSD due to their smaller engine sizes, such as the tugs used by Hawaiian Tug & Barge / Young Brothers Ltd. International ships within 200 nm of shore are required to use MGO starting in January, 2015 which will further reduce pollution from those sources.

2.4 Fuel Cost

There are multiple options for providing the electrical needs of ships at berth and the economics of any solution must be considered. The options considered here are:

1. Ship auxiliary engine with bunker oil (IFO 180 or 380 HS)
2. Ship auxiliary engine with low-sulfur bunker oil (IFO 180 or 380 LS)
3. Ship auxiliary engine with low-sulfur distillate fuel (MGO)
4. Shore power via electrical grid
5. Shore power via hydrogen fuel cell

Other possible options include ship auxiliary engines that use CNG or LNG, and shore power via fossil-fueled distributed generation such as diesel generators. The fuel types and costs for the first three options are shown in Table 2-6.

Table 2-6: The most common maritime fuel types with sulfur content and cost.

Common Fuel Name	Type	Max. Sulfur (%)[a]	Cost ($/kg) Gibraltar[b]	Cost ($/kg) Los Angeles[b]
IFO 380 HS	Residual/distillate blend	< 3.5	0.60	0.62
IFO 180 HS	Residual/distillate blend	< 3.5	0.64	0.66
IFO 380 LS	Residual/distillate blend	< 1.5	0.65	0.72
MDO	Distillate	1.0 – 1.5	0.95	N/A
MGO	Distillate	0.1 – 1.0	0.97	1.02
ULSD	Distillate	0.0015 (15 ppm)	1.10[c]	

[a] Values shown are what is sold today, sulfur levels change with changing regulations, in some locations the same-named fuel will have a different sulfur level. [b] Costs are bulk costs at the terminal on Dec. 10, 2012 from [63]. [c] ULSD cost is more volatile and varies more by region probably because it is also used by land-based off-road vehicles. The value here is an approximation based on various sources and corresponds to about $3.50/gallon.

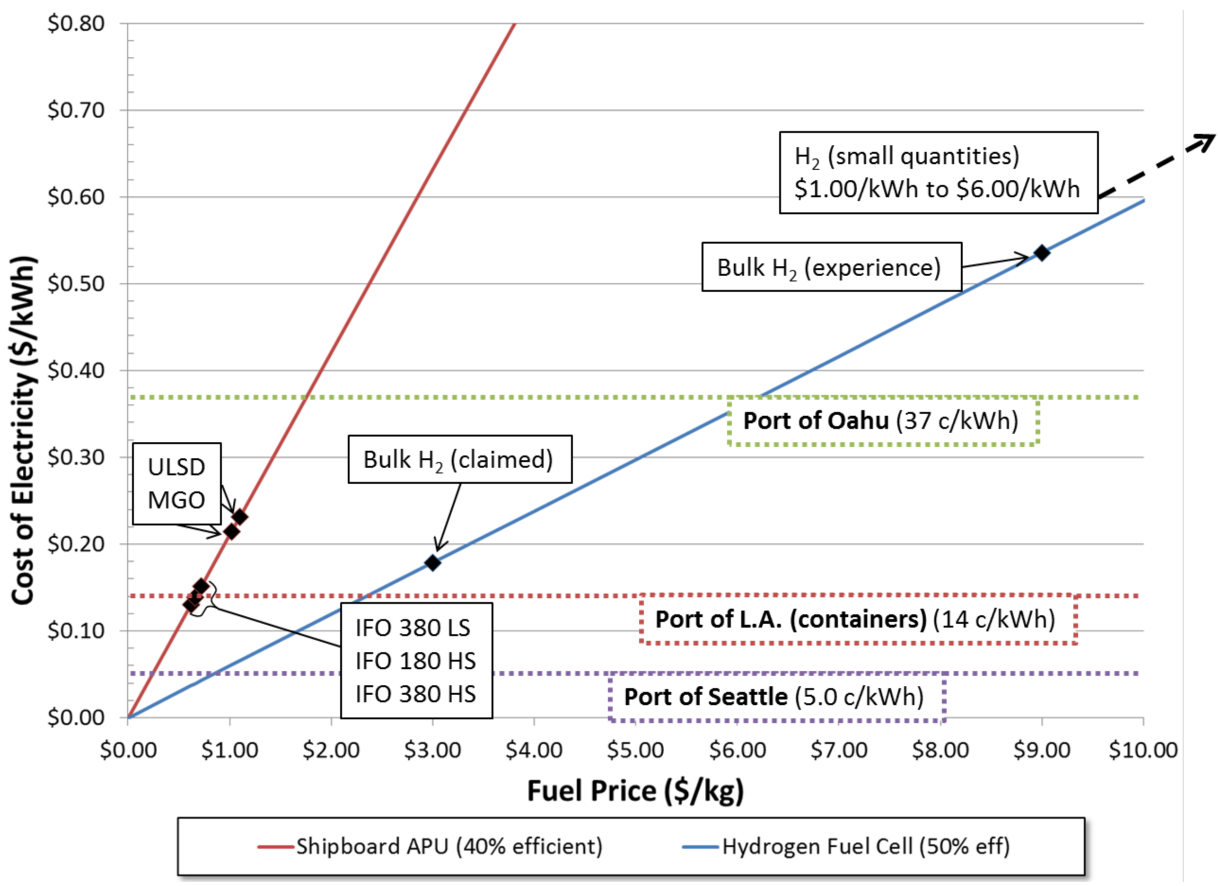


Figure 2-23: Fuel-only cost of electricity comparison for maritime fuels and hydrogen, with grid-delivered electricity rates shown for reference. See text for detailed description.

Figure 2-23 shows a comparison of the cost of electricity when generated using ship-based auxiliary engines and maritime fuels, using fuel cells and hydrogen, and as-delivered by the electrical grid at three representative ports. Assumptions behind this figure are as follows:

- Shipboard APU efficiency estimated from data from Caterpillar and Wartsila for their marine gensets from 600 kW to 4 MW (LHV basis).
- Fuel cell efficiency based on the authors' experience with PEM fuel cells (LHV basis).
- Fuel prices from Table 2-6. The heating values are taken to be approximately the same at 42,780 kJ/kg.
- Port electricity prices are from port sources [20, 22, 64] and can be taken as representative for the respective regions with reasonable accuracy. The Port of Portland's maritime facilities pay $0.083/kWh [59].
- Some utilities charge based on peak demand to ensure capacity is available when needed [17, 65]. This means that if shore power is installed but not frequently utilized, the average electrical cost to the ship would be higher than the rates shown in the figure.
- Cost estimates of hydrogen vary widely so those data points given should be considered approximations at best. The "claimed" bulk H_2 price as advertised by Air Products [66] and the "experience" bulk H_2 price is based on the authors' experience, assuming on-site generation.
- The final cost of electricity generated by the ship or by the fuel cell will be higher due to capital cost amortization, and equipment operating and maintenance costs. The effect of those costs will be to push the black triangles up the respective lines without changing the price of electricity delivered by the grid where O&M costs are already included.
- The costs also do not include any ship- or shore-based retrofits for new technology. Including these costs will increase the costs of the H_2 fuel cell solution as well as the price of grid power.
- The slope of both lines will be increased for lower diesel generator or fuel cell efficiencies, although the effect does not change the qualitative conclusions within reasonable efficiency ranges.

For a measure of the level of confidence in these assumptions, it can be noted that the estimate given here for the cost of electricity using MGO ($0.2146) closely matches that estimated by the Port of Los Angeles ($0.2154) in a completely independent analysis [65].

Conclusions that can be drawn from this approximate cost analysis are:

- The costs of electricity using marine diesel and hydrogen fuel cells (at the claimed cost of bulk H_2) are relatively close to each other. Adjustments for O&M and capital costs are not expected to change this overall observation.
- If $3/kg hydrogen can be obtained, it will likely be less expensive to use a hydrogen fuel cell to generate electricity than to use the shipboard engines burning MGO or ULSD. The IMO's 2015 mandate to use MGO is expected to cause a spike in MGO price that will further give an advantage to hydrogen fuel cells, and some projected H2 delivery costs place hydrogen at less than $2/kg.
- For domestic vessels, the most cost-effective solution to providing electrical power to the ship while in port in California and the Pacific Northwest will be grid-supplied shore power, provided the infrastructure already exists.
- For international vessels, the same will be true once the MGO mandate takes effect.
- In Hawaii, grid-supplied electricity for shore power is not likely to make economic sense compared to using the ship's auxiliary engines no matter what the fuel.

2.5 Stakeholders

The stakeholders involved with deployment of cold-ironing for ships at berth include:

- Safety officials
- Equipment operators
- Organized labor
- Terminal operators
- Fleets
- Harbor vessels
- Ports

The roles of each of these stakeholders and their effects on cold-ironing are described in this section.

2.5.1 Safety Officials

For land-based cold-ironing, the jurisdiction having authority over the safety of the project would typically be the same as for any port infrastructure project. The codes to be followed would be the same as, for example, those governing installation of a land-based distributed generation system. For cold-ironing where the source of power is located on a vessel or barge, the U.S. Coast Guard has authority over safety. They may or may not refer to land-based codes and standards in the design and operation of such systems. Because atypical maritime fuels such as natural gas or hydrogen are not well-established in the USCG jurisdiction, initial projects involving them may require special authorization from the local USCG authority. While potentially adding effort to deployment of an initial project in this realm, it is also an opportunity to collaborate with the USCG to guide development of reasonable regulatory requirements.

2.5.2 Equipment Operators

Equipment operators are likely to be familiar with maritime operations and common industrial equipment but will likely lack specialized training to be familiar with advanced technology such as fuel cells. This should not present a problem since most hydrogen fuel cell systems today are designed to be operated by the layperson. However, safety will be a paramount concern and education will likely benefit those unfamiliar with hydrogen.

2.5.3 Organized Labor

Labor at ports is typically unionized. There are well-established boundaries that define which work belongs to which trade. For example, the majority of work related to the vessel at berth such as loading and discharging cargo is under the jurisdiction of the International Longshore and Warehouse Union (ILWU). However, when a new technology or procedure is introduced, there may be disputes between unions over who can perform the new work. For example, an argument could be made that electrically connecting a vessel to a shore power system would fall into the jurisdiction of the International Brotherhood of Electrical Workers (IBEW) union. At the same time, the ILWU could propose (successfully) that because this work involves a vessel at berth, whose operations are primarily under their control, that it falls into their jurisdiction. At the Port of Portland, a long-term existing labor agreement with the IBEW giving them the jurisdiction over shore power connections was similarly challenged but allowed to stand until its expiration [59].

Regardless of who does the work, the labor associated with making and overseeing the connection will add cost to each shore power hook-up, and may make shore power more expensive than that generated by auxiliary engines [34]. A system that requires little labor or oversight will be preferred to one that is labor intensive.

