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Challenges towards fuel cell adoption on board merchant ships

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CHALLENGES TOWARDS FUEL CELLS ADOPTION ON BOARD MERCHANT SHIPS

By

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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ABSTRACT

Title of Dissertation	:	**Challenges towards fuel cells adoption on board merchant ships**
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This dissertation is attempting to focus on fuel cells adoption onboard merchant ships, illustrate current status, prove future opportunities, investigate the barrier, and find solution for promoting fast adoption.

The qualitative approach was utilized to review the development and identify the barriers. Further research was conducted through a survey for which respondents were chosen from maritime administrations, classification societies, shipbuilders, ship owners and fuel cells makers. Statistical analysis was conducted in descriptive and chi-square analysis.

There are 41 existing fuel cells projects in surface ships which were identified from open literature. Those projects were dominated by small vessels, mostly yachts or sailboats, with few numbers of water taxis, a whale watching ship, an offshore vessel and a car carrier. However, this could demonstrate different fuel cells technology in different applications; furthermore, current increasing number of projects shows opportunity on future development.

The environmental issues act as the main driver of fuel cells adoption; however, technical and economic considerations such as fuel and infrastructure, volumetric size, ships integration issues, lifetime, high initial cost and operational cost effectiveness are still a significant barrier. Additionally, regulations and legislation also remain a challenge.

Through a questionnaire, it was significantly proven that different job categories have different levels of familiarity. Different opinions mostly occurred on technical factors. Respondents with low level of familiarity tend to have less confidence to technical capability of fuel cells. The identified factor which was perceived differently by them was reliability. In addition, different job categories tend to pay more attention on different factors.

Considering the existing development, for the short term, fuel cells could be promoted to be adopted in vessels which take advantage of noiseless and less vibrations, and also for less emission in harbors and inland waters. Furthermore, diffusion of existing technology should be forwarded through wider publicity taking into consideration the focus attention of maritime stakeholders.

Key words : fuel cells, adoption, barrier, merchant ships

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LIST OF ABBREVIATIONS

AC	Alternating Current
AFC	Alkaline Fuel Cells
AIP	Air Independent Propulsion
APU	Auxilary Power Unit
AUV	Autonomous Underwater Vehicle
BoP	Balance of Plant
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAFC	Direct Alcohol Fuel Cells
DC	Direct Current
DCFC	Direct Carbon Fuel Cells
DNV	Det Norske Veritas
DWT	Dead Weight Tons
E/S	Environmentally sound Ship
FC	Fuel cell
FCS	Fuel Cell Ship
GHG	Green House Gas
GT	Gross Tonnage
H_0	Null Hypothesis
H_2	Hydrogen
IMO	International Maritime Organization
kW	Kilo Watt
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas
MCFC	Molten Carbonate Fuel Cells
MEPC	Marine and Environmental Protection Committee MEPC Marine and Environmental Protection Committee
MW	Mega Watt
NYK	Nippon Yusen Kabushiki Kaisha
NO_x	Nitrogen Oxide
PAFC	Phosphoric Acid Fuel Cells
PEFC	Polymer Electrolyte Fuel Cells
PEM	Polymer Electrolyte Membrane / Proton Exchange Membrane
$PM_{2.5}$	Particulate Matter with particles smaller than 2.5 µm
ppm	Part per millions
R&D	Research and Development
SOFC	Solid Oxide Fuel Cells
SO_2	Sulphur Dioxide
EU	European Union

1. INTRODUCTION

1.1 Background

The environmental challenge particularly related to ship emission remains an essential problem which has to be solved. Carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), hydrocarbons, and primary and secondary particulates are noted as the most important ships emission pollutants due to their role as e.g. greenhouse gas, their contribution to acid rain, and/or their impact on human health. Some studies recently showed that ship emissions lead to an increase in ambient air concentrations of fine particles with diameter less than 2.5 μm ($PM_{2.5}$) which are responsible for premature deaths increasing due to cardiopulmonary diseases and lung cancer (Mathias, 2010). If measures are not taken to counter these environmental problems, it is clear that in the future the impact from global shipping will be getting worse.

A great deal of research has been done to deal with emission problems and it seems that opportunity remains open to solve these problems economically. As an example, in December 2009 Det Norske Veritas (DNV) issued *Pathway to Low Carbon Shipping* where their study shows that in 2030 CO_2 emission can be reduced by 500 MT or 30% below the baseline in a cost effective way. Almost 60% identified measures are included and although there is no single measure that could reach that figure, aggregated effect of all measures will be significant (DNV, 2009). In this study, the fuel cells as auxiliary engine have been chosen by DNV as one of the measures.

Fuel cells technology, which is already applied in many land based systems, is one of many green technologies that have started to be introduced on board vessels. Zero emission ships as one of the future goals of the maritime sector definitely position fuel cells application as one of the alternatives to achieve this goal. One of the advantages of fuel cells over other technologies is environmental effect of it. The fuel cells have minimum impact of the environment; the only 'exhaust' is water and heat. If carbon contains fuel, for instance natural gas used as fuel, there will be CO2 in its exhaust; however compared to diesel engines run on marine bunker fuel, it will be reduced up to 50% (Marine, 2009). People may argue that nowadays there are several onboard cleaning technologies for conventional marine machinery, such as scrubber technology and catalytic reactors to reduce air emission. However, this technology is generally effective only for specific pollutants; several systems need to be installed to reduce several pollutants (Tronstad, 2004). Other advantages of fuel cells are minimized noise, vibration and less maintenance is required. Fuel cells also offer greater efficiency, have good modularity/part load performance and it have a multi fuel choice.

Actually the invention of fuel cells technology has started in beginning of 19th century and there must be a reason why this technology has not developed faster than others, especially onboard ship. Technology tends to increase faster if it is proven reliable and affordable. One of the possible reasons is there are many people still doubting its future prospect, both technically and economically.

In case of fuel cells adoption, Weaver (2002) in his book "World Fuel Cells: An Industry Profile with Market Prospects to 2010" has observed that apart from the established application of fuel cells in submarines, maritime applications have been slow to develop and any significant market is not expected to emerge until after 2010.

Nevertheless, realizing the opportunity offered by fuel cells application, the real reason for slow adoption should be discover, whether there is any significant technical and operational disadvantage acting as barrier of its adoption or other economic reason giving significant effects on the new technology adoption.

Additionally, all maritime stakeholders have contribution to the adoption. It is possible that among these people have different opinions regarding fuel cells adoption onboard merchant ships, which could cause contra productive action in accelerating the adoption. The fuel cells makers are the one who really know about recent fuel cells development. They could have different perceptions with ship owners and ship builders who use the technology, as well as maritime administrations and classification societies who establish regulation and legislation to support the adoption. Although there are many papers written about fuel cells, none of them uncover the perception of maritime stakeholders on this issue to find solution in promoting this green technology.

Therefore, this dissertation is attempting to focus on fuel cells adoption onboard ships, investigate the barrier, prove future opportunities and find a solution for promoting fast adoption.

1.2 Objectives of the study

The objectives of the study are to:

a. Illustrate current status of fuel cells by reviewing the development and existing demonstration project of fuel cells on board ships
b. Find reasons of its slow adoption by identifying the barrier of fuel cells implementation onboard ships
c. Identify whether there are different opinions of maritime stakeholders (ship owners, ship builders, maritime administrations, classification societies and fuel cells makers) which possibly influence acceleration of fuel cells adoption on board merchant ships.
d. Identify how to promote adoption of fuel cells on board merchant ships.

1.3 Research methodology and organization of dissertation

Firstly, the research utilized a qualitative approach in reviewing the development of fuel cells. Barriers and challenges of fuel cells adoption are identified through information gathered from literature review such as journals, books, research reports, IMO conventions and documents, classification standards, and all related documents.

Then, further research will be conducted through a questionnaire which contains close and open ended questions regarding factors influencing adoption/application of fuel cells on board merchant vessels. Respondents will be chosen from maritime administrations, classification societies, shipbuilders, ship owners and fuel cells makers. Statistical analysis will be conducted in a descriptive and chi-square analysis using an SPSS program. In addition to identification of barriers and challenges towards fuel cells adoption on board ship, through this questionnaire different points of view from different stakeholders who could influence barriers and challenges will also be identified.

Accordingly, the dissertation work is divided in five chapters. The topic is introduced in chapter one, with preliminary background and the identified problem. The objective of study is also explained in this chapter. Chapter two presents literature review regarding fuel cells basic explanation and history of its development. An existing demonstration project on surface ships is presented to show future opportunity as an emerging technology.

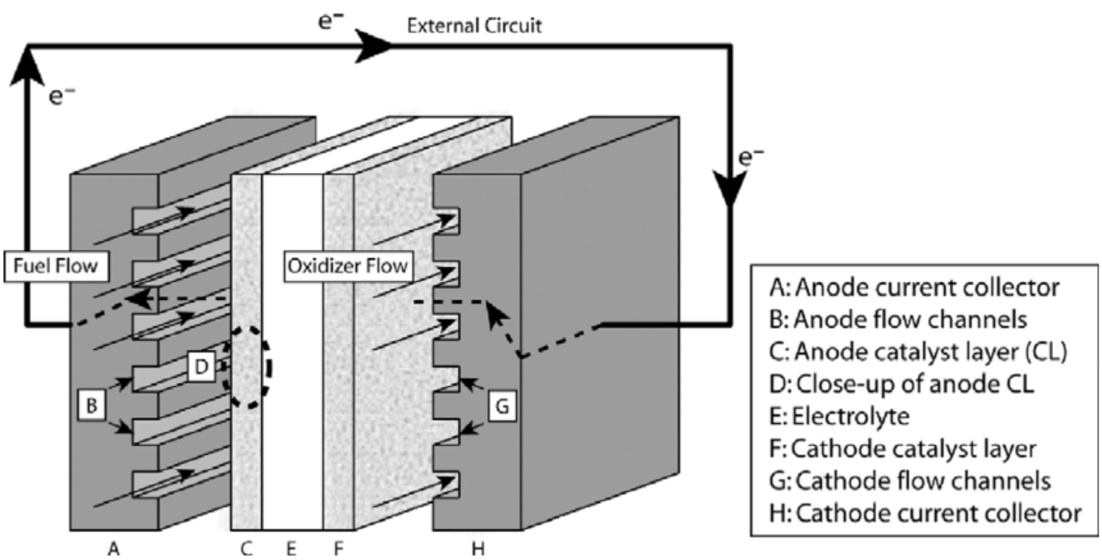
In chapter three, factors influencing the adoption are being analyzed. All barrier factors which make people tend to doubt fuel cells application onboard ships are identified. Then, existing scientific invention and other possible driving forces are utilized to negate the barrier. Referring to road transport application, projection of fuel cells penetration in marine application is also being reviewed in this chapter.

Chapter four focuses on survey of maritime stakeholders toward fuel cells adoption onboard merchant ships. It explains how the survey was conducted and analyzes the result of the survey. Finally, compiled findings and analyses from questionnaires and literature review will be concluded in chapter five.

2. FUEL CELLS BASIC PRINCIPLES AND ITS DEVELOPMENT ON MARINE APPLICATION

2.1 Basic principle of fuel cells

Fuel cells are electrochemical devices that directly convert chemical energy in fuels into electrical energy. Since the intermediate steps of producing heat and mechanical work typical of most conventional power generation methods are avoided, fuel cells are not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. In addition, because no combustion process is involved, fuel cells produce power with minimal pollutants (EG&G, 2004).



(Mench, 2008)

Figure 2.1 Schematic of an individual generic fuel cells

Basic physical structure of generic fuel cells is shown in Figure 2.1. Figure 2.1 shows that fuel cells consist of an anode (negative electrode) and a cathode (positive electrode) which are sandwiched around an electrolyte. Fuel is fed to the anode and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons. Electrons go trough the external circuit creating electricity flow. Protons migrate trough electrolytes to the cathode. Protons then reunite with oxygen and the electrons to produce water and heat (IEA, 2004).

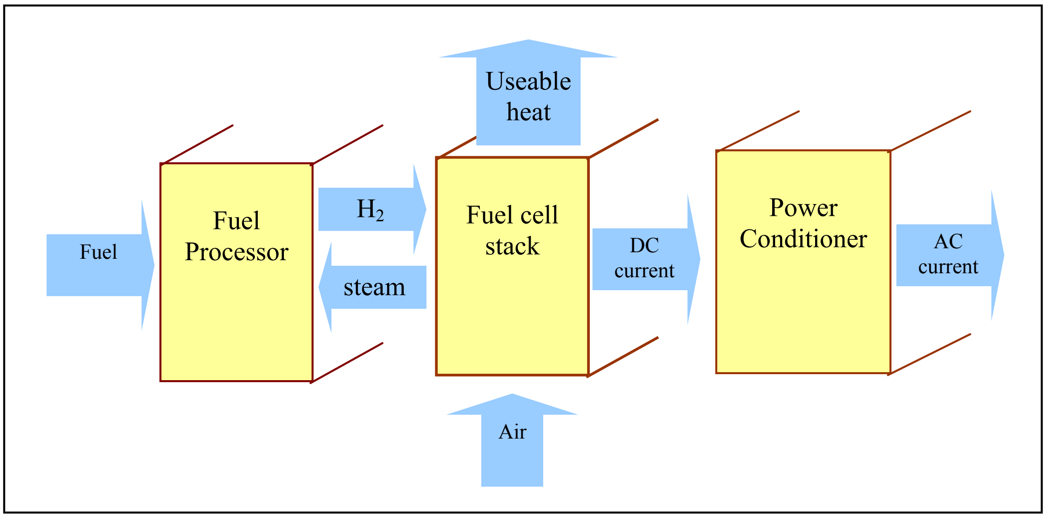


Figure 2.2 Major components of fuel cells power system

As shown in Figure 2.2, fuel cells power systems usually comprise a number of major components:

1. Fuel cells stacks, in which individual cells are modularly combined by electrically connecting the cells to form units with the desired output capacity. Theoretically, single fuel cells can achieve whatever current and power by increasing the size of electrode area and reactant flow rate. However, limited by fundamental electrochemical potential, for realistic operating condition, output voltage of individual fuel cells is always less than 1 volt. Therefore fuel cells stack consist of several individual cells connected in series.
2. Balance of plant (BoP) which comprises components that provide :
    - Feed stream conditioning (including a fuel processor if needed). The fuel processor or reformer has two important functions, namely to convert fuel to a hydrogen rich gas and to remove impurities from the hydrogen rich gas prior to its delivery to the fuel stack

- Air supply. In most practical fuel cells systems, this includes air compressors or blowers as well as air filters.
- Thermal management. All fuel cells systems require careful management of the fuel cells stack temperature.
- Water management. Water is needed in some parts of the fuel cells, while overall water is a reaction product. To avoid having to feed water in addition to fuel, and to ensure smooth operation, water management systems are required in most fuel cells systems.
- The power conditioner receives electrical power from the fuel stack and converts it to the required output. As fuel cells produce direct current (DC), if DC current is used in the application, the current may be used directly from the stack after providing voltage and power monitor and control, as well as power cut off devices. If alternating current (AC) is required, the inverter is incorporated into the power conditioner.
- Fuel cells controller with a number of functions: control supplemental power during start up operation, stack cooling and gas flowing during power and hold on operation, also during control close-down operation. In performing its function, temperature, gas flow and other sensors and microprocessors are used.

Although BoP has not become the focus of most development efforts, it represents a significant fraction of the weight, volume, and cost of most fuel cells systems.

2.1.1 Basic comparison with heat engines

In the heat engine, through combustion, fuel and oxygen react to generate heat, which is then converted to useful work via some mechanical processes. In a diesel engine, which is commonly used in merchant ships, combustion expands the gas in the combustion chamber, which moves the pistons and is then converted to rotational motion to propel the vehicle or as prime mover in the electrical generator. Conversely, in a fuel cell, the same enthalpy of reaction is directly converted into electrical energy via an electrochemical oxidation process.

This direct conversion of energy from chemical to electrical energy has a profound impact on the maximum theoretical efficiency of electrochemical devices. With simple thought, there is heat given off to the environment which is considered as a waste product. Thus, the waste heat given off as inefficiency in the fuel cells is less than the combustion engine. (Mench, 2008)

As a simple picture, Figure 2.3 shows energy transformation comparing fuel cells with the diesel generator. The diesel generator converts chemical energy to heat energy, then heat energy into mechanical energy and finally from mechanical energy to electrical energy. On the other hand, fuel cells convert chemical energy directly to electrical energy.

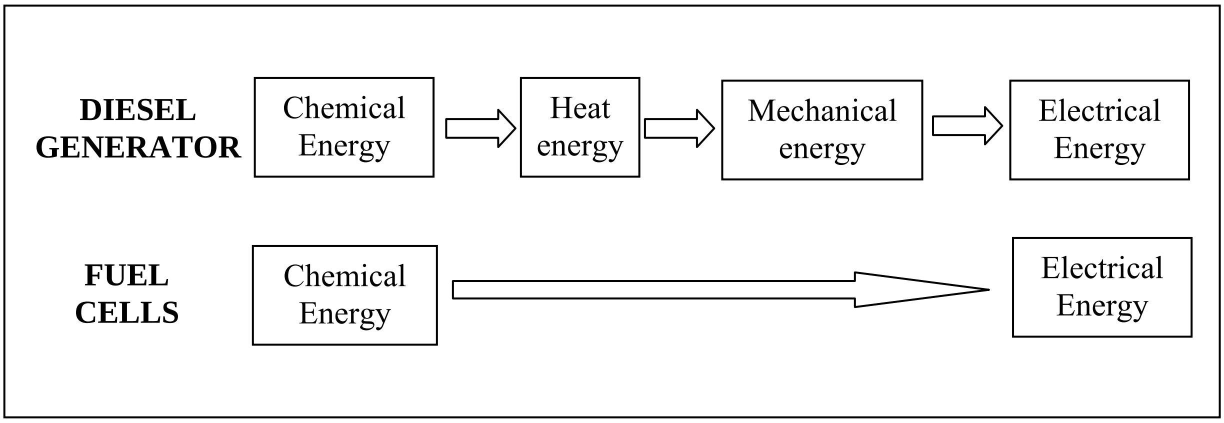


Figure 2.3 Comparison of diesel generator and fuel cells energy transformation process

2.1.2 Basic comparison with batteries

Fuel cells differ from other Electrochemical Power Sources such as batteries and accumulators for two reasons. They use a supply of gaseous or liquid reactants for the reactions rather than the solid reactants (metals and metal oxides) built into the units. And fuel cells may be operated for a rather extended time without periodic replacement or recharging since a continuous supply of the reactants and continuous elimination of the reaction products are provided (Bagotsky, 2009).

2.2 Types of fuel cells

Fuel cells can be classified based on type of electrolyte and type of fuel used in the fuel cells. The most common classification of fuel cells is by the type of electrolyte used in the cells. Generally, the choice of electrolyte dictates the operating temperature range of the fuel cells. This operating temperature and useful life of a fuel cells will determine the physicochemical and thermo-mechanical properties of materials used in the cell components (i.e., electrodes, electrolyte, interconnect, current collector, etc.). Because of high vapor pressure and rapid degradation at higher temperatures, Aqueous electrolytes are limited to temperatures of about 200 °C or lower.

The operating temperature is also dictating the degree of fuel processing required. In low-temperature fuel cells, all the fuel must be converted to hydrogen prior to entering the fuel cells. In addition, the anode catalyst in low temperature fuel cells (mainly platinum) is strongly poisoned by CO. In high-temperature fuel cells, CO and even CH_4 can be internally converted to hydrogen or even directly oxidized electrochemically. Some of the typical characteristics are explained in table 2.1

Table 2.1 Types of fuel cells and its typical characteristics

Type	**Electrolyte-catalyst - electrode**	**External Reformer for hydrocarbon fuels**	**Operating temp.**	**Electrical efficiency**	**Combined heat & power efficiency**	**Advantage**	**Disadvantage**	**Typical application**
Polymer Electrolyte Membrane (**PEM**)/ Proton Exchange Membrane / Polymer Electrolyte Fuel Cells (**PEFC**)	Solid polymer - Platinum - carbon	Yes (Pure hydrogen from storage tanks or onboard reformers)	Low temperatures, around 80°C (50-100°C)	53-58% (transportation) 25-35% (stationary)	70-90% (low-grade waste heat)	Start quickly (less warm-up time), better durability, favourable power-to-weight ratio, high H_2 power density	Expensive catalyst, extremely sensitive to CO poisoning, Low temperature waste heat (not suitable for CHP), thermal and water management	Primarily for transportation applications and some stationary applications.
Alkaline Fuel Cells (**AFC**)	potassium hydroxide in water – Platinum – Transition metal	Yes	90-100°C	60%	>80% (low grade waste heat)	high-performance, can use variety of catalyst	Easily poisoned by carbon dioxide (CO_2), must run on pure oxygen	Military space
Phosphoric Acid Fuel Cells (**PAFC**)	Liquid phosphoric acid – platinum - carbon	Yes	150-200°C	>40%	>85%	more tolerant of impurities than PEM, good quality waste heat, demonstrated durability	Expensive platinum catalyst, expensive investment costs, slow start-up time, typically large and heavy	stationary power generation large vehicles such as city buses

Type	Electrolyte-catalyst - electrode	External Reformer for hydrocarbon fuels	Operating temp.	Electrical efficiency	Combined heat & power efficiency	Advantage	Disadvantage	Typical application
Molten Carbonate Fuel Cells (**MCFC**)	Liquid solution of lithium, sodium, and/or potassium carbonates – electrode material – nickel & nickel oxide	No, for some fuels	600-700°C	45-47%	>80%	CO tolerant, can use variety of catalyst fuel flexibility, high quality waste heat (suitable for CHP), inexpensive catalyst	High temperature speeds corrosion and breakdown of cell components Complex electrolyte management extremely long start-up	Electric utility Large distributed generation, continues power application
Solid Oxide Fuel Cells (**SOFC**).	Perovskites (Ceramics)– electrode material – Perovskite and perovskite / metal cermet	No, for some fuels and cells designs	600-1000°C	35-43%	<90%	Fuel flexibility, Can use a variety of inexpensive catalysts, Solid electrolyte reduces electrolyte management problems, high quality waste heat (Suitable for CHP Hybrid/GT cycle)	High temperature enhances corrosion and breakdown of cells components, Slow start-up, Brittleness of ceramic electrolyte with thermal cycling	Auxiliary power Electric utility Large distributed generation, continues power application

Some fuel cells are also classified by the type of fuel used:

1. Direct Alcohol Fuel Cells (DAFC)

   DAFC (or, more commonly, direct methanol fuel cells or DMFC) use alcohol without reforming. Mostly, this refers to PEFC-type fuel cells in which methanol or another alcohol is used directly, mainly for portable applications.

