Hydrogen Based Shipping Industry

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Abstract With environmentally clean ocean going vessels becoming a requirement for future generations of cargo and other types of ships, the maritime industry is interested in hydrogen as potential fuel for future technologies. An advanced system used to create a viable shipping economy based on hydrogen is the subject of this paper. The combined use of tidal, wind, wave and solar energy for generating electricity will provide sufficient power to generate hydrogen to use as fuel for ships.

Keyword: *hydrogen, ships, maritime industry, cargo, renewable, sustainability*

1. Introduction

Historically, the shipping industry relied on wind power for commerce. Large sail boats carried goods from Asia to Europe and other destinations. The Industrial Revolution and subsequent trade expansion by end of twentieth century resulted in the creation and use of powerful cargo ships and tankers to carry goods between continents. Although this transition from sails to combustion drive was a necessary part of human history and the development of the shipping industry, it is not a sustainable option and contributes to environmental problems that carry consequences for humans and wildlife.

Confidential data from maritime industry insiders indicates that, based on engine size and the quality of fuel, fifteen of the world largest ships may now emit as much pollution as all 760 million cars currently on the road worldwide. Pollution from the world‘s 90,000 cargo ships has been shown to contribute to 60,000 deaths a year in United States of America alone and costs $330 billion per year in health costs [1]. The average family in US has 110 tons of carbon foot-print, and the average family of four in the rest of the world has a 22-ton carbon footprint. Compare this to a 150‘ (45.7m) yacht to running for 1000 hours at 12 knots and producing 50 times more of a carbon footprint than the average world family of four! [2] The transportation sector accounts for a large fraction of air pollutant emissions. Health and environmental effects of air pollutants (NOx, CO, VOCs particulates) are leading to stricter restrictions on tailpipe emissions worldwide [5].

These statistics, supported by the fact that transportation and heating contributes about two thirds of all greenhouse gas emissions, make it apparent that that low- or zero- current carbon fuels will be needed to meet future carbon emission reduction goals.

The following statements place emphasis on how important it is to jump start a new era of hydrogen shipping in maritime industry:

"A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy resources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants."

-The National Academies The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D

Needs February 2004

"Imagining the hydrogen energy economy is easy enough for visionaries and dreamers, but ultimately it doesn't happen unless scientists and engineers overcome technical obstacles, entrepreneurs take risks, corporate boards commit capital, and consumers choose. What is remarkable about our efforts is that the visionaries and the pragmatists are working together, in close partnership, to make the hydrogen energy economy a reality."

-David K. Garman, Under Secretary, U.S. DOE May 23, 2005

New pivotal projects such as the Low Power Recreational Fishing Boat presented at International Conference on Ecologic Vehicle and Renewable Energies in 2007[3] and the Small Hydrogen and Solar Boat that uses sails as primary propulsion (July 2008) [3,4 have established a new, economically feasible green options and support the above sentiments. Hydrogen refueling infrastructure demonstrations are now commonly conducted as part of hydrogen vehicle demonstrations. Thousand Palms, California is building a hydrogen refueling station to convert methane to hydrogen using a partial oxidation reformer as part of the California Fuel Cell Partnership. A list of worldwide hydrogen fuel stations is published in reference [6]. The Clean Urban Transport in Europe (CUTE) program is planning demonstrations of 27 hydrogen fuel cell buses in nine European cities, including hydrogen infrastructure demonstrations. The Global Environment Facility is planning demonstrations of 30 fuel cell buses in developing countries. [7] These developments highlight the movement to use new, eco-friendly technologies and apply them to the transportation industry. Many can be translated to the maritime shipping industry. While having undergone reasonable improvements through new technology leading to better fuel economy, maritime shipping still producing an unacceptable amount of waste thereby negatively impacting the environment and contributing to downstream health and sustainability issues. Laying down the foundation for hydrogen based commercial shipping will serve to improve an industry that is in need of drastic change.