On the West Coast and in Hawaii it is common for harbor vessels and tugs to be crewed by members of the Inlandboatmen's Union (IBU), the "Marine Division of the ILWU". This relationship with the ILWU potentially means that the hookup of a barge-mounted shore power system to that on a vessel may be less contentious than a shore-based system.

Ports are very sensitive to labor issues. Disputes can interrupt normal operations due to resulting work slowdowns or strikes which can, in the highly competitive shipping environment, result in direct loss of business. For example, at the Port of Portland, a ILWU work slowdown in the summer of 2012 caused the Port to lose business to competing ports in the Puget Sound [59]. Therefore, while cooperation of organized labor is expected on any project, the risk of a labor dispute could impact the preferred implementation plan of a shore power project.

2.5.4 Terminal Operators

Ports usually are not involved in day-to-day operations at the docks. Instead, docks are leased long-term (20 years or so) by the port to terminal operators, who are companies or joint ventures that make a business out of the logistics of vessels and their cargo. In some cases, terminal operators can be fleet operators and that terminal will exclusively serve vessels belonging to that fleet, but this is not typical. Even if a fleet operator is a terminal operator, it may still welcome vessels of other fleets. And there are many terminal operators who, while they may have long-term agreements with fleets, are wholly independent companies. At each port there is typically a limited number of docks or a wharf where the Port is the terminal operator, but usually these docks are not the ones that serve large commercial vessels.

Because the terminal operator is responsible for the operations on the dock, operation of the shore power system is also their responsibility. They may also be required to contribute to the installation of equipment for land-based systems. Thus terminal operators have a stake in both the installation and operation of shore power systems.

2.5.5 Fleets

Fleets operate the vessels that travel between ports. A fleet may consist of a single vessel (usually a charter in that case) or hundreds (e.g., Maersk's fleet).

Fleets have logistical challenges and opportunities. The more efficient a fleet is at maximizing utilization of its vessels, the more profitable it will be. Shore power can hinder this utilization if it:

- Results in a particular vessel sailing on limited routes or to a limited number of ports regardless of cargo volume.
- Reduces the cargo-handling capacity of the vessel.
- Impedes movement into/out of the port, such as requiring extra maneuvering to line-up with shore power infrastructure.

- Increases the time spent at the dock, which increases the fee that must be paid to the terminal operator.

Fleets generally look favorable upon any “green” measures such as cold ironing because it can give them a competitive advantage for several reasons. The first is that the high costs of maritime or diesel fuel can mean that reducing consumption of these fuels can make economic sense. Another is that as consumers demand products with less overall carbon footprint, reducing a fleet’s carbon footprint can make that fleet more attractive to companies who want to ship their product. A last reason is the green image that companies can project to the public when showcasing green energy products.

2.5.6 Harbor Vessels

Harbor vessels could have a stake in shore power developments in two ways. The first is if the harbor vessels are the ones connecting to shore power, and in that case the same issues that affect fleets will affect them. The other is if the shore power system is water-based, such as on a barge, and a harbor vessel (tug) must maneuver the barge to connect to a vessel at berth and most likely also be the operator of the shore power system. In this case, their concerns will include those of equipment operators.

2.5.7 Ports

As explained in Section 2.3, port emissions are becoming more regulated, both by external authorities and by internal initiatives. Shore power is seen as an important measure to meet these regulations and ports have the authority to dictate shore power requirements to terminal operators and visiting vessels. However, ports are also cost-sensitive and some ports cannot afford the capital cost required to provide power at the docks without raising costs for customers and thus potentially losing business. Thus, while ports are generally supportive of any shore power initiative in principle, they are delighted if it can also reduce costs and/or attract more customers.

3 PEM FUEL CELL BARGE CONCEPT AND DESIGN

This chapter describes the concept and design of the PEM fuel cell barge, including practical applicability to the vessel types discussed in Section 2.1.

3.1 Concept

The basic concept of a fuel cell barge is shown in Figure 3-1. It consists of hydrogen storage, a PEM fuel cell, power conditioning equipment, and cable system. The figure shows the equipment housed in two separate shipping containers, which would then be secured to the top of a flat-top barge. The size and number of shipping containers would depend on the power and energy required for the application, with the power demand affecting the size of the fuel cell and the duration of the shore power visit affecting the size of the hydrogen storage. Regardless, the stakeholders interviewed in this study were unanimously in favor of housing the equipment in standard size shipping containers (open- or closed-sided) that can be handled by methods that are familiar in the shipping environment.

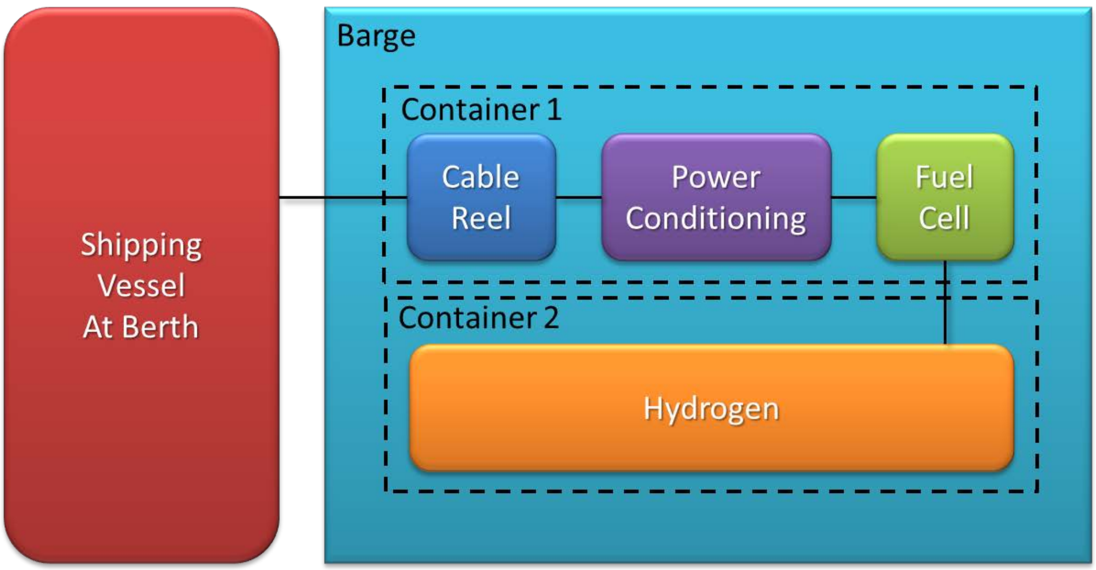


Figure 3-1: Basic concept of a fuel cell barge. Although two containers are shown here, the actual number of containers would depend on the power and energy requirements of the vessel to be powered.

The flexibility of servicing different vessels that may have different voltage, frequency, and hook-up needs will also affect the required equipment and overall size. To have the flexibility to service multiple voltages and frequencies, more power conditioning equipment would be needed. To ensure connection to vessels with different locations and configurations of the shore power connection, multiple sets of cables and plug configurations may be needed. However, because of the recent development of the IEC/ISO/IEEE 80005-1 standard (see Section 2.2.1), this may not be as much of an issue as it once was.

3.2 Size and Capability

The size of the required equipment and hydrogen storage will in turn affect the size of the barge. But there is a limit on the maximum barge size that depends on the application and location of deployment. For example, in the narrow waterways between berths typical at many ports, a barge that has a length smaller than the width of the ship can fit behind the vessel and not obstruct the waterway. A standard container vessel can hold 16 containers across with 8 ft. widths, giving an overall width of about 130 ft. [19]. Therefore a barge no longer than this would be preferred, which in this case would have room for six 40 ft. containers at two abreast. This could be considered a maximum limit, although maneuverability or other reasons may dictate smaller sizes. Shipping containers can also be stacked to increase the number, but system complexity and safety become more apparent issues then.

The amount of hydrogen that can be stored in the form of a standard 40-ft shipping container is estimated to be 650 kg in the form of 250 bar (3600 psi) gas, an example of such a storage system is shown in Figure 3-2. There are other configurations that allow for more flexibility such as 20-ft container lengths and 40-ft half-tall container sizes. For these sizes the amount of hydrogen to be stored is assumed to scale linearly. Other storage mediums could also be used, such as liquid and metal hydride. A liquid tank with size equivalent to a 40-ft container would store 2,500 kg [67] and the same size with a classic metal hydride is estimated to hold approximately 1,300 kg.

Figure 3-2: The TITAN gas storage module from Lincoln Composites, in the profile of a standard 40-ft shipping container, which can hold approximately 625 kg of hydrogen at 3,600 psi (250 bar) [68].

The size of the fuel cell that can be accommodated must also be estimated. Figure 3-3 shows a recent installation of a 1 MW fuel cell by Nedstack in Belgium. The fuel cell unit appears to be contained in approximately the same volume as a 40-ft shipping container. However, behind the fuel cell is another container that is assumed to be a necessary part of operating the fuel cell. Therefore it seems that in this case, to house 1 MW of PEM fuel cell would require two 40-ft shipping containers, which averages to 250 kW per 20-ft container. Hydrogenics has designed a 150 kW fuel cell in a 20-ft shipping container as shown in Figure 3-4. This unit was not optimized for maximizing volumetric power density, and Hydrogenics estimates that the capacity could be increased to more than 500 kW. For purposes of this preliminary analysis we will assume that 400 kW of fuel cell could be fully-contained within a 20-ft shipping container.

Figure 3-3: A 1 MW PEM system by Nedstack recently installed at a chlorine plant in Antwerp, Belgium [69].

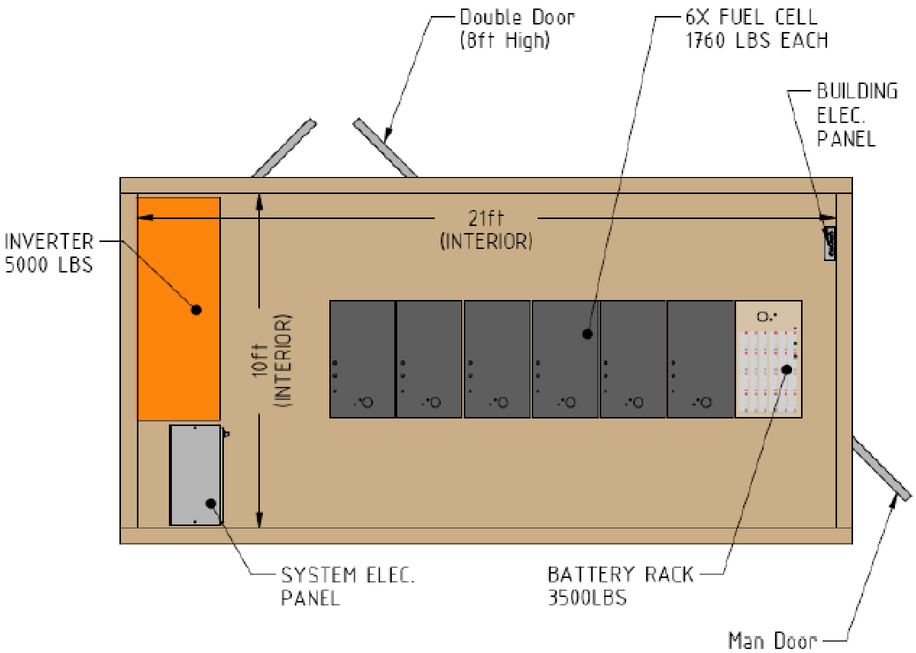


Figure 3-4: A self-contained 150 kVA fuel cell system in a 20-ft shipping container by Hydrogenics. The manufacturer believes a system optimized for the available space could have a capacity of more than 500 kW.