2. Direct Carbon Fuel Cells (DCFC)

   In direct carbon fuel cells, solid carbon (presumably a fuel derived from coal, pet-coke or biomass) is used directly in the anode, without an intermediate gasification step. Concepts with solid oxide, molten carbonate, and alkaline electrolytes are all under development. The thermodynamics of the reactions in a DCFC allow very high efficiency conversion. Therefore, if the technology can be developed into practical systems, it could ultimately have a significant impact on coal-based power generation (EG&G, 2004).

2.3 History of fuel cells & existing adoption on marine application

2.3.1 Early development

According to the US Department of Energy, in 1838 it was Christian Friedrich Schönbein, the German chemist who conducted the first scientific research on the phenomenon of fuel cells. His work was published in Philosophical Magazine in the January issue of 1839. However, many references asserted that it was Sir William Robert Grove, who introduced the concept of hydrogen fuel cells. He discovered that by immersing two platinum electrodes on one end in a solution of sulphuric acid and the other two ends separately sealed in containers of oxygen and hydrogen, a constant current was found to be flowing between the electrodes.

In 1896, William W. Jacques developed the first fuel cells with practical applications, and in 1900, Walther Nernst first used zirconium as solid electrolyte. Then in 1921, William W. Jacques and Emil Baur built the first molten carbonate fuel cells. In early 1933, Bacon developed the first fuel cells made of hydrogen and oxygen, with practical use. The fuel cells converted air and hydrogen directly into electricity through electrochemical processes. He began his work by investigating alkaline fuel cells.

In 1955, Thomas Grubb used a membrane made of ion exchange polystyrene sulphated as an electrolyte. Three years later, another GE chemist, Leonard Niedrach, conceived a way of depositing platinum on the membrane. Then, in 1961, G.V. Elmore and H.A. Tanner introduced a phosphoric acid fuel cells.

2.3.2 Marine transport application

As other technology developments, fuel cells started through military developments. Although the principle was discover in the early 19th century, the application just started in the mid 20th century.

The US Navy has been carrying out fuel cells R&D since the 1960s. On the other hand, in the 1970s the German submarine industry and the German Ministry of Defence decided that fuel cells offered the most effective solution for providing an air independent propulsion (AIP) system for electric diesel submarines, which allows longer underwater endurance; and The Canadian Department of National Defence (DND) has been involved in the development of PEMFC technology since the mid 1980s (Weaver, 2002).

There was also one fuel cells system developed by UTC, using the alkaline fuel cells technology developed by NASA, for use in a deep submergence search vehicle for the U.S. Navy, In 1978, Lockheed installed and tested the UTC 30 kW alkaline fuel cells on board its deep submergence search vehicle, Deep Quest (US Congress, 1986).

Although Andudjar (2009) noted that during World War II, Bacon developed fuel cells to be use in submarines of the Royal Navy, one paper show that The British Royal Navy adopted PEM technology for their submarine fleet in early 1980s (Smithsonian, 2004).

In 1970, the PEMFC system was choosen for Air Independent propulsion (AIP) on German navy submarines. Integration of a plug-in fuel cells section on the German Navy's submarine U1 and subsequent operational testing was conducted for 9 months during 1988-1989. It was the first time in the world that an AIP system had been integrated into a commissioned submarine and piloted by the naval crew. Integration of the individual mature components into a submarine system that constitutes a fuel cells propulsion system capable of meeting all requirements of submarine operations was successfully demonstrated with the original components for the first Class 212 submarine. Production began on the Class 212 vessels in the summer of 1998.

Although it seems most of the first developments happened in naval submarines, actually, in 1964, *Star I* was the world's first submersible powered by fuel cells. It was a one-man submarine research equipped with fuel cells power developed by Allis-Chalmers and a test vessel owned by General Dynamics/Electric Boat Division of Groton. The fuel cells produced 750 watt, which were running on liquid hydrazine-hydrate and gaseous oxygen (Crowe, 1973).

Other recent developments on undersea vehicles is *Urashima*, a commercial autonomous underwater vehicle (AUV) prototype develop by Japan's Mitsubishi Heavy Industries. It was first delivered in 2000 with Lithium Battery as power source. In March 2003 the power source was replaced by fuel cells in order to extend its cruising range. *Urashima* used the PEFC type with an output rate of 4 kW with the hydrogen gas supplied as fuel from the metal hydride contained in a pressure vessel (Maeda, 2006). Other AUVs are *HUGIN* 3000 and 4500 AUVs from Kongsberg Maritime (Horten, Norway) and the FFI Norwegian Defence Research (McConnel, 2010).

In case of surface ships, compared to land based application fuel cells adoptions in marine civil developments surface vessels are very slow. Fuel cells adoption on surface ships just started to be investigated in 1996. In Germany, the Association of Mussel Fishers decided in 1996 to aim to equip the mussel-fishing fleet with the most environmentally friendly propulsion possible. One possible solution is the use of fuel cells instead of conventional diesel generators.

In 1997, the Office of Naval Research (ONR) initiated an advanced development program to demonstrate a ship service fuel cells (SSFC) power generation module (EG&G, 2004)

Further, stimulated by the increasing number of lakes in Europe on which motor boating with internal combustion engines is either strongly regulated or forbidden to prevent pollution, several FC-powered passenger vessels have been developed and demonstrated. In Switzerland the first prototype was the Hydroxy 100, a pedalo-style boat powered by PSI's 100 W PEMFC stack and a small fuel cell-powered boat has been demonstrated by the AFC manufacturer Hydrocell Oy in Finland (Weaver, 2002).

EU started with project "Fuel Cell technology for SHIPs" (FCSHIP), a two-year duration project which commenced in July 2002. The project consortium consists of 21 partners headed by the Norwegian Shipowners' Association. It aimed to enable EU fuel cell technology providers to be more competitive in the prospective market for maritime applications, enable EU ship owners to utilise this new technology and have the competitive advantage, and assist the EU in meeting sustainable development, energy saving and air pollution reduction objectives (Marine, nd).

Sailboats or yachts probably have the biggest number of fuel cells demonstration project. Some of them are presented in Appendix A. In 2002, Malt's Mermaid III a 5.8 m sailboat was developed by Yuasa Corporation Japan, using DMFC as Auxilary Power Unit/APU (Cropper, 2004). Another example, MTU CFC presented PEM fuel cells powered 12 m sailing boat in October 2003. The boat is powered by 20 kW unit, jointly develop with Ballard, enabling a range of 225 km at speed 6 km/h and become the first fuel cell power craft certified by GL. The *Haveblue XVI* sailboat prototype was launched in 2005 (Adamson, 2005). In 2007 Voller fitted their Emerald PEM APU to a Beneteau Oceanis yacht, which they sailed across the Atlantic Ocean as part of the engineering trials for the fuel cells system. In addition, in Iceland, Icelandic New Energy has overseen the installation of the hybrid hydrogen fuel cells APU to the Smart H_2 whale watching boat (Hydrogen, 2008). Many other yachts using fuel cells are listed in Appendix A.

Another application is in water taxis. In Germany, the excursion ship ‘‘MS Weltfrieden’’ is being fitted with a PEM fuel cells propulsion plant as a project for Expo 2000. While in Italy, there is a boat with a range of about 300 km, with a capacity of carrying 90 passengers. This boat was modified to take a hybrid propulsion system in 1998 (Sattler, 2000).

On 4 April 2009, the Alster Touristik GmbH (ATG) started its regular line service at the Hamburg inland waters again. Within the ATG fleet counting a total of 18 ships, the FCS “Alsterwasser” is the first ship propelled by an innovative fuel cells hybrid drive (FCS, 2009).

Recently, in Turkey, UNIDO International Centre for Hydrogen Energy Technologies has awarded Hydrogenics to supply their 50 passanger sightseeing boat with six 30 kW PEMFC power modules (McCOnnel, 2010).

For commercial ships, the Viking Lady is the first commercial ship ever with a fuel cells specially adapted for marine use. The Norwegian ship owner Eidesvik Offshore took delivery of the Viking Lady on 29 April 2009. The ship is classed by DNV and is in operation as a supply vessel in the North Sea. Viking lady is the result of the FellowSHIP project initiated in 2003 with aims to develop power packs with a significant potential to reduce CO_2 emissions (up to 50%) and improve energy efficiency (up to 30%) when compared to conventional power generators. Emissions of harmful substances, such as nitrogen oxides (NOx), sulphur oxides (SOx) and particles, will be completely eradicated. FellowSHIP also includes extensive work to integrate the power package into the ship, as well as safety and reliability studies and approval and rule development (Facts, 2009).

Many other fuel cells research projects on board ship are being conducted in different parts of the world. MC-WAP, for example, is a 6 year project started in 2005 which has been submitted and approved for funding within the 6th Framework Programme (FP6) of EU. It aimed at the study of the application of Molten Carbonate Fuel Cells technology on-board large ships, as Ro-Pax, Ro-Ro and Cruise, and fast vessels (Mc-Wap, nd). There are also other projects such as the Dutch green tug project and the Smit E3 Tug project.

Another important field of eco-innovation is progressed with a National Innovation Program (NIP) for hydrogen and fuel cell technology. Clean Energy for Ships project, “e4ships”, is the first marine R&D project within the NIP which was launched in July 2009 which will run until 2016, is to demonstrate that fuel cells can function in power supply systems of ships under everyday conditions in order to facilitate the introduction of cleaner energy generation in merchant shipping (IMO, 2009b). The project is a cooperative venture between well-known German shipyards and shipping companies, leading manufacturers of fuel cells, universities, associations and classification organizations such as GL, DNV, MTU On site energy, ZBT and other 17 institutions (e4ship, 2009).

The most recent, in June 2010, a 20 kW SOFC has been installed in a car carrier, *Undine*. This is the result of a joint project by the international METHAPU consortium, comprising Wärtsilä, Wallenius Marine, Lloyd’s Register, Det Norske Veritas (DNV), and the University of Genoa in Italy. The project aims to validate and demonstrate new technologies for global shipping that can reduce vessels’ environmental impact, a further key aim is to establish the necessary international regulations for the use of methanol onboard commercial vessels, and to allow the use of methanol as a marine fuel (Wärtsilä, 2010).

Overall, from open literature there are 41 identified existing demonstration projects of fuel cells application on surface ships and other ongoing projects which have been developed since 1997. A complete list is attached in Appendix A. It is possible that there are many other unlisted projects or research on fuel cells application on board surface ships. However, this could represent constant developments and future opportunities of fuel cells as an emerging technology for solving environmental problems.

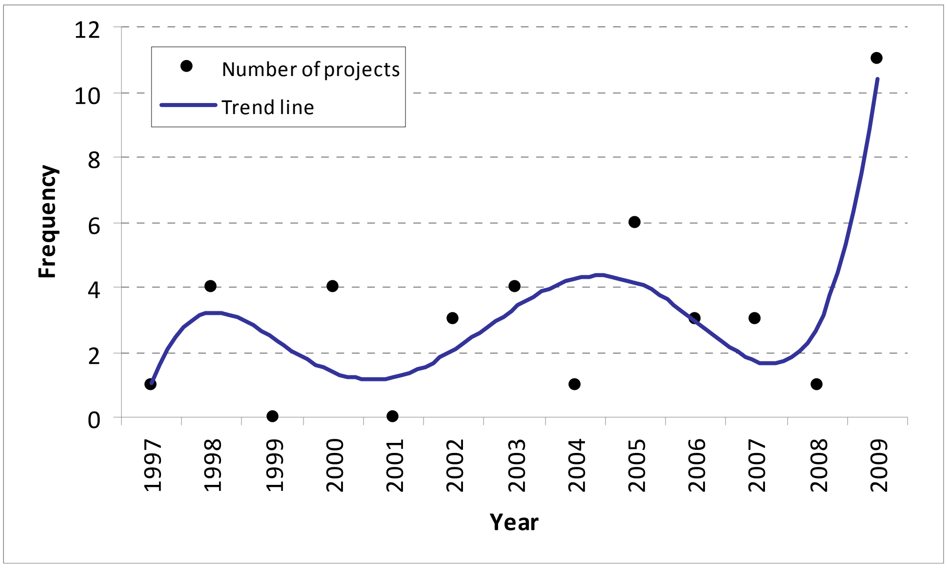
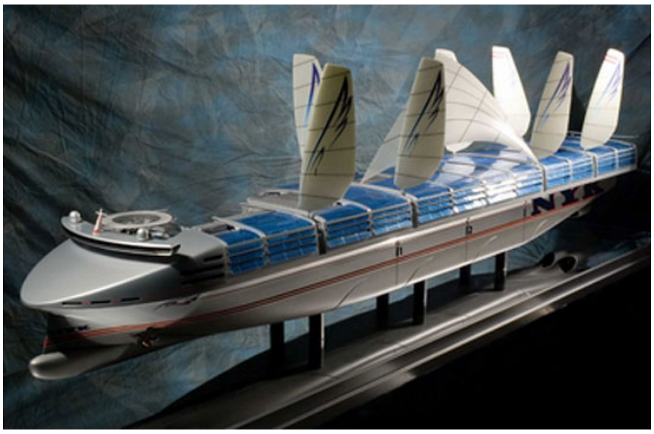


Figure 2.4 Number of identified fuel cells projects on surface vessel

Figure 2.4 shows a number of fuel cells projects on board surface ships each year from 1997 to 2009, which are identified from open literature. There is a possibility that fuel cells development was affected by economic recession. For example, the lowest graph on the trend line could be influence by the recession in the early 2000s, which occurred mainly in developed country. Another down turn could also be correlated with the recession in the late 2000s

While until 2008 the average projects were only 3 projects each year; fortunately, in 2009 there was a significant increasing number of demonstration projects arising. Among all 41 identified projects in 13 years, 11 projects were launched in 2009. This booming year shows positive optimism on fuel cells to be used on board ships. The reason behind this booming probably is increasing environment awareness of maritime stakeholders. It was started when the UN through the United Nations Framework Convention on Climate Change (UNFCCC) agreed at a conference in Bali, Indonesia, in 2007, to shape an ambitious and effective international response to climate change, to be agreed at the Copenhagen Conference in 2009. Then, since emissions from international civil aviation and maritime transport largely take place outside national territories, reduction obligations for these two transport sectors were left, to the special agencies of the UN responsible for regulating both industries, namely the International Civil Aviation Organization and the International Maritime Organization (IMO, 2009). IMO itself through the Marine Environment Protection Committee, at its fifty-ninth session (July 2009), approved the Second IMO GHG Study and agreed that the study would constitute a significant document and become the paramount reference to the Committee for information in developing and pursuing IMO's strategy to limit and reduce GHG emissions from international Shipping (IMO, 2009a).

Furthermore, fuel cells are also being utilized in several future environmental friendly concepts of future ships. In April 2009, NYK released an initial exploratory design for its *NYK Super Eco Ship 2030*, an energy-efficient ship expected to emit far fewer CO_2 emissions than current vessels. It will make use of progressive technologies that have the potential of being realized by 2030. The power needed to propel the ship can be lessened by decreasing the weight of the hull and reducing water friction. Propulsion power can be increased through use of LNG-based fuel cells, solar cells, and wind power, all of which will lead to a reduction of CO_2 by 69 percent per container carried (NYK, 2009).



(NYK, 2009)

Figure 2.5 NYK Super Ecoship design concept

Wallenius Wilhelmsen also introduced a futuristic concept in designing the E/S Orcelle, This vessel is a car carrier which is capable of transporting up to 10,000 cars on eight cargo decks. It has a pentamaran hull design which eliminates the traditional stern propeller and rudder allowing that no ballast water will be required on board.

(Wallenius, 2010)

Figure 2.6 E/S Orcelle design concept

The E/S Orcelle will be clean sailing with zero emissions. Powered by the sensible utilisation of energy from renewable sources, including solar energy, wind energy and wave energy, and it will be used in combination with a fuel cells system powered by hydrogen. Wallenius Wilhelmsen envisions that future technologies will be able to transform solar, wind and wave energy into hydrogen for immediate use and/or storage on board (Wallenius, 2010).

2.4 Chapter conclusion

To conclude this chapter, fuel cells application seems to be in positive development. There are 41 fuel cells surface ships projects arise started in 1997. Existing fuel cells project in surface ships still dominate by small vessels, mostly yacht and sailboat, with few numbers of water taxi, a whale watching ship, an offshore vessel and a car carrier. So far fuel cells on marine application are still in demonstration phase; however this could demonstrate different fuel cells technology in different applications include in merchant/commercial vessel. Considering continuous development showing by increasing number of project using fuel cells technology, it seems that people has realize the advantage and feasibility of fuel cells to be used onboard ships. Furthermore, although both future concept by NYK and Wallenius Wilhelmsen will not yet to be realize in the mean time, fuel cells has been expected to be contributed in the future super green ships project.

3. FACTORS INFLUENCING ADOPTION/APPLICATION

In principle, to be adopted on board merchant ships, new technology must be proven reliable and affordable. Although environmental issues are the main driving force of fuel cells application to be adopted onboard ships, technical and economic considerations mostly give influence to the speed of the adoption. In order to accelerate fuel cells adoption on board merchant ships, barriers towards its adoption should be identified. This chapter will discuss all aspects which perhaps act as a driver or barrier towards fuel cells application. Challenges after implementation may also arise and will be discussed as well.

3.1 Environmental consideration

Buhaug and Eyring in Tzannatos (2010) describe that shipping is an important contributor to global anthropogenic emissions, with around 15% for NOx, 4-9% for SO_2 and 2.7% CO_2. Between 1990 and 2007, the emissions of basic pollutants (NOx, SO_2, PM) and GHGs (mainly CO_2) from global shipping increased from 585 to 1096 million tons and emission scenario calculations up to the year 2050 show that a significant increase has to be expected in the future if ship emissions remain unabated. Low emission of fuel cells definitely acts as main driving force of its implementation to contribute against existing environmental problems where the only emission from fuel cells is water and heat if hydrogen is used as fuel.

It is clearly proven in a great deal of literature that in operational stage fuel cells have a highly positive potential environmental impact. However, the environmental impact on the full life cycle of fuel cells starting from manufacturing until the end-of-life stage should be investigated. There is still a limited number of research dealing with this problem. It is understandable since due to the early stage of system development and commercial confidentiality reasons, it is currently difficult to obtain reliable data.

Alkaner (2006) in his specific research on Life Cycle Analysis of MCFC found that there is no significant difference between the environmental impacts of fuel production and supply for both the MCFC type and the Diesel engine. Comprehensive life cycle inventories including the weight breakdown of stack and Balance of Plants (BoP) components of the MCFC systems are required for further detailed studies.

Waste at the end-of-life stage hierarchy should follow the order of environmentally friendliness, i.e. reuse, recycling, incineration with energy recovery and disposal. The MCFC for example, as other fuel cells, it normally uses high value materials, such as aluminium, nickel, chromium and lithium for electrodes, and stainless steel for bipolar and casing. Stainless steel is a 100% recyclable material, so recycling is the most likely option for bipolar plates. Recycling of insulation materials has been reported not as cost effective as they are silica-based materials. Recycling of aluminium, nickel, chromium and lithium has a high economic and environmental value. However, there has been no data available for their extraction processes, energy requirements and cost-benefit effectiveness of end-of –life strategy.

There is also a challenge in the hydrogen production process; since the efforts will be worthwhile only if the hydrogen is produced in a sustainable way. It means that the production has to be based on renewable raw materials and/or renewable energies as well as on efficient conversion technologies in the proper scale. At present hydrogen production is mainly based on reforming of fossil fuels and the steam reforming of natural gas is the most common state of the art technology for hydrogen production. There are ongoing research on the hydrogen production process such as alkaline electrolysis, steam reforming of biogas and gasification gas, the coupled dark and photo fermentation as well as the coupled dark and biogas fermentation (Miltner, 2010).

3.2 Technical consideration

All systems on-board must be designed and installed in such a way to ensure that general safety is not prejudiced in any way. Therefore, fuel cells systems should meet the specific requirements including such criteria as operational conditions on-board, e.g., temperature, humidity, salinity, system concepts, redundancies, operating methods and noise. Actually, generally speaking, fuel cells are inherently capable of fulfilling most technical requirements for operation onboard a ship, as it becomes clear if considering their main features: clean, quiet, small, modular and efficient (Sattler, 2000). However, this statement can be discussed further, as some of the technical considerations will still probably arise as a barrier; and contrary to some common problems which people thought as fuel cells deficiencies that have actually already been solved and proven in some demonstration projects.

3.2.1 Safety issues

There are several safety issues related to fuel cells including fire, explosion, toxic and electrical hazard. However of most concerned are lay on fire and explosion hazard due to hydrogen used in the system. Hydrogen is a flammable gas and readily forms an explosive mixture with air. The range of air/hydrogen concentrations that will explode is extremely wide. Mixtures containing from as little as 4% v/v hydrogen up to as much as 75% v/v will readily explode. For the bulk of this range (18-69% v/v) there is a significant risk that a confined hydrogen/air mixture will detonate. Moreover, ignition energy necessary to initiate a hydrogen/air explosion is very low, 0.02 mJ. Relative to air, hydrogen is also very buoyant; therefore, any leak of hydrogen will rapidly dissipate upwards. If the leak occurs in an open or well-ventilated area, these properties will help to reduce the likelihood of a flammable atmosphere being formed. On the other hand, there is a serious risk of explosion when hydrogen leaks occur within enclosed areas containing electrical equipment or other sources of ignition. The risk is particularly high when the source of ignition is close to a ceiling or other impervious high-level barrier (Newsholme, 2004).