I propose the use of small scale underwater tidal generators, wind turbines, wave energy conversion mechanisms and photo-voltaic devices placed along coastal areas to produce electricity and supply energy to hydrogen reformers. The hydrogen produced by many low kilowatts generators can be pumped into large underground storage containers. Hydrogen fuel cell powered boats can stop to be refueled by such hydrogen service stations. These boats are also able to supplement hydrogen fuel by using electricity produced by solar and wind energy on their on board, low scale hydrogen generating plants. This wave of hydrogen 'farming' will not only supply emission free fuel to the shipping industry, it will create a new market that provides jobs to hydrogen 'farmers' along coastal areas. It also provides a new vision for the next generation of small to medium horse power ships produced. It may sound far fetched for application in the near future, but the technology exists for such an endeavor.

Globally, the number of cargo ships and subsequent energy needs are projected to grow rapidly in the next few decades. We have witnessed a rapid rise in the price of oil just a year ago, and continued reliance on carbon fuels for shipping drive technologies will have significant impact on air and water pollution and greenhouse gas emissions,. Fossil fuel supplies are being depleted at an exponential rate and our reliance on foreign fuel supplies is not realistic for the future; therefore, the prospect of shipping fueled by a secure, sustainable energy source is one of great interest to the maritime industry.

2. Hydrogen Based Shipping Technology

A variety of renewable energy sources such as tidal, wind, wave energy and solar power can be used to produce sufficient energy for hydrogen production from water or other reforming technologies. The hydrogen acts as fuel for Proton Membrane Fuel Cell and the output is usable electricity. This energy, combined with electronics, will be used to drive a variable frequency three-phase electric motor as seen in

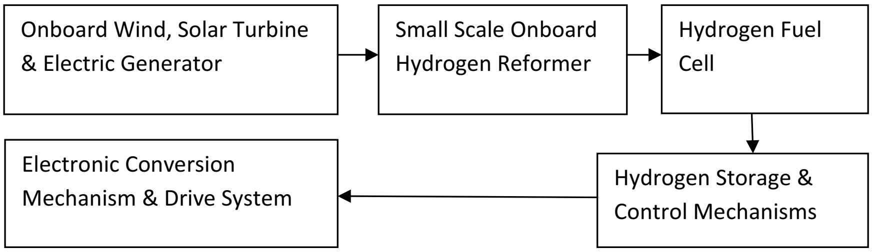

Fig.1 Onboard fuel generation and conversion mechanism and drive system

One notable issue to address is scale weight loss in conversion. For example, an internal combustion car engine (ICEV) of the same size and capacity requires 74% more parts than Hydrogen Fuel Cell engine and is fifty percent more efficient than ICEV. Existing research and software simulations studies suggest new ways to improve on this efficiency.

Classifying vessels by their specific power needs will also aid in determining what is needed to develop a hydrogen based shipping infrastructure. In particular, the locations of fueling ports and development of the ships' drive systems need to be established.

Using technology developed for automobile hydrogen refueling stations and applying it to Marine Energy and Refueling Port (MERP) is feasible, however, more studies need to be conducted to relate the two systems. Here are a few proposed models:

1. The first model is suitable to coastal areas where a hydrogen pipeline is part of an existing infrastructure to bring energy to urban and coastal areas. The MERP's can be integrated into this system and could simply contain small storage and fueling stations.
2. The second model is based on a distributed, small scale local supply for hydrogen shipping. This model encourages complete reliance on renewable energy resources such as tidal, wind, solar and, where available, wave energy.

Marine Energy & Refueling Ports can be non-intrusive, small islands attached to coastal or off-coastal area where maximum energy yields can be harvested from wind, wave and tidal currents. The MERP will house a compatible hydrogen reformer, low pressure hydrogen storage and a fueling station. In addition, these structures should house a vertical axis wind turbine, a vertical axis tidal turbine, photo voltaic panels and the appropriate electronics necessary for control and conversion. The technology needed to create this infrastructure already exists and funding for future development of technologies is readily available.

3. Shore-Side Infrastructure

The Department of Energy (DOE) has made it clear that it intends to make hydrogen the dominant fuel for maritime transportation. The following are statements have been issued by the DOE:

- *Develop large-scale, cost-effective hydrogen production methods that make the cost of hydrogen competitive with gasoline. A significant component of this production must ultimately come from sources that are not dependent on fossil fuels or do not produce carbon emission.*

- *Develop storage methods for hydrogen to provide an adequate capacity for the next generation vehicles.*
- *Develop technologies that use hydrogen efficiently for the wide range of industrial and for hydrogen Transportation."*

In order to demonstrate the feasibility and commercial viability of hydrogen as fuel for commercial maritime shipping industry, we should build a few small floating ports which supports, tidal generators, vertical axis wind turbines and a number of solar panels, a hydrogen reformer, a low pressure hydrogen storage and fueling station. The electric energy generated by solar, tidal and wind will generate electricity to be used for hydrogen production as seen in the diagram below.