Therefore several options exist for design of the system. Table 3-1 summarizes some possible configurations with rated power output. It also includes low and high run times at rated power assuming gas and liquid hydrogen storage, respectively (the metal hydride solution falls between these two extremes and is not shown). Run time assumes 0.02 kgH_2/kWh. These numbers should be considered best approximations at this point and detailed layout design may result in better or worse performance.

Table 3-1: Approximate power and run time of various containerized PEM fuel cell and hydrogen storage systems.

Standard Container Configuration		Rated Power	Stored Hydrogen and Run Time			
			Low (Gas H_2)		High (Liquid H_2)	
Fuel Cell	Hydrogen		kg	hr.	kg	hr.
¼ of a 20’	¾ of a 20’	100 kW	183[a]	91[a]	750[a]	375[a]
Half of a 20’	Half of a 20’	200 kW	122[a]	31[a]	500[a]	125[a]
¼ of a 40’	¾ of a 40’	200 kW	366[a]	91[a]	1500[a]	375[a]
Half of a 40’	Half of a 40’	400 kW	244[a]	31[a]	1000[a]	125[a]
1 x 20’	1 x 20’	400 kW	325	41	1250	156
1 x 40’	1 x 40’	800 kW	650	41	2500	156
1 x 40’	3 x 40’	800 kW	1950	122	7500	469
2 x 40’	2 x 40’	1.6 MW	1300	41	5000	156
3 x 40’	1 x 40’	2.4 MW	650	14	2500	52

[a] In these cases, where the hydrogen and fuel cell are stored within the same container, hydrogen volume is reduced by 25% to account for reduction of scale losses and space needed for interconnection and interior access.

3.3 Possible Vessel Applications

It is useful to compare the estimated fuel cell system capabilities shown in Table 3-1 with the needs of the various vessels that are potential applications for shore power. Table 3-2 summarizes the findings of Section 2.1, showing vessel type, power requirement, and required run time.

Table 3-2: Summary of vessel types with power requirements and times needed to run on shore power.

Vessel Type	Power Required			Run Time (hr)		
	Typical	Low	High	Typical	Low	High
Harbor Tug	100 kW	7.5 kW	410 kW	4	1	6
Tug-Barge	115 kW	-	-	N/A	-	-
Fishing Trawler	200 kW	75 kW	670 kW	continuous	48	months
Bulk	200 kW	150 kW	300 kW	48	-	-
Tanker (steam pumps)	700 kW	550 kW	800 kW	48	24	72
Auto/RoRo	800 kW	700 kW	890 kW	24	24	36
Container	1.4 MW	500 kW	8.4 MW	48	24	72
Reefer	3 MW	900 kW	5.6 MW	60	48	72
Cruise	6 MW	3.5 MW	11 MW	10	10	12
Tanker (elec. pumps)	7.8 MW	-	-	48	24	72

A comparison of the two tables reveals:

- Fishing trawlers, tug-barges, and harbor tugs could be easily met with a PEM fuel cell system. For fishing trawlers at berth for long periods, it is assumed that the system would be configured in such a way as to make hydrogen refueling possible while running.

- Bulk carriers and tankers with steam discharge pumps are also good fits, but their erratic schedules and infrequent visits mean they are not likely to be successful applications.
- The power needs of auto/RoRo carriers could easily be met with a solution of three or four 40-ft containers, and probably just two. However, not many fleets have frequent RoRo visits to the same port to justify retrofitting the ship to accept it, so this would be a more limited application.
- Container ships may be a good fit, but the varying range of on-board reefer containers make them somewhat risky if a fuel cell system is sized at the lower end of the range. In addition, the run time required by a container ship would likely require liquid hydrogen storage. Container ships are frequent visitors at all ports and more amenable to retrofitting shore power capability, so a way to address these concerns could be found this would likely be a successful application.
- Tankers with electric pumps, cruise ships, and reefer vessels are probably outside the power range of a practical PEM system today.

3.4 Benefits and Drawbacks

The positive attribute about a barge-mounted PEM fuel cell system that was most commonly cited among interviewees is its flexibility to service ships that are either oriented incorrectly or are berthed at a location with no shore power. Other cited benefits included:

- No electrical infrastructure required.
- Potentially less expensive to operate than the clean fuels in auxiliary engines.
- Does not require dock space.
- Temporary solution to shore power while the port undergoes construction or maintenance.

Some cited drawbacks to a barge-mounted PEM fuel cell system were:

- It may obstruct/constrict vessel traffic in the waterway.
- Potential restrictions on use due to on-board hydrogen tanks.
- Barge crew and maintenance costs.
- Potential organized labor issues.
- May not be as fast to hook up as shore-based systems.
- Size required by the vessel may be too large for a barge.

Overall, the barge concept may have an advantage to shore-based systems primarily when electrical infrastructure is either not available or is incapable of meeting the needs of all vessels that call there. However, it would need to be appropriately matched to an application and the implementation and operation of the system must be agreeable to all stakeholders.

3.5 Design Variations

Besides the basic concept of powering vessels at berth, other options for using barge-mounted PEM fuel cell systems exist and are explored in this section:

- Shipping vessels at anchorage
- Harbor craft at anchorage
- On-board power for refrigerated cargo containers

In addition, two non-barge based variations are also explored:

- Shore-based power for at-berth vessels
- On-board auxiliary power

3.5.1 Shipping Vessels at Anchorage

Another application of the system shown in Figure 3-1 would be to move the barge to anchorage sites, designated zones within a harbor where shipping vessels may wait for berths to be available or for favorable weather conditions for loading and discharging cargo. Analysis of the vessel types described in Section 2.1 reveals that bulk carriers and tankers are the most common carriers to spend time at anchorage. However, these vessel types are also least-likely to have the same vessel make frequent visits to the same port, making it unlikely that they will be equipped with shore power capability. Therefore this application, while technically feasible, will not likely make economic sense.

3.5.2 Harbor Craft at Anchorage

In some cases harbor craft may also utilize anchorage sites. For example, at the Port of Oakland, the assist tugs of Foss Maritime often wait at anchorage between times when they are needed rather than make the several-hour round-trip back to their berth, and a similar situation exists at the mouth of the Columbia River at Astoria, OR [33]. They require electrical power while waiting and run auxiliary generators to provide it. A PEM fuel cell system on a barge at anchorage could potentially allow multiple tugs or other harbor craft to shut down their auxiliary engines while waiting. Such a system concept is shown in Figure 3-5.

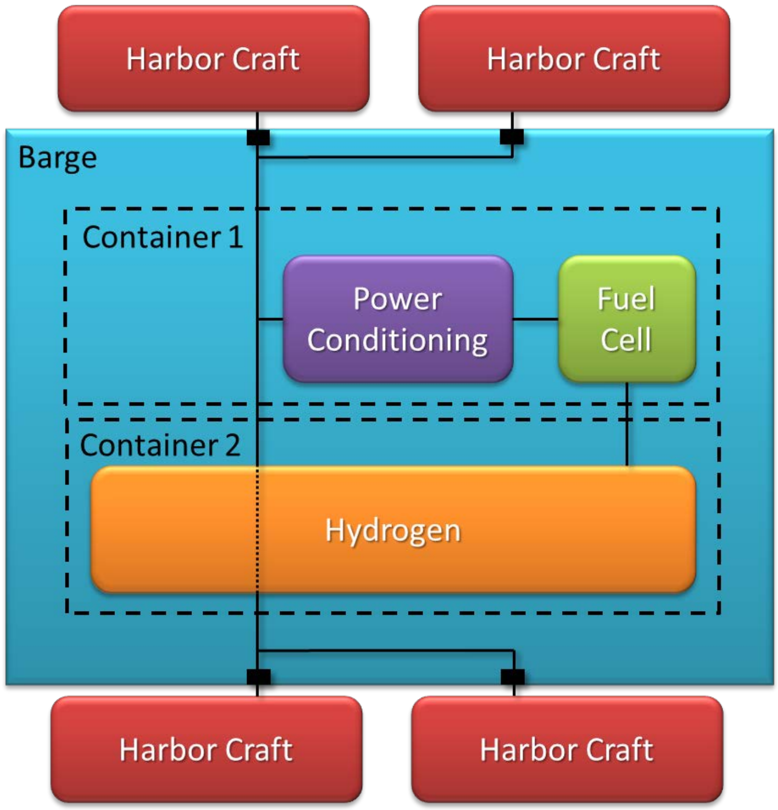


Figure 3-5: Concept for a PEM fuel cell system mounted on a barge to supply multiple harbor craft at anchorage. The same size considerations at the barge for ships at berth apply.

3.5.3 On-Board Power for Refrigerated Cargo Containers

Cargo voyages between ports are sometimes made with barges loaded with shipping containers pulled by ocean going tugs, such as shown in Figure 3-6. When refrigerated containers ("reefers") are on board, electricity must be provided to keep the refrigeration system running during transit; each reefer can draw up to 16 kW but on average require about 10 kW [51]. Because barges do not usually have generators built-in, containerized generators are loaded on-board with the reefers and run throughout the voyage, see Figure 3-7. In this case a containerized PEM fuel cell system like those in the previous two sections could provide reefer power during the voyage as opposed to powering vessels for cold ironing. A concept of this system is shown in Figure 3-8.

Current diesel generators used in this application (Figure 3-9) provide about 300 kW for 84 hrs. Analysis of the system configurations options shown in Table 3-1 shows that a single 20-ft container could supply 100 kW for over 90 hours of operation with gaseous storage, or 200 kW with over 100 hrs of operation with liquid storage. The liquid solution may be able to be optimized to reduce the run time to that needed (84 hrs) and increase the power required closer to 300 kW. Therefore, this application is nearly equivalent to the diesel solution when using liquid hydrogen, and is feasible using gaseous hydrogen provided the operator is willing to have additional 20-ft containers on-board to make up for the lower capacity.

