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Master Degree Project in Logistics and Transport Management

Alternative Energies or Fuels for Future Deep Sea Container Shipping

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Abstract

Concerning the container shipping industry, two problems have been raised in recent years. One is the increasing bunker price and the other is more and more serious environmental problem. There have been some solutions for these two problems such as slow steaming, strict regulation or using low sulphur fuels. However, all of these solutions have their own limitations, which prompt the authors of this thesis to look for another solution: finding an alternative shipping fuel or energy for deep sea container shipping industry in the future. After assessing potential shipping fuels and selection criteria, the authors find out that nuclear power, LNG and renewable energy such as wind and solar power can be seen as the potential candidates. The result contains three parts: a comparison table of fuels under different criteria, a survey followed by analytical hierarchy process analysis and interviews with professional people. After a deep analysis of three findings, it is able to see that nuclear power is the most feasible alternative in terms of the academic research. However people still worry about its high initial cost and safety issues. Regarding the high initial cost, the authors made a calculation to show that although the capital cost for one nuclear ship is high, nuclear ship still shows economic benefits when counting on a fleet on a certain route during a life cycle. Regarding the safety issues, the authors find that it is not technical but emotional problem, which make the safety problem become solvable. In general, using the nuclear power could be the most feasible solution for future deep sea container shipping sector.

Key word: shipping fuel, nuclear, LNG, wind or solar power.

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Best regards

Gothenburg, 11th May, 2014

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1. Introduction

1.1 Shipping History Overview

Shipping is a hoary and fascinating business. With a 5000 years old history, it has always accompanied with the development of whole civilization and economy. The first shipping trade network originated from 3000 BC ([Stopford 2009](#)). During following decades, shipping had opened and boomed the Mediterranean trade ([ibid](#)). In the fifteenth century, the foundation of the global trade network by shipping had already been established. Navigation technique and size of the voyage had achieved a significant progress. By eighteenth century, the map of shipping had extended to almost every part of the world, which opened the world market and promoted the development of the world economy. By then the major propulsion power of ship was from sail and wind. Nineteenth century was a historic period in shipping history. Due to industrial revolution, steam ship replaced sail in shipping; development of deep-sea cables revolutionized communication; and the whole shipping market was divided into three segments including tramp shipping, cargo liners and passenger liners. The total seaborne trade had been through a great leap from 20 million tons in 1840 to 550 million tons in 1950 ([ibid](#)). The fuel for ships in that time changed to coal. From 1950 to now, the shipping industry has ushered in a golden age. The fuel of shipping switched from coal to crude oil products, such as heavy fuel oil (HFO). Shipping technique and design of the ship continue developing. Improved communication system facilitated the global shipping industry. Airplane replaced the passenger liners and the development of bulk transport system as well as containerization of general cargo substituted the tramp shipping and cargo liner. The total seaborne trade had reached 8.2 billion tons until 2010 ([Stopford 2010](#)).

Nowadays, the world is running under global economy, which is supported by the global trade and the shipping industry. According to a report from [International Maritime Organization \(IMO\) \(2012\)](#), more than 90 per cent of global trade is carried

by sea, making shipping become lynchpin of the global economy. The increasing industrialization and liberalization increase the world trade demand. Without shipping, international trade, the flow of raw material and manufactured product and the import/export could not be afforded (IMO 2012). In order to achieve the maximum economic benefit, studies and researches in recent years focus on understanding the various aspects of shipping industry, designing the most efficient shipping strategy, providing solutions to the existing problems and forecasting the future development. This thesis aims to discuss future aspects of a certain part of shipping industry.

1.2 Containerization

Perhaps no term has been more frequently mentioned in the field of maritime transport than containerization in the past few decades. Containerization can be defined as the unitization of general cargoes by utilizing standard containers. In broad level, containerization also refers to the evaluation of conventional transportation system. It promotes the development of intermodal freight transport, in which more than one mode of transportation are involved in the single and seamless journey (Jones et al. 2000). The conflict between the unacceptable performance of cargo liner system and the increasing demand of sea transport was one of the most important incentives which stimulated the development of container shipping. Major problems during the late of the cargo liner era can be summarized into three points, including high labor intensity, long port time and poor service quality (Stopford 2009). Solution for these shortcomings in liner business is to unitize goods with containers. Containerization started in the United States of America in 1956 (Ham & Rijssenbrij 2012). According to Schirach-Szmigiel (1979), the fundamental principle of containerization is to homogenize general cargo flows and enable the mechanization of cargo handling to replace labor-intensive operation in the ports. Nevertheless, the impact of containerization is not restricted to the sea leg and port, but extends to entire transport chain. Besides standard load units and cargo-handling facilities, the integrated transport system is also a critical component for the new system.

Significant influences of containerization on the development of hinterland transport have been witnessed in past years (Blumenhagen 1981).

Although using of container excludes all cargoes that cannot be fitted in, the consequence of containerization is positive in general. It is widely recognized that the main benefits brought by containerization comprising integrated door-to-door service, reduced port time, enhanced cargo safety and automation in the port (Dick 1983; Levinson 2006; Stopford 2009). Moreover, containerization also offers possibility of pursuing further economies of scale, which dramatically decreases the transport cost and finally promotes the progress of globalization (Schirach-Szmigiel 1979; Ham & Rijsenbrij 2012).

It is undeniable that container shipping occupies a very important position in maritime transport. It has experienced an astonishing booming in last two decades. The world container traffic increased from 28.7 million TEU in 1990 to 152 million TEU in 2008 with an average annual increase of 9.5 per cent (Ducruet & Notteboom 2012 pp. 77-100). Although the share of container vessels in world's maritime fleet is relatively small, about 12 percent, more than half of the world trade value is now transported by container ships (Stopford 2009). Therefore, the importance of container shipping is obvious in not only maritime transport but also global economy. Moreover, container ships normally operate with a higher speed thus consume more fuels, which makes it has more impact on the environmental sustainability. Based on these points, the authors of this thesis hence have strong willingness to put their efforts in the research regarding the future development in container shipping industry.

1.3 Research Problems

Regarding the future of container shipping industry, there are two unavoidable problems that impede its future development.

First, bunker price keeps increasing in recent years. Since the bunker cost is usually

quite high and occupies about 60% of total operation cost, the raising of the bunker price puts intense pressure on the ship owners and ship operators. It affects financial performance of the shipping industry and operation decision such as port selection, shipping route selection, ship speed, freight adjustment and so on. Currently, most of bunker fuels are extracted from crude oil therefore the oil price will have a great influence on bunker cost. Stricter regulations also add the price of bunker fuel. Under this situation, other alternative fuels or energies applied in ship propulsion may become competitive in the aspect of fuel cost, which leads to a deep thought on how minimize operation cost in order to reap the largest economic benefits.