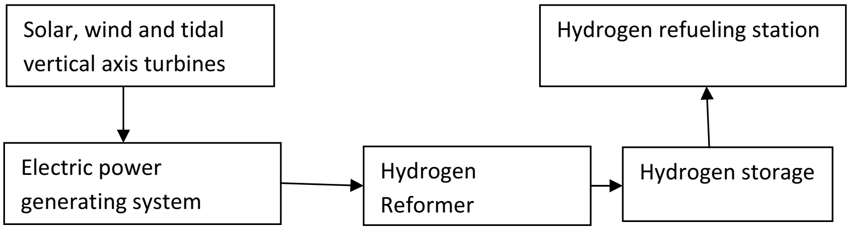

Fig. 2 Marine Energy & Refueling Port

4. Hydrogen Reforming Techniques

Hydrogen is abundant in nature. The best source is water, although the hydrogen density in gasoline, methane and other hydrocarbons are higher. But in the maritime shipping industry water will suffice. To understand the basics for measuring energy related question, let us compare hydrogen to gasoline.

There are different technologies for hydrogen production. Detailed discussion and capacities of hydrogen reformers is addressed in recently published findings [8, 9, 10]. Here is a brief look at most promising technologies that could be utilized in commercial shipping:

I. Electrolysis is an efficient and emission free method for generating hydrogen. In this process, electricity is used to separate water into its constituent elements (hydrogen and oxygen) by passing an electric current between positively and negatively charged electrodes. The hydrogen and oxygen are isolated from each other after electrolytic reaction using a highly efficient inorganic membrane and then channeled to separate hydrogen and oxygen vessels. This technology produces very pure hydrogen at pressures of 363 psi [9]. Power consumption is 4.8 kilowatts-hour per 10,000liters/hr, which are approximately 167 standard liters/minutes. This amount of hydrogen production is enough to supply fuel to an 8KW (10.7 hp) hydrogen fuel cell. There are reformer units that produce up to 60,000 liters/hr. These units are the size of a typical container (20-ft in length).

II. Methanol cracking technology for hydrogen generation is another on-site, on-demand method. This technology was reported in 2002 [10]. For the production of 1000 Nm^3/h H2 = 16,700liters/minutes from methanol the following utilities are required:
650 kg/h methanol, 360 kg/h de-mineralized water, 13 m^3/h cooling water and 50kW/h of electricity.

This plant will supply hydrogen to twenty one 65 Kilowatts hydrogen fuel cell units

(HyPM-HD65 model). The total power delivered to the vessel will be 1380.8 KW which is equivalent to 1853 horse power per container, sufficient to power ships

III. Steam Reforming Technology operates at higher temperatures 800-900 C. It produces hydrogen at 10-25 bar and requires 0.46Nm^3 methane to produce 1Nm^3 of hydrogen. There are small scale reformers, which works at lower temperatures as well. This process is used for large scale hydrogen production.

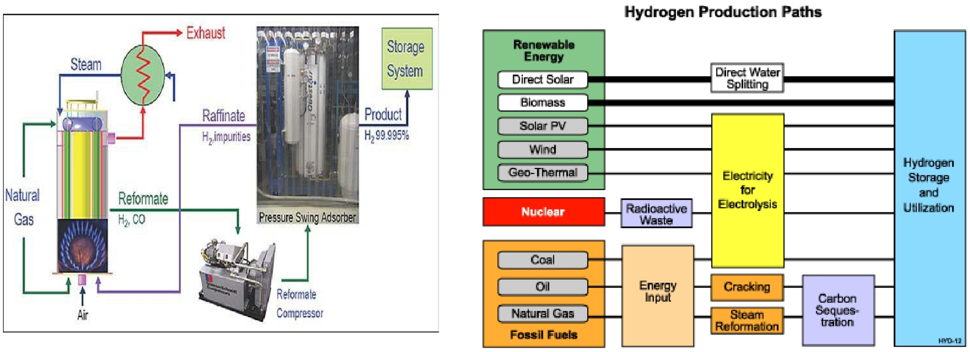

Fig. 3 left- H2 Natural Gas, steam reformer, right- H2 production path ways. Source DOE