Figure 3-6: Short voyages between neighbor ports, for example the inter-island transports in Hawaii shown here, often utilize container-laden barges pulled by tugs.

Figure 3-7: Transport barge loaded with containers. The refrigerated containers ("reefers") are kept running with containerized diesel generators that are loaded and discharged with the reefers.

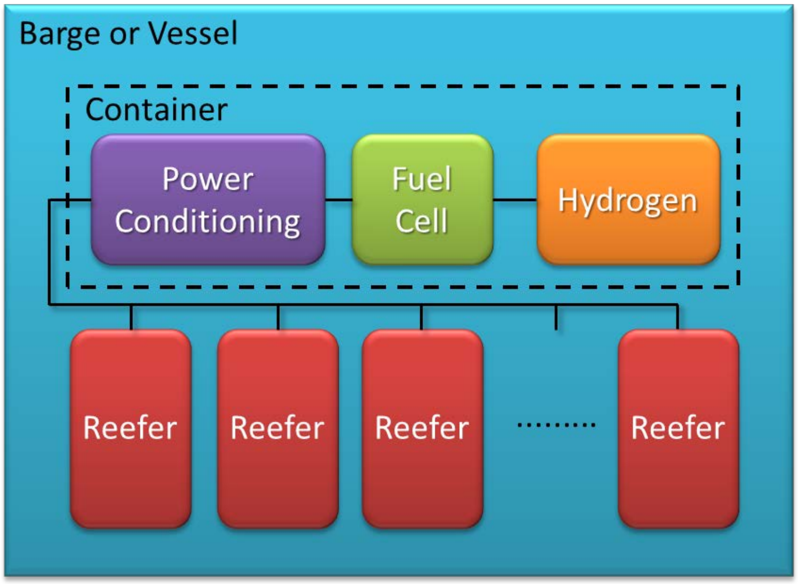


Figure 3-8: A containerized PEM Fuel cell system could power refrigerated containers ("reefers") during transit, which would replace diesel generators on board barges or other vessels without built-in electrical generation capacity.

Figure 3-9: A containerized, 300 kW diesel generator with a 1,800 gallon diesel tank, used to provide power for 20-30 reefer containers while on the dock and during transit.

3.5.4 Shore-Based Power for At-Berth Vessels

This concept is identical to the basic one shown in Figure 3-1, except that a barge is not utilized. Rather, a containerized PEM fuel cell system and hydrogen storage is located on the dock next to the vessel. A single unit could power a single large vessel or multiple small ones, depending on the size. At a wharf with multiple berths such as that shown in Figure 3-10, the system would ideally be moveable so that different vessels can be powered depending on daily or weekly traffic. From the data shown in Table 3-1, a single 40-ft container solution could provide 200 kW for nearly four days at a time when gaseous storage is used. If separate containers were used to house the fuel cell and hydrogen, a single 20-ft container housing the fuel cell connected to a 40-ft container with hydrogen would be able to provide 200 kW for nearly one week, and almost four weeks when using liquid hydrogen.

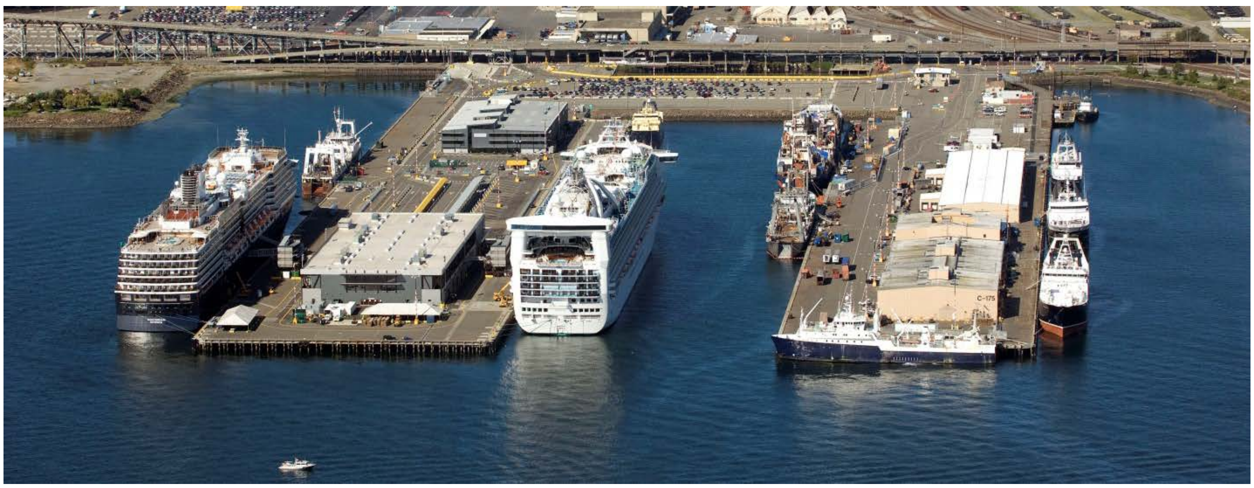


Figure 3-10: The Port of Seattle's Pier 91, which is home to a multitude of vessels that vary throughout the year, including fishing trawlers, cruise ships, government vessels, private yachts, tugs, construction vessels, research vessels, icebreakers, and supply vessels [70], picture from Ref. [71]. A containerized PEM fuel cell system could be transported from berth to berth as needed.

4 SITE EVALUATION

In this chapter the various sites that were explored are described and their suitability for deployment of a hydrogen-fueled PEM fuel cell system is evaluated.

The nine sites evaluated in this study are:

1. Port of Los Angeles/Port of Long Beach
2. Port of Oakland
3. Port of Portland (OR)
4. Port of Tacoma
5. Port of Seattle
6. Port Hawaii – Honolulu Harbor
7. Suisun Bay Reserve Fleet
8. California Maritime Academy
9. RiverQuest *Explorer*

Many other West Coast ports were excluded from the study, and it is expected that numerous alternatives to in-port applications are also possible. The over-arching assumption is that this small sample of sites represents general opportunities in the maritime environment.

Exclusion of smaller ports has some justification as it was found that they typically have smaller operating budgets and lower traffic volumes. Lower traffic volume means that a shore power project is not likely to be economically favorable. And a project that must be subsidized by the port because of this will not be likely to succeed at these areas. Examples of such ports are Portland (surveyed) and Hueneme, who was not surveyed but whose financial difficulties are documented.

Exclusion of the ports of San Diego and San Francisco has additional justification in that they are both subject to the CARB regulation requiring installation of shore power infrastructure, and both ports are committed to grid-supplied solutions which would preclude a barge solution as found at the other California ports studied.

4.1 Port of Long Beach/Port of Los Angeles

Figure 4-1: Satellite view of the ports of Long Beach (POLB) and Los Angeles (POLA) (image from Google).

Port Attributes: 5th and 8th largest ports in the U.S., 1st and 2nd on the West Coast (POLB/POLA, respectively). Primarily international, import traffic.
Vessel Traffic: All kinds.
Shore Power Status: Developing grid-supplied shore power at all container and cruise berths (POLA only) and some liquid bulk terminals. POLA pays $0.14/kWh for electricity.
Hydrogen and/or Fuel Cell Projects: Class 8 drayage trucks by Total Transportation Services, Inc. and Vision Industries.
Hydrogen Availability: Hydrogen pipeline from nearby refinery cluster planned to extend to the port to supply a hydrogen fueling station.

The Port of Los Angeles (POLA) and Port of Long Beach (POLB) are grouped together because they have similar characteristics and are geographically connected. They are also close to a refinery sector in Los Angeles County and its available source of hydrogen, and are participating in other hydrogen fuel cell projects. Both ports are heavily committed to green measures and would support any project that furthers this mission, and POLA has previous experience with a shore power barge (housing a transformer and cabling). However, they are also both actively installing electrical infrastructure for shore power at all container, cruise, and some bulk liquid berths. Therefore, a shore power barge there would only be used in spot duty or for short-term instances where dock construction was underway and may not make long-term economic sense.

(Most information in this section comes from personal communications with on-site personnel [20, 21, 72])

4.2 Port of Oakland

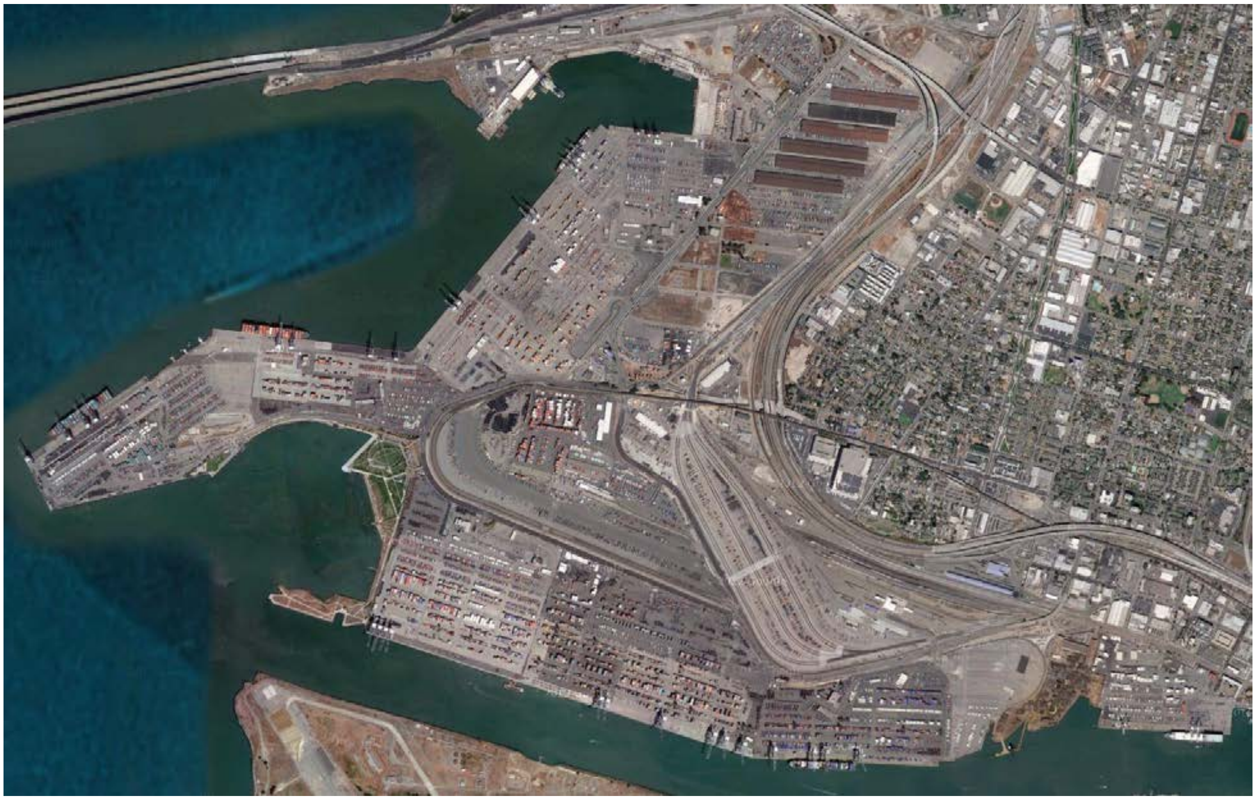


Figure 4-2: Satellite view of the Port of Oakland (image from Google).