Second, the arising issue regarding environmental concern such as greenhouse gas (GHG) emission and air pollution. Various organizations and nations have addressed the importance of emission monitoring and controlling from shipping industry. For example, [United Nation \(1998\)](#) stated in the Kyoto Protocol Article 2.2 that “*the Parties included in Annex I shall pursue limitation or reduction of emission of greenhouse gases...from marine bunker fuels, working through...the International Maritime Organization.*” Another example could be the establishment of European Sulphur Emission Control Area (SECA) in Baltic and North Sea. It is an area regulated by IMO in order to control and minimize airborne emissions from ships. The European Commission also announced that owners of large ships calling EU ports should report their emissions from 2018 ([European Commission 2014](#)). Much stricter interventions and control of emission in respect of taxation and emission permit will show in coming years. All these environmental regulations bring great challenges to the application of crude oil products in shipping industry.

1.4 Research Purpose and Research Questions

Considering these problems mentioned above and related knowledge accumulated during the courses, the authors believe that it is necessary and worthwhile to study a clean, economic acceptable and long lasting energy as the power source for maritime

propulsion, and that such study should be done as early as possible, since the transaction will be complex and time-consuming.

The research **purpose** for this thesis is to evaluate currently available alternative fuels or energies in order to find out the most feasible solution to solve the two problems, high bunker cost and environmental issue, for container shipping segment in the future. Furthermore, this thesis also discusses the application of the selected new energy in container shipping.

In order to fulfil the research purpose, the authors conclude three research questions that need to be answered during this study. The object for the following research questions is container shipping lines.

1. What are main criteria that can be used to evaluate different fuels applied in container shipping industry?
2. Which alternative fuel will be most economically feasible for as the source for maritime propulsion in future?
3. What are key challenges for the most feasible alternative fuel to be applied nowadays and what could be possible solutions?

1.5 Research Scope

Within container shipping sector, two major segments are deep sea container shipping (DSCS) and short sea container shipping (SSCS) (Gouveral et al. 2010). Characteristics of these two segments are significantly different. DSCS offers high volume transocean services on main streams between the large ports in major industrial regions, while SSCS provides transport within regions normally on feeder routes (Stopford 2009). Hence, vessels for DSCS are usually larger than that of SSCS in order to pursue maximum economies of scale. Furthermore, DSCS is widely considered as the only economic transport option between continental landmasses. Airfreight cannot be considered as a true substitute for DSCS. Nevertheless, SSCS is

often in direct competition with land-based transport mode, such as train and ro-ro shipping. Since huge differences do exist between DSCS and SSCS, it will be inappropriate to do the research on a general container shipping level. Therefore, the authors in this research choose to focus on DSCS segment.

1.6 Research Structure

In following paragraph of this thesis, a description of methodology used in this research will be firstly offered. The next part after methodology will be literature review, in which the information from massive reading will be summarized and presented. Then findings based on the knowledge obtained from the literature review, questionnaires, and interviews will be concluded. In the analysis section, a comparison among all the selected alternative energies will be done and a further analysis of the recommended alternative energy regarding its application will be offered. Finally, the conclusion regarding the necessity, feasibility, prerequisite, benefit and risk of applying the new energy in DSCS will be given.

2. Methodology

2.1 Research Strategy

According to [Blumberg et al. \(2008\)](#), a scientific research can be defined as a systematic inquiry in order to supply the required information that can enable the problem solving. An appropriate methodology is vital for researchers to conduct research successfully. However, before entering deeper discussions, it is necessary to first clarify two critical terms, methodology and method, in this research. Even though some professional researchers may be confused about differences between these two concepts. A research method can be defined as the technique with purpose of collecting and/or analysing data, while a research methodology refers to the approach to process of the research, comprising a group of methods ([Collis & Hussey 2009, p.73](#)). With this basic knowledge in mind, readers can then avoid unnecessary

misunderstandings in following reading.

2.1.1 Research Paradigm

Defined by [Collis and Hussey \(2009\)](#), a research paradigm is a philosophical framework which guides how research should be conducted according to researcher's philosophies and assumptions regarding the world and the nature of knowledge. Since the choice of research methodology will be affected by researcher's philosophical assumption of his paradigm ([Collis & Hussey 2009](#)), it is definitely necessary to discuss research paradigm of the authors before selecting the methodology.

There are two major paradigms have been identified, namely positivism and interpretivism ([Galliers 1991](#)). According to [Creswell \(1994 & 1998\)](#), a major difference between a positivist and an interpretivist is that they hold opposite viewpoints on five philosophical assumptions, including ontological assumption (the nature of reality), epistemological assumption (the recognition of valid knowledge), axiological assumption (the role of values), rhetorical assumption (the language of research) and methodological assumption (the process of research). Among these assumptions, the ontological and epistemological ones are most important for researchers. According to [Collis and Hussey \(2009\)](#), positivism is the paradigm that created in the natural science. It agrees on the assumption that social reality is singular and objective; meanwhile, it will not be affected by the act of investigation ([Levin 1988; Creswell 1994](#)). The goal of positivist is to discover theories which can explain and/or predict the social phenomena by establishing cause and effect relationship among different variables. Moreover, this paradigm is often linked with quantitative methods. Nevertheless, there are perceived inadequacy of positivism to satisfy requirement of researchers in social science. There are five main criticisms of positivism indicated by [Collis and Hussey \(2009, p.56\)](#), such as impossibility to separate people from the social context and subjective impact from the researchers on the research caused by their own interests and values. Therefore, a remedy is developed with the purpose to fill gap. The alternative to positivism is labelled as

interpretivism. Interpretivist holds assumption that social reality is highly subjective. It exists in your mind and is shaped by our perceptions, thus it is multiple (Collis & Hussey 2009). Furthermore, under interpretivism, researchers think they interact with the object being researched because it is too hard to separate what exists in social world from what is in researcher's mind (Smith 1983; Creswell 1994). Interpretivism focuses on exploring the complexity of the social phenomena in order to obtain interpretive understanding within a particular context. Hence, interpretivism is usually associated with qualitative methods.

However, it is not compulsory that researchers must be categorized into either positivist or interpretivist. People can think of positivism and interpretivism as two extremities of a continuous line of paradigms which can exist simultaneously (Morgan & Smircich 1980; Collis & Hussey 2009, p.57). This means researchers can be neither extreme positivist nor extreme interpretivist, but neutral. The authors of this thesis also hold this neutral standpoint, since the authors believe that reality is established on integration of physical world and projection of human imagination, and that the interaction between researchers and research object is conditional.

2.1.2 Selected Research Approach

Since the research paradigm of the authors is between positivism and interpretivism, the methodology applied in this research is neither pure quantitative nor pure qualitative. A mixed methods research approach is adopted in this thesis. The development of mixed methods research experiences a long history in the social sciences (Creswell 2009; Jick 1979; Johnson et al. 2007). Definition of mixed methods research is comprehensively discussed in the article of Johnson et al. (2007). In this paper, mixed methods research is defined by many academic experts as the research approach that utilize both quantitative and qualitative method in data collection. The weakness of single quantitative or qualitative approach is that it is often insufficient to understand research problems, while the mixed methods research combines strength of both approaches through integration, which increases likelihood

of collecting richer, more meaningful and eventually more useful data to effectively answer research questions (Bradt et al. 2013; Johnson et al. 2007). Therefore, readers shall find that both quantitative and qualitative methods were used in this research. The details about each specific data collection method are offered in the following paragraph.