This reforming technique could be used to produce hydrogen from other liquid fuels

Methane: $CH_4 + H_2O + HEAT \rightarrow CO + 3H_2$

Propane: $CH_8 + 3H_2O + HEAT \rightarrow 3CO + 7H_2$

Ethanol: $C_2H_5OH + H_2O \rightarrow 2CO + 4H_2$

Gasoline $C_8H_{18} + 8H_2O + HEAT \rightarrow 8CO + 17H_2$

Carbon-monoxide is removed by water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

The goal set by DOE for \$2-\$3 per gallon of gasoline equivalent (gge) for hydrogen will be achieved [11]. There is no doubt that if small scale reforming facilities mainly using electrolysis are in placed along coastal areas, the combination of wind, wave, solar and tidal energies could produce hydrogen at lower prices.

Hydrogen Storage

Hydrogen storage is critical for use in transportation. The storage of hydrogen is one the most contentious topics in debate about the safety of hydrogen based shipping industry. The sooner we could come to a conclusion on this subject, the better it is for all sides in this debate. There are compact safe storage tanks built for cars and buses currently in use. The hydrogen storage tank designed and manufactured by Quantum Storage, a California based company, is used in the GM Sequel, the NASA Helios Plane and many other automobiles. These light weight storage tanks give GM cars a range of 300 miles per filling. There are other trends in hydrogen storage research and developments which could revolutionize transportation sectors. These technologies include: hydrogen storage in magnesium clusters [12], micro-porous metal-organic structures [13], and carbon nano tubes [14].The status of storage technology and final goals put forth by DOE are well documented in [15]. There are many other studies on hydrogen storage techniques and technologies. Here are a few described by the DOE:

Compressed tanks [5000 psi (~35 MPa) and 10,000 psi (~70 MPa)] have been certified worldwide according to ISO 11439 (Europe), NGV-2 (U.S.), and Reijikijun Betten (Iceland) standards and approved by TUV (Germany) and The High-Pressure Gas Safety Institute of Japan (KHK). Tanks have been demonstrated in several prototype fuel cell vehicles and are commercially available. Composite, 10,000-psi tanks have demonstrated a 2.35 safety factor (23,500 psi burst pressure) as required by the European Integrated Hydrogen Project specifications. The energy density of hydrogen can be improved by storing hydrogen in a liquid state. However, the issues with LH_2 tanks are hydrogen boil-off, the energy required for hydrogen liquefaction, volume, weight, and tank cost. The energy requirement for hydrogen liquefaction is high; typically, 30% of the heating value of hydrogen is required for liquefaction. New approaches that can lower these energy requirements and thus the cost of liquefaction are needed. Hydrogen boil-off must be minimized or eliminated for cost, efficiency, and vehicle-range considerations, as well as for safety considerations when vehicles are parked in confined spaces. Insulation is required for LH_2 tanks, and this reduces system gravimetric and volumetric capacity. Liquid hydrogen (LH_2) tanks can store more hydrogen in a given volume than compressed gas tanks. The volumetric capacity of liquid hydrogen is 0.070 kg/L, compared to 0.030 kg/L for 10,000-psi gas tanks. Liquid tanks are being demonstrated in hydrogen-powered vehicles, and a hybrid tank concept combining both high-pressure gaseous and cryogenic storage is being studied. These hybrid (cryo-compressed tanks) insulated pressure vessels are lighter than hydrides and more compact than ambient-temperature, high-pressure vessels. Because the temperatures required are not as low as for liquid hydrogen, there is less of an energy penalty for liquefaction and less evaporative losses than for liquid hydrogen tanks.