Fortunately, several classification societies have produced guidelines for ensuring safety issues in fuel cells application. From a safety point of view, similar with gas piston engines, fuel cells also represent a potential for gas leakage and formation of explosive atmospheres. The main philosophy of the rules is that there is no way to decrease the safety level when gas is used, compared to conventional machinery.

As a complement to existing an “intrinsically gas safe” system applied for piping containing explosive gas, another concept named “emergency shutdown protected machinery (ESD)” has been introduced. Emergency shutdown protected machinery spaces are considered gas safe under normal conditions, but under certain abnormal conditions such space may have a potential to become gas dangerous. In such cases, emergency shutdown of all ignition sources and machinery is to be automatically executed, except for explosion protected designs.

Another alternative is using the traditional “intrinsically gas safe machinery space” arrangement. This system fulfills the requirements that machinery spaces under normal and abnormal condition are considered gas safe. One of the requirements among others isthat all gas supply piping within machinery space must be double walled (Tronstad, 2004).

Similarly, in the Zemship project, GL used the two barrier principle which consist of double-walled piping system, a gas pipe within the ventilation duct and a separation of the system including gas tight (2nd barrier) in the H_2 storage room and FC room / FC enclosure (Vogler, 2008)

On board surface ships, use of pure hydrogen storage is impractical. Other commercially available cells use hydrogen that is produced using reformer-type technology located adjacent to the fuel cells stack. In the reformer, typically hydrocarbon fuel, such as methane or LPG, steam through a high (>300 °C) temperature catalyst bed. The reactions in the reformer produce hydrogen and carbon dioxide. It is necessary to ensure that the carbon dioxide stream is effectively discharged and does not generate asphyxiation risk when it is accumulate within the enclosure.

Natural gas (methane) is lighter than air and will tend to diffuse upwards, but much more slowly than hydrogen. The explosive limits for natural gas (5-15% v/v) and LPG (2-10% v/v) are also much narrower than those for hydrogen. Consequently, in systems using hydrogen and methane, ventilation arrangements that are suitable for hydrogen will usually also prove adequate for methane. LPG vapour is considerably heavier than air, especially when cold e.g. when taken directly from a liquid storage vessel rather than from a heated evaporator. In the event of a leak, LPG vapor can percolate downwards and may accumulate on the floor or in low-lying sumps producing a flammable atmosphere.

Another fuel is methanol, which is a highly flammable liquid that is also toxic, especially by skin absorption. Appropriate precautions should be taken to prevent the accumulation of flammable methanol/air atmospheres, e.g. containment and ventilation, and to minimize the risk from ignition sources, e.g. through the use of appropriate electrical equipment.

Another hazard where the operator should not fail to notice is the presence of the life-threatening hazard of electricity. Electrical hazards arise from two distinct areas within fuel cells installations; the normal 240 volt mains A.C. supply and the immediate output of the fuel cells stack. Although the voltages and currents produced by each element in the stack are very small, the total output from the stack can be of the order of 200-400 volts and 500 amps. Poor access control into dangerous areas, such as where unprotected bus bars are present, is a common area of concern that must be addressed (Newsholme, 2004).

Although fuel cells application presenting other unwanted hazards, it seems that generally speaking this problem could be handled with adequate and strict followed rules in the design and operation.

3.2.2 Ship integration issues

The opportunity of using fuel cells on board ship together with suitable fuels was investigated in Germany in 1995 by a joint by with Messrs. Ballard & HDW. They investigated the use of fuel cells on merchant ships. The results of this investigation showed that fuel cells are especially well-suited to certain applications:

- emergency power supply, e.g., passenger ships, ferries;
- electric energy generation, particularly for environmentally conscious use in harbours with heavy, contamination levels, e.g., container ships;
- electric energy generation propulsion power for ships with special noise-reduction requirements, e.g., passenger ships, research vessels; and
- propulsion plant on ships with hydrogen or methane ‘‘boil-off’’, e.g., LH tankers, LNG tankers

In integrating the system on board, fuel cells can normally fulfill the required environmental conditions to be placed on board ships. It is necessary that all machinery and systems applied on board ship should be designed to operate under certain environmental conditions, such as:

- Ambient temperature in machinery space between 0°C and 55°C
- Relative humidity or air in machinery spaces up to 96%
- List, rolling, trim and pitch as showed in Table 3.1

Table 3.1 Angle of inclination

	Angle of inclination (degrees)			
	Athwartships (from side to side)		Fore and aft	
Main and auxiliary machinery	±15	0 ± 22,5	±5	0 ± 7,5

Table 3.2 Performance range for ships

Surface ships	Merchant ships/ Naval ships	Propulsion	5-50 MW
		Electrical supply	<10 MW
		Emergency power supply	0.1-1MW
Sub-surface Vessel	Submarines	Mono propulsion	2-5 MW
		Hybrid propulsion	200-400 kW

(Sattler, 2000)

In terms of power used for ships, although it is widely varied, the general performance range is shown in Table.3.2.

To some extent fuel cells performance range can be utilized in all type of ships. Mostly fuel cells are employed as propulsion system power generation or as Auxiliary Power Unit (APU). Table 3.3 shows the main characteristics of major propulsion systems for various maritime transports and the requirements of the FCs based APU system. Of course the application of fuel cells in each ship will vary in type, size and whether used in a hybrid system or not.

Table 3.3 Main characteristics of various maritime transport propulsion and APU system

	Tourist crafts	Leisure crafts	Offshore support vessels	Research and survey vessels (icebreakers)	Fast ferries	Ferries	Passengers cruise vessels	Coastal cargo vessels	International cargo vessels
Low speed diesel engine								X	X
Medium speed diesel engine			X	X	X	X	X	X	
High-speed diesel engine	X	X	X	X	X				
Simple cycle gas turbine		X	X	X	X		X		
Advanced cycle gas turbine							X		
Mechanical propulsion	X	X	X	X	X	X	X	X	X
Electric propulsion			X	X		X	X		
Fuel cells	X	X	X	X	X	X	X	X	X
FCs-based APU systems	X	X	X	X	X	X	X	X	X

Bensaid (2009)

Furthermore, functional and operational characteristics of every ship should be considered, so that the main advantage of fuel cells can be maximum utilized. A simple example is on cruise ships where the comfort parameter, such as less noise and vibration are highly important will be suit to the fuel cells characteristics.

However, other characteristics should also to be measured. Table 3.4 shows the rating of functional and operational parameter importance for various ships.

Table 3.4 Rating of functional and operational parameter importance for various ship. When 1 denotes high importance, 3 low

	Power Flexibiity	Low Emissions	Low Noise & Vibration	Maintain-ability	Power Density	Rapid Response	Tolerance for cyclic operation	High Power Output	Fuel Economy	Capital Cost
Inter-Continent. Carriers	3	2	3	1	2	3	3	1	1	2
Short-Sea	1	2	3	1	2	1	2	2	1	2
Cruise Vessels	1	1	1	2	2	2	1	1	2	3
Ferries	1	1	1	1	1	1	1	1 (2)	1	1
Fishing Vessels	1	1	1	2	1	1	3	3	1	2
Research Vessels	1	1	1	2	2	1	1	2	2	3
Offshore Support Vessels	1	2	2	2	2	1	1	2	2	3

(Tronstad, 2004)

Existing demonstration projects also show the use of several types of fuel cells onboard different types of ships with various power ranges. Appendix A resumes some of the existing fuel cells surface ships projects ranging from the smallest 100W to the biggest power used 2.5 MW. Probably there are several projects not listed in this table due to lack of details in published literature.

It clearly shows that PEM fuel cells are the most popular type. They were selected due to high power density, system simplicity and advanced state-of-the-art. MCFCs have been demonstrated for large power units (300 kW and upwards). The technology is not considered viable for small-scale applications (Hansen, 2002). The MCFCs efficiency is also higher than that of PEMFCs and does not need noble metals as catalysts. Furthermore, the MCFC working temperatures are optimal for carrying out the reforming inside the vessel in case of feeding light hydrocarbons or CH_4, thus exploiting the amount of heat released by the cells stack itself (Bensaid, 2009).

SOFC for the auxiliary power unit in commercial vessels with methanol fuel is now being developed under Methapu project (Fontell, 2010). SOFCs are known to have higher efficiency. In terms of fuel used, for small power fuel cells, hydrogen is used as fuel, but because of its volumetric problem in the bigger power fuel cells LNG, methanol and Diesel fuel are used with the reformer system. Fuel issues will be discuss further in section 3.1.4

3.2.3 Power density

One of deficiencies of fuel cells is that they are volumetrically inefficient. Not only influenced by the size of Balance of Plant in the overall system, but also by the characteristics of its fuel especially hydrogen with its low power density. Figures 3.1 and 3.2 show comparison of gravimetric and volumetric power density of fuel cells and other marine propulsions.

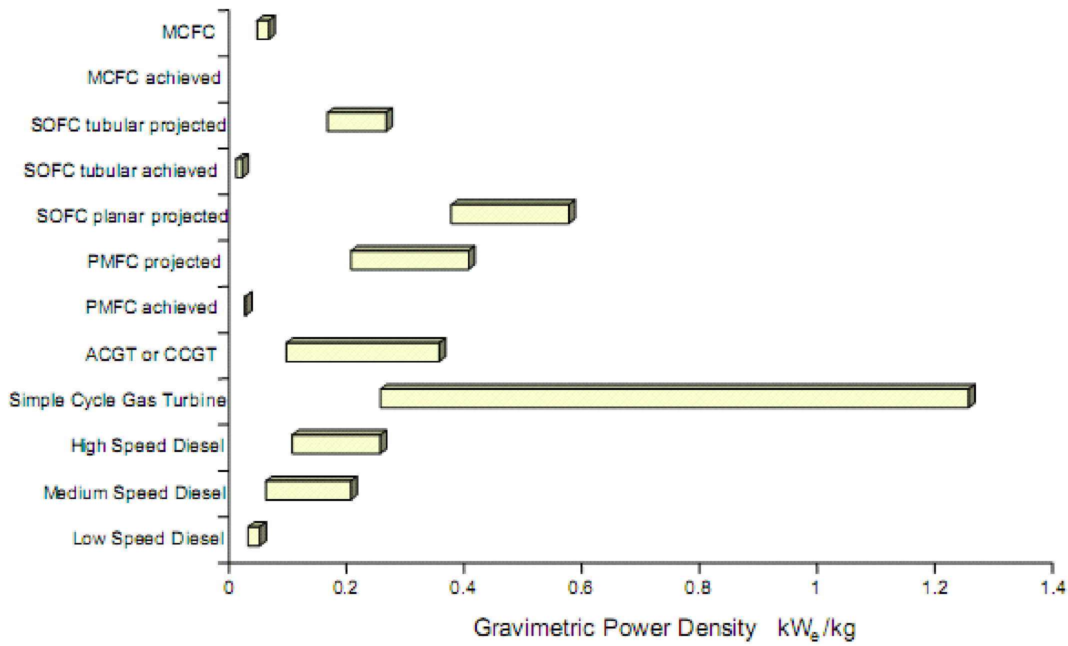


Figure 3.1 Comparison of gravimetric power density

The figure given for fuel cells are typical for stationary fuel cells based power generation demonstration. Labeled "achieved" are existing demonstration plants. In terms of weight and space, the fuel cells based system generally performed poorly and is only competitive with slow and the larger medium speed diesels (Bourne, 2001).

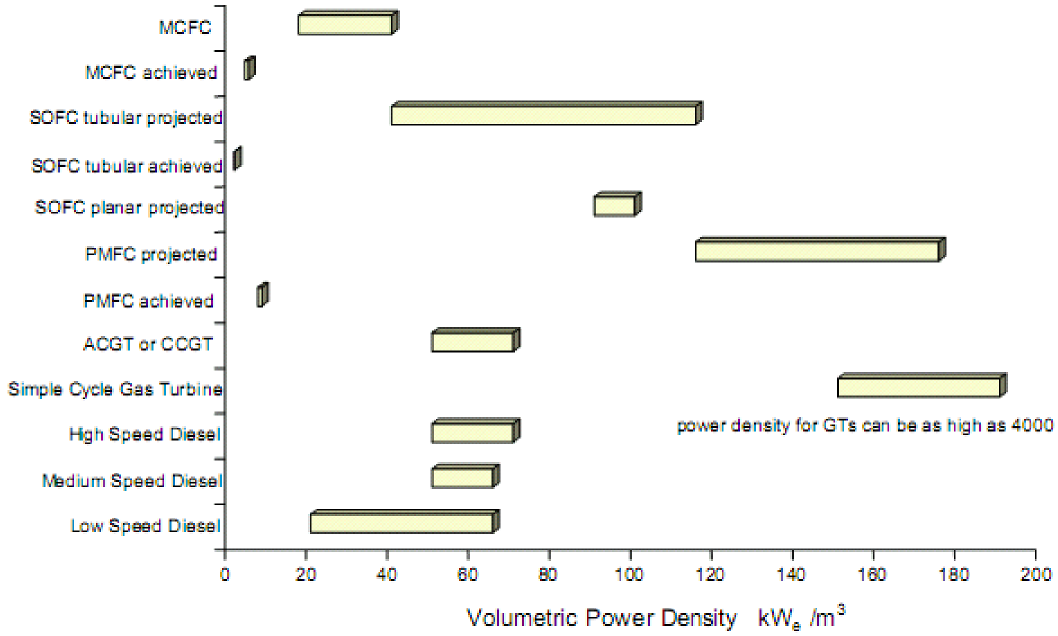
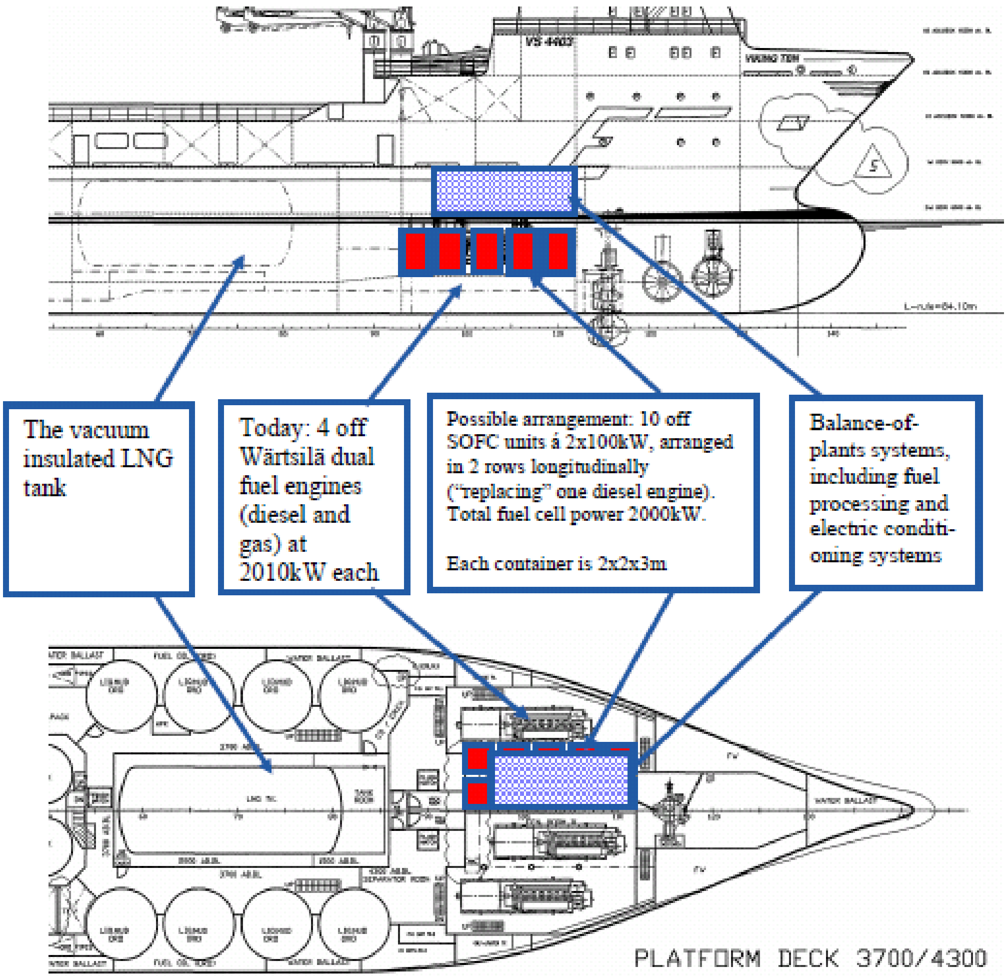


Figure 3.2 Comparison of volumetric power density

As an example from the existing demonstration, Tronstad (2004) explained that the SOFC system installed in Viking energy with 8 MW total power onboard has a dimension 1x1x1.5 meters for each 100kW unit, excluding fuel processing and electric conditioning. The volumetric size of SOFC technology is still somewhat lagging behind conventional machinery size. However, there is a possibility that a realistic vessel design can provide a transformation of the entire machinery lay out.



(Tronstad, 2004)

Figure 3.3 Excerpts from the general arrangement drawing of the PSV "Viking Energy" with a possible future SOFC plant superimposed

Regarding different types of fuel used, Yuan (2004) compared power density of various choices of fuel supply as shown in Table 3.5. Hydrogen has the highest gravimetric power density; however, it is clearly volumetrically inefficient and therefore impractical. Methane seems to be the highest power density; nevertheless, other issues such as fuel cells reformers should carefully be taken into account.

Table 3.5 Comparison of various choices of fuel supply

Fuels	Symbol	Power density (MJ/kg)	*Unit volume(ltr/kg)	*Unit mass (kg/kg)
Hydrogen (gas)	H_2	51.8	10500	1.00
Methane	CH_4	50.0	14.08	1.00
Methanol	CH_3OH	21.1	10.01	7.95
Ethanol	C_2H_5OH	27.7	9.55	7.62
Diesel	$C_{12}H_{26}$	43.3	8.69	6.50
Titanium hydride	$TiFeH_2$		9.59	52.46

*unite volume/mass represents liter or kg per kg of hydrogen

3.2.4 Fuel supply and fuel reformer technology

Although pure hydrogen is the best fuel for fuel cells, hydrogen cannot be stored on board high power or during long range operations. It will require too large a volume. Therefore, one of key challenges in fuel cells adoption is to create an efficient reformer. The reforming technology which is capable of using logistic fuels will become an important breakthrough for fuel cells adoption on board ship.

Current conventional marine fuels, even those deemed "low sulphur" , have relatively high concentration of sulphur (0.5-6%) and heavy metal. A fairly low sulphur concentration, 30 ppm, can poison the fuel cells catalyst and any heavy metal present will generate further detrimental effect. New fuel adoption will require new procedures for storage and handling (Bourne, 2001). Moreover, availability and distribution of new fuel types in the market will be more problematic.

Methanol has various advantages, e.g. it can be derived from several sources, such as natural gas, coal, wood and other renewable resources. It is also clean and relatively easy to store. Moreover, it can be reformed at low temperatures using a conventional heat exchanger. Ethanol is more difficult to reform; furthermore it is not widely available and at present there is no existing network. Diesel oil which is widely available and relatively inexpensive is an attractive fuel to be reformed in the future (Yuan, 2004).

Kickulies (2005) noted that in the diesel reformer project carried out by HDW GmbH and the University of Duisburg-Essen, the demonstrator system has operated successfully with diesel fuel. It has also been coupled to small PEM fuel cells. The processor efficiency reaches 82% at full load. As shown in Figure 3.4, it consists of a Subsystem for diesel evaporation, a Reactor for hydro-desulfurization (HDS), a Reactor for pre-reforming, a Steam reformer including burner, a CO removal unit, consisting of shift reactors (LTS, HTS) and a Preferential oxidation reactor (PROX).

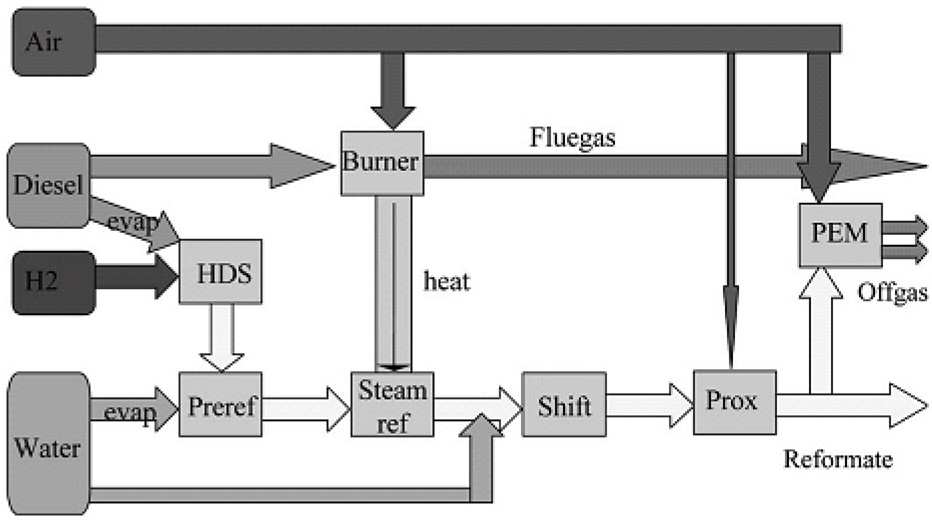


Figure 3.4 Diesel reformer demonstrator system

These results show that the diesel was converted by the total CO removal unit to a reformate gas with <10 ppm CO under all operating conditions, which is pure enough to run fuel cells. An exception was during the dynamic load change in which the higher CO concentration was found temporarily. Final fuel cells plant on this project will be in the power range of 300-500 kW electrical output. The challenge remains to improve and scale up to the existing system.

However, from the ONR project a succesfull story can be seen for bigger power range when diesel fuel processing system was demonstrated in the 2.5 MW MCFC using NATO F76 fuel. According to the NATO specification, F76 diesel fuel world wide contains up to 1 wt.% sulphur and Europe up to 0.2%. The low sulphur content more or less helps the conversion, since the key components are the desulphurization and the prereformer.