2.2 Research Design

Research design is defined as “the blueprint for fulfilling objectives and answering questions” (Blumberg et al. 2008, page 69). It involves designing of large variety of methods, techniques, procedures, protocols and sampling plans. By conducting research design, researchers could achieve better insight of their research (Blumberg et al. 2008).

In order to achieve the purpose of this research and give answers to all the research questions, the whole design of this research was divided into two steps. The first step was to review all kinds of alternative energy for ship propulsion and to analyse their advantages and disadvantages in order to select the most feasible fuel or energy. The second step was to discuss the application of the selected new energy in deep sea container shipping segment by conducting assumptions and analysing future scenarios under these assumptions.

There are four types of research generally: reporting, descriptive, exploratory and predictive research (Blumberg et al. 2008). For this research, the first step was based on descriptive research and the second step was based on predictive research. Reasons and methods that used in the research are explained in following part.

2.2.1 Descriptive Research

A descriptive research is trying to describe phenomenon and answering the question such as who, what, when, where and how (Blumberg et al. 2008). It involves collecting data, examining the data, and observing characteristic. The powerful

inference may have potential to be drawn during the descriptive research (Blumberg et al. 2008).

The descriptive research in this thesis firstly described the background of DSCS and focused on the bunker price and environmental problems. Then this thesis assessed all kinds of alternative fuel or energy that could possibly be used on ship. Furthermore, some criteria for selecting alternative fuel in DSCS were described. Finally a comparison table was presented so that the most feasible fuel or energy was explored.

In this descriptive research, both qualitative and quantitative research methods were used. For qualitative method, literature review was used to gain a comprehensive understanding about DSCS, various kinds of alternative fuel or energy and the criteria for selecting them. The quantitative method was used to select the most favourable propulsion energy by comprising and evaluate these alternative energies in mathematical way. Questionnaires and interview were used in quantitative method.

2.2.2 Predictive Research

A predictive research is to predict in which situation will an event occur. It is based on the theory and usually involves high level of inference (Blumberg et al. 2008). There are two ways of prediction. One is looking back for theory to support the prediction, and the other one usually uses scenario models and expert survey (Blumberg et al. 2008).

The predictive research in this thesis focused on the application of the selected fuel or energy in future DSCS. Major gaps in the future application of the suggested alternative fuel or energy were identified and discussed.

2.3 Data Collection Methods

The definition of data refers to facts which need to be translate into information so

that it can be utilized in the scientific research (Crowther & Lancaster 2012). Research data can be categorized into two major groups, primary and secondary data. This paragraph introduces the data collection methods used in this research in terms of these two categories.

2.3.1 Primary Data

According to Collis & Hussey (2009, p.73) primary data refers to the data generated from the original source. Typical examples could be data from interview, survey, focus group and experiment. Two data collection methods were applied in this research in order to obtain the primary data. They are interview and questionnaire.

Interview

Interview is a kind of data collection method that used to get first hand data from interviewees. There are various kinds of interview method such as personal interview, telephone, mail, computer or combination (Blumberg et al. 2008).

In this research, a personal interview, also called face-to-face communication was used. It is a two-way communication method between interviewer and interviewee to obtain data. There are some advantages of personal interview. For example there will be a good cooperation from respondents. The interviewer could communicate with interviewees, answer questions about survey and use follow-up questions. However there are also some disadvantages. The cost of interview will be a bit high and there may be a geographic problem. Moreover, some people may not comfortable to talk with strangers (Blumberg et al. 2008).

The personal interview was adopted in this research to find out what professional people think about the alternative fuels. The researchers selected three people with professional knowledge about alternative fuels or energies and interviewed them separately. The interviewees were found through two main approaches. First, the authors searched the potential candidates by themselves on the university's or

company's websites. Second, the supervisor of this thesis also recommended several qualified interviewees to the authors. Then all these candidates were contacted for an appointment. Finally, due to time limitation and some experts' availability, three experts, two from academia and one from shipping industry were selected. The detailed information about the three interviewees can be found in [Appendix 1](#). The questions were pre-prepared and there were some follow-up questions during the interviews. The recording device was used to record the interview.

Questionnaire

Questionnaire refers to method for collecting primary data in which a sample of respondents answers a group of questions ([Collis & Hussey 2009](#)). Through a questionnaire researchers can know what respondents think, do or feel. This information will help researches to answer specific research questions or have better understanding on research phenomenon.

The purpose of the questionnaire applied in this research is to collect the data for further evaluation of different alternative fuels or energies for DSCS. The main content in the questionnaire was pair-wise comparison between different evaluation criteria and between different potential marine fuels, which took approximately 15 to 20 minutes to finish. The potential respondents in this questionnaire were not randomly chosen, but carefully selected. Experts from related industry, government and academic areas were involved, since the questions in the questionnaire required advanced knowledge and experience regarding shipping and ship engineering. The industrial experts are from shipping companies and port authorities. The researchers from universities are mainly specialized in sustainable logistics or transport management and shipping engineering. And policy makers from national transport department were included as well. The reasons for such selection is that the questionnaire in this research requires advanced level knowledge regarding the research topic, otherwise, the data collected from non-experts would be invalid. The authors sent the questionnaire to all the 30 potential respondents, but only 13 valid

samples were obtained. Detailed information of the valid respondents is listed in [Appendix 2](#). The questionnaire was well tested before distribution. The authors tested the questionnaire by doing it themselves in a real context, for example, with required time limitation. Furthermore, the authors invited some students with corresponding knowledge background to test the questionnaire as well. The supervisor of this thesis also reviewed the questionnaire and gave suggestions. Feedbacks from these tests and review, such as comments regarding the use of words or order of questions, were adapted in the improvement of the questionnaire design.

According to [Collis & Hussey \(2009\)](#), there are six main distribution methods in questionnaire, including post, telephone, Internet, face-to-face, group distribution and individual distribution. Online distribution was applied in this research by using the web-based tools - [SurveyGizmo](#). The major advantages of online questionnaire are convenience. Questionnaire can be send to the respondents directly and result can be easily collected through statistic tools, such as Excel. However, disadvantages also do exist. The email of the questionnaire may be blocked by mail system and cannot reach the targets in some cases. Moreover, the email may also be neglected if the respondents do not check email frequently or have too many emails to handle. Therefore, regular reminding was applied as preventing approach.

2.3.2 Secondary data

According to [Collis & Hussey \(2009, pp.23\)](#) “Secondary data are data collected from an existing source (for example publications, databases and internal records). The advantage for using a secondary data is that it is the easier and cheaper way to collect. There are two kinds of secondary data collection method used in this thesis. One is literature review and the other one is using database. The sources of literatures are mainly from books, published scientific articles, and official websites. The authors searched the literatures mainly through the Gothenburg University Library with key words related with shipping industry, shipping emission, alternative maritime fuel and shipping economics. All selected articles are published by reliable journals. The other

sources are the databases of shipping lines and other related organizations. Quantitative data, such as route information and oil price, are obtained through these databases. The secondary data usually have less accuracy and reliability than primary data. So in order to keep the validity and reliability, all secondary data used in this thesis were collected from reliable resources and clearly referenced without modification both in text and in reference list.