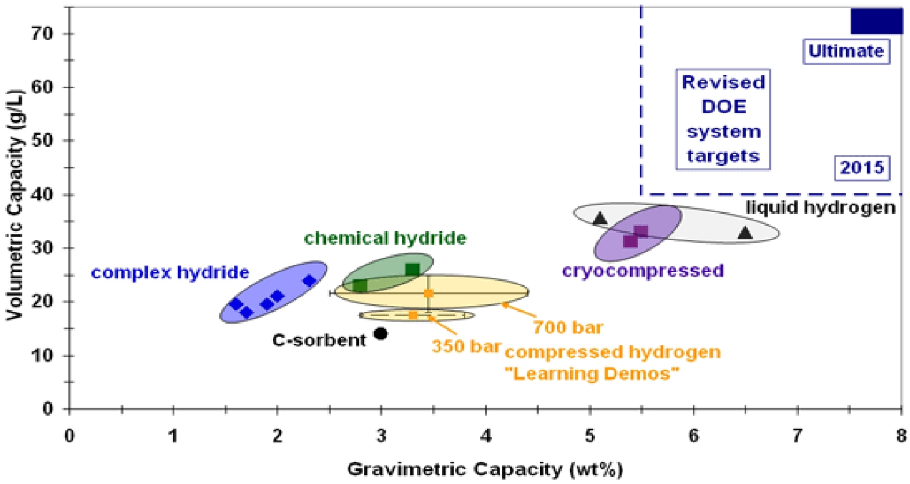

Fig. 4 Hydrogen Storage status

5. Proton Exchange Membrane Fuel Cells (PEM)

The hydrogen fuel cell is the heart of this technology. It converts hydrogen to electricity. There are many types of fuel cells [16]. This technology was invented by General Electric in the 1950s and was used by NASA to provide power for the Gemini space project. It is now the fuel cell type auto companies consider to be the most promising replacement for the internal combustion engine. PEM fuel cells are also known as Polymer Electrolyte Membrane, solid polymer electrolyte and polymer electrolyte fuel cells. In the PEM fuel cell, the electrolyte is a thin polymer which is permeable to protons, but does not conduct electrons. The electrodes are typically made from carbon. Hydrogen flows into the fuel cell on to the anode and is split into hydrogen ions (protons) and electrons. The hydrogen ions permeate across the electrolyte to the cathode, while the electrons flow through an external circuit and provide power. Oxygen, in the form of air, is supplied to the cathode and this combines with the electrons and the hydrogen ions to produce water. PEM cells operate at a temperature of around 80°C. At this low temperature the electrochemical reactions would normally occur very slowly so they are catalyzed by a thin layer of platinum on each electrode. This electrode/electrolyte unit is called a Membrane Electrode Assembly (MEA) and it is sandwiched between two field flow plates to create a fuel cell. These plates contain grooves to channel the fuel to the electrodes and also conduct electrons out of the assembly. Each cell produces around 0.7 volt to run a light emitting diode, in contrast to around 300 volts needed to run a car. In order to generate a higher voltage, a number of individual cells are combined in series to form a structure known as a fuel cell stack. PEM fuel cells have a number of attributes that make them ideal candidates for use in automotive applications and small domestic applications, such as replacements for rechargeable batteries. They operate at relatively low temperatures which allow them to start up rapidly from cold and have a high power density which makes them relatively compact. In addition, PEM cells work at high efficiencies, producing around 40-60 per cent of the maximum theoretical voltage, and can vary their output quickly to meet shifts in power demand. There are many companies offering fuel cells ranging from low kilowatts to 250 kW fuel cell units. Department of energy lists the following reforming techniques, as leading technology to be implemented: [17, 18]

Alkaline (AFC)	10-100 KW
Phosphoric acid	250 KW modules
PEM	250 KW modules
Molten carbonate	250 KW modules up to 1 MW
Solid oxide	up to 3MW

Studies show that the price of fuel cells will dramatically fall and will be comparable to $30/kW, the price for ICE. The studies also point to the fact that in many cases hydrogen fuel cell technology surpasses goals set by DOE.