3.2.5 Response to abrupt change or accident

It is proven in some literature that existing fuel cells demonstration can cope with normal environmental conditions on board. Privette (1999) stated that 2.5 MW PEMFC used in a ship service fuel cells power generation project under the Office of Naval Research are successful surface ship fuel cells demonstrations under salt-air, shock and vibration conditions, which prove the suitability of PEM fuel cells in these naval marine environments. Even the test conditions were more severe than any expected shipboard conditions. Therefore, it should be applicable to a variety of shipboard applications.

A shock and vibration test of 500W PEM fuel stack was done by Rajalakshmi (2009) in order to screen and ascertain the reliability of the stack, mechanical integrity and also to assess the mounting requirements. The result showed that the mechanical integrity of the stack is good. The physiochemical properties like electrochemical performance of the stack are in good agreement before and after the vibration and shock test revealing that the individual components of all the 30 cells are intact after the test. Although there was a minor compression force release at the bolts, it is suggested that they can be prevented by damping the vibrations to protection equipment like padding or spring suspension.

However, there is still little information available regarding fuel cells response to abrupt changes, such as temperature change due to sudden or large load change during ship manning (Yuan, 2004). There is also not enough literature to show fuel cells resistance to flood, fire and collision or other accident scenarios. Damage scenarios should be investigated to assess the possibility of the initial circumstance leading to further hazard e.g. from fuel escape, release of hazardous materials, and secondary effect of flooding increasing fire hazard (Bourne, 2001).

3.2.6 Operational matter

It is well known that FCs required less maintenance, around 80-85% less than a diesel electric system (Zhou, 2004). However, some issues regarding operational matters still arise. From an operational point of view, system start-up time and ability to respond to rapid load change may be an issue for certain fuel cells systems. In high temperature technologies, such as MCFC and SOFC, thermal inertia implies a start-up disadvantage relative to low temperature stacks (Bourne, 2001). It is main challenges for an SOFC maritime installation to combine the requirements for low thermal transient with sudden shedding of major loads, or the safety requirements of shutting down in case of a gas leakage/fire (Tronstad, 2004). The diesel fuel reformer which uses a steam reformer also has the main disadvantage to be slow in response to load change (Krummrich, 2006).

Periodic fuel replacement is an operational problem in specific cases. For ships which use hydrogen or methanol as fuel, supply availability should be prepared and considered. Since for small ships and short journeys, where using a reformer is not really suitable, hydrogen storage seems still the best choice since hydrogen is also non toxic, non poisonous and delivers higher chemical energy per unit mass than natural gas .

3.2.7 Maturity of technology

With several demonstration projects all over the world, it seems that fuel cells diffusion on board ships is still in a model stage, which is still in the bottom of the S-curve type in innovation adoption. It is obvious that the fuel cells system on board is still considered an immature technology. And to compete with the existing well understood, proven and reliable technology, with well established infrastructure and well define economy is really not an easy thing.

Small scale existing prototypes will require extrapolation for large commercial ships, with the assumption that fuel cells will behave rationally. Furthermore, performance characteristics traditionally based on historical data, especially those for availability, reliability and maintainability (ARM) with derivation of Mean time to overhaul (MTTO), Mean time between overhaul (MTBO), and Mean time between failure (MTBF) are highly desirable. If supporting evidence is not available, the assessment may be viewed with suspicion (Bournre , 2001).

3.2.8 Fuel cells technology penetration

The past two decades show fast development of fuel cells. On surface ships many demonstration projects have proven the feasibility of using fuel cells on board. However, it is not know how fast and how far it has gone relative to its upper limit. The technique of mapping S-curves is one approach to forecast diffusion of fuel cells technology to the market.

Hollinshead (2005) explained that diffusion of technology tends to follow the specific pattern of expectations around the S-curve as shown in Figure 3.5. There are two important S-curve parameters: Δt and Δs. Here Δt is the time taken to go from 10% to 90% of the market or maximum population, while Δs is the time to go from 0% to 10%. For example, existing studies show that Δt of Sailing ship to steam ship takes 80 years and Δs takes 19 year. In the beginning, new technologies lead to excessive expectations and high investment. However, being immature, the technology sometimes can not deliver. As in fuel cells, new technology usually did not simply do a better job at less cost. To begin with, they were universally more expensive, less powerful and of smaller capacity than existing technologies. Δs is determined by the rate of organizational and societal learning regarding the nature of the new technology and how it is best used. In many cases of transportation field, the niche market was impelled by the capacity of the new technology to deal with the negative externalities created by the existing technology. In the case of steam ships, the externality was deforestation. Regulations to deal with the externalities will raise the costs and reduce the system efficiency of the old technology. For fuel cells, emission should be the externality factor, and regulation for emission control is one big opportunities to accelerate Δs.

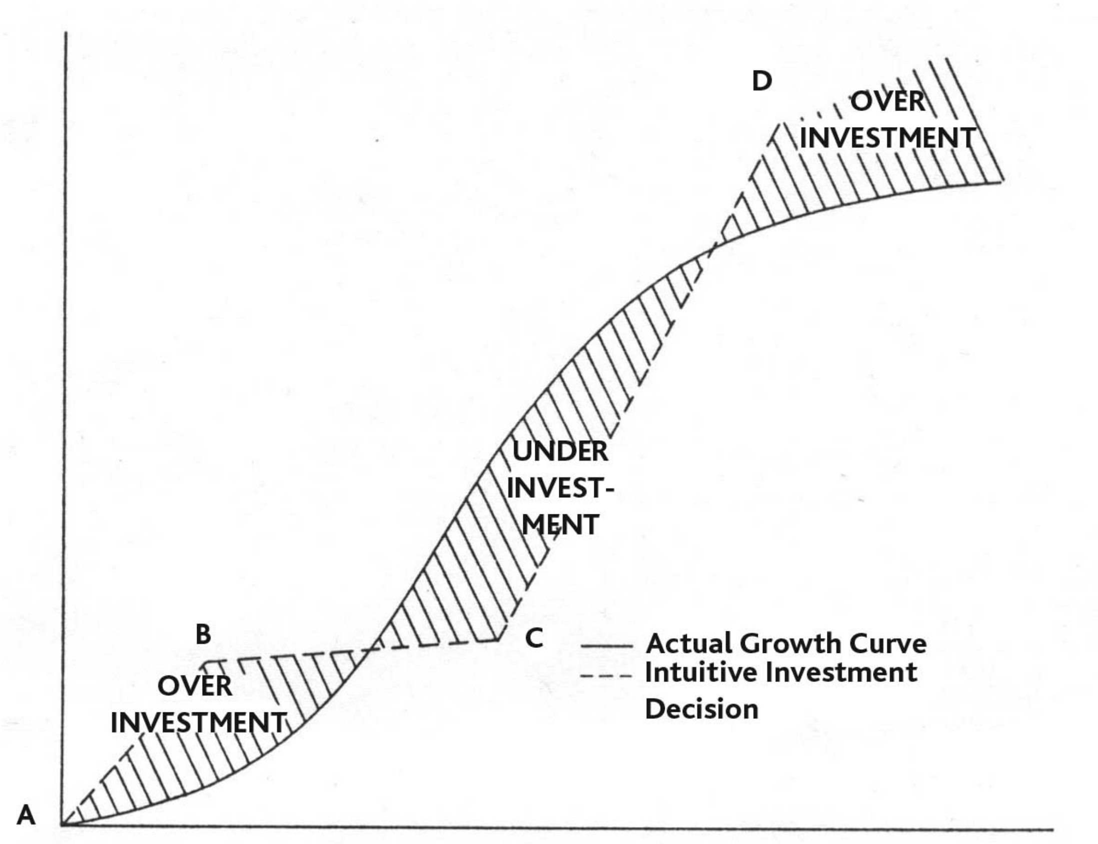


Figure 3.5 Expectation and S-curve

On the other hand, Δt is a matter of how much new infrastructure is required, If the basic infrastructure is inadequate and requires significant additions, Δt can be very long. Fuel cells technology development will greatly influence the needs of infrastructure; if conventional marine fuel can be used in the fuel cells system, Δt will significantly decrease. When new technology can use the same infrastructure as the old, substitution can be very rapid (Δt = 12 years). FC can probably satisfy this condition.

Some studies have made projections of fuel cells penetration in road transportation. Figure.3.6 shows Hydrogen vehicle penetration rates. Different scenarios regarding market penetration of hydrogen passenger cars until 2050, as developed by the HyWays project for the EU in 2007, and a more optimistic scenario was developed by the International Energy Agency in 2005 (Wietschel, 2009)

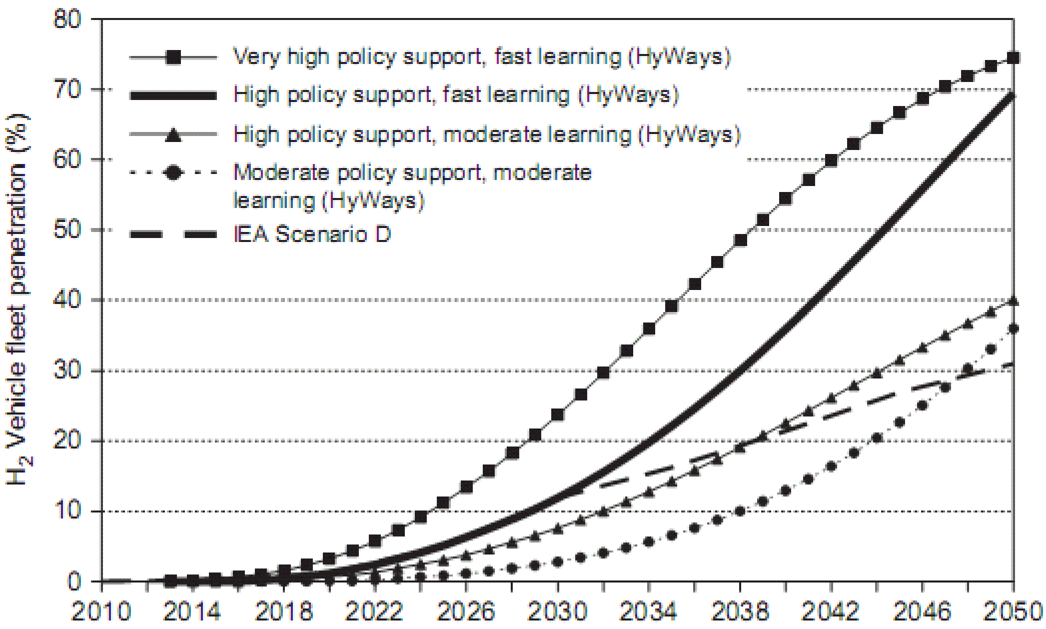


Figure 3.6 Hydrogen vehicle penetration rates

Application of fuel cells on board surface ships could perform different figures for some reasons. Technologically, fuel cells on board ships have to fulfill certain higher requirements of space taken, weight and more severe environmental (e.g.high corrosion) and operational conditions (e.g. dynamic load).

Overall, market penetration could be realized; however, it will require technical breakthroughs, significant cost reduction, supporting policies and deployment of dedicated infrastructure to enter the market.

3.3 Economic consideration

The main barrier of fuel cells application onboard ships is due to its high cost. Since it is still new technology, not yet being commercialized and being confidential information, it is not easy to find the exact cost of fuel cells system on board ships. However, Kristine Bruun, who has been working for years on the technology of Viking Lady gave the estimation that as rule of thumb fuel cells power costs around 10,000 Euro for each installed kilowatt (Skinner, 2010). With similar figure, Simbolotti (2009) noted that as for MCFC and SOFC power systems, the cost of a small-scale production of 200–300 kW units is between $12 000 and $15 000/kW, with the fuel cells stack accounting for 50 per cent of the total. It is clear that the cost is too high to be competitive with other power generation systems. The cost of fuel cells electricity generation is 3 to 10 times more than other methods (Zhou, 2004).

This price is also directly connected with the high cost of basic fuel cells materials. For example, Polymer membranes which working at less than 80°C need platinum (Pt) as a catalyst, which is expensive and sensitive to poisoning. Current costs can reach $800/m2 ($250–$300/kW), but large-scale manufacturing would reduce this cost to $50/m2.

Furthermore, in case of using hydrogen as fuel, it will require an array of expensive technologies and infrastructure for hydrogen production, distribution, and storage. Figure 3.7 shows hydrogen production costs based on different production methods for 2007. Based on an oil price level 2008, $60–70/bbl, decentralized production costs can be considerably higher than $50/GJ ($1.6/lge2) (Simbolotti, 2009)

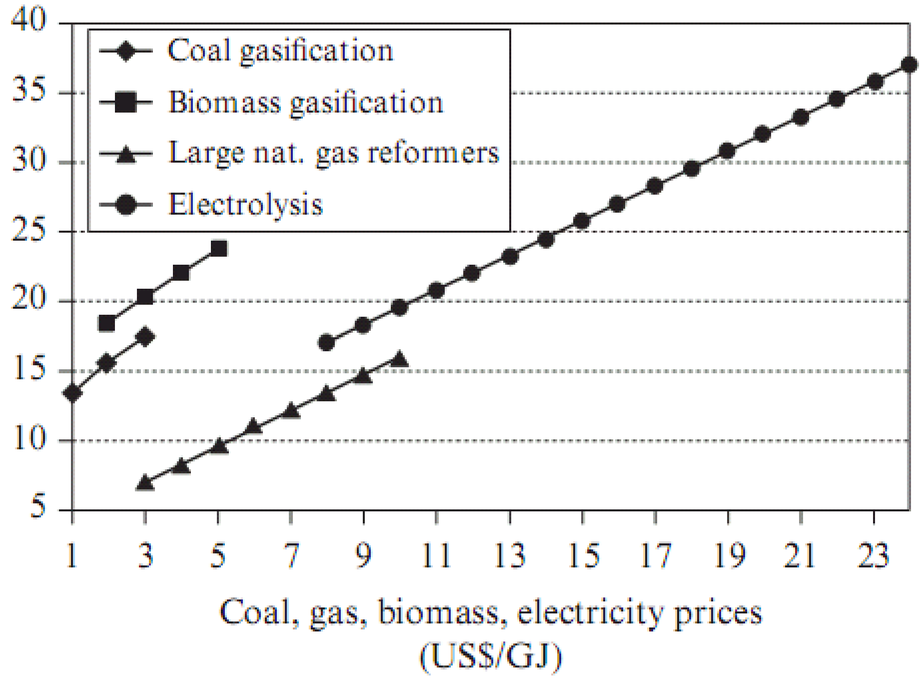


Figure 3.7 Hydrogen production cost-2007 (US$/GJ)

The specific hydrogen supply costs in the early phase are high due to the required overcapacity of the supply and refueling infrastructure and the higher initial costs for new technologies because of the early phase of technology learning. Prediction around 2030, hydrogen costs range from €10 to 16 ct/kWh ($3.6–5.3 kg). At these supply costs, hydrogen becomes competitive in the long run with crude oil prices above $80–100 barrel (Wietschel, 2009).

Schoots (2010) did the assessment of past and potential cost reduction trough analyzing the technology learning curve of fuel cells. The learning curve expresses the hypothesis that the cost of technology decreases by a constant fraction with every doubling of cumulative installed capacity or exercised activity. He analyzed the global learning curve and the learning curve of three manufacturers (Pratt & Whitney Aircraft, UTC Power and Ballard) with the result as shown in Table 3.6.

Table 3.6 Summary of the results of our fuel cells learning curve

Fuel cells type	Development start	Period investigated	Progress rate	R^2
Manufacturer				
AFC	1952	1964-1970	82±9%	0.84
PAFC	1965	1993-2000	75±3%	0.75
PEMFC	1959	2002-2005	70±9%	0.83
Global				
PEMFC	1959	1995-2006	79±4%	0.73

(Schoots, 2010)

The progress rates have been sustained over a period of over 40 years. However, there is some discussions trough out this result. First, there may be more components like platinum of which the costs are not subject to learning, but merely depend on fluctuating market prices. Overall, he concluded that R&D efforts will continue to yield fuel cell cost reductions and for fuel cell technology the dynamics of learning by searching remains important to complement the cost reduction anticipated on the sole basis of pure learning by doing.

3.4 Legislation and regulation

The US Navy/US Coast Guard made a report titled Codes and Standards for Marine Fuel Cells published in February 2001. This report documents a survey of US and international regulatory bodies, government agencies, and commercial and military sources for existing and developing codes and standards applicable to marine fuel cell power plants. It was mentioned that standards tailored to marine fuel cell design and construction, installation, and operations did not exist at that time (Codes, 2001).

GL is the first classification society who launched Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats, and the Guidelines came into force on March 1st, 2003 (GL, 2003). GL has certified the fuel-cell system of "FCS

Alsterwasser", Yacht "No 1", "Hydra" and "Elding" according to this guideline. Since the mid-1980s GL has been involved in developing ships, storage and transfer facilities for hydrogen. The certification comprises the assessment of the safety system, fuel-cell components, and electrical equipment, as well as pressure testing and explosion protection (GL, 2008).

BV launched New Guidance Note NI 547 Guidelines for Fuel Cell Systems Onboard Commercial Ships in Edition April 2009 (BV, 2009). Other classification societies such as DNV and Lloyd Register are still developing the guidelines in accordance with the fuel cell ships project.

Unfortunately, there is no specific international regulation covering fuel cells ships. Mostly international regulations, such as ISO or IEC cover road transport and stationary application. However, general rules published can be a reference. For example IEC-Technical Committee 104 in 2004 working group #2 established IEC 62282-2 titled Fuel Cell Modules and Working Group #6 now developing Fuel Cell Systems for Propulsion and Auxiliary Power Units (Hydrogen, nd).

Until now, IMO with SOLAS, Part 1, Chapter II-2, Part B, Regulation 4, gives limitations in the use of oils as fuel that no oil fuel with a flashpoint of less than 60°C should be used and in emergency generators, oil fuel with a flashpoint of not less than 43 °C may be used. The international Code of Safety for Gas-fuelled Engine Installations in Ships (IGF Code) is still in progress. Several proposals such as from Sweden as well as from the Community of European Shipyards Associations (CESA) has pointed that in order to utilize the full potential of fuel cells technology, the scope of the future IGF Code should be as broad as possible. Besides containing a dedicated chapter for fuel cell systems, the Code should also cover all relevant fuel types including low flashpoint liquids (IMO, 2009b).

Recently, in Resolution MSC.294(87), which was adopted on 21 May 2010 titled Adoption of Amendments to the International Maritime Dangerous Goods (IMDG)

Code, fuel cells and fuel cells engines are two new definitions which are inserted in alphabetical order. In this amendment, fuel cells are classified as other substances or articles presenting a danger during transport, but not meeting the definitions of another class. It classified under UN number 3166 and other provisions have been change which involved fuel cells in it. (IMO, 2010)

These guidelines and codes, definitely give more guaranty in safety aspect. However, it can not be maximized as a driver for implementing green technology. Carbon pricing/fuel levies and more stringent air emission restrictions could be a good driver to encourage fuel cells adoption. The right policy support from states and IMO will promote all maritime stakeholders to be more interested in fuel cells as one of the green solutions. In addition, certified crew competence under STCW remains a future challenge of fuel cells implementation.

3.5 Chapter conclusion

In this chapter, the following issues as shown in Table 3.7 have been identified as factors which influence fuel cells adoption onboard merchant ships.

Table 3.7 Identified factors which influence fuel cells adoption

Factors	**Environmental consideration**	**Technical consideration**	**Economic consideration**	**Regulation& Legislation**
Weakness & challenges				
Safety Aspect		√		
Reliability		√		
Fuel and infrastructure		√		
Volumetric size		√		
Ships integration		√		
Power Density		√		
Lifetime			√	
High initial cost			√	
Cost effectiveness in operation			√	
Recent economic recession			√	
Full life cycle environmental impact	√			
Use of renewable Hydrogen	√			
Strength & Opportunity				
Low emission	√			
Low noise & vibration	√			
High efficiency		√		
Technical development		√		
Technology dissemination & publicity		√		
Existing demonstration project		√		
Safety rules & regulation				√
Legislation approach				√
High policy support				√

4. ATTITUDE OF MARITIME STAKEHOLDERS TOWARDS FUEL CELLS ADOPTION

Hua (2008) did the survey regarding prospects of renewable energy in the maritime industry with a case study in Taiwan. The result shows that there is a high degree of preference for renewable energy sources over fossil fuel for both ship power and household electricity. While hydrogen combustion (80%) is the most supported alternative for powering commercial shipping, the fuel cells is the next highly favored (64%) alternative energy that is applied onboard ships as perceived by the Taiwanese maritime industry. Even though the survey is limited only to the Taiwanese industry, it raises the question to dig deeply what the reason behind this attitude is and what actually the barrier of fuel cells adoption is on board merchant ships in maritime stakeholders' point of view.

To investigate each stakeholder's opinion the survey was conducted in order to identify which criteria they judged as a significant barrier factor towards fuel cells adoption on board merchant ships.

4.1 Method of survey

A questionnaire was developed with close and open questions and intended to cover the following issues:

- Factors act as barrier of fuel cells adoption on board merchant ships
- Solutions to accelerate fuel cells adoption onboard merchant ships
- Level of significance on each driving and restraining factor of fuel cells adoption on board merchant ships

In the first question, the respondents were also being asked to indicate their level of familiarity with fuel cells technology. A three point Likert scale was used to define the level of significance so that even two respondents identify the same issues; there is a weighting factor to justify the preference of respondents.

Respondents consisted of a number of stakeholders in the maritime and fuel cells industry, classified in 5 job categories: ship owners, shipbuilders, maritime administrations, classification societies and fuel cells makers/developers

At the end of June 2010, a pilot survey was done to check whether the questionnaire met the objective and supported the analysis. The pilot survey was also useful to check whether the questionnaire contained any bias or confusing questions. Eight persons from different institutions and backgrounds participated in this pilot study. Minor change was added to the questionnaire draft.

The main survey was conducted in July 2010 by email with an electronic questionnaire. Sample of a blank questionnaire is attached in Appendix B. There were 272 emails sent to various persons and institutions, and there were 63 usable responses received. The response rate was 23.2%.