2.4 Data Analysis

Analysing and interpreting data is a major part of a research. It is also an important part since the exact understanding of the data collected will lead to correct information that can support researchers to answer the research questions accurately. The methods of data analysis applied are decided by the research paradigm and the type of the data collected (Collis & Hussey 2009). In this research, the authors' paradigm is neutral and both kinds of data were gathered, hence qualitative data analysis methods as well quantitative data analysis methods were performed.

2.4.1 Qualitative Data Analysis

Qualitative data are data in the nominal form (Collis & Hussey 2009, p.63). In this research, qualitative data were mainly collected from literature reading and interviews. The first step in qualitative data analysis was data reduction and restructuration. It is necessary to sharpen, sort, focus, discard and reorganize the data in the very beginning, because a mass of qualitative data are obtained during literature review and interviews and some of these data may be less valuable or irrelevant (Miles & Huberman 1994). Then a data display technique was applied on the data generated from literatures. According to Miles & Huberman (1994, p.91), a data display is a summary of data in a visual format that presents information systematically, thus the user can draw valid conclusions and take necessary actions. In the data display, researchers can choose to use either a network or a matrix to visualize data. In this research, the authors chose matrix as the tool to show the summarized data. For the

data collected from interviews, a quasi-judicial method was applied. The quasi-judicial method is suggested by Bromley (1986) and defined as the method of analysis that involves the use of rational argument to interpret qualitative data (Collis & Hussey 2009, p.174). The principle of this method is to find a most compatible explanation that can fit all the evidence (Robson 1993).

2.4.2 Quantitative Data Analysis

Quantitative data are data in the numerical form (Collis & Hussey 2009, p.63). The quantitative data collected in this research were mainly from questionnaires and databases. The first step of quantitative data analysis is data cleaning. The purpose of this step is to find out missing data and apply imputations. Missing data means the value for a specific variable is not available for analysis, while imputation refers to the remedy method that helps to estimate the missing values based on valid values of other variables or cases in sample (Hair et al. 2010). The missing data will lead a reduction of sample size and biased result, so it must be fixed before further analysis is carried out. The mean substitution approach was accepted as the imputation method in this research. The respondents were contacted again if missing values were found in the questionnaires. Finally, both descriptive statistics and inferential statistics were applied in this research. The former refers to the methods used to summarize, describe and display quantitative data, while the latter helps to draw conclusions about a population from the quantitative data (Collis & Hussey 2009; Kervin 1992).

2.5 Validity

Given (2008, pp.909) has described Validity as “*being dependent on the degree to which a study actually measures what it purports to measure/whether the truth is accurately identified and described*”. In Collis & Hussey (2009, pp.64-65), Validity refers to “*an effect or test is valid if it demonstrates or measures what the researcher thinks or claims it does*”. There are generally two questions to ask when identify the validity of the research. The first one is “*whether the means of measurement are*

accurate” and the second one is “*whether they are actually measuring what they are intended to measure*” (Golafshani 2003, pp. 599).

Regarding the first question, the authors think that the means of research are accurate due to the following reasons. First, the content of the research refers to academic content, which is suitable for master level. Second, the construct of the means of the research includes literature review, questionnaire, and interview. The features of methods and the type of research together determine that these methods are valid and suitable for solving the research questions.

Regarding the second question, the authors tried to maximum the validity by ensuring that the methods used are actually measuring what they were intended to measure. There was a clear research design that guided the process of the research. The authors improved validity through avoiding bias as well. For instance, all of literatures that used in the research were from shipping academic and industry fields. The target people for questionnaire and interview are experts from related areas. And there was a clear explanation and description of the research before questions in the research to ensure all the respondents know exactly what the research is. There are two supervisors providing guidance to ensure the authors fully access the knowledge and understand the meaning of the phenomenon.

2.6 Reliability

Reliability is related with research findings and is one of the two important aspects of the credibility of the findings. In Collis & Hussey (2009, p.64), reliability is defined as the absence of differences in results if the research were repeated. In other words, the repetition of a reliable research should be able to produce a same outcome. In this paragraph, the reliability of all the data collection methods is discussed.

In the literature review, a large quantity of reliable literatures was adopted with

references. Moreover, the types of literatures used in this research are comprehensive as well, including book, journal article, newspaper article, governmental report, commercial report and Internet resources. These two points enhanced the reliability of the qualitative data gathered from the literature review. However, the time span of these literatures is also long. Some of the articles used in this research are relatively old. The data from such articles may have reliability problem because the old knowledge may not be applicable nowadays and the credibility changes as well.

For the interview method, all the stakeholders who are closely associated with the research topic were involved as the interviewees. The interview was conducted in a neutral manner without any inducing or misleading. All the interviews were taped and entered into computer. The interviewees were contacted again as long as the authors could not recognize or understand the content of the interview. These characteristics increased the reliability of the data from interviews. Regarding the data from questionnaires, the reliability is relatively low since the sample size is small and the sampling is not random. The reason behind it is that the questionnaire requires high knowledge and experience in the research area, while the availability of this population is low for the authors. But the validity of the data is enhanced due to this sacrifice. On the other hand, the authors tried their best to compensate the weakness of reliability in the questionnaire design and data handling. Finally, the databases used in this research are from organization and shipping lines' official websites, which could be considered as reliable data sources. Based on the above discussions, the authors can safely declare that the general reliability for this research is acceptable and meets the academic requirement.

3. Literature Review

In this chapter, literatures regarding key elements of this research will be reviewed. The key elements include major challenges faced by container shipping nowadays, possible solutions for these challenges and theoretical framework.

3.1 Major Challenges

For today's container shipping industry, two of the major challenges are the stricter regulations on its emissions and the continuously increasing bunker fuel price.

3.1.1 Emissions

It is generally accepted that more than 90% of global trade is carried by sea (IMO 2012). Therefore, even though shipping is a much cleaner transport mode than road and air, the emission of exhaust gases and particles from seagoing vessels still contribute dramatically to the total emission of the transport sector (Corbett and Fischbeck 1997; Eyring et al. 2005a). Container shipping, as one of the fastest growing sectors (Fransoo & Lee 2013) in the industry also suffers from the same problem. The major compounds in the shipping emission comprise carbon dioxide (CO₂), sulphur dioxide (SO₂), nitrogen oxides (NO_x) and particulate matter (PM) (Lloyd's 1995; Eyring et al. 2005a; Lack et al. 2009; Tzannatos 2010). The emission from maritime transport can bring serious impact to climate, ecosystem, and our health (Eyring et al. 2010). According to the estimate from Corbett et al. (2007a), approximately 60,000 premature deaths globally are caused by the shipping emission. For example, the exhausts from vessels lead to excess risks of emergency hospitalizations for cardiovascular diseases (CVD) in Hong Kong (Tian et al. 2013). About 70% of shipping activities take place within 400 kilometers from land where the population density is usually high (Corbett et al. 2007b; Wang et al. 2008; Endresen et al. 2003) so that maritime transport has great potentials to create significant pollution to the coastal communities, especially port cities (Eyring et al. 2010). On the other hand, since the land based emissions are declining, the ratio of emissions from shipping is increasing (Eyring et al. 2010), while both the importance and pressure of emission reduction for shipping become high. Moreover, the seaborne trade is predicted to grow (Burgel 2007; Eyring et al. 2005b) which makes the situation even worse. Unfortunately, it is very hard to control emissions from ships. Possible reasons for such difficulties are summarized by researchers as following.