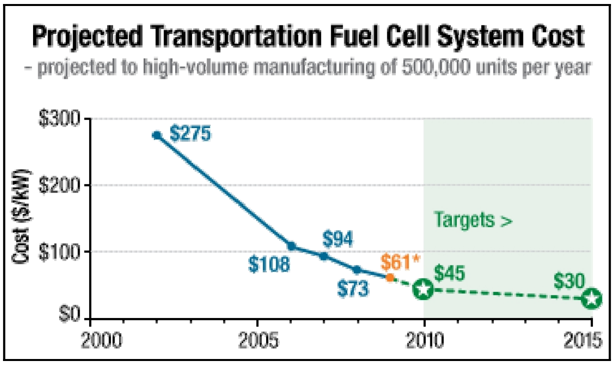

Fig. 5

6. The Drive System

The diagram below depicts all necessary control and drive mechanism. The output of the fuel cells is fed into inverters and transformers to produce high voltage variable frequency power for a synchronous three-phase motor. A typical drive system will be compromised of the components depicted in fig. (6)

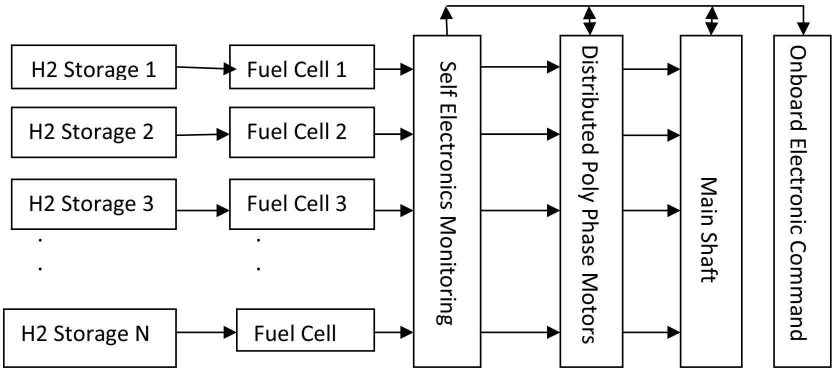

Fig. 6 Drive System

The idea here is to design a distributed storage, fuel cell and motor drive system. Sections of the main shaft will serve as the rotors of multiple stators of the three phase motors, which deliver power to the ship. Each section will have a separate fuel cell and hydrogen supply. The use of three phase or multi-phase motors will allow the bridge operator to supply torque on demand and therefore increase the system efficiency. The human operator will be complemented by an electronic auto pilot. Each motor has an independent fuel cell, electronic conversion mechanism and hydrogen generating unit . The individual drive station will have Self Electronic Monitoring Unit (SEMU) and reports the operating characteristics to an Onboard Electronic Command Unit (OBECU).

The challenge is up to naval architects to design a hydro and aerodynamic cargo ships, with double hulls. This will serve two purposes. First it will house the cover while the cargo ship is loading and unloading. Second, it will further provide protection in case of accidents and promotes safe shipping. The aerodynamic cover serves as holding surface for high efficiency solar panel and will be retrieved to the spacing between hulls while in port. Once the cargo ship leaves the port the photo-voltaic surfaces will generate some power to support on board hydrogen production.

Cost analysis

At this point the only reference for commercial shipping we have is the energy balance. One gallon of gasoline is equivalent to approximately 120,000 BTU and hydrogen produces 116, 000/kg. It could be estimated that the price of one million BTU is about $8-$9 in US, assuming one US dollar per gallon of gasoline. Hydrogen production by means of electrolyses is the cleanest and the cost will be $20/million BTU and $28/million BTU including liquefying process and storage costs. Most of the cost is the cost of electricity which we estimated at $0.045/kWh. If wind, wave and tidal energies are used to produce electricity, the price will drop to $13/million BTU, and the environment will not be polluted by the 2.9 kg /1Nm3 of CO2 produced if fossil fuel is used for generating electricity. If we look at the larger picture of hydrogen shipping economy versus fossil fuel, it becomes clear that after adding carbon tax and health care costs, the move towards a hydrogen economy make sense.

There is no cost analysis for the shipping using hydrogen as fuel, but there are extensive studies related to land transportation [14, 15]. They show fuel options for cars and discusses different options and detailed analysis of:

a. Extra vehicle cost
b. Fuel cost
c. Infra-structure investment cost
d. Air pollution on local level
e. Greenhouse emissions
f. Oil imports/ national security
g. Long term sustainability

The paper considers three options for hydrogen fuel used in cars.

1. Direct hydrogen fuel cell vehicle
2. Gasoline partial oxidation Fuel cell vehicle
3. Methanol FCV

7. Conclusion and Recommendations

(1) It is clear that there is a need for new ships to use alternative energy resources. This need is based not only on environmental considerations, but on security considerations and inadequate fossil fuel supply.