A descriptive analysis was used to illustrate the factors perceived by each job category. In addition, the chi-squared test of independence was used to assess whether or not there was any relationship or association between groups and their answers.

The chi-squared test for an r x c category table, an r x c contingency table can be written as:

		Column variable			
		1	..	C	Total
Row	1	n_{11}	..	n_{1c}	$n_{1.}$
Variable	2	n_{21}	..	n_{2c}	$n_{2.}$
	:	:	..	:	
	r	n_{r1}	..	n_{rc}	$n_{r.}$
	Total	$n_{.1}$	..	$n_{.c}$	N

Under the null hypothesis, H_0 of the analysis was that two variables (row and column variable) being test were not associated. Estimated expected values, E_{ij}, for the *ij*th cell can be found as

$$E_{ij} = \frac{n_{i.} n_{.j}}{N}$$

Then the test statistic for assessing independence is

$$X^2 = \sum_{i=j}^{r} \sum_{j=1}^{c} \frac{(n_{ij} - E_{ij})^2}{E_{ij}}$$

Under the null hypothesis of independence, X^2 has an asymptotic chi-square distribution with (r – 1) (c – 1) degrees of freedom. The way how to analyze the result from the chi-square test will be explained further in the following discussion.

The confidence level in this study is 90%; therefore, the predetermined cutoff for *p*-value is 0.1. If p-value less than 0.1, the data has the power to stand up against H_0, since the *p-value* is a measure of the strength of the evidence against H_0.

4.2 Profile of respondents

Among the 63 responses received, 29 (46%) were from management and 34 (54%) from engineering positions. They came from 55 different institutions and 30 different nationalities. Figure 4.1 shows the number of respondents from the five groupings designated by this study.

In the maritime administrations category, there are 20 persons (31.7% of all respondents) from 17 different nationalities responding to the questionnaire. Only 10 (15.9%) fuel cells makers and developers from 7 different countries responded. 15 persons (23.8%) from 11 different classification societies and 12 persons (19%) represented ship owners from 7 countries participated in this survey. Unfortunately, only 6 replies came from shipbuilders (9.5%) in 4 different countries. Final list of respondents' institutions and nationalities that participated in this survey are attached in Appendix C.

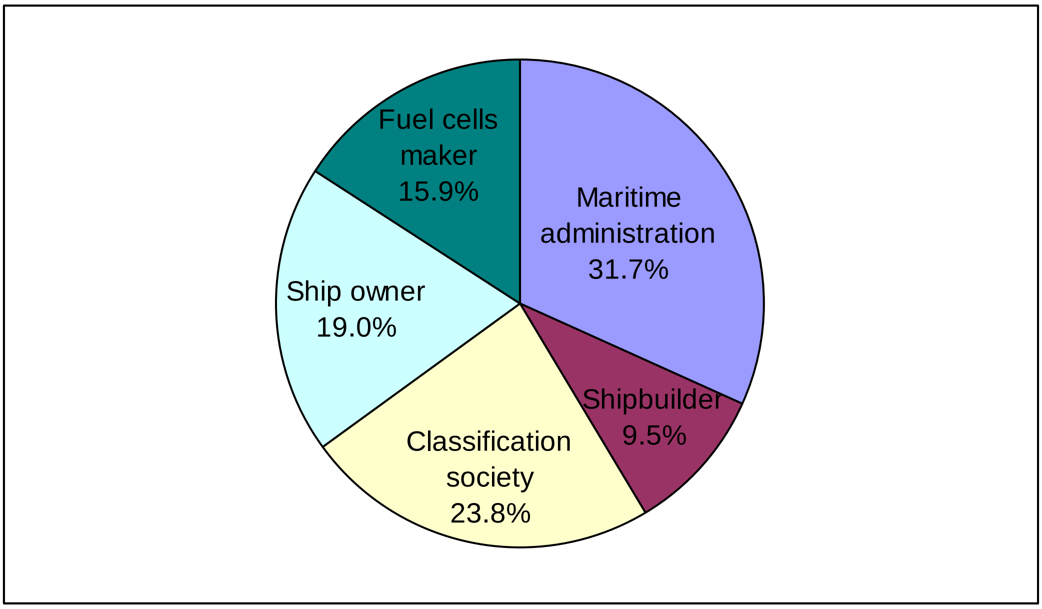


Figure 4.1 Composition of respondents in five job categories

Table 4.1 shows the number of the respondents of each job category based on their regions. Respondents' nationalities mostly dominated by Asia Pacific, followed by European countries. Except for classification societies, mostly they came from Europe, followed by Asia Pacific countries. Fuel cells makers and developers are dominated by Europe and North American country.

Table 4.1 Region of Respondents' nationality

	Africa	Asia Pacific	Europe	North America	South America	Total
Maritime administrations	1	14	3	0	2	20
Classification societies	0	7	8	0	0	15
FC makers	0	1	6	3	0	10
Ship builders	0	5	0	0	1	6
Ship owners	0	9	2	1	0	12
Total	1	36	19	4	3	63

4.3 Analysis of survey result

4.3.1 Level of familiarity

Respondents have different levels of familiarity regarding the fuel cells system. In the questionnaire, a three point Likert scale was used in defining levels of familiarity which are: familiar, heard-of, and not familiar. Only 28 respondents (44.4%) were familiar with fuel cells and the rest were categorized as heard-of or not familiar. In analyzing the result respondents who are in the heard-of and not familiar group was categorized as not familiar.

However, the subjectivity of the respondents in answering this question is unavoidable. The decision of the level of familiarity was fully based on the respondent judgment. Therefore, it should be noted that in this survey with the respondents from various countries and different fields of industries, the results can contain a degree of subjectivity.

Table 4.2 and 4.3 show cross tabulation and chi-square analysis results from the SPSS program which are presented as an example for the rest of the SPSS results in the following discussion through this chapter.

Table 4.2 is a cross tabulation between job category and level of familiarity. Cross-tabulation is one of the most frequently used methods of analysis for questionnaire data. It makes it possible to examine the relationship between categorical variables in greater detail than simple frequencies for individual variables. Then, Table 4.3 shows chi-square analysis results from the SPSS program for job categories and level of familiarity.

Table 4.2 Job category vs level of familiarity cross-tabulation

			Level_familiarity		Total
			Not familiar/ heard of	Familiar	
Job_category	Classification societies	Count	8	7	15
		Expected Count	8.3	6.7	15.0
		% within job_category	53.3%	46.7%	100.0%
	FC makers	Count	0	10	10
		Expected Count	5.6	4.4	10.0
		% within job_category	.0%	100.0%	100.0%
	Maritime administrations	Count	15	5	20
		Expected Count	11.1	8.9	20.0
		% within job_category	75.0%	25.0%	100.0%
	ship owners	Count	7	5	12
		Expected Count	6.7	5.3	12.0
		% within job_category	58.3%	41.7%	100.0%
	shipbuilders	Count	5	1	6
		Expected Count	3.3	2.7	6.0
		% within job_category	83.3%	16.7%	100.0%
Total		Count	35	28	63
		Expected Count	35.0	28.0	63.0
		% within job_category	55.6%	44.4%	100.0%

Table 4.3 Chi-square test for job category vs level of familiarity

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	17.505[a]	4	.002
Likelihood Ratio	21.629	4	.000
N of Valid Cases	63		

a. 3 cells (30.0%) have expected count less than 5. The minimum expected count is 2.67.

The chi-square (represented as $\chi 2$) applies a statistical test to cross-tabulation by comparing the actual *observed* frequencies in each cell of tables with *expected* frequencies. Expected frequencies are those that would be expected if data is 'randomly distributed' (Greasley, 2008)

In Table 4.3, the values to be analyzed are along the top *Pearson chi-square* row. The Pearson chi-square value is 17.505, with a significance or *probability* (p) value of 0.002. This means that, according to the chi-square calculation, the probability of this distribution of values occurring by chance is less than 0.002 – or 2 in 1000, so probability (p) = 0.002. With a confidence level of 90%, since p value was less than 0.1, H_0 can be rejected. In the other words, it can be concluded that there is significant association between job categories with their level of familiarity.

To see how the difference between job categories is, Figure 4.2 shows the pie chart comparison of each job category and their level of familiarity on fuel cells system. It is obvious that different groups have a different tendency on the level of familiarity.

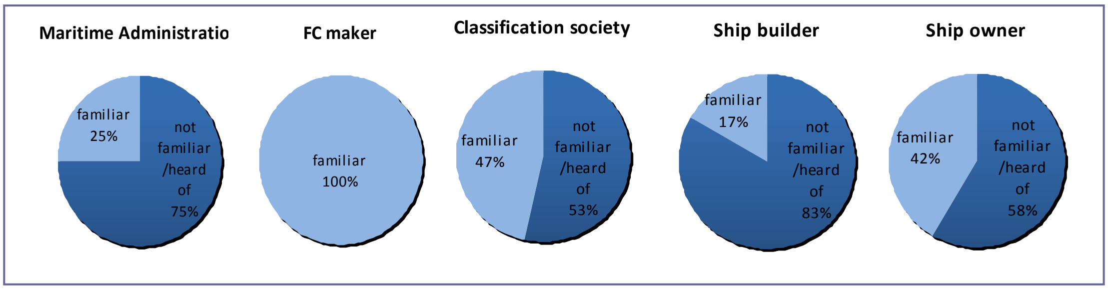


Figure 4.2 Level of familiarity of each job category

For sure fuel cells makers and developers should be most familiar, followed by classification societies. Some ship owners who replied to the questionnaire have experience in installing fuel cells or have special organization for support their innovation/technical improvement; therefore, level of familiarity of ship owners was relatively high. Maritime administrations and ship builders have the least familiarity with fuel cells technology.

4.3.2 Technical aspects

Respondents were being asked whether they agreed that technical aspects act as a barrier towards fuel cells adoption onboard merchant ships. Responding to this question, 92.1% of the respondents believed that technical aspects act as a barrier. This shows that most maritime key players still doubt the technical capability of fuel cells to be adopted onboard merchant ships.

Figure 4.3 shows the pie chart of different job categories responding to this question. All maritime stakeholders tend to agree that technical aspects act as a barrier toward fuel cells adoption on merchant ships. Only 20% of the fuel cells makers have the maximum confidence in current technical capability of fuel cells, and maritime administrations have the least confidence on fuel cells technical capability. However, the chi-square independence test can not prove that there is different opinion among these 5 grouping category ($p=0.357$).

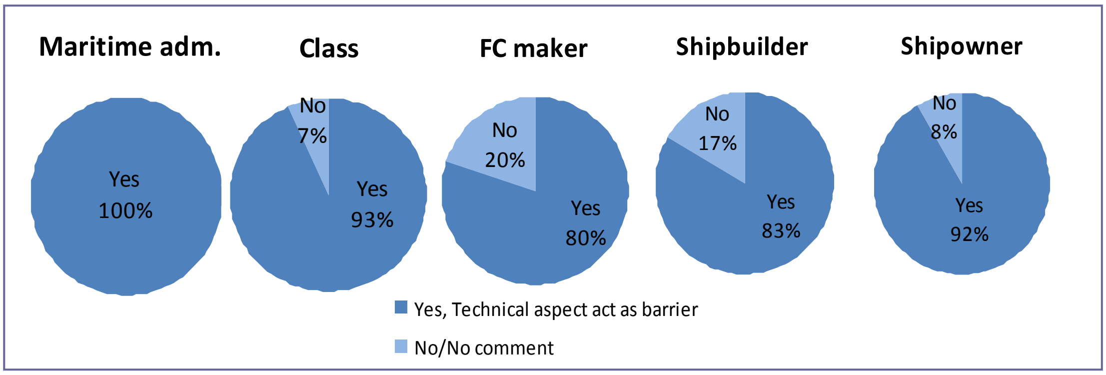


Figure 4.3 Job category vs Opinion regarding technical aspect as barrier

Although there is no significant difference between job categories, the chi-square test shows significant results on the analysis of the respondents' level of familiarity and their opinion regarding technical aspects as a barrier. P value 0.009 is definitely small enough to reject H_0, which proves that there is a significant association between the level of familiarity with their opinion regarding technical aspects as a barrier of fuel cells adoption.

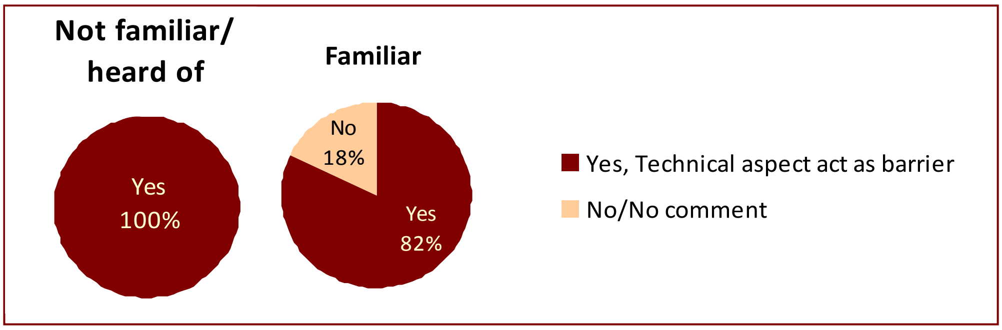


Figure 4.4 Level of familiarity vs Opinion regarding technical aspect as barrier

Figure 4.4 shows that all respondents who are not familiar or in 'heard of' category believe that technical aspects act as a barrier. Although statistically proven there is significant difference between people who are familiar and not, only 18% of persons who are familiar with fuel cells have the opinion that technical aspects do not act as a barrier toward fuel cells adoption onboard ships.

4.3.3 Economic aspect

Respondents also gave their opinion regarding economic aspects as a barrier towards fuel cells adoption onboard merchant ships. 93.7% of the respondents agreed that economic aspects of fuel cells act as a barrier of its adoption. This number is even more significant than the respondents' opinion regarding technical aspects of fuel cells.

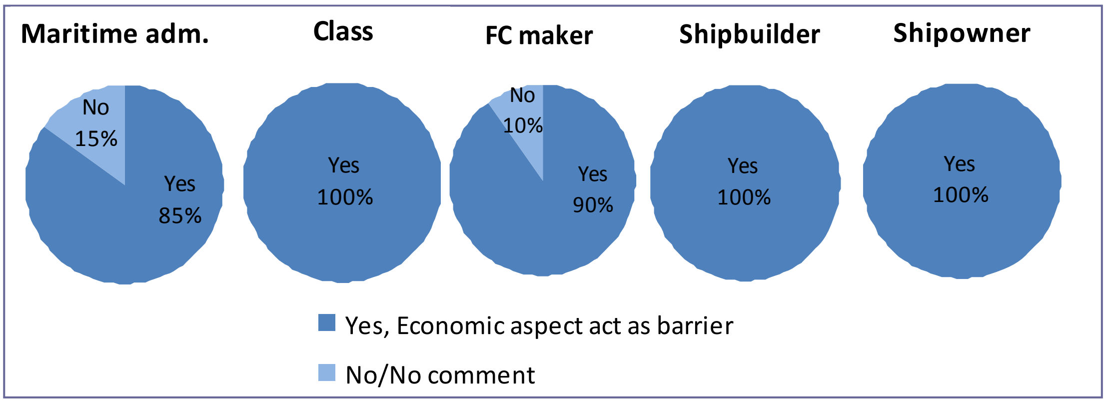


Figure 4.5 Job category vs Opinion regarding economic aspect as barrier

Series of pie charts in Figure 4.5 show how different job categories responding to this question. It is obvious that almost all maritime key players agree that economic aspects act as a barrier towards fuel cells adoption, and the chi-square test of job category versus economic aspects also shows that there are no significant differences between the groups ($p=0.290$). While the level of familiarity has influenced the opinion on technical aspect, it does not apply to economical aspect. The chi-square test result shows $p=0.817$.

This result proves that all maritime stakeholders whatever their job category or their level of familiarity believe that fuel cells are an expensive technology, and this issue influence its adoption onboard ships.

4.3.4 Comparing the significance of technical aspects and economic aspects

Most of the respondents agreed that technical and economical aspects both act as a barrier on fuel cells adoption. Then, this part will explore which aspect is giving more influence to the respondents. Figure 4.6 shows that from all of the respondents, 52% agree that economic aspects give more significant influence than technical aspects and only 21% believe that technical aspect are more significant, while the rest 27% believe that both aspect have equal significance.

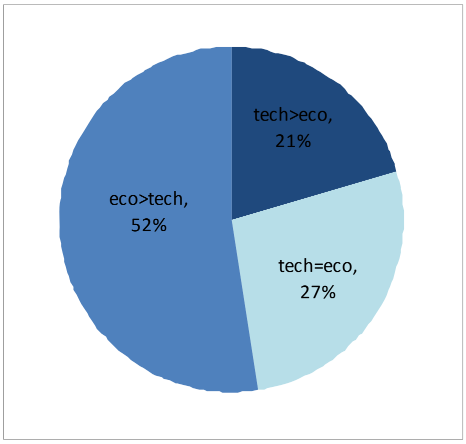


Figure 4.6 Comparison of technical aspect and economic aspect significance

Figure 4.7 illustrates the comparison of significance between these two aspects on each job category. If reviewing the answer in each job category, it seems that the majority of respondents in each category agree that economic considerations are more significant than technical considerations. The chi-square test resulting p=0.726 which mean that there is no association between job category and their opinion.

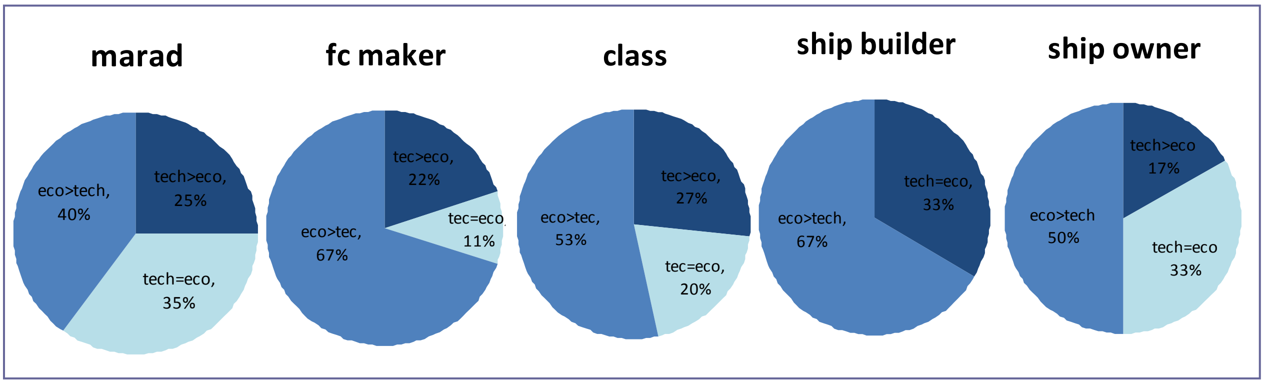


Figure 4.7 Comparison of technical and economic aspect significance on each category

Fuel cells makers and shipbuilders are most concerned with economic aspects. Although the majority of maritime administrations and classification societies also agree with the statement, among all the respondents, they have the biggest concern regarding technical aspects.

4.3.5 Factors in technical aspect

Figure 4.8 shows the opinion of all the respondents regarding factors in technical aspect which influence as a barrier towards adoption of fuel cells onboard merchant ships.

Six factors were mentioned in the questionnaire, and among those factors, fuel and infrastructure and reliability take the biggest proportion in the pie chart.

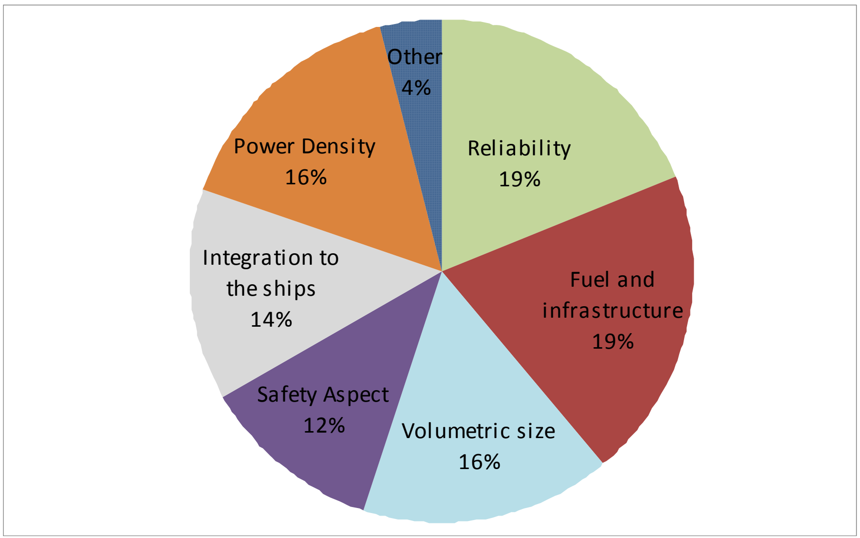


Figure 4.8 Factors in technical aspect (all respondents)

Some other identified aspects are operational hindrance, such as reluctance to load change and starting time for certain types of fuel cells, lack of maintenance infrastructure, and maximum power available which are too low to power a big ship.

Figure 4.9 shows the data of each job category opinion regarding factors in technical aspect. Fuel and infrastructure seem to be a problem for maritime administrations and fuel cells makers. Classification societies tend to worry about power density and ships integration issues. While shipbuilders put volumetric size as the biggest problem, ship owners pay attention to reliability and fuel infrastructure. These results seem really rational if associating them with the job category. However, different opinions on each factor will be elaborated and analyzed in the following discussion using the chi-square test to prove whether there are significant differences between them.