Heitmann & Khalilian (2011) mentioned that a big part of exhausts from the vessels are emitted on high sea where no jurisdiction can be applied. Moreover, the multiple nationalities involved in shipping industry also bring complexity to regulation and legislation (Wignolst & Wergeland 1997). According to Oberthuer (2003), the exclusion of international shipping in Kyoto Protocol is a barrier as well. For financial consideration, compliance with emission reduction regulations will also lead to extra cost and may affect the international trade once the additional expense is reflected in the freight rate (Gallagher 2005). The following paragraphs will introduce the literatures regarding the key emissions separately.

Carbon dioxide

Carbon dioxide (CO₂) is the key element in greenhouse gases (GHG) that lead to global climate change on our planet. Anthropogenic emissions of GHGs contribute to global warming which increases temperature by more than 2°C compared to the pre-industrial levels, and such augmentation will bring catastrophic consequences at a worldwide level (Walker & King 2008). Substantial increases in CO₂ emissions from shipping industry has been witnessed in the past few years due to the booming of international trade arising from globalization (Eyring et al. 2005a; Chiffi & Fiorello 2009; Wang & Wang 2010). Report from Intergovernmental Panel on Climate Change (IPCC) indicates that the shipping industry had doubled its GHG emissions from 1990 to 1995, which is the highest increase among all industries (Chang 2012). The Second IMO Greenhouse Gas Study conducted by Buhaug et al. (2009) provided a comprehensive and authoritative evaluation of the level of GHGs emitted from maritime transport in the world. In the report, it was estimated that 1046 million tonnes of CO₂ were emitted by shipping in year 2007, which equals to approximately 3.3% of the global emissions, or more than 12% of total CO₂ emissions in transportation sector (Wang 2010). More specifically, international shipping accounts for about 2.7% of the total emission in 2007 (Buhaug et al. 2009). Similar assessment can also be found in e.g. Eyring et al. (2005a) and Solomon et al. (2007). To make matters worse, since CO₂ emission from international shipping currently still remain

unregulated (Heitmann & Khalilian 2011), many researchers have forecasted the emission of CO₂ from maritime transport may increase dramatically in the future. Burgel (2007) stated in his article that the fuel consumption of the world merchant fleet is anticipated to rise to 250 - 300 million tons per year that can be translated into 800 - 960 million tons of CO₂ emissions per year. Buhaug et al. (2009) predicted that if no policy measures are implemented, the international shipping CO₂ emission would lie 6% - 22% higher in 2020 than in 2007 and this percentage may become extremely high by 2050, reaching 119% - 204%. Lindstad et al. (2011), Eyring (2010) and OECD (2010) have also made similar growth prospect reports. In order to avoid worst situation, ambitious target for CO₂ emission reduction has been made. European Commission (2011) mentioned in its white paper that CO₂ emissions should be cut by 40% (if possible 50%) by 2050 compared to 2005 levels. IPCC (2007) estimated that GHGs emission needs to be reduced by around 50 - 85% in 2050, compared with current levels, in order to maintain the stabilization of the temperature. This means if all sectors accept the same reduction rate, the total emission of shipping in 2050 cannot exceed more than 15 - 50% of current levels (Lindstad et al. 2011). Containerships are generally agreed as the largest and the only continuously growing maritime CO₂ emitters when compared to other types of vessel (Psaraftis & Kontovas 2009; Kalli et al. 2013). Two reasons can be concluded for this point. According to Corbett et al. (2009), CO₂ emissions from containership fleet in total are about 1.3, 2.2 and 2.5 times greater than those from bulk shipping, crude oil tankers, and general cargo ships respectively. Similar result can also be found in De Meyer et al. (2007). Furthermore, the carrying capacity of world container fleet has grew from 4.7 million TEUs (20-foot equivalent unit) in 1999 to 14.7 million in 2009, which has resulted in significant increases in CO₂ emissions (Song & Xu 2011).

Sulphur oxide

The Protocol of 1997 (MARPOL Annex VI), which entered into force on 19 May 2005, regulates the emission of sulphur oxide (SO_x), mainly SO₂, from shipping (IMO 2014) and also demonstrated the severity of sulphur pollution from maritime transport.

Again, although shipping is widely accepted as a more environmental friendly transportation when compared with other modes, it still represents a significant contribution of global SO₂ anthropogenic emissions (Corbett et al. 1999; Endresen et al. 2003; Corbett & Koehler 2003). Several researchers have pointed that, over the last years, SO₂ emissions from land-based sources have declined, while the emissions from shipping have increased (e.g. Olivier & Berdowski 2001; Smith et al. 2004) and this highlights the importance of shipping as the source of SO₂ emission (Burgel 2007). It is estimated that world merchant fleets account for 4% - 9% of global anthropogenic SO₂ emissions (Eyring et al. 2005a; Corbett & Koehler 2003; Endresen et al. 2003; Endresen et al. 2007). The situation in South Asia is even worse with 11.7% of the total SO₂ emission is contributed by shipping (Streets et al. 1997). Sulphur emissions from shipping have negative impacts in both remote oceanic areas and coastlines, especially locations close to heavily travelled shipping lane. It leads to the acidification in the surrounding atmosphere which has harmful effects to the environment, buildings and human health (Endresen et al. 2005; Gilbert 2014). The major reason for the high emission of SO₂ from shipping is that the average rate of sulphur content in widely used marine heavy fuel oil (HFO) is relatively high, about 2.4% - 2.7% (Endresen et al. 2005; Gilbert 2014).

Nitrogen oxide

Nitrogen oxide (NO_x) is another exhaust from shipping regulated by MARPOL Annex VI (IMO 2014). It is estimated that about 15% of all global anthropogenic NO_x emissions comes from shipping activities (Eyring et al. 2005a; Corbett & Koehler 2003; Endresen et al. 2003; Endresen et al. 2007). In Baltic Sea area, shipping contributes to about 5% of the total atmospheric deposition annually on average (Kalli et al. 2013), while the percentage can be over 50% in the peak years (Stipa et al. 2007). Emission of NO_x is demonstrated to bring severer problems to our society. First, it will lead to or aggravate the acid rain, especially for port cities (Burgel 2007). Second, the deposition of NO_x from shipping contributes to eutrophication as well (Kalli et al. 2013). Furthermore, NO_x is also catalyst in the formation of tropospheric

ozone which has both health and climate impacts (Solomon et al. 2007). The root cause for the high emission of NO_x from shipping is that most marine engines operate at high temperatures and pressures without effective reduction technologies (Eyring et al. 2010).

Particulate matter

Shipping generates considerable amount of particulate matter (PM) through burning of fossil fuels as well. Like other exhausts, PM can also lead to both environmental and health problems. Regarding the environment, it can damage forests and crops, increase the acidity of lakes and reduce the diversity in ecosystems (USEPA 2013). For human health, PM with an aerodynamic diameter of less than 2.5 μm, namely PM_{2.5}, is most harmful, while approximately 90% - 94% of the PM emitted by ship can be located in that category (Whall et al. 2007; Sharma 2006). According to USEPA (2004), exposure to particulate matter causes more mortality and morbidity than any other regulated environmental pollutant. In Europe, around 49,500 deaths in 2000 were considered to be related with shipping emissions, and this number may rise to 53,400 in 2020 (Brandt et al. 2011). The major reason for these mortality rates is the increasing concentrations of ultrafine particulate matter (Kalli et al. 2013).