Port Attributes: 36th largest port in the U.S., 8th on the West Coast. Primarily international, more export than import.
Vessel Traffic: Mostly container.
Shore Power Status: Developing grid-supplied shore power at all container berths.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Nearby refineries and gas suppliers.

The Port of Oakland is primarily a container port, with 88% international traffic. It has grid-supplied shore power installed or pending at its container berths in order to be ready to comply with the CARB shore power regulation. Therefore, while a barge-mounted system to supply power to container ships may be used when vessels cannot orient correctly, it is not likely to be utilized enough to make it economically viable.

However, a second application of a shore power barge is possible near the Port of Oakland. The assist tugs of Foss Maritime that guide ships within the harbor are based at the Port of Richmond.

Between assignments they will wait at anchorage (Anchorage 9, see Figure 4-3) and run their auxiliary engines for electrical power. In this case, a barge that could supply electrical power to these tugs while waiting would decrease the fuel they consume and is likely to be heavily utilized each day. The power requirement of a tug is estimated to be 100-200 kW (Table 3-1) which means that a barge with two 40-ft containers (one for the fuel cell and one for the hydrogen) could supply four tugs continuously for over a day when using gaseous storage (Table 3-2). When the tugs return to their home port each day, the barge could be refilled. Alternatively, a larger storage system, or using liquid hydrogen, would enable the barge to stay at anchorage for longer periods between refills.

Foss Maritime has already explored the possibility of utilizing a diesel generator for this application and is highly interested in using a hydrogen-fueled PEM fuel cell instead due to emissions reductions and potential cost savings. They also have barges available for retrofit. Because of the ease of integration into their current operations, a likely source of local hydrogen near their Port of Richmond base (close to refineries), and support of the Port and the company, this appears to be a favorable application for a barge-mounted fuel cell shore power system.

Figure 4-3: Satellite view showing relative location of Anchorage 9 to the Port of Oakland (image from Google, anchorage location from NOAA chart 18649 [73]).

(Most information in this section comes from personal communications with the Port [34] and Foss Maritime [33])

4.3 Port of Portland

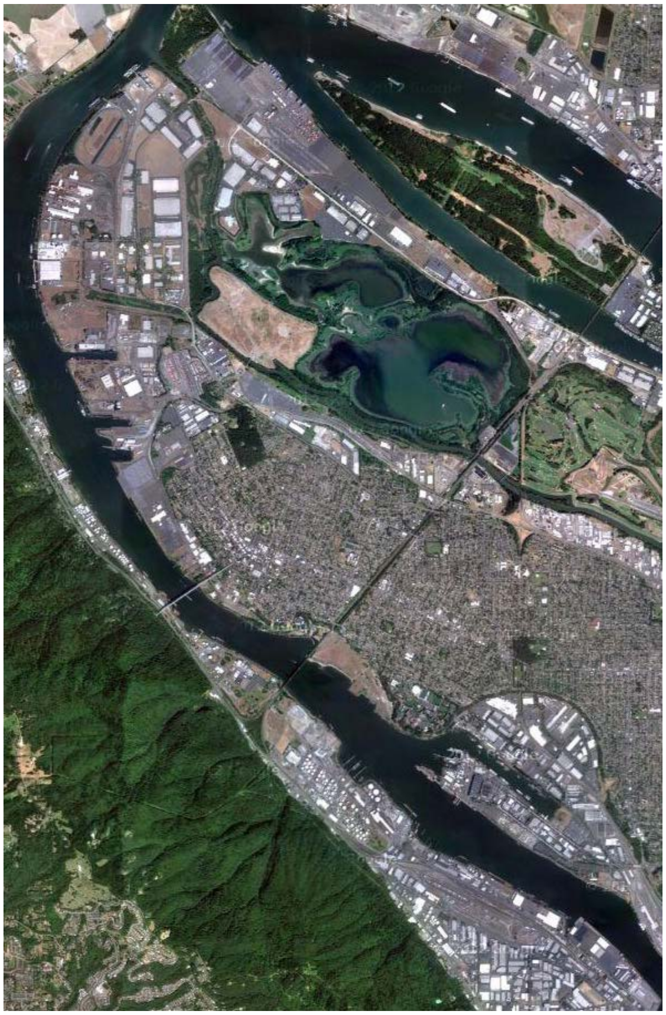


Figure 4-4: Satellite view of the Port of Portland, OR (image from Google).

Port Attributes: 28th largest port in the U.S., 5th on the West Coast. Two-thirds international, mostly exports (80%).
Vessel Traffic: Bulk, RoRo, some container.
Shore Power Status: For barges only. Cable trays installed at one terminal for future possibility. The Port's maritime facilities pay $0.083/kWh for electricity.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Nearby small-scale.

The Port of Portland is located on the Columbia River, approximately 100 nm from the Pacific Ocean. Contrary to other West Coast ports, its traffic is primarily export, and primarily bulk cargo via charter vessels. It also has three auto facilities and auto carriers are frequent visitors with visits of the same vessel estimated to be up to six times per year. The Columbia River limits container traffic to vessels less than 6,500 TEU so container ships are not as common as other ports. It does not have any long term agreements with fleets and has stiff competition with the Puget Sound ports. The Port is very environmentally conscious and has recently commissioned a LEED Platinum office building. They would be receptive to an alternative energy shore power installation but realize a decision to proceed would have to be based entirely on economics, and such a decision would need to come from a fleet operator. Because of the low volume of traffic, this is unlikely to occur.

(Most information in this section comes from personal communications with on-site personnel [59])

4.4 Port of Tacoma

Figure 4-5: Satellite view of the Port of Tacoma (image from Google). The large waterway in the middle is the Blair Waterway, which terminates at the Pierce County Terminal, operated by Evergreen.

Port Attributes: 30th largest port in the U.S., 7th on the West Coast. Primarily international, mostly exports.
Vessel Traffic: All types, mostly container (70%).
Shore Power Status: At Totem Ocean Trailer Express (TOTE) terminal only.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Unknown. On-site U.S. Oil refinery has potential, unconfirmed.

Tacoma does not have shore power installed except at the Totem Ocean Trailer Express (TOTE) terminal. TOTE is a U.S. flag carrier and provides supplies to Alaska via the Port of Anchorage and is in the process of converting their vessels to LNG. The Port has considered adding the electrical infrastructure required to equip berths but has found the cost to be prohibitive.

The Port of Tacoma has regular calls from major container shipping lines, visited by 8-10 container ships per week. Several of the fleets, such as Evergreen (Figure 4-6), will have the same vessel visiting the port about 10 times each year. Many of the fleets are the same that visit California ports, so they will already have some shore-power retrofitted vessels in place. The fleet would like the flexibility to deploy shore-power equipped vessels outside of California if shore power were available at other ports, so the Port of Tacoma is interested in providing this service and see it as a benefit to business. Therefore, the Port sees the shore power barge idea as an ideal solution to their needs.

Figure 4-6: The Evergreen *Ever Elite* at the Port of Tacoma's Pierce County Terminal, a terminal at the end of the Blair Waterway with ample space alongside for a shore power barge.

The challenges with deployment at the Port of Tacoma are that (1) a source of hydrogen is not yet well-defined and (2) the particular challenges of supplying a container ship's power needs with practical fuel cell and hydrogen needs (see Section 3.3). However, if both of these can be overcome the Port of Tacoma would seem to make a successful deployment site for container ship shore power.

(Most information in this section comes from personal communications with on-site personnel [19])

4.5 Port of Seattle

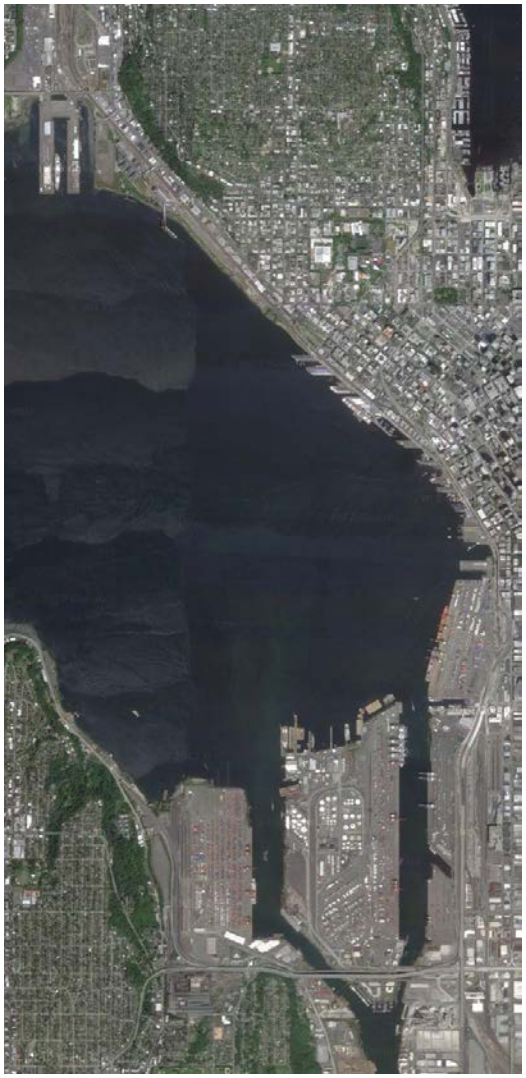


Figure 4-7: Satellite view of the Port of Seattle, which has facilities all around Elliot Bay. At the lower middle and right are the primary cargo facilities, in the middle is a cruise terminal, and at the upper left is another cruise terminal and multi-purpose wharf (Pier 91, see also Figure 4-8). Image by Google.

Port Attributes: 26th largest port in the U.S., 4th on the West Coast. Primarily international, mostly exports.
Vessel Traffic: Container, cruise, fishing, one grain (bulk) terminal.
Shore Power Status: Installed at Pier 91 for cruise ships, fishing trawlers, and other compatible vessels. The Port and tenants pay about $0.05/kWh for electricity.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Unknown. Refineries north of Seattle (Cherry Point) are a likely source.