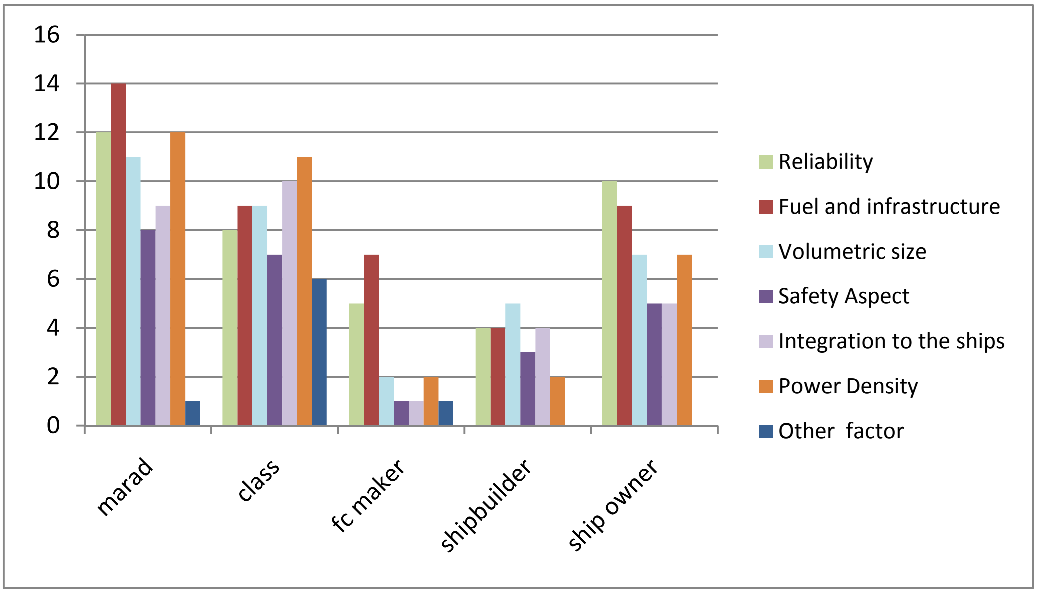


Figure 4.9 Factors in technical aspect on each job category

4.3.5.1 Reliability

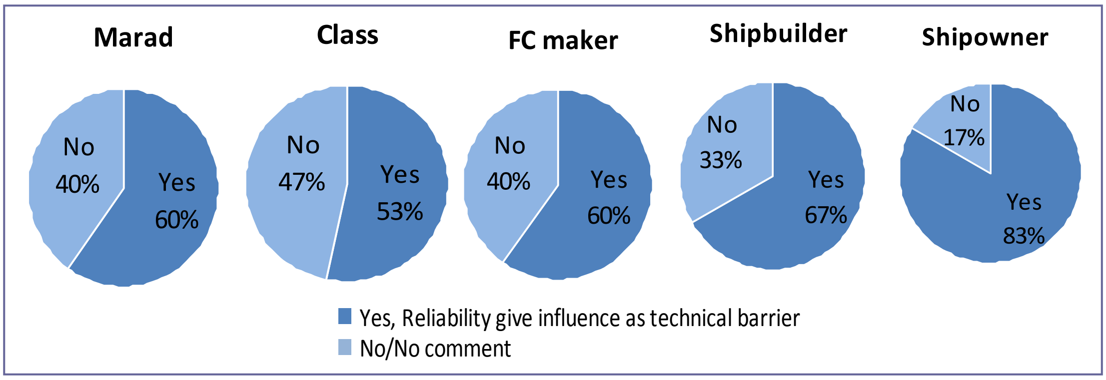


Figure 4.10 Opinion regarding reliability on each job category

Figure 4.10 shows the opinion of each job category regarding reliability. It seems that the majority of all maritime stakeholders agree that reliability still give influence as a technical barrier; therefore, no significant difference between them, as proven by the chi-square test with p=0.576

However, when the chi-square test has been done with level of familiarity as variable, the p value is 0.047, which is small enough to reject H_0. In other words, there is significant association between respondents' levels of familiarity with their opinion regarding reliability.

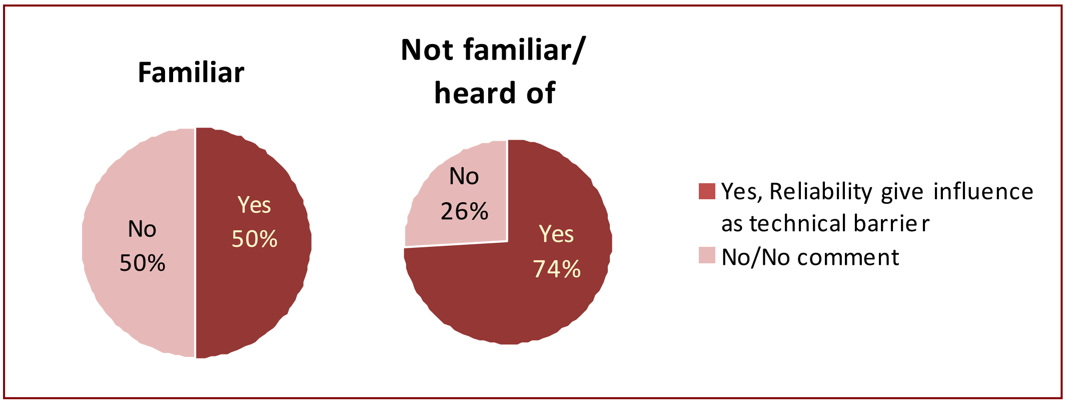


Figure 4.11 Level of familiarity vs opinion regarding reliability

As shown in Figure 4.11, 74% of the respondents who were not familiar agree that reliability give influence as a technical barrier, while only 50% of the respondents who were familiar with fuel cells technology agree with this statement.

4.3.5.2 Fuel and infrastructure

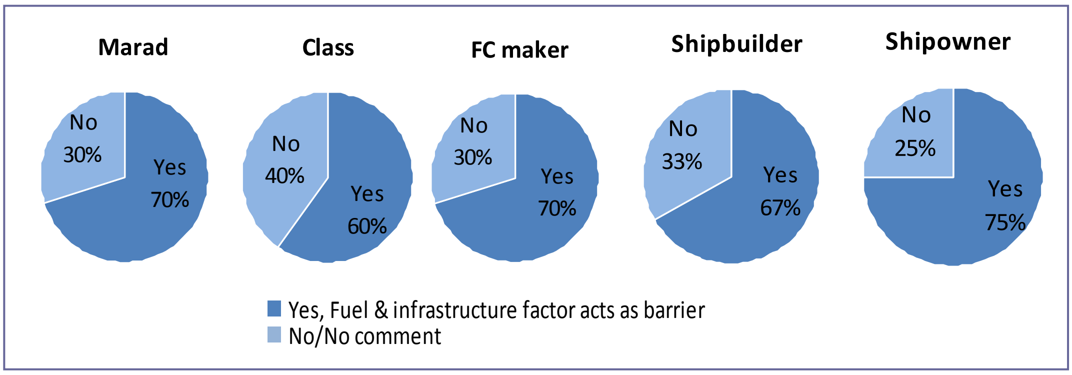


Figure 4.12 Opinion regarding fuel and infrastructure on each job category

It seems that all maritime stakeholders agree that fuel and infrastructure are problem for fuel cells adoption. The chi-square test of the job category and opinion regarding fuel and infrastructure resulted in p=0.942, which means there are no significant different opinions among job categories.

Issues mentioned by respondents are choice of fuel and difficulty to use one type of fuel on board, quality and availability of H_2 (its production and supply network) and H_2 storage capacity. The challenge will be put on fuel processing technology and also development of renewable H_2 to minimize GHG on the production part.

4.3.5.3 Volumetric size

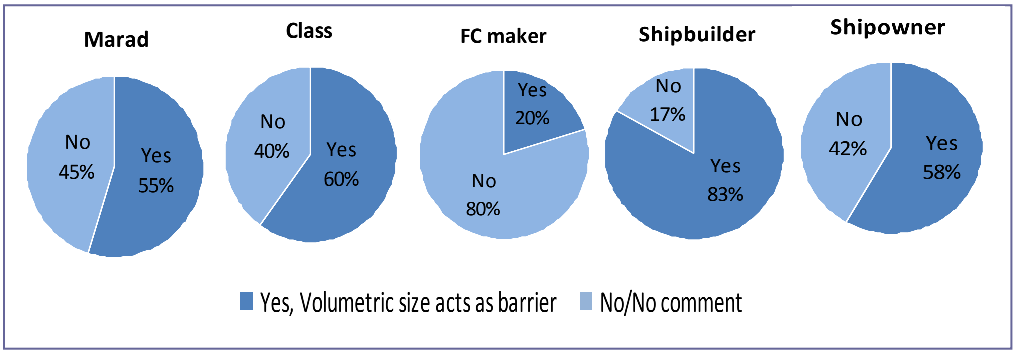


Figure 4.13 Opinion regarding volumetric size on each job category

In the volumetric size factor, while the majority of the respondents agree that this factor becomes a problem for fuel cells adoption, 80% of the fuel cells makers and developers believe that this factor does not act as a barrier towards fuel cells adoption. However, the chi-square test can not pass the 90% confidence level since the p value resulting from the test is 0.133. In other words, the H_0 can not be rejected, so it can not be concluded that there is a significant difference among job categories.

4.3.5.4 Safety aspect

Although some safety issues arise in the questionnaire response, such as H_2 safe storage and fear of dealing with gas fuel, as shown in Figure 4.14 the majority of all respondents agree that safety problems do not act as a barrier toward fuel cells adoption. The chi-square test also supports this conclusion with p=0.697 so that it can be concluded that there are no different opinions on this safety aspect.

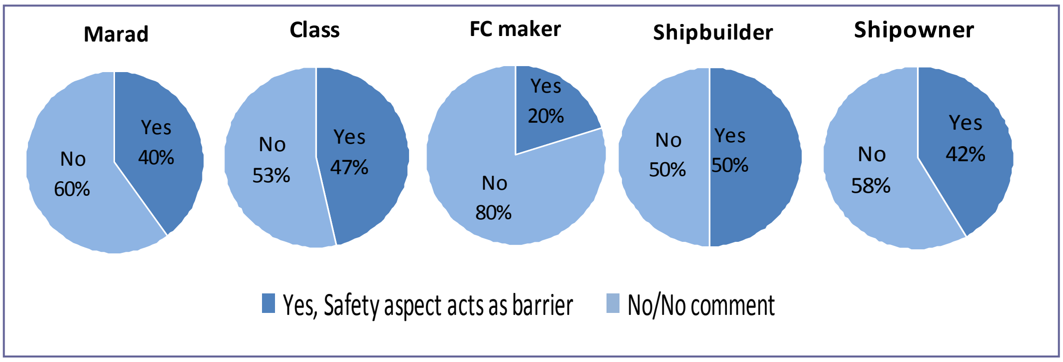


Figure 4.14 Opinion of safety aspect as barrier on each job category

4.3.5.5 Ships integration issues

Figure 4.15 shows the opinions of maritime stakeholders regarding ships integration issues. The response between job category is quite different, as the chi-square test result in p=0.063, which is proof that there are significant difference between them regarding this issue. Classification societies and shipbuilders have the least confidence about integrating fuel cells on board ships, while the majority of other job categories believe that this issue will not act as a barrier. Sturdiness for marine atmosphere and ability to withstand shipboard working conditions are one of the reasons mentioned by the respondents.

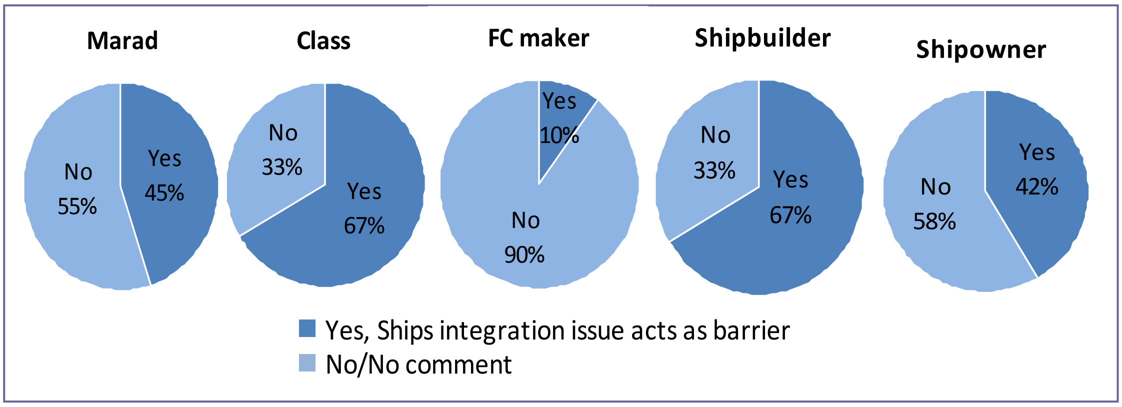


Figure 4.15 Opinion regarding ship integration issues on each job category

As shown in Figure 4.16, when analyzing using variable level of familiarity, there is a slight different opinions between respondents who are familiar and not. of Among the respondents who are familiar with fuel cells technology, 63 % of them believe that ship integration issues will not act as a barrier; on the contrary, only 46% of respondents who are not familiar with fuel cells agree with this statement. However, with the chi-square test p=0.142, H_0 can not rejected; so it can not be concluded that there is a significant difference between people who are familiar or not familiar in responding this issue.

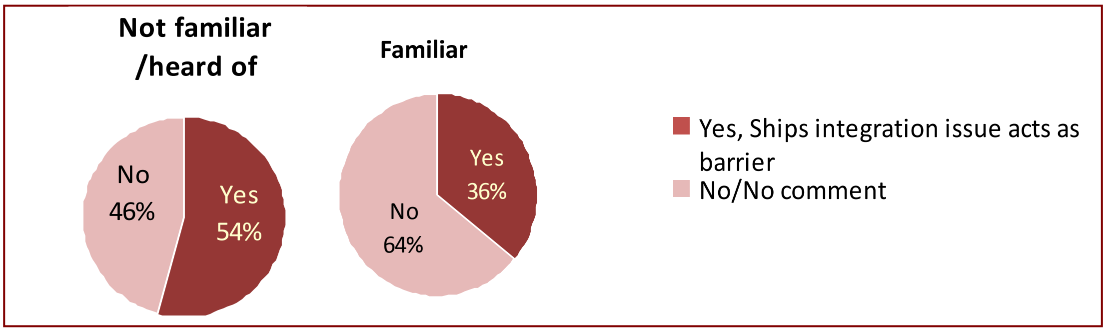


Figure 4.16 Level of familiarity vs opinion regarding ships integrating issues

4.3.5.6 Power density

There are also slightly different opinions between maritime key players regarding their power density issues. The majority of maritime administrations, classification societies and ship owners believe that the power density of fuel cells is too low, so that it will act as a barrier towards fuel cells adoption on board ships; however, fuel cells makers and shipbuilders seem to have more confidence in this issue. The difference between them was supported by the chi-square test value p= 0.080 for different job categories.

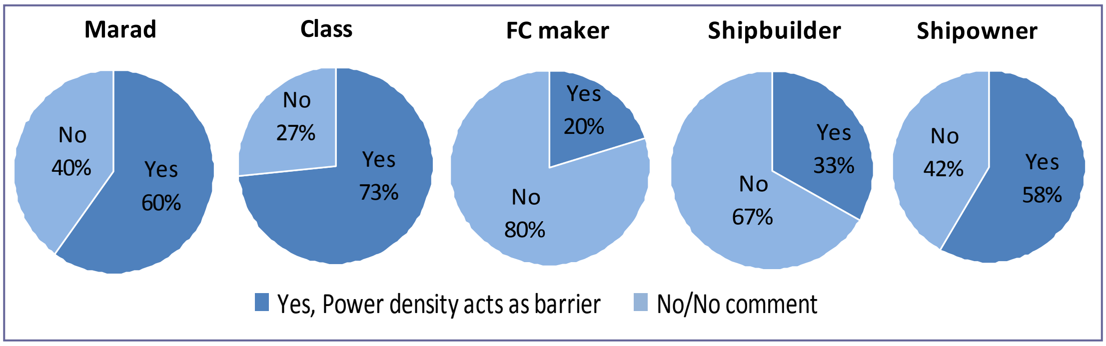


Figure 4.17 Opinion regarding power density on each job category

However, referring to Section 3.2.3, from Figure 3.1 and Figure 3.2, in terms of volumetric and gravimetric power density, PEMFC and SOFC are possible to compete with diesel engines.

Therefore, it is necessary to check whether the level of familiarity influences the respondents' answers. Figure 4.18 shows comparison between respondents who are familiar and respondents who are not familiar with fuel cells technology. People who are familiar with fuel cells technology tend to agree that power density will not act as a barrier, while people who are not familiar do not agree with this statement. Although in comparing levels of familiarity, there are different opinions that arise, the chi-square test result does not pass the confidence level with p=0.114. Therefore, it can not be concluded that there is significant difference between people with different levels of familiarity in responding power density issues.

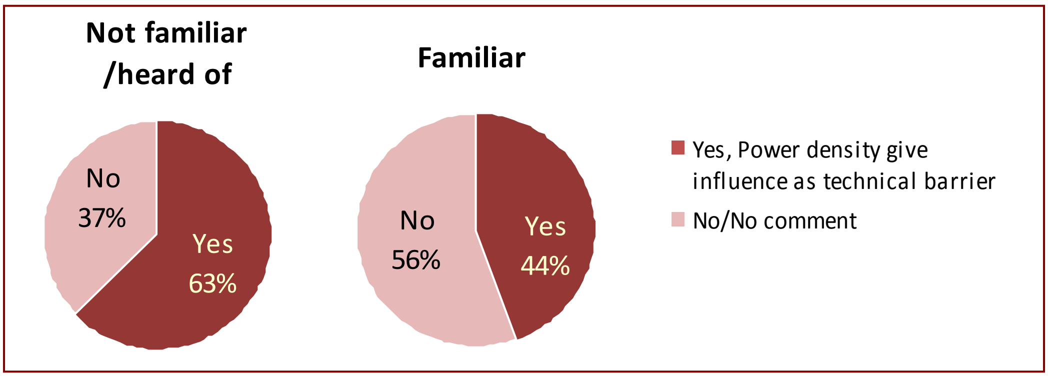


Figure 4.18 Level of familiarity vs opinion regarding power density

4.3.6 Factors in economic aspects

Three factors being mentioned in the questionnaire are high initial cost, cost effectiveness in operation, and recent economic recession as factors influencing the adoption.

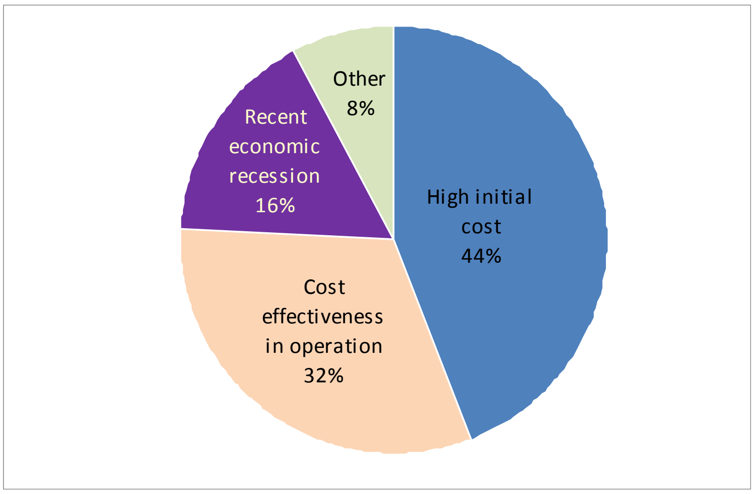


Figure 4.19 Factors influencing economic consideration (all respondents)

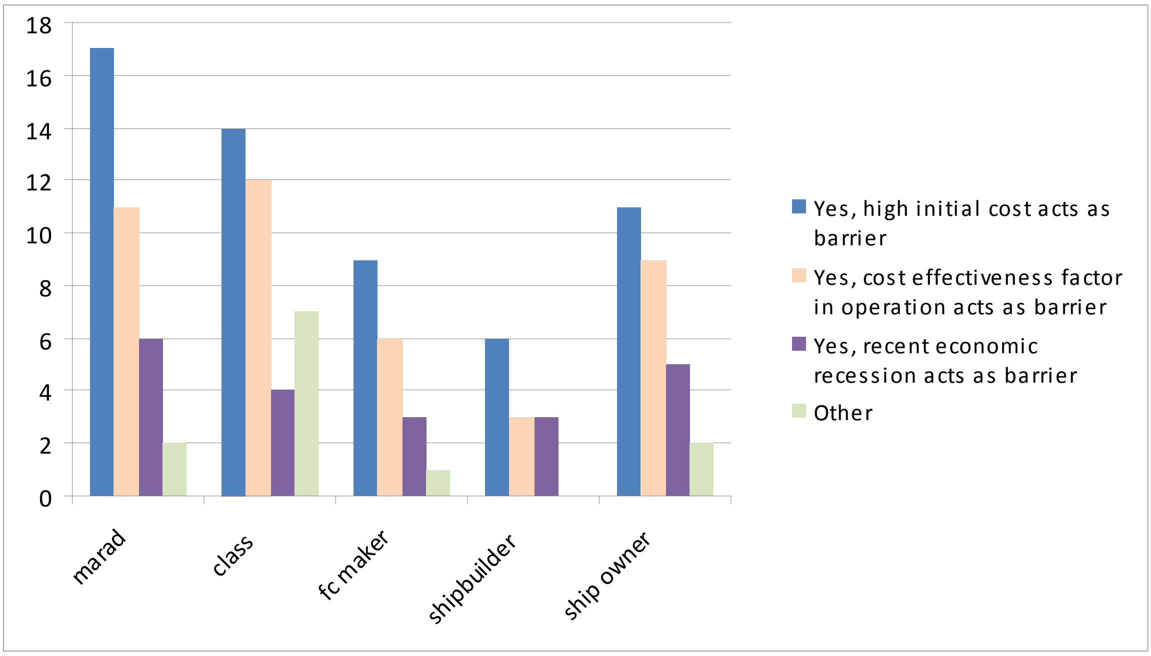


Figure 4.20 Factors in economic aspect on each job category

Among these factors, as shown in Figure 4.19, high initial cost has been chosen as factor in the economic barrier by the majority of the respondents. Other factors mentioned by the respondents were mostly regarding lifetime of fuel cells which influence fuel cells life cycle cost.