3.1.2 Bunker Fuel Price

Bunker fuel has captured the industries and academic interest in recent years due to a continuously increasing bunker price and its significant position in container shipping industry. Before reviewing any bunker fuel problem, first the definition and classification of bunker fuel are elaborated in the following paragraph.

Mazraati (2011, page 1) defined bunker fuel as “*technically any type of fuel used by international seagoing ships and acquired its name from the containers used to store fuel on-board or in ports*”. Currently, crude oil is the only commonly used energy source in transocean container shipping (Kolwzan & Narewski, 2012).

According to the [Haglund \(2008\)](#), [Stefanakos & Schinas \(2014\)](#), and [Kolwzan & Narewski \(2012\)](#), the currently used bunker fuel can be classified as distillates and fuel oil. Distillates fuels usually contain a low level of impurities which including sulphur, water, metals, ashes and carbon residues. It usually divided into marine gas oil (MGO) and marine diesel oil (MDO). Both of them are light while the difference is that MDO is a little heavier and may contain little residual fuel oil. MGO and MDO are both considered have a low level of sulphur emission. The fuel oil, on the other hand, refers to residual fuel oil that manufactured at the bottom end of refining process. Heavy fuel oil (HFO) is a kind of residual fuel oil that is the heaviest and contains high level of impurities. Intermediate fuel oil (IFO) is another kind of residual fuel oil that blended with distillates. IFO380 and IFO180 are the most commonly used bunkers in container shipping industry. Some researchers such as [Mazraati \(2011\)](#) and [Notteboom & Vernimmen \(2009\)](#) categorize bunkers roughly into MGO, MDO and residual fuel oil (HFO).

The bunker cost is quite large and usually takes around 60% of total operational cost of containership, which gives the bunker cost a unique and significant role in the container ship operation ([Carlton et al. 2013](#), [Mazraati 2011](#), [Stefanakos & Schinas 2014](#) and [Notteboom & Vernimmen 2009](#)). [Stefanakos & Schinas \(2014, page 178\)](#) indicates, *“The bunker prices affects economic planning and financial viability of ventures and determine decisions related to compliance with regulations.”* Bunker price, together with vessel price, interest rates, currencies, and freight rate, construct the fluctuation and high risk of container shipping industry. [Besbes & Savin \(2008\)](#) also described that bunker price would affect shipping route selection and refuelling problem. [Yao et al. \(2012\)](#) considered that bunker cost is important for port selection, bunker amounts determination and ship speeds adjustment.

With this importance, both industry and researchers pay great interest to current and future situation of fuel development. Currently, bunker fuel prices are fluctuating and have a general trend of rising ([Yao et al., 2012](#)). A figure of the trend of bunker price

at major bunker ports is shown in [Figure 1](#). The rising bunker price increases the operational cost, which has a negative impact on container shipping ventures and influences the ship operation strategy ([Stefanakos & Schinas, 2014](#)).

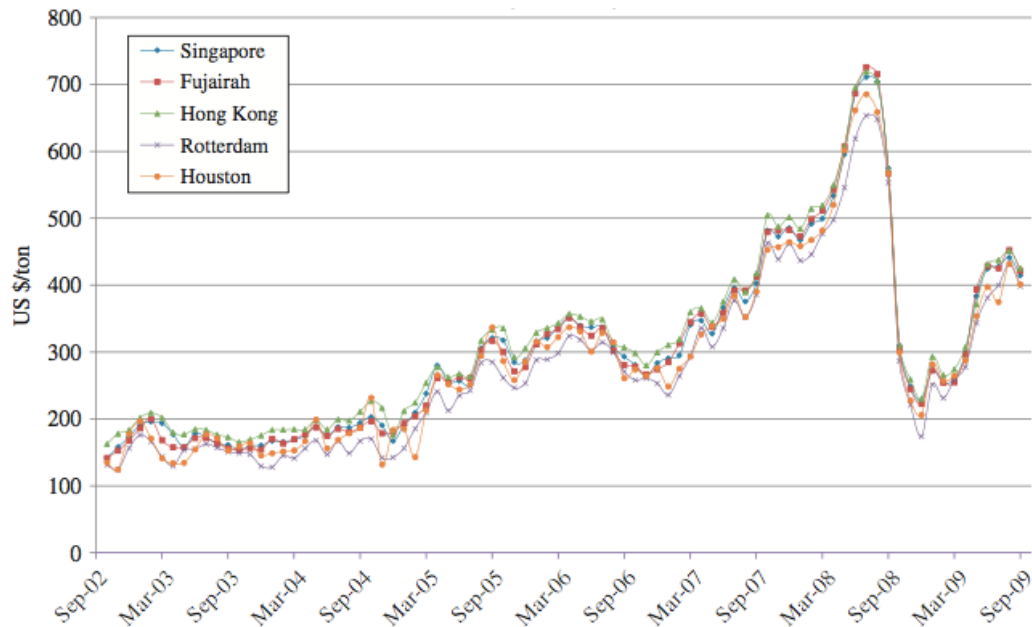


Figure 1: bunker fuel prices (380 CST) at major bunker ports (2002-2009).

Source: [Yao et al. \(2012, page 1161\)](#).

There are normally two major reasons for the bunker price increasing. One is the increasing crude oil price. In the last couple years, there is a positive liner correlation between the crude oil price and bunker price ([Notteboom & Vernimmen 2009](#), [Notteboom, 2006](#), and [Golias et al. 2009](#)). Another reason is due to strict regulations of sulphur emission control. The increasing environmental concerns have resulted in more and more regulations and policies, especially for sulphur emission. The strict regulation and policy force ship owners and operators to change fuel, shifting from High Sulphur Fuel Oil (HSFO) to Low Sulphur Fuel Oil (LSFO). Because of the different refining process, LSFO has a much higher cost than HSFO, which significantly influences financial and operational aspects of container shipping industries ([Notteboom & Vernimmen 2009](#), and [Haglund 2008](#)).

Previous researches also proposed some feasible solutions to manage high bunker

price. Some suggested to change the widely used IFO 380 to other low sulphur fuel with lower cost, such as IFO 500 (Notteboom & Vernimmen 2009). Other researchers considered other alternative bunker fuels rather than crude oil. For example, Germanischer Lloyd SE (2011) believes that LNG is expected to cost less than MGO, and almost same as HFO. When the price of HFO continues increasing, LNG could become more competitive. Notteboom & Vernimmen (2009) also proposed that improving the vessel design and propulsion system could maintain the economic profitability of the fuel. There is another solution that has already been widely used – slow steaming. Normally ship consumes more fuels when increasing the speed so that slow steaming could be a feasible solution brought up by lots of researchers such as Notteboom & Vernimmen (2009), Yao et al. (2012) and Cariou (2011).