Like the Port of Tacoma, the Port of Seattle receives many container ships from fleets that also operate in California and have frequent visitors. This provides a similar opportunity to make effective use of a PEM fuel cell barge solution. However, concerns about space in the narrow waterways make it imperative to find a solution that will not obstruct other vessel traffic.

The Port has shore power installed at Pier 91 (Figure 4-8), which is at the northwest side of Elliot Bay. The capacity is about 21 MW, of which 16 MW is for two cruise ship berths and 5 MW is for the multitude of other vessels that utilize the facility. Cruise ships are only at port from May through September. The Port was the first in North America to provide shore power simultaneously to two cruise ship berths.

Figure 4-8: Close-up satellite view of Pier 91 at the Port of Seattle (image by Google).

While the existence of shore power at Pier 91 would seem to preclude the need for a PEM fuel cell solution, the infrastructure already developed combined with the Port's desire for green energy measures, presents a unique opportunity and has the following advantages:

- Many types of smaller vessels frequent these berths and are already equipped for shore power.
- The power requirements of the smaller vessels well-match the capabilities of a fuel cell – hydrogen solution.
- Placing a containerized solution on the pier could easily replicate the existing connections (Figure 4-9), and there is ample space available.
- The pier has frequent traffic and a containerized solution that could be moved from berth to berth along the dock would be heavily utilized.

- The co-location with the cruise terminal means that the technology could be easily showcased to approximately 600,000 cruise passengers passing through the facility each year (Figure 4-10).

Figure 4-9: Small-vessel shore power disconnect box being utilized by a fishing trawler at the Port of Seattle's Pier 91.

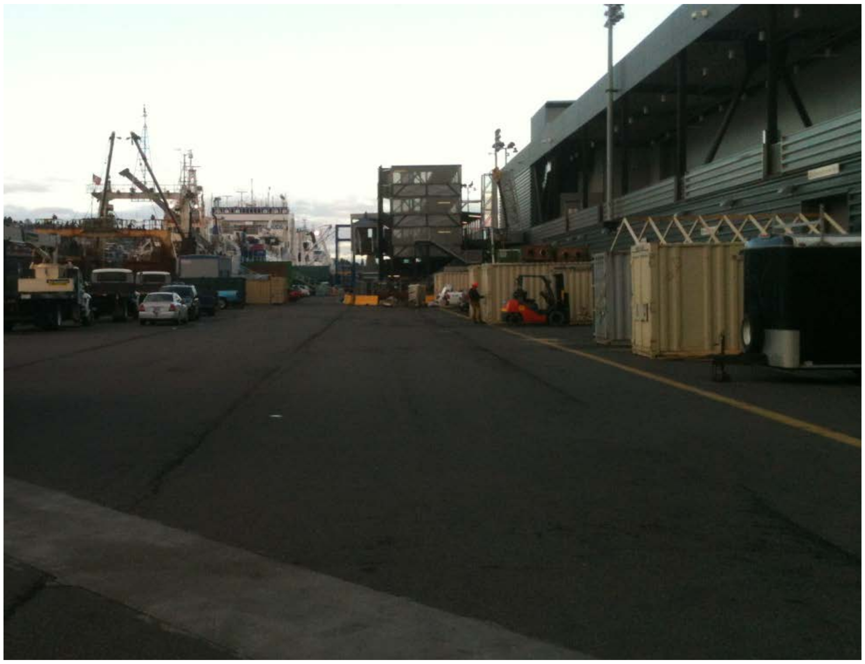


Figure 4-10: Frequent vessel traffic, ample dock space, easy access, and co-location of the cruise terminal (building on the right) would make a PEM fuel cell shore power solution feasible, heavily utilized, and highly visible at the Port of Seattle's Pier 91.

The Port has the desire to provide shore power at other berths, but is having difficulty in some locations because of the lack of capacity in the provider's electricity grid. Pier 66 is a cruise berth on the city's waterfront that is a prime target for shore power due to its visibility in the community, but infrastructure requirements are daunting: from required electrical utility upgrades to limited pier space. At that location, a barge would not have any space constraints if alongside (see Figure 4-11). Unfortunately, as a comparison of Table 3-1 and Table 3-2 illustrates, a PEM fuel cell system designed to supply the power required by the cruise ships berthing here, approximately 13-14 MW [22] for 10-12 hrs, would require about 20-25 40-ft containers and is not practical.

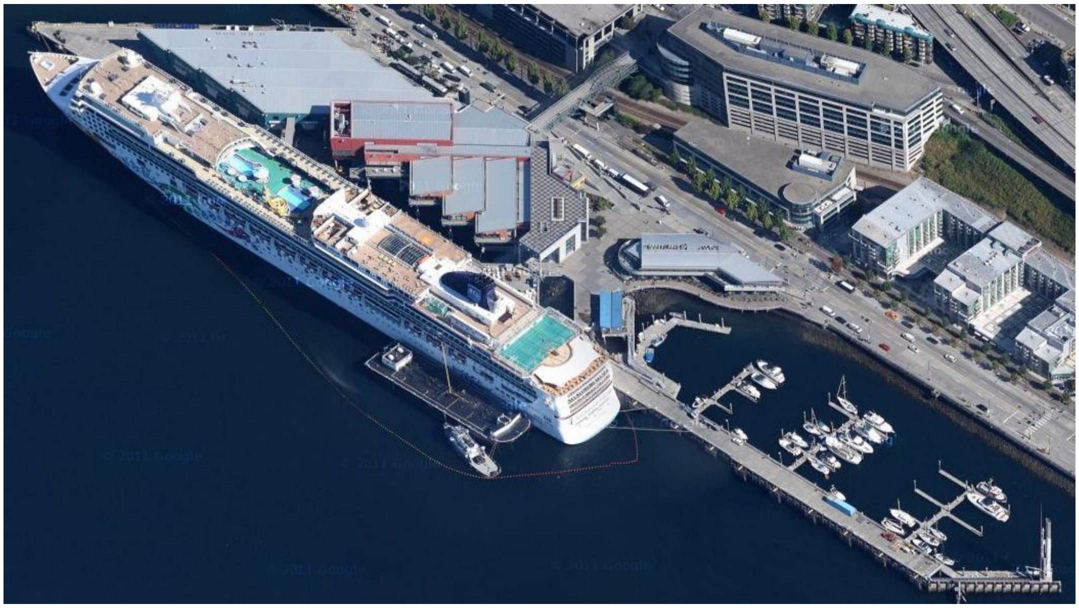


Figure 4-11: A cruise ship berthed at the Port of Seattle's Pier 66 (image from Google).

At Harbor Island, to the south, electrical capacity is also limited. A PEM fuel cell barge stationed here could service the container ships that berth at the terminals. The deployment faces similar challenges to that at Tacoma – narrow waterways, vaguely defined container ship electrical requirements due to varying number of reefers, and an undetermined source of hydrogen. If these challenges can be overcome then Seattle could also be an option for a hydrogen-fueled PEM fuel cell barge for container ship power.

(Most information in this section comes from personal communications with on-site personnel [22, 70])

4.6 Port Hawaii – Honolulu Harbor

Figure 4-12: Aerial view of Honolulu Harbor. In the foreground is Sand Island, home to the major container terminals. Near the top, middle right a cruise ship at berth can be seen at the cruise terminal.

Port Attributes: 53rd largest port in the U.S., 11th on the West Coast. Predominantly imports, domestic vessels.
Vessel Traffic: Primarily containers including inter-island transport barges.
Shore Power Status: None. Port tenants pay about $0.37/kWh for electricity.
Hydrogen and/or Fuel Cell Projects: None at the port.
Hydrogen Availability: Refinery at Barber's Point may be a possibility. Possible new generation facility on the Big Island.

Port Hawaii is actively pursuing energy efficiency measures for its facilities, but not at docks or for visiting vessels. Because most traffic is domestic, most vessels in the port have been using ultra low sulfur diesel since July 2012, which means the ports have lower emissions compared to those on the West Coast who see more international traffic. At the same time, trade winds blow emissions off-shore so they are not thought of as an immediate problem by the state government. The high cost of electricity on the island also makes it hard to justify a switch to shore power (see Figure 2-23). Therefore, while the Port would support such a project, it would be the responsibility of a fleet and would have to be economically justifiable.

With regards to fleets, the Hawaiian Islands rely on barges to transport goods from Honolulu Harbor to the neighbor islands which present a unique opportunity that a fuel cell system could provide as described in Section 3.5.3. At the Young Brothers/Hawaiian Tug & Barge facility on Pier 40, barges sail regularly to and from neighbor islands and containerized diesel generators provide power for the reefer containers while on the dock and on the barge during transport. This facility also has 150 kW of photovoltaic panels installed on its maintenance shed roof (see Figure 4-13), with the ability to expand to 300 kW, giving the company a source of renewably-generated hydrogen if connected to an electrolyzer. The company is strongly interested in reducing its use of costly diesel and as a whole has a policy favoring environmentally-friendly measures. Combined with its experience in containerized power systems and a nearly-ready source of hydrogen, a PEM fuel cell system providing on-board power for reefer containers seems a feasible and favorable application.

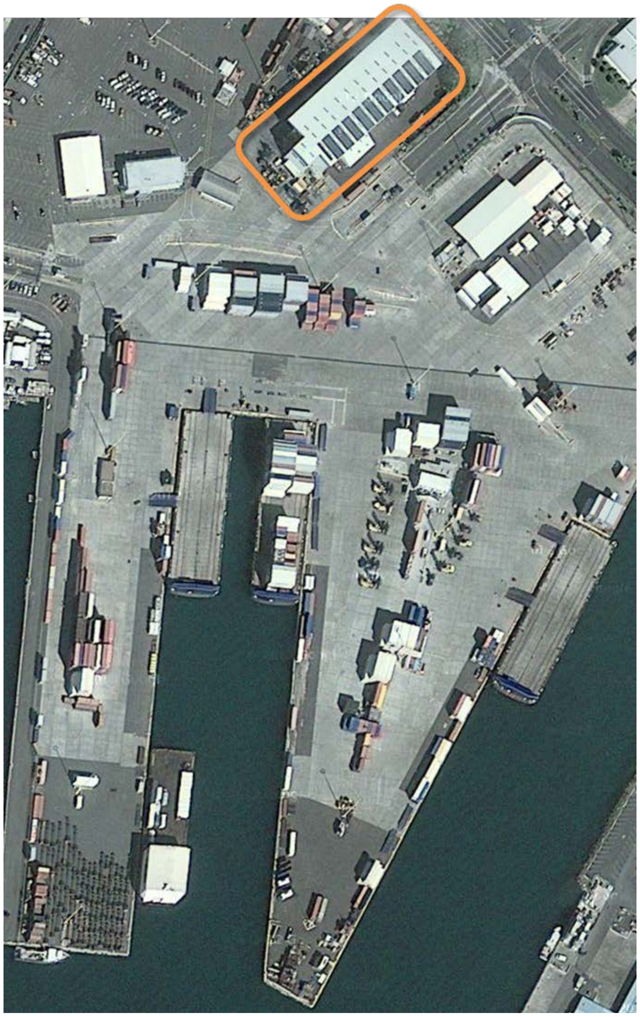


Figure 4-13: Pier 40 at Honolulu Harbor, where Young Brothers/Hawaiian Tug & Barge operate inter-island transport barges. The maintenance shed, circled at the top, has 150 kW of photovoltaic capacity installed with room to expand to 300 kW, available to provide electricity for renewable hydrogen generation (satellite image by Google).