From Figure 4.20 it can be seen that all maritime stakeholders tend to have similar opinions in economic aspects. However, the comparison specifically on each factor will be discussed to ensure this conclusion.

4.3.6.1 High initial cost

Figure 4.21 shows no different opinion between maritime stakeholders. The majority believe that high initial cost act as a barrier toward fuel cells adoption onboard ships. This conclusion was supported by the chi-square test with p=0.828, which definitely supports H_0 that there is no significant difference on their opinion regarding initial cost.

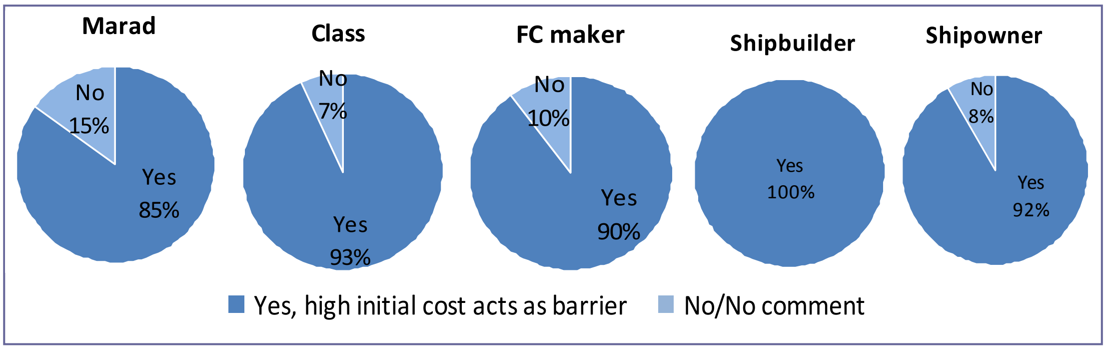


Figure 4.21 Opinion regarding high initial cost on each job category

4.3.6.2 Cost effectiveness in operation

Although the majority of respondents agree that cost effectiveness in operation will act as a barrier, the proportion of each job category is relatively different. Most respondents (80%) from classification societies agree that this factor will act as a barrier and only half of the respondents from shipbuilders agree with this statement.

The chi-square test on this factor resulting in p=0.463 to conclude that there are no significant difference between each job category.

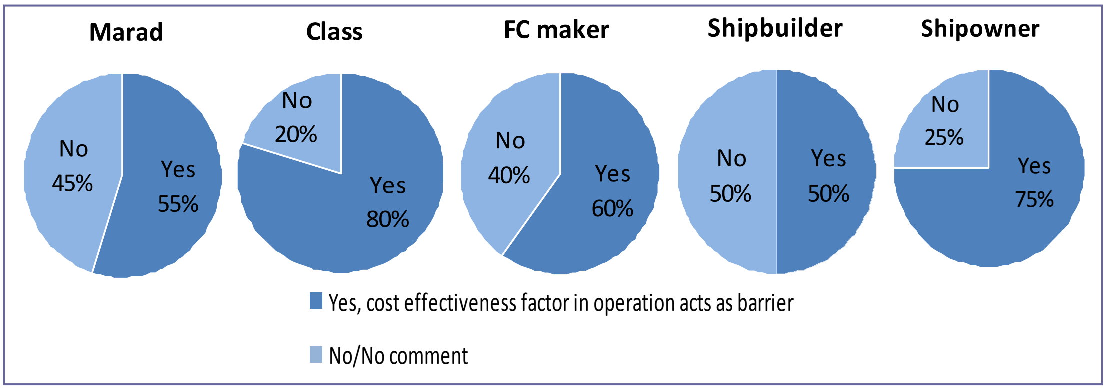


Figure 4.22 Opinion regarding cost effectiveness in operation on each job category

4.3.6.3 Recent economic recession

Figure 4.23 shows the opinion of maritime stakeholders in the recent economic recession. Most of the respondents agree that this factor did not act as barrier toward fuel cells adoption. The chi-square test result, p=0.813, can not prove that there is significant different opinions among maritime stakeholders.

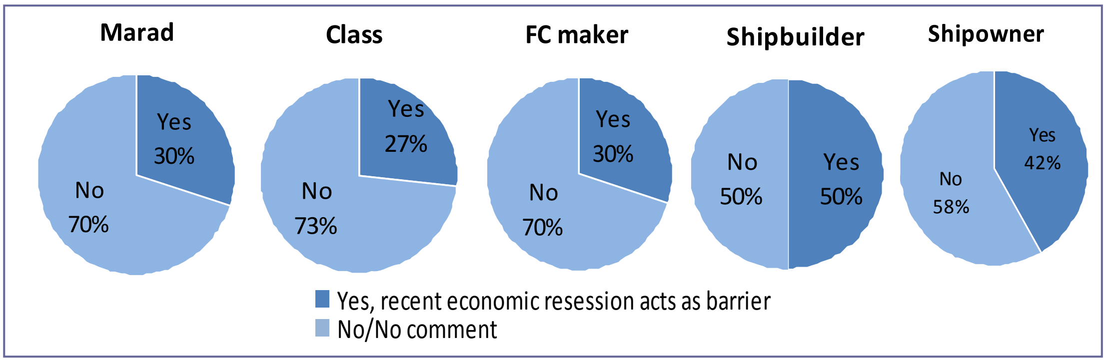


Figure 4.23 Opinion regarding recent economic recession on each job category

4.3.7 Other identified aspect

In addition to the factors mentioned in technical and economic aspects of fuel cells, there are several other things appearing in the respondents' responses. Regulation and legislation, crew capability, natural tendency of industry to be conservative with new technology and oil lobby also give influence in fuel cells adoption onboard merchant ships.

4.3.8 Factors to accelerate fuel cells adoption

Respondents were also being asked for the solution which could accelerate fuel cells adoption. As previous questions, which are categorized in technical and economic consideration, the solution is also correlated with these two aspects. There are 5 different options: technical improvement, innovation-support organization, lower price of fuel cells, proof of cost effectiveness in operation and high policy support.

Figure 4.24 shows raw data of respondents' responses to this question. To clarify the difference, each factor will be discussed further.

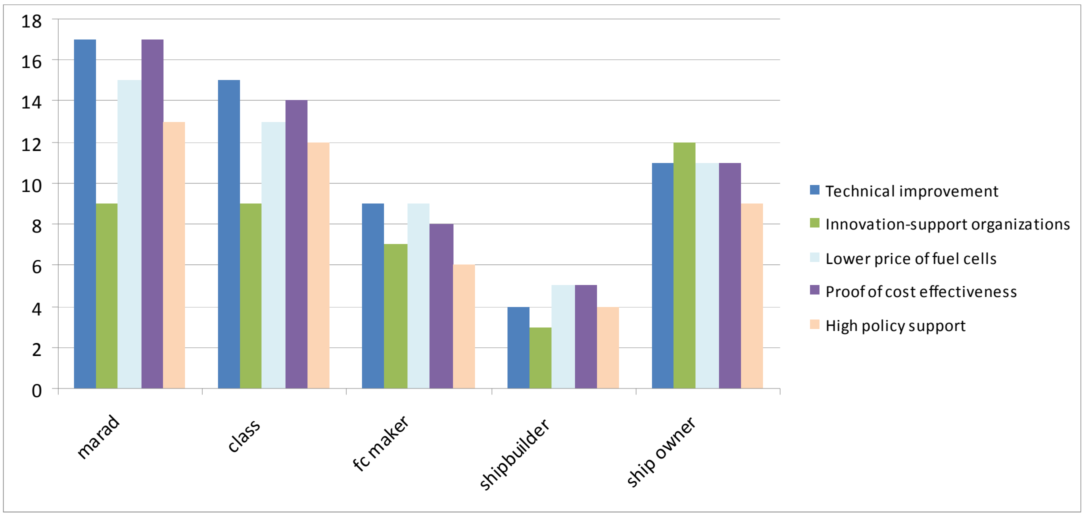


Figure 4.24 Opinion regarding factors to accelerate fuel cells adoption

Respondents also put the level of significance on each factor, whether this factor was very significant, significant or less significant. To measure the significance, weighting factors are put on each level. Figure 4.25 represent the composition respondents' responses with multiplying number of response with the weighting factor. Less significant was multiplied by 1, significant was multiplied by 2 and very significant was multiplied by 3. Top three responses are technical improvement and proof of cost effectiveness, followed by lower price of fuel cells.

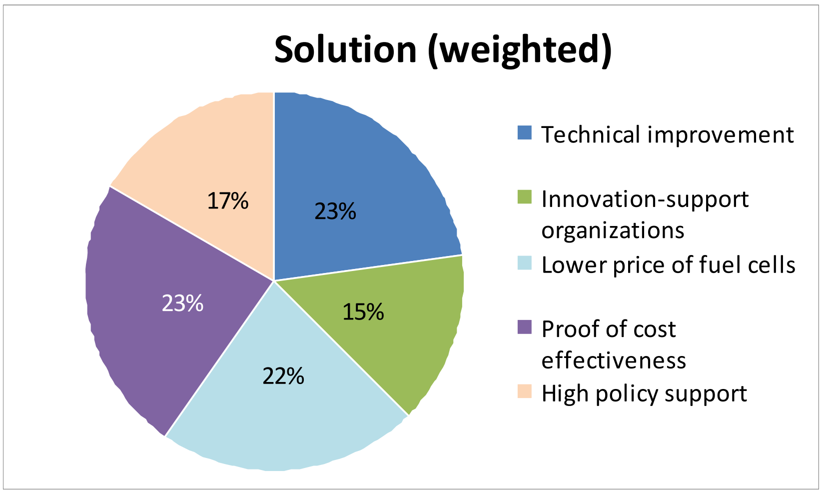


Figure 4.25 Number of response multiply with weighting factor

4.3.8.1 Technical improvement

Correlating with the respondents' response on the technical barrier, the majority of the respondents agreed that technical improvement is the solution to accelerate fuel cells adoption. There was no significant different opinion between maritime stakeholders as supported by the chi-square test p=0.259

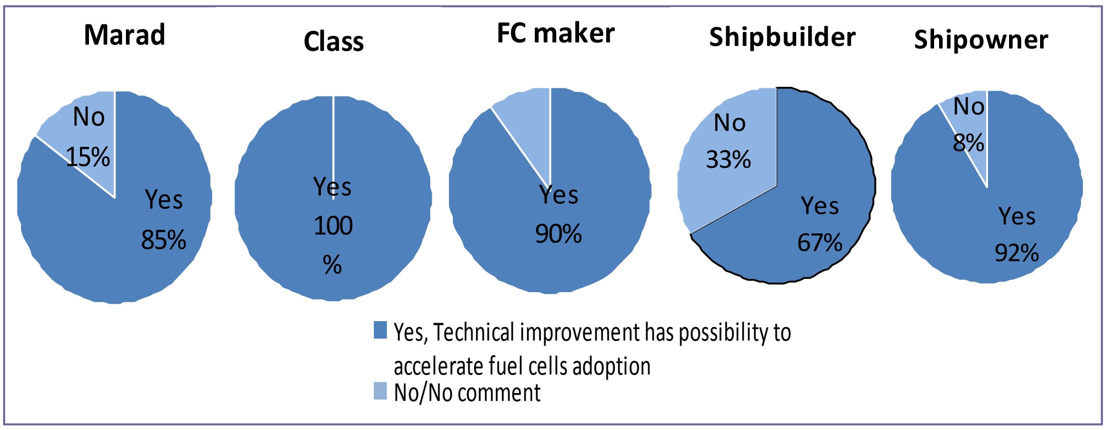


Figure 4.26 Opinion regarding technical improvement as solution

4.3.8.2 Innovation-support organization

Respondents were also being asked whether an innovation-support organization can accelerate fuel cells adoption. Slightly different with the previous solution, respondents have a variety of opinions responding to this question.

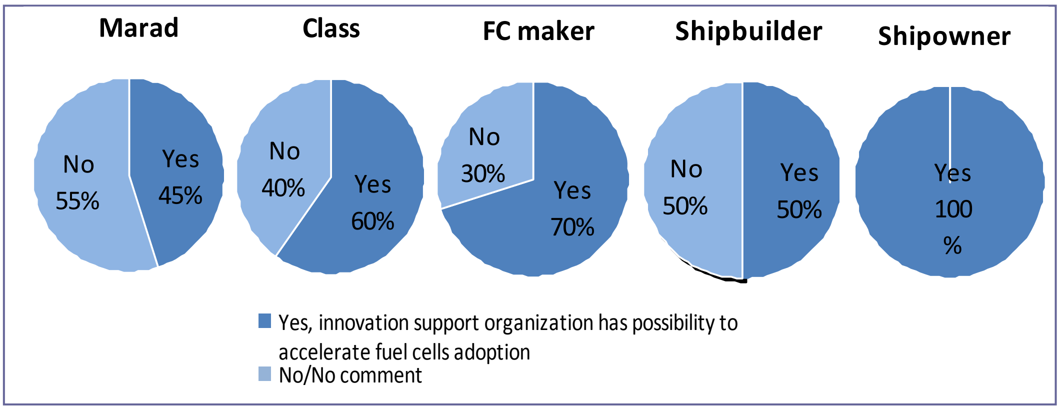


Figure 4.27 Opinion regarding innovation-support organization as solution

While 55% of the maritime administrations did not fully support this solution, majority of maritime stakeholders agreed that an innovation-support organization as a factor to accelerate fuel cells adoption, and even all the respondents from ship owners agree with this solution. These answers are rational since many ship owners usually have such appointed organization for developing their fleets, for example to optimize fuel efficiency. The chi-square test on this solution gives p=0.032 which is small enough to pass the 90% confidence level to reject H_0, so it can be concluded that there are different opinions among job categories regarding the innovation-support organization.

4.3.8.3 Lower price of fuel cells

As shown in Figure 4.28, it is obvious that all maritime stakeholders have a similar opinion about this solution. The respondents who rejected or not giving comments on this question range between 8% - 25% in each job category; the rest are agreed that the price of fuel cells should be lower to accelerate fuel cells adoption. The chi-square result p=0.719 proves that they have a similar response on this factor.

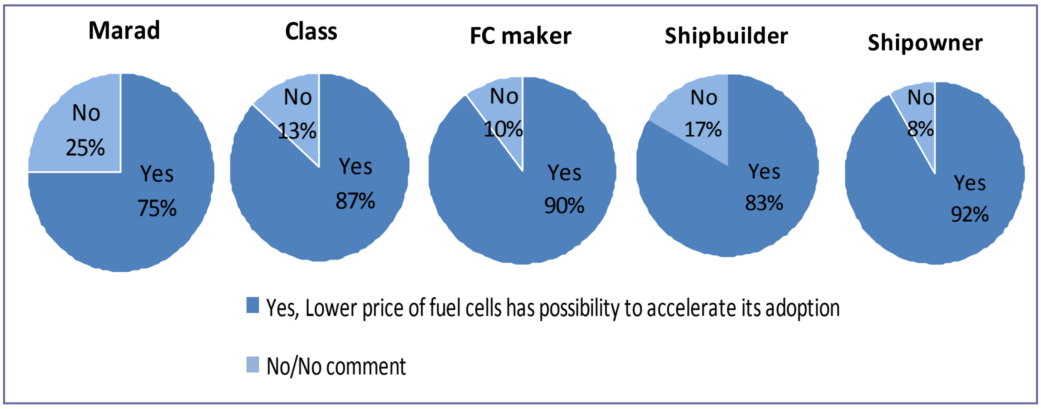


Figure 4.28 Opinion regarding lower price of fuel cells as solution

Although there is no different opinion between job categories, the chi-square analysis shows that there is a different opinion between respondents who are familiar and those who are not. The p value = 0.090, which is small enough to pass the 90% confidence level shows that there are different opinions between respondents who are familiar and not with their opinion regarding the lower price of fuel cells. As shown in Figure 4.29, 93% of the respondents who are familiar with fuel cells technology agree that the lower price of fuel cells will accelerate fuel cells adoption. While only 77% of the respondents who are not familiar with fuel cells technology agree with the statement. Probably the rest, 23%, really has less confidence in the technical capability of fuel cells; therefore, they believe that although the price is lower, it will not accelerate fuel cells adoption.

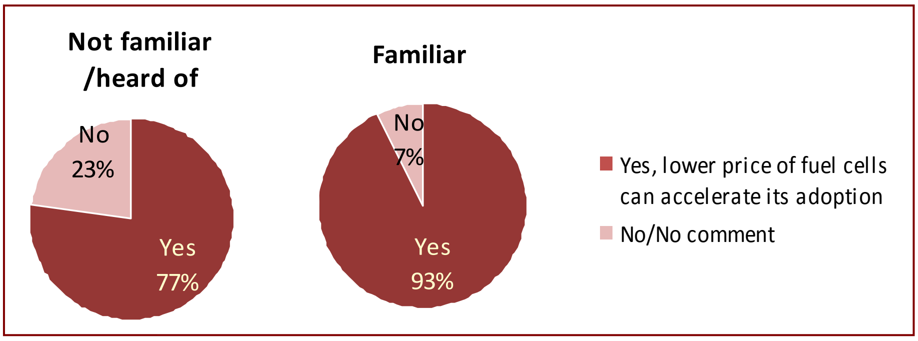


Figure 4.29 Level of familiarity vs lower price of fuel cells as solution

4.3.8.4 Proof of cost effectiveness

Similar with the previous question, the majority of maritime stakeholders tend to agree with this solution, with the chi-square test result p=0.851

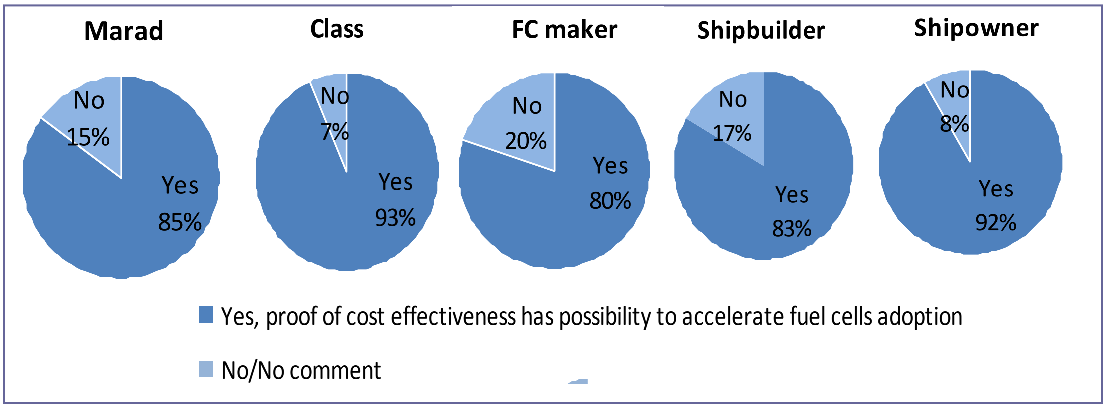


Figure 4.30 Opinion regarding proof of cost effectiveness as solution

4.3.8.5 High policy support

The last option in the question is regarding high policy support. As shown in Figure 4.31, all maritime stakeholders tend to agree that high policy support can accelerate fuel cells adoption onboard merchant ships. Classification societies have the most percentage supporting this option, followed by ship owners and shipbuilders. Unfortunately, maritime administrations as policy makers were in the fourth position supporting this solution.

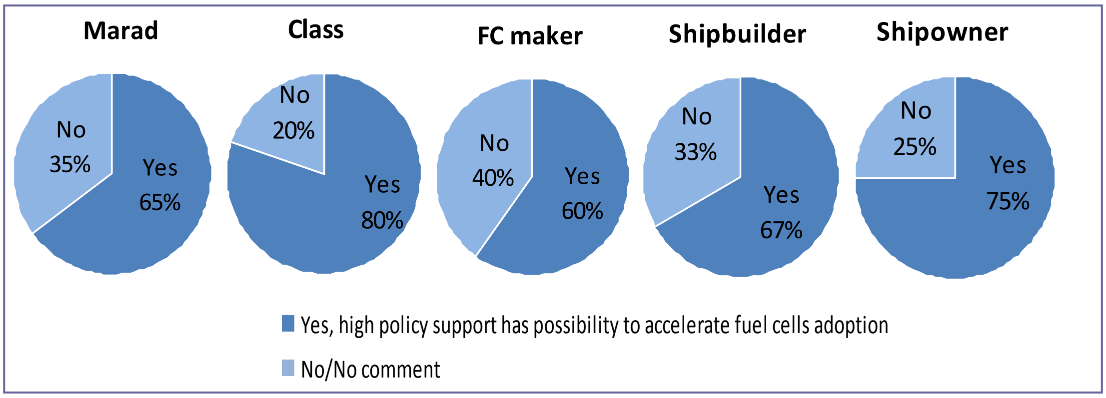


Figure 4.31 Opinion regarding high policy support as solution

4.4 Chapter conclusion

To sum up this chapter, significant differences between maritime stakeholders' opinions were proven by the chi-square independence test in the following issues:

- Different job categories have different levels of familiarity
- Different levels of familiarity have different opinions regarding technical aspects as barrier of fuel cells adoption. It seems that people with less familiarity tend to have less confidence in technical capability of fuel cells.
- Opinion regarding reliability has been identified as one of factors which was perceived differently by different levels of familiarity
- Different job categories have different opinions regarding ship integration issues and fuel cells power density. It seems that job characteristics have influenced their opinion of positioning influence aspects. For example, classification societies and shipbuilders have the least confidence about integrating fuel cells on board ships, while the majority of other job categories believe that this issue will not act as a barrier.
- All maritime stakeholders tend to have a similar opinion of all solutions offered, except the innovation-support organization and lower price of fuel cells.
- Different job categories have different opinions regarding innovation-support organization, where all ship owners agreed with this solution.
- Different levels of familiarity also have different opinions regarding lower price of fuel cells; where more respondents who are not familiar do not agree that lower price of fuel cells can accelerate fuel cells adoption. However, this opinion could be influenced by their less confidence of technical aspects; therefore, even if the price is low it will not be adopted unless technical capability has been proven.