(2) Hydrogen is the future fuel, based on the latest advances in fuel cell design and hydrogen reforming techniques. There are many options for hydrogen reforming. Research shows that on-site, on-demand hydrogen production is not just a vision for future, but it is a reality. More research is needed to miniaturize the hydrogen production facilities. The trend in cost of hydrogen will go down as the capacity of hydrogen generating stations increases. There are many hydrogen fueling stations in operation and researchers are working to improve the efficiency of hydrogen production using solar energy for methanol based fueling stations. Many such stations are functioning in Europe, and some has been installed in California.

(3)Collaboration among marine engineers, electrical engineers, naval architects and hydrogen related specialists is the key to initiate a vigorous debate and construct a cargo ship with onboard hydrogen generating station, fuel cells, photovoltaic panels and electric motors. There are safe storage devices for hydrogen, so the ship could be designed to have its own hydrogen storage instead of carbon based fuels.
(4)Organizations and groups should be formed to establish worldwide standards and criteria for shipping, parallel to Department of Energy DOE and International Energy Agency (IEA) components destined to be used on hydrogen commercial marine ships and Marine Energy & Refueling Ports.

References

[1] Jennifer Guevin — Global shipping pollution ain't pretty Green Tech. Feb.26, 2009
[2] Jean-Francois — compact hydrogen fuel cell solutions for recreational fishing boats International Conference on Ecologic Vehicle & Renewable Energies, March-April 2007
[3] John Vidal, Environment editor , guardian.co.uk
[4] Mike Horn — Solar and hydrogen fuel cell boat prepares for voyage Plenty Magazine, July 17, 2008
[5] Dr. Joan M. Ogden , Center for Energy and Environmental Studies, Princeton University,
[6] www.fuelcells.org
[7] www.thegef.org
[8] Jaesung Han, Sue-Kim, Keun-Seob Choi — High purity hydrogen generator for on-site hydrogen production Science Direct, Jan. 2002
[9] T. Tani, N. Sekiguchi, M. Sakai and D. Ohta — Optimization of Solar hydrogen based on hydrogen production. 2000 Elsevier Science Ltd.
[10] Edward G. Skolnik , Christina Y. TeMaah, Bryan G. Towns —Analysis of a hybrid production system using a solar reactor and steam methane reformer,
Energetics, Inc.
[11] *Peter Neumann, Florian von Linde* Options for economical supply of hydrogen
www. caloric.com
[12] Hydrogen Resources Assesment, Technical Report, NREL 2008
[13] Anne C. Dillon, Director Lin J . Simpson, Deputy Director National Renewable Energy Laboratory. Overview of the DOE Hydrogen Sorption Center of Excellence, May 2009
[14] Michelle V. Buchanan, The Hydrogen Economy: Opportunities for Fundamental Research to Address some Grand Challenges. Chemical Sciences Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
[15] DOE, April 2009 Technical Plan — Storage
[16] Hydrogen Fuel Cells www.hydrogen.energy.gov
[17] C.E. Thomas, Brain D. James, Frank Lomax Jr, Ira F. Kuhn — Fuel Options for Fuel Cell Vehicle, hydrogen, methanol or gasoline? International Journal of hydrogen energy, 25(2000)
[18] www.hydrogenics.com
[19] Robert Rose, Breakthrough Technologies Institute www.fuelcells.org
[20] HYDROGEN, FUEL CELLS & INFRASTRUCTURE TECHNOLOGIES (HFCIT) ROGRAM Pathways to Commercial Success
[21] www. eere.energy.gov/ hydrogen
[22] C.E. Thomas, Brian D. Lomax Jr, Ira F. Kuhn, Fuel Option for the Fuel Cell. Hydrogen, methanol or Gasoline? International Journal of Hydrogen Energy 25(20000 551-567
[23] **Low-Cost Hydrogen Distributed Production System Development**Frank Lomax, Ph.D., P.E. – Principal InvestigatorC.E. Thomas, Ph.D., Maxim Lyubovsky, Ph.D., Rick Todd, Ph.D., Chris Van Dyke, Ed McCullough, Nick SazdanoffH2Gen Innovations, Inc.May 15, 2007PD2