(Most information in this section comes from personal communications with on-site personnel [51, 64, 74])

4.7 Suisun Bay Reserve Fleet

Figure 4-14: Satellite view of the Suisun Bay Reserve Fleet, a DOT – MARAD facility near Benecia, CA (image from Google). At the end of the pier is the Auxiliary Personnel Lighter (office barge), and the reserve fleet is grouped in rows offshore.

Attributes: Maintains U.S. vessels in reserve.
Vessel Traffic: Small personnel carriers to service the fleet; fleet vessels.
Shore Power Status: The office barge and all fleet vessels are connected to shore power.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Nearby refineries and gas companies could provide ample supply.

The Maritime Administration (MARAD) of the U.S. Department of Transportation (DOT) is contracted by other government agencies, such as the Department of the Navy, to maintain vessels in a reserve status when they are not part of the active fleets. The Suisun Bay Reserve Fleet (SBRF) is one such installation and is located near Benecia, CA, in the San Francisco bay region. The vessels are anchored in rows as can be seen in Figure 4-14 and Figure 4-15 and are almost never manned nor operated during this time. At the end of the pier jutting into the bay is the Auxiliary Personnel Lighter (APL) which is used as an office for day-to-day operations.

Figure 4-15: Vessels at anchor in a row at the Suisun Bay Reserve Fleet, view from the APL.

All vessels at SBRF are maintained with cathodic protection, lighting, and alarm systems, and some are also equipped with dehumidification equipment, all of which require electrical power. Because the vessels are not operating, the power must be supplied from the shore. Power is routed to a row via 3,500 ft underwater cables at 12.47 kV. At each row, a floating junction box receives the underwater cable with another cable up to one of the vessels. On board the vessel, a skid-mounted power distribution center (PDC) transforms the 12.47 kV to 440 V and has plugs that are routed to serve 3-4 vessels per PDC. This system is problematic, mainly because the cables break an average of once per year due to debris floating in the river and cause an average outage of two months. In 2003 the Fleet considered installing an underground cable system to eliminate this hazard but it was cost prohibitive at $12M. Thus a barge-mounted PEM fuel cell system could be a cost-effective solution for the Fleet, and greatly improve the reliability of the electrical system and fleet maintenance.

The Fleet has identified barges that could be dedicated to a PEM fuel cell system. However, one challenge that must be overcome is that there is currently nowhere to berth the barge where it could be refueled with hydrogen, Figure 4-16 shows available space at the facility. The footings for a dock are installed, but a dock would have to be constructed as well as a method for transferring hydrogen from the supply truck to the barge tank. There is no space for a permanent hydrogen storage facility at the point of use; it would have to be piped along the 1,300 ft. pier if accommodations for a refueling truck could not be made.

An alternative to a system that would power the fleets is one that would power the APL. Such a system could be mounted at the end of the pier as shown in Figure 4-16, on the roof of the APL (Figure 4-17), or on a barge next to the APL (Figure 4-18). The APL requires less than 250 kW of electricity, so according to Table 3-1 this could be met with a 20-ft containerized fuel cell and as much storage as the fleet desired between refills. Any of the three locations have the space to house this, although finding a place for an adequate amount of hydrogen storage on the end of the pier may be a challenge.

Figure 4-16: SBRF facility, view from the APL looking towards shore.

Figure 4-17: The roof of the APL could house a fuel cell system to provide the 250 kW needed by the APL.

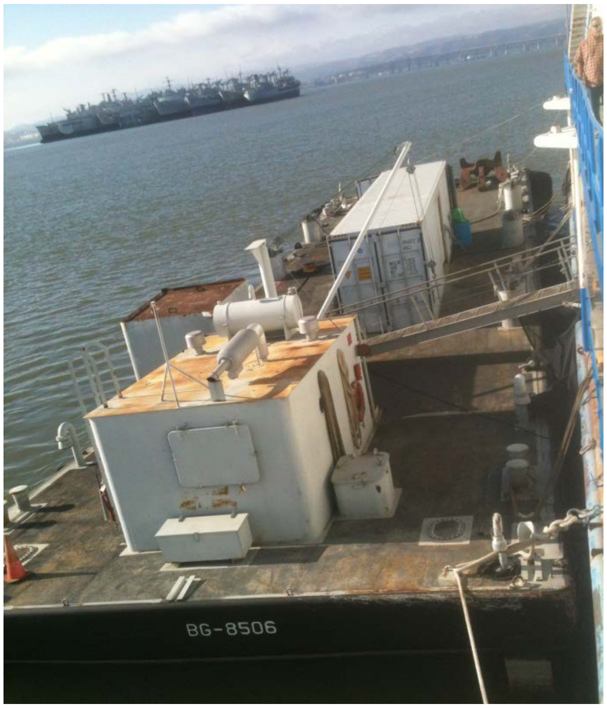


Figure 4-18: A barge next to the APL could house a PEM fuel cell system to provide power to the APL. A row of fleet vessels can be seen in the background.

Using a PEM fuel cell system to power the APL seems to be a feasible and favorable application provided any issues with hydrogen fueling are properly addressed during design. Powering the fleet with a barge appears to also be an advantageous application, but the lack of a dock where a barge could be refueled would necessitate added infrastructure to make it feasible. In either case, SBRF personnel are enthusiastic about the possibility and would provide their support.

(Most information in this section comes from personal communications with on-site personnel [75])

4.8 California Maritime Academy

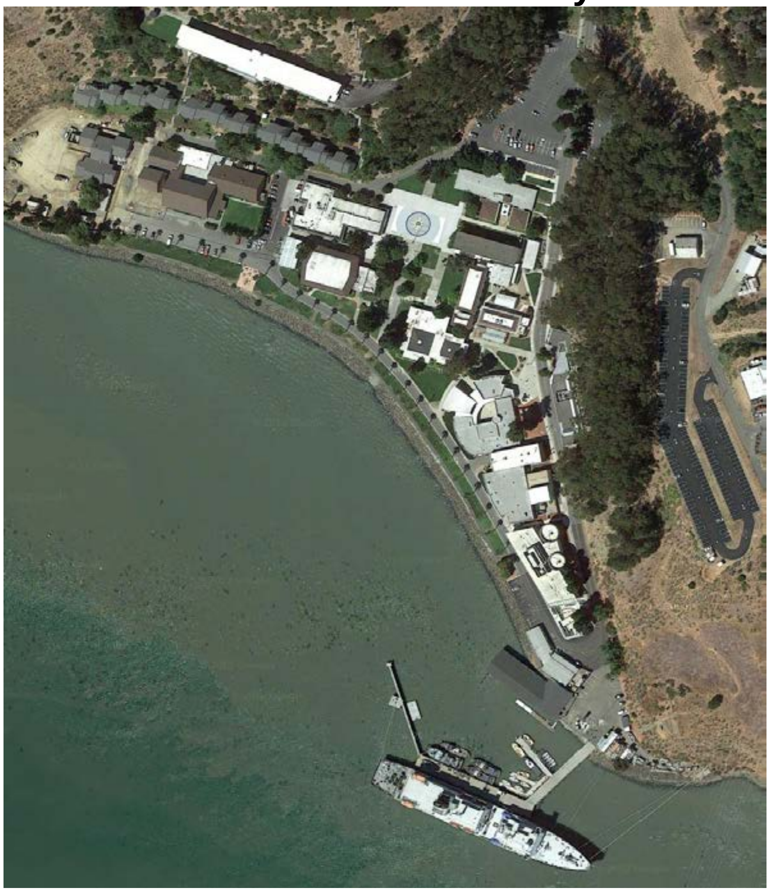


Figure 4-19: A satellite view of the California Maritime Academy, in Vallejo, CA. The *Training Ship Golden Bear* can be seen at berth at the bottom. Image by Google.

Attributes: One of seven governmental maritime academies in the United States and the only one on the West Coast.
Vessel Traffic: The Training Ship Golden Bear is berthed for about 10 months a year.
Shore Power Status: Grid-supplied for the TS Golden Bear.
Hydrogen and/or Fuel Cell Projects: None.
Hydrogen Availability: Nearby refineries and gas companies could provide ample supply.

The California Maritime Academy (Cal Maritime) is one of seven degree-granting maritime schools in the U.S. It offers a specialized curriculum that aims to provide each student with a deep understanding of the transportation industry. Each student takes part in at least one two-month summer training cruise in the Pacific Ocean aboard the Training Ship Golden Bear (TSGB). Other than this cruise and other short excursions, the TSGB is berthed at the school's dock as shown in Figure 4-19 and Figure 4-20. While it is berthed, it is fully utilized as a student residence, classroom, and provides hands-on vessel operation education.

Figure 4-20: The Training Ship Golden Bear berthed at the California Maritime Academy in Vallejo, CA (image from Google). Ample spaces at the stern and just aft of the stack are on-board location options for a PEM fuel cell system.

The TSGB is connected to shore power while at berth, and has a base load of 600-700 kW with a peak of 1.2 MW. There is ample space on-board or on the dock to hold a containerized hydrogen-fueled PEM fuel cell system. The Chief Engineer noted that the electrical circuits are easily isolated so a fuel cell would not have to meet the entire load but could directly service a dedicated circuit without being grid-tied. For example, the lighting circuit has a steady 200-300 kW load, which could easily be serviced with a 20-ft. containerized fuel cell alongside the amount of hydrogen to achieve the desired time between refills. While there is space (see Figure 4-21), there are many activities around the dock and vessel and a review of requirements for hydrogen storage and separation distances is needed to verify any potential location.

Figure 4-21: The dock area next to the TSGB. The current location of the white container would be the preferred option for a containerized hydrogen-fueled PEM fuel cell system. Electrical tie-in to the vessel is just behind and to the right of the photographer; cables would be run under the dock.

If the system were located on-board it could also be configured to utilize it during voyages, displacing diesel fuel cost and emissions. However, refueling an on-board hydrogen storage vessel would be challenging, and the amount of hydrogen needed to run a 200 kW fuel cell for 60 days would require approximately three 40-ft shipping containers full of liquid hydrogen, likely making it infeasible for safety and logistical reasons.