5. CONCLUSIONS

To conclude the research activity in this dissertation, the findings are described in the following logical sequence based on the objective of this study:

1. Chapter 2 reviewed current status of fuel cells development. There are 41 existing fuel cells projects in surface ships which were identified from open literatures. Those projects were dominated by small vessels, mostly yachts or sailboats, with few numbers of water taxis, a whale watching ship, an offshore vessel and a car carrier. So far fuel cells on marine applications are still in a demonstration phase; however, this could demonstrate different fuel cells technology in different applications including in merchant/commercial vessels. In addition, an increasing number of ongoing projects and demonstration vessels show opportunity of fuel cells on future developments.

2. The driving force and restraining force of fuel cells adoption are being investigated in Chapter 3. Identified factors that influence the adoption of fuel cells are included but not limited to factors which have been categorized in environmental, technical, and economic aspect, as well as regulation and legislation issues as shown in Figure 5.1.

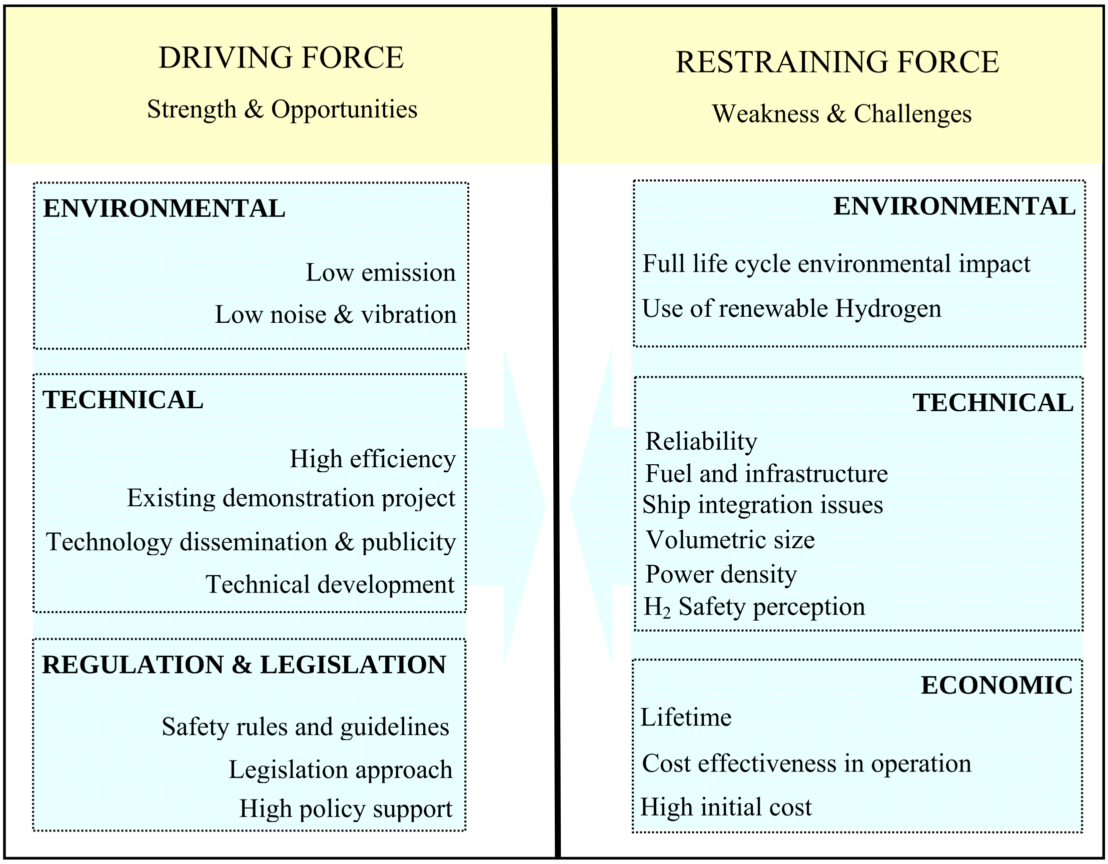


Figure 5.1 Driver and barrier of fuel cells adoption on board merchant ships

3. In chapter 4, statistical analyses using descriptive and the chi-square independence test have been done to questionnaire responses. Different opinions between maritime stakeholders have been identified. Firstly, it is significantly proven that different job categories have different levels of familiarity. While all maritime stakeholders tend to have similar opinion regarding economic aspects, mostly different opinions happened on technical factors and solutions.

   Respondents with low level of familiarity tend to have less confidence in technical capability of fuel cells and the identified factor which was perceived differently by them is reliability. In addition, different job categories tend to pay more attention to different factors, which seems really rational if associating them with their job category. For example, in technical aspects, fuel and infrastructure seem to be a problem for maritime administrations and fuel cells makers. Classification societies tend to worry about power density and ships integration issues. While shipbuilders put volumetric size as the biggest problem, ship owners pay attention to reliability and fuel infrastructure.

For sure, incomplete or outdated information regarding fuel cells development could influence acceleration of fuel cells adoption on board merchant ships.

However, it should be noted that in this survey with respondents from various countries and different fields of industries, the results can contain a degree of subjectivity.

4. Considering existing technology developments, for the short term, fuel cells application could be promoted to be adopted in vessels which take advantage of noiseless and less vibration power generation, and also for less emission in harbors and inland waters, such as small passenger vessels, research vessels, tugs and cruise vessels. In addition, to accelerate its adoption, diffusion of existing technology should be forwarded through wider and open publicity which take into consideration the focus attention of maritime stakeholders.

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APPENDIX A – Existing fuel cells on surface ship demonstration and other ongoing project

No	Project / Country	Ship Specification	FC type	Power	Year	Fuel use	Reference
1	Switzerland – PSI, IGS, OFEN	Hidroxy 100, Pedalo (without pedals) style boat, dimensions 2,58 x 1,65 m, weight : 40 kg, speed 5,5 km/h, 1 passenger.	PEMFC	100 W	1997	H_2	Affolter, 2000, 2007
2	US - Office Naval Research	Navy ship service, USCG cutter ‘‘Vindicator’’	PEMFC	2.5 MW	1998	Naval Distillate Fuel – Sulfur free Diesel - NATO F-76	Privette, 1999 & Sattler, 2006
3	Italy	Boat range about 300 km, with a capacity for carrying 90 passengers	For Propulsion system, hybrid	40 kW	1998	Liquid H_2 storage	Sattler, 2000
4*	US-MARAD	Feeder ship on the New York–Boston route, diesel-electric 434 TEU container ship	MCFC		1998	LNG	Sattler, 2000
5	Switzerland – PSI	Hydroxy 300, dimensions 6 x 2,5 m, weight: 130 kg, speed 10-12 km/h, 2 passengers.	PEMFC	300 W	1998	H_2	Affolter, 2000, 2007
6	Germany	MS Weltfrieden	PEMFC	10 kW	2000	Hydrogen in two metal hydride storage	Sattler, 2000
7	Finland - Hydrocell Oy	Two different motorboats using HC-100 cylindrical fuel cells with Yamaha electric motor	AFC	30 kW	2000	Metal hydride H_2 Storage	McConnel,2010
8	Germany - Etaing GmbH	*Hydra*, 22 passengers, 9 km/h speed	AFC	6.9 kW	2000	Metal hydride H_2 Storage	McConnel,2010
9*	Japan	1500 DWT merchant ship, 499 GT coastal vesse	PEMFC for propulsion plant	2x500 kW	2000	Methanol reformer	Sattler, 2000

10	Japan – Yuasa Corporation	Malt's Mermaid III, sailboat 5.8 m long	DMFC as APU	30 W	2002	Methanol	Cropper, 2004
11	Switzerland – IESE-EIVD	Branec III sail boat	PEMFC as APU	300 W	2002	H_2	McConnel,2010
12	Switzerland - Federal Office of Energy	MW-Line Alpha boat, dimensions 6 x 1,45 m, weight: 150 kg, speed 9-11 km/h, 4 passengers.	PEMFC	2 kW	2002	H_2	Affolter, 2000, 2007
13	Germany/Canada - MTU CFC/Ballard	Christined ¨no 1¨ 12-metre yacht has range of 225 kilometres at a speed of six km/h. The first fc power craft certified (by GL)	PEMFC for propulsion plant	20 kW	2003	H_2	Cropper, 2004
14	USA - Duffy Electric Boat Co/Anuvu/ Millennium Cell	Duffy water taxi for 18 passengers	PEMFC	3 kW	2003	sodium borohydride, Hydrogen on Demand® system	McConnel,2010
15	Switzerland/UK - IESE–EIVD/ZeTek Power	*Hydroxy 3000* catamaran, two earlier *Hydroxy* craft	PEMFC	3 kW	2003	H_2	McConnel,2010
16	Germany – Max Power	Mamelie, sailboat 15 long in DaimlerChrysler North Atlantic Challenge race	DMFC	1.2 kW	2004	Methanol	McConnel,2010
17	Switzerland/Germany - Brunnert-Grimm/zebotec	*COBALT 233 ZET* - sports boat with a system is undergoing certification by Germanischer Lloyd	hybrid propulsion system : electrical engine, batteries and fuel cells.	2 x 12-kW propulsion	2005	Hydrogen	

18	US- San Francisco Bay Area Water Transit Authority	Double decker Ferry San Francisco-Treasure Island. 79 feet long, 149 passenger	hybrid for main propulsion	240 kW	2005	metal hydride battery to absorb and store hydrogen,	Adamson, 2005
19	USA-Haveblue	Haveblue XV1 sail boat	PEMFC	10 kW	2005	Metal hydride H_2 Storage	Adamson, 2005
20	Switzerland – PSI	Hydroxy 2000, dimensions 7 x 2,5 m, type catamaran, speed 10-15 km/h, 6 passengers.	PEMFC	2 kW	2005	H_2	Affolter, 2000, 2007
21*	EU	MC-WAP	MCFC	150 kW	2005 (project start)	Diesel reformer	
22	Germany – H2Yacht GmbH	H2 Yacht 540, 6.75 m, 5 persons	PEMFC	1.2 kW	2005	H_2	H2Yacht, 2008a
23	Germany – H2Yacht GmbH	H2 Yacht 675, 6.75 m, 8 persons	PEMFC	2.4 kW	2006	H_2	H2Yacht, 2008
24	UK - University of Birmingham, student project	Ross Barlow -Canal Boat	PEMFC	5 kW	2007	metal hydride solid-state hydrogen store	Protium, 2008
25	Singapore/USA - Horizon Fuel Cell/Plug Power	Trolling boat propelled by electric motors	PEMFC	300 W	2007	H_2	McConnel,2010
26	UK – Voller Energy	Emerald Beneteau 411, sailboat 12 m long, in 3000 nm ARC transatlantic rally, running on	PEMFC	5 kW	2007	reformed LPG	McConnel,2010
27	Germany- Proton motor-Alster Touristik GmbH – Zemship Project	FCS “Alsterwasser” 100 passengers,	PEMFC e for primary propulsion, with lead gel battery	2x48 kW	2008 (project start 2006)	Hydrogen storage tank	FCS, 2009

28*	Netherland	Hydrogen Hybrid Harbour Tug (HHHT)	PEMFC	2x200 kW	2008	H_2	Fuel, 2008
29	Austria - Fronius International/Bitter GmbH	*Riviera 600* motor boat (16 m long), part of Future Project Hydrogen	PEMFC	4 kW	2009	H_2 in high-pressure cartridges	McConnel,2010
30	Germany/Norway-FellowShip-DNV, Wartsila, Eidesvik, MTU	Viking Lady, Supply vessel, Length: 92.2m, Width: 21m, Depth: 7.6m, Gross tonnage: 6100t, Dead weight: 5900t, Berths: 25 persons	MCFC Hybrid, tandem with gas fueled generator supply main switchboard (APU).	320 kW	2009 (project started 2003)	LNG (LiquefiedNatural Gas)	Skinner, 2010
31	USA-Rensselaer Polytechnic Institute	*New Clermont,* 6.7 m Bristol 22 sailboat outfitted as student project with two Plug Power fuel cells	PEMFC	4.4 kW	2009	H_2	McConnel,2010
32	Denmark - IRD Fuel Cell Technology	Chaloupe boat (6.4 m long) using DMFC to charge electric motor batteries	DMFC	500 W	2009	Methanol	McConnel,2010
33	Germany-SFC Smart Fuel Cells	*Pogo 2* using EFOY 2200 second in Transat 6.50 solo transatlantic race (7800 km). Also EFOY 1600 on Nightlife wins class in Atlantic Rally for Cruisers	DMFC	1.6-2.2 kW	2009	Methanol	McConnel,2010
34	Greece Tropical Green Technologies	Testing RFC-1000 unit on motorboat,	PEMFC	1 kW	2009	H_2 from reformed LPG	McConnel,2010
35	UK/Germany- Base UPS system/SFC	Nightlife - yacht won the prestigious Atlantic Rally for Cruisers (ARC) racing division	DMFC to power navigation, computer & communications equipment	65 W	2009	Methanol	UPS, 2010

36	Iceland/Canada – Icelandic New Energy/Ballard – Smart H2 Program	*Elding*, 125-tonne whale watching ship	PEMFC hybrid with battery as APU	10 kW	2009	H_2	McConnel,2010
37	Netherland - Fuel Cell Boat BV	*Nemo H*2, 22 m long, 82 passenger capacity	PEMFC, hybrid for main propulsion	60–70 kW	2009	H_2	McConnel,2010
38*	Turkey – UNIDO/ICHET	Sightseeing boat 50 passengers	PEMFC	6x30 kW	2009	H_2	McConnel,2010
39	France – Universite Joseph Fourier	*Zero* CO_2 , 12 m yacht for collecting scientific data on pollution	PEMFC Hybrid with lithium battery - as propulsion	30 kW	2009	H_2	McConnel, 2010
40	Germany - GL, MTU On site energy, ZBT and other 18 institutions	*E4ship project*	PEMC		2009-2016		e4ship, 2009
41	Finland/Sweden/Norway /UK/Italy – Wärtsilä/Wallenius Marine/ Lloyd's Register/ Det Norske Veritas (DNV)/ University of Genoa in Italy. –Methapu projec5t	*Undine,* Car carrier	SOFC as APU	20 kW	2010 (project started in 2006)	Methanol	Wärtsilä, 2010

* ongoing development project or unknown result/limited information

APPENDIX B – Sample of blank questionnaire

Nationality :		
Company/Organization:		
Position Category :		(management/engineering?)

Note: This Survey consists of 6 questions, some of the answers are multiple-choice with the following abbreviations, but you can also choose it from the dropdown list in each blank box

Y	= YES	⇒	(for question 1)	⇒	(for questions 2 & 5)
N	= NO	1	= not familiar	1	= less significant
		2	= heard of	2	= significant
		3	= familiar	3	= very significant

1 Please specify your level of familiarity with fuel cell technology? [ ] 1/2/3 ?
(1=not familiar, 2=heard of, 3=familiar)

2 In your opinion, what factors act as barrier toward fuel cells adoption onboard merchant ships? (if you choose more than 1 choices please mark the level of significance on each issue.

1=less significant, 2=significant, 3=very significant)

- Technical aspect of fuel cells [ ] Y/N? [ ] 1/2/3 ?
- Economic aspect of fuel cells [ ] Y/N? [ ] 1/2/3 ?
- Other (please mention the key words) [ ]

3 If TECHNICAL ASPECT of fuel cells acts as barrier, which issue give influence?

- Reliability [ ] Y/N?
- Fuel and infrastructure [ ] Y/N?
- Volumetric size [ ] Y/N?
- Safety Aspect [ ] Y/N?
- Integration to the ships [ ] Y/N?
- Power Density [ ] Y/N?
- Other (please mention the key words) [ ]

4	If ECONOMIC ASPECT acts as barrier, which issue give influence?			
	- High initial cost	Y/N?		
	- Cost effectiveness in operation	Y/N?		
	- Recent economic recession	Y/N?		
	- Other (please mention the key words)			
5	In your opinion what factor actually has possibility to accelerate fuel cells adoption onboard merchant ships? Please mark level of significance on each issue (1=less significant, 2=significant, 3=very significant)			
	- Technical improvement	Y/N?		1/2/3 ?
	- Innovation-support organizations	Y/N?		1/2/3 ?
	- Lower price of fuel cells	Y/N?		1/2/3 ?
	- Proof of cost effectiveness	Y/N?		1/2/3 ?
	- High policy support	Y/N?		1/2/3 ?
	- Other (please mention the key words)			
6	Please feel free to give additional information based on your opinion regarding other issues affecting fuel cells adoption on board merchant ship			

THANK YOU VERY MUCH

* Questionnaire was used in electronic format

APPENDIX C – List of respondents institution

No.	Nationality	Institution
1	Malaysian	Marine Department of Malaysia
2	Filipino	Maritime Industry authority of Philippines
3	Chinese	China Maritime Administration
4	Sierra Leonean	Sierra Leone Maritime Administration
5	Japanese	MLIT - Japan
6	Korean	Ministry of mainland and transportation and maritime – Republic of Korea
7	Peruvian	General directorate of captaincies and coast guards – Peru
8	Norwegian	Norwegian Maritime Directorate
9	Egyptian	Egyptian Authority for maritime safety
10	Syrian	General directorate of port - Syria
11	British	Maritime and coast guard agency - UK
12	Swedish	Swedish Transport Agency
13	Iranian	Port & Maritime Agency - Iran
14	Brazilian	Diretoria de Portos e Costas - Brazil
15	UEA	Dubai Maritime Authority - UEA
16	Vietnamese	Vietnam maritime administration
17	Indian	Indian maritime Administration
18	Malaysian	Ship Classification Malaysia
19	German	Germanischer Lloyd
20	Chinese	China Classification Society
21	Norwegian	Det Norske Veritas
22	British	Lloyd Register
23	Cypriot	Dromon Bureau of Shipping
24	Indonesian	Biro Klasifikasi Indonesia
25	Italian	RINA Services SPA
26	Korean	Korean Register of Shipping
27	French	Bureau Veritas
28	Croatian	Croatian Register of Shipping
29	Netherland	Nedstack fuel cell technology BV
30	USA	UTC Power Corporation
31	German	Proton motor fuel cell gmbh
32	USA	EnerFuel
33	Canadian	Palcan Energy
36	USA	Teledyne Energy System
37	Taiwan	Asia Pacific Fuel Cell Technologies, Ltd.
38	British	Rolls Royce
39	German	Zentrum für Sonnenenergie- und Wasserstoff-Forschung

40	Finnish	Oy Hydrocell
41	Indonesian	PT Adiluhung
42	Sri Lankan	Colombo Dockyard
43	Indonesian	PT. PAL Indonesia
44	Chinese	Taizhou Wuzhou Shipbuilding Industry Co.,Ltd.
45	Peruvian	SIMA Peru
46	Indonesian	PT. Pertamina Indonesia
47	Korean	Korean Shipowners Association
48	Indonesian	PT Pelindo II
49	Indian	The Great Eastern Shipping Co. Ltd.
50	Canadian	Canadian Shipowners Association
51	Japanese	NYK Line
52	Icelandic	Elding Reykjavik Whale Watching
53	India	Shipping Corporation of India Ltd.
54	Indian	D&K Shipping Ltd.
55	British	Mubarak Marine LLC

APPENDIX D – Pearson chi square result

No	Variable of cross tabulation	p (asymp. sig.)
1	Job category vs Level of familiarity	0.002
2	Job category vs Technical aspect	0.357
3	Level of familiarity vs Technical aspect	0.009
4	Job category vs Economic aspect	0.290
5	Level of familiarity vs Economic aspect	0.817
6	Job category vs Compare Sig. tech & Eco	0.726
7	Level of familiarity vs Compare Sig. tech & Eco	0.488
8	Job category vs opinion regarding reliability	0.576
9	Level of familiarity vs opinion regarding reliability	0.047
10	Job category vs opinion regarding fuel and infrastructure	0.942
11	Level of familiarity vs opinion regarding fuel and infrastructure	0.952
12	Job category vs opinion regarding volumetric size	0.133
13	Level of familiarity vs opinion regarding volumetric size	0.572
14	Job category vs opinion regarding safety aspect	0.697
15	Level of familiarity vs opinion regarding safety aspect	0.645
16	Job category vs opinion regarding ships integration issue	0.063
17	Level of familiarity vs opinion regarding ships integration issues	0.142
18	Job category vs opinion regarding power density	0.080

19	Level of familiarity vs opinion regarding power density	0.114
20	Job category vs opinion regarding high initial cost	0.828
21	Level of familiarity vs opinion regarding high initial cost	0.773
22	Job category vs opinion regarding cost effectiveness in operation	0.463
23	Level of familiarity vs opinion regarding cost effectiveness in operation	0.679
24	Job category vs opinion regarding recent economic recession	0.813
25	Level of familiarity vs opinion regarding recent economic recession	0.720
26	Job category vs opinion regarding technical improvement	0.259
27	Level of familiarity vs opinion regarding technical improvement	0.929
28	Job category vs opinion regarding significance of technical improvement	0.233
29	Level of familiarity vs opinion regarding significance of technical improvement	0.321
30	Job category vs opinion regarding innovation-support organization	0.032
31	Level of familiarity vs opinion regarding innovation-support organization	0.682
32	Job category vs opinion regarding significance of innovation-support organization	0.169
33	Level of familiarity vs opinion regarding significance of innovation-support organization	0.588
33	Job category vs opinion regarding lower price of fuel cells	0.719
34	Level of familiarity vs opinion regarding lower price of fuel cells	0.090
35	Job category vs opinion regarding significance of lower price of fuel cells	0.642
36	Level of familiarity vs opinion regarding significance of lower price of fuel cells	0.335
37	Job category vs opinion regarding proof of cost effectiveness	0.851
38	Level of familiarity vs opinion regarding prove of cost effectiveness	0.735
39	Job category vs opinion regarding significance of	0.118

	proof of cost effectiveness	
40	Level of familiarity vs opinion regarding significance of proof of cost effectiveness	0.103
41	Job category vs opinion regarding high policy support	0.707
42	Level of familiarity vs opinion regarding high policy support	0.545
43	Job category vs opinion regarding significance of high policy support	0.431
44	Level of familiarity vs opinion regarding significance of high policy support	0.867