3.2 Alternative Fuels and Energies

In this chapter, literatures regarding different alternative fuels and energies that could be used to replace crude oil products in maritime propulsion were reviewed. These alternative fuels include liquefied natural gas (LNG), nuclear power, renewable energy (solar/wind) and biofuels.

3.2.1 Liquefied Natural Gas (LNG)

The interest and demand for alternative fuel applied in maritime propulsion have increased considerably in the recent years due to new emission regulation and establishment of sulphur emission control area (SECA) within the Baltic Sea and the North Sea regions (Rozmarynowska 2010). Among all alternatives, LNG is currently one of the most popular options. The principal constituent of LNG is methane (CH₄), about 70% - 90%. Burning of natural gas in internal combustion engines is not a new technology. It has been used in the diesel electric propulsion or mechanical drive systems for vessels. (Carlton et al. 2013). The application history of LNG as a marine fuel is about fifty years, but it is primarily used on LNG carriers (Herdzik 2011). Nowadays, there are two major types of marine engines that can support using LNG as fuel. They are dual fuel engines (e.g. Wärtsilä, Man) and lean-burn gas engine (e.g.

Rolls-Royce, Mitsubishi) (Rozmarynowska 2010). Both heavy fuel oil (HFO) and LNG can be used in a dual fuel engine; hence it has higher flexibility and is more adaptive in regions where the supply of LNG is not stable. However, the lean-burn gas engine is much simpler to install when compared with the dual fuel engine. It can be well used in LNG sufficient areas. Quite a few vessels are using LNG as their fuel today, such as platform supply vessel owned by Eidesvik in Norwegian (Hovda 2008) and container ship developed by TOTE (2010) in U.S.

One of the most important advantages of applying LNG in maritime transport is emission reduction. This advantage has been extensively discussed and widely accepted by many researches in their articles or reports (e.g. Hovda 2008; Veritas 2007; Masaki 2011; Banawan et al. 2010; Lennerås 2008; Herdzik, 2011; Carlton et al. 2013; Kumar et al. 2011). First of all, if people replace crude oil products with LNG as the fuel for ships, the emission of carbon dioxide (CO₂) will approximately decrease by 20 to 25 percent during the combustion in the engine. In terms of Energy Efficiency Design Index (EEDI), the use of LNG as fuel and its CO₂ saving potentials would reduce the actual EEDI for a vessel by 25% (Carlton et al. 2013). Additionally, NO_x emission will also be reduced dramatically (by 80% - 90%), since compression ratios and combustion temperatures for CH₄ will lead to lesser volume of nitrogen in combustion process (Carlton et al. 2013). Lastly, burning LNG as fuel will generate no SO_x emission, because there is no sulphur content in it. In the meantime particulate matter (PM) exhaust is also totally removed. Therefore, replacing crude oil products, such as HFO, with LNG can help shipowners to survive stringent emission regulations, even comprising the tier 3 NO_x limits and SO_x requirements of MAPROL Annex VI, without any external assistant to filter the exhaust gases (Lennerås 2008). Table 1 shows a more straightforward comparison among the three main types of fossil fuel regarding their emission status (Kumar et al. 2011). It is easy to find that LNG has obvious advantage in almost all kinds of emissions, only except carbon monoxide (CO), in which its performance is slightly worse than oil. Similar results can also be found in a case study comparing emissions from diesel engine and LNG

engine for the ferry between Egypt and Saudi Arabia on the red sea (Banawan et al. 2010). However, some researches also present different point of views. Beer et al. (2002) conducted a research about the emission of different alternative fuels, including low sulphur diesel (LSD), ultra-low sulphur diesel (ULSD), compressed natural gas (CNG), liquefied petroleum gas (LPG), ethanol, biodiesel, waste oil and LNG, on a heavy-duty truck. They stated that LNG has the highest greenhouse gases (GHG) emission among all the alternative fuels tested in the research. Beer et al. (2002) used life cycle analysis methodology in this research and found that although LNG emits less GHGs during the combustion, the liquefaction process requires a large amount of energy, during which massive GHGs are produced. Arteconi et al. (2010) found in his research that if LNG is supplied by small-scale plant, then its life cycle GHGs emission has no obvious improvement comparing with diesel oil. Only if the LNG is produced through re-gasification terminal, its life cycle GHGs emission will reduce. In case a LNG-powered vessel is lying at anchor or stuck in port and has no re-liquefaction plant on board, then LNG needs to be vented or burnt off to maintain tank pressures, which will add extra burden to global warming (Carlton et al. 2013).

Table 1: Comparison of fossil fuel emission. Source: Kumar et al. (2011)

Comparison of fossil fuel emissions (in PPB Btu of Energy Input).

Pollutant	LNG	Oil	Coal
Carbon dioxide	117,000	164,000	208,000
Carbon monoxide	40	33	208
Nitrogen oxides	92	448	457
Sulfur dioxide	1	1112	2591
Particulate	7	84	2774
Mercury	0.000	0.007	0.016

Another distinguished benefit of LNG is that fuel price of LNG will be lower than oil price; especially when the world oil price is volatile (Carlton et al. 2013; Banawan et al. 2010; Kumar et al. 2011; Lennerås 2008). Furthermore, the maintenance cost can also be lower if LNG is used as marine fuel. After converting vessels from oil to LNG

powered, the shipping company can decrease fuel cost and maintenance cost by 39% and 40% respectively under the same circumstance (Banawan et al. 2010). Herdzyk (2010) predicted that LNG would enjoy the price advantage over HFO in the next two decades. Thus, LNG is also an economic competitive alternative in terms of operation.

Nevertheless, the LNG-powered vessel has a weakness of high initial capital cost (Masaki 2011). No matter converting an old ship or building a new ship requires considerable investment. For conversion cost, there is no standard for conversion cost. Banawan et al. (2010) asked the quotation for the leading companies with high technology in the conversion field, such as MARINTEK and Wärtsilä in Norway and Proserve in the USA and the answer about conversion cost is about \$200 per kW. Similar cost information can also be found in Tawfik (2007). To build a new LNG-powered vessel requires 10% - 15% additional cost compared with building a conventional vessel (Rozmarynowska 2010; Lennerås 2008).

Another major drawback of using LNG as ship fuel is that the space requirement for bunker increases significantly. Compared with the HFO tanks, LNG tanks need about 2.5 times bigger space since the energy density of LNG is smaller than HFO and the storage of LNG on board requires thermal shield (Herdzyk 2011). Similarly, by comparison to marine diesel oil (MDO), LNG with equal energy content requires 1.8 times more volume as well, and this number will increase to 2.3 times if tank insulation is considered (Levander 2006; Lennerås 2008). Actually, practical space required in the LNG-powered ship may increase four times due to the squared space around the cylindrical LNG tank as the safe area in case of accidental spillage (Stuer-Lauridsen et al. 2010; Carlton et al. 2013). The bigger space requirement leads to several problems. First, it increases the difficulty and complexity significantly in ship conversion (Levander 2006). Second, the larger bunker rooms can be translated into smaller space for cargo. For example, approximately 3% of the container ship's capacity will be blocked due to the larger LNG tanks (Stuer-Lauridsen et al. 2010).

Last, if shipowners want to guarantee the cargo capacity, then they may have to sacrifice operational range due to the energy limitation (Rozmarynowska 2010). Otherwise, vessels will need to refuel too frequently in a single voyage.

Currently, LNG supply is also a barrier for the application of this alternative fuel in maritime transport (Herdzik 2011). Natural gas is normally stored in compressed form if it is just for local use, since liquefaction of natural gas requires extra infrastructure and cost. It is usually liquefied when natural gas needs to be transported, such as export, because the liquefied form of natural gas has smaller volume (Tawfik 2007). Nowadays, only few ports have the capability to offer LNG refuelling service. If the calling port does not have LNG terminal, then LNG powered vessel will have refuelling problem. To solve this problem needs large investment in all the major ports (Carlton et al. 2013).

The safety issues of LNG in shipping have also been discussed in recent literatures. European Commission (2013) mentioned that LNG-powered ship has an excellent safety record so far. However, Pitblado et al. (2004) stated that a LNG spill might also lead to great damage due to its combustible characteristic. There is also a change that the low temperature of LNG may frostbite crew on board in case of leaking accident (CEC 2014).

3.2.2 Nuclear

Nuclear energy is not a new technology for the world. After people discovered the possibility of nuclear fission in 1938, research for the utilization of this form of energy developed rapidly (Cole 1988). Nuclear power applied in ship propulsion has a long history as well. It was first applied in the submarine environment by United States Navy in 1955 and from that time, about 700 nuclear reactors have been used to offer propulsion power at sea, meanwhile, still approximately 200 reactors are still in services installed in different ships or submarines today. (Carlton et al. 2013). These facts lead to a considerable body of experience of nuclear propulsion in maritime

context.

For civil use, there are in total four nuclear-powered merchant ships, namely N.S. Savannah, Otto Hahn, Mutsu and Sevmorput. N.S. Savannah is the first nuclear-powered merchant ship in the world (Godwin et al. 1959b). She was built in late 1950s with a cost of \$46.9 million, in which \$28.3 million was used on nuclear reactor and fuel core. Mentioned by Science (vol. 130, no. 3371, p. 322 - 323, 1959), the main purpose of building N.S. Savannah is to demonstrate technical feasibility of nuclear propulsion for merchant ships, hence she was not expected to be commercially competitive. The N.S. Savannah had been in service from 1964 to 1972 (Sawyer et al. 2008), during which she produced nearly \$12,000,000 in revenue. The ship can navigate for 2 to 3 years without any refill with an average speed of 20 knots (Godwin et al. 1959b). The radioactive liquid waste was fed to a storage tank and would be handled on land rather than discharged at sea, while the radioactive gases were diluted and filtered before emitted (Robinson 1959). According to Godwin et al. (1959a), the contributions of N.S. Savannah are impressive. First, she demonstrated the technical feasibility of nuclear application in merchant shipping. Second, her excellent safety record proved that nuclear-powered ship is reliable and safe. Last, she helped to accumulated considerable experiences in nuclear ship design, operation and crew training. Major parameters of N.S. Savannah are listed in Appendix 3. Otto Hahn is the second nuclear trade and research vessel built by Germany. The purpose of building this ship is similar to that of N.S. Savannah. Based on RadiationWorks (2009), she entered service in 1968 and finished her first port of call in Casablanca in 1970. The first refill happened in 1972, 4 years after the launch. In 1979, the reactor was removed and the ship was converted into marine diesel engine powered. During 9 years service life, Otto Hahn had travelled 650,000 nautical miles (1,200,000 km) and visited 33 ports in 22 countries, most of which are in South American and Africa. Major parameters of Otto Hahn are listed in Appendix 4. Mutsu was Japan's first, and only nuclear-powered ship launched in 1972 (Matsuura 2001). She was built as a nuclear merchant ship, but a leak of neutrons and gamma rays occurred in 1974. The

accident was minor with no significant radiation exposure. However, it finally became a social and political issue and so that the entire project was forced to stop (Matsuura 2001). Major parameters of Mutsu are listed in Appendix 5. The latest nuclear powered merchant ship is Sevmorput built by Russia. The ship was defined as an icebreaking container ship with research and testing purpose (Makarov et al. 2000), and entered service in 1988. Although the Sevmorput is the first ship built following the IMO 1981 Code of Safety for nuclear merchant ships, the permission applications for calling four major ports including Nakhodka, Vostochny, Magadan and Vladivostok in far east of the Soviet Union were denied, since the local government and port stevedores refused to accept the visiting and offer any service due to the bad influence of Chernobyl disaster (Parks 1989). Finally, the ship made her first call at port of Vladivostok in 1989, but her international transport plan, for example to visit Canada, was never approved by the local authorities. Sevmorput was in service for a very long period and eventually retired in 2012. Makarov et al. (2000) states that the protective shell of the reactor on Sevmorput was innovatively designed and could withstand maximum excess pressure in the case of a rupture. This claim was supported by the ship's accident-free record during her 24 years service life (Papkovskii 1997). Sevmorput had sailed 302,000 miles and transported around 1.5 million metric tonnes of cargo in her service period with only one refuelling. The similar conventional ships may need to consume 100,000 metric tonnes of oil fuel in order to transport the same amount of goods (Mitenkov et al. 2003). The major parameters of Sevmorput are listed in Appendix 6. Besides merchant ships, nuclear power also enjoys the success in icebreaker application, especially in Russia, with zero accident record (Khlopkin et al., 1975).

Safety issue is always a concern related with nuclear power. Berman & Hydeman (1960) pointed out that the promising future for maritime nuclear application will not come until nuclear-powered ships can operate safely at sea. The radioactive nuclear fuels in the reactor is extremely hazardous to health. Once the radioactive particles escape from the core constitutes, serious consequences may occur, as in the cases of

Chernobyl (Ukraine) and Fukushima (Japan) (Carlton et al. 2013). Therefore, if nuclear-powered ships are used, severe results may occur in the port in case of nuclear accident. The dockers, port staff and crews may be injured. The operation of the whole port will be forced to stop for a long time. Moreover, the citizens of the port city may need to be evacuated. However, Khlopin & Zotov (1997) explained in their paper that the current protection design for nuclear reactor has dramatically reduced the probability of accident to a very low level. Based on the statistics from WNA (2014), more than 12,000 reactor years of marine operation has been accumulated. The four nuclear-powered merchant ships and other nuclear ice breakers all have zero accident and personal injury record. So far, exaggerated fears about safety have caused people's prejudice and development barriers on application of nuclear energy in maritime transport (WNA 2014). In general, regarding the safety risk of nuclear power ship, both consequences and possibilities of accident should be considered.

Radioactive waste disposal is a significant challenge for the nuclear energy. The radioactivity of the waste derived from spent nuclear fuel can last hundreds of thousands of years and may lead to catastrophic health and environment impacts without proper disposal (Féron et al. 2008). According to Schaffer (2011), the most widely used measures to handle the nuclear wastes from the power plants in U.S. are to either bury them deep underground in water container pools or store them in concrete steel-lined casks on the surface near the reactors. However, long-term accumulation of these toxic materials may lead to severe problems