Cal Maritime is developing a sustainability center and an academy professor could be leveraged to provide project operation data and outreach. The fuel cell unit would become a showcase of the environmental initiatives of the campus and incorporated into the curriculum. Students, many of whom will become vessel operators themselves, will become familiar with fuel cell and hydrogen technology and the broader idea of cleaner ships. Overall deployment of a shore-based PEM fuel cell system at Cal Maritime to power a dedicated circuit aboard the TSGB seems a feasible and attractive option.

(Most information in this section comes from personal communications with on-site personnel [32])

4.9 The RiverQuest *Explorer*

Figure 4-22: The RiverQuest *Explorer* (90 ft. long) at berth on the Ohio River in Pittsburgh (image by RiverQuest).

Attributes: An educational/tour boat, claimed to be the first vessel in the world to be designed to LEED standards.
Power Status: Diesel-battery electric hybrid power plant, 300 kW capacity for propulsion (150 kW normally used), 55 kW auxiliary power.
Hydrogen and/or Fuel Cell Projects: Vessel is designed to accommodate a future fuel cell to be tied-in to the existing electrical bus.
Hydrogen Availability: Probable

The RiverQuest Explorer is a platform for "river-based educational adventure programs." It is unique in that it was designed not only with a diesel-battery electric hybrid propulsion system at its heart but also with provisions for future additions of fuel cells, solar photovoltaic, wind, and other alternative electrical generators (see Figure 4-23). The concept calls for the fuel cell to be mounted on the roof (see Figure 4-24). The educational mission of the vessel could include a highlight of the hydrogen and fuel cell technology on-board providing widespread visibility to the public and school groups.

It is unknown what volume or weight the roof can accommodate but it seems reasonable to expect that at least a 50-100 kW fuel cell would be acceptable. Vessel sailings last from 60-90 minutes. With a 100 kW fuel cell, about 3 kg of hydrogen would be needed and could be supplied by common gas cylinders. One aspect that deserves consideration is the method of refueling an on-board hydrogen tank or moving the delivered hydrogen to its on-board storage location. Provided these details are resolvable, the Explorer seems to be a straightforward and attractive application.

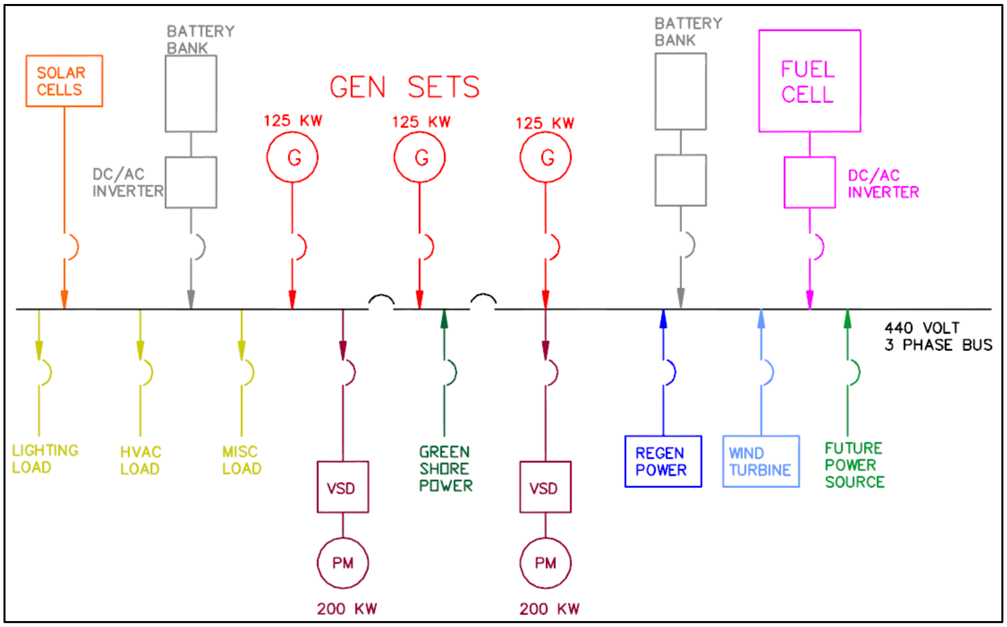


Figure 4-23: Electrical design schematic of RiverQuest's *Explorer*, showing provisions for fuel cell connection among other alternative energy sources [76].

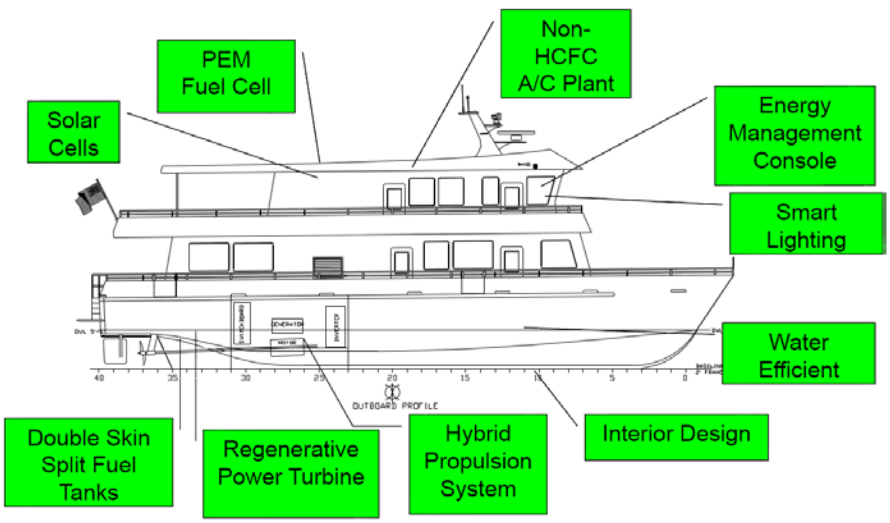


Figure 4-24: Outline design schematic of RiverQuest's *Explorer*, showing intended location of a PEM fuel cell (on the roof) to be added in the future [76].

5 CONCLUSIONS

This study has shown that a hydrogen-fueled PEM fuel cell system mounted on a barge can be a technically feasible option to provide electrical power for some types of vessels at berth or at anchorage. Vessels that are not likely to be technically feasible are cruise ships, refrigerated bulk carriers (reefer vessels), and some types of liquid bulk tankers. This is because their multi-megawatt power requirements and potentially long run times would necessitate multiple MW-class fuel cell units and impractically-large stores of hydrogen. Container ships are likely to be feasible, but their power demand depends primarily on the number of refrigerated containers (reefers) on-board. Estimates of average power use (1.4 MW) make them feasible but if estimates of maximum power (over 8 MW) are realized they would not be. Other vessels such as traditional liquid bulk tankers, auto/RoRo carriers, break and dry bulk carriers, fishing trawlers, ocean tugs, and harbor vessels are all technically feasible applications due to their sub-megawatt power requirements. For example, it was shown that two 40-ft shipping containers, one with a fuel cell and one with hydrogen, could provide 800 kW for nearly 2 days when using gaseous hydrogen, and for nearly a week with liquid hydrogen storage (see Table 3-1).

In addition to technical feasibility it is important for a solution to also be commercially attractive, because while technology demonstrations are valuable, the ultimate goal is successful industrial commercialization of a fuel cell solution. The consideration of commercial feasibility revealed that some target vessel types are not as favorable as others. These include all the bulk liquid tankers, reefer vessels, both dry and break bulk carriers. The reason is that to utilize shore power, any vessel needs to have specialized on-board equipment installed, and to achieve a reasonable return on investment for this additional cost, shore power would need to be frequently utilized. These types of vessels are typically not frequent visitors to a single port, meaning that investment in the infrastructure required is not likely to make economic sense for the vessel owner/operator. Although there are exceptions, auto/RoRo carriers typically are also not frequent visitors so it is likely they would not make commercially-successful applications either.

Finally it must be noted that of the remaining types (harbor vessels, ocean tugs, fishing trawlers, and container ships) the first three usually have shore power infrastructure installed at their home berths already. That means that a shore power barge would be most applicable to container ships at berth, assuming that their power needs can be adequately defined or restricted.

On the positive side, the current regulatory situation has resulted in a high likelihood of enthusiastic participation by the container fleets, especially those that have vessel traffic to/from California ports. Ironically, however, the applicability for these vessels would be when they are visiting ports outside of California (such as Portland (OR), and Tacoma and Seattle (WA)) since the major California ports are currently installing grid-supplied shore power capability at all container terminals. Thus, with proper design and coordination, a shore power barge with a hydrogen-fueled PEM fuel cell system for powering container ships at berth could become a commercially viable product.

It should be noted though, due to the upcoming regulations fleets are currently looking at alternatives and if a fuel cell solution is not presented soon it may not be adopted. Instead fleets may turn to other solutions, such as diesel-electric hybrids or CNG/LNG. Therefore, there currently exists a window of opportunity for PEM fuel cell cold-ironing that may not exist in a year or two.

Through the course of this study other technically and potentially economically feasible applications of a containerized fuel cell system for maritime power have been discovered. These include providing power for tugs while at anchorage using a barge-mounted system (Foss Maritime at the Port of Oakland), providing power for reefers on the dock and during transit aboard barges not equipped with electrical outlets (Young Brothers/Hawaiian Tug & Barge at Honolulu Harbor and neighbor islands), and providing power for Reserve Fleet vessels at anchorage (Suisun Bay Reserve Fleet). The first two options provide the most opportunity for commercial product success because they are (1) competing with higher-cost alternatives – diesel engines – and (2) have wide applicability outside of an initial host location. The last option, while potentially solving some maintenance issues is already grid connected and is a unique application.

In addition, several attractive shore-based PEM fuel cell system applications have been identified including powering fishing trawlers and other various vessels at berth (Pier 91 at the Port of Seattle), powering a maritime university training ship at berth (T.S. Golden Bear at the California Maritime Academy), and providing power for a DOT-MARAD office barge (Suisun Bay Reserve Fleet). In these cases, because an alternative source of electricity is already available, the addition of a fuel cell solution is not likely to result in a cost savings. However, a demonstration is likely to succeed and perhaps similar applications that are commercially viable will be found.

Finally, installation of a PEM fuel cell on a vessel for propulsive power is another feasible option (RiverQuest's *Explorer*). This fuel cell-ready application is an easy first step for a demonstration, but the commercialization potential is unknown. The potential market for on-board fuel cell power may be worth examining in more detail since the number of boats sold in the U.S. each year is large - in the hundreds of thousands.

Overall, a containerized hydrogen-fueled PEM fuel cell system would seem to have several technically feasible applications in the maritime environment that can be leveraged into commercial products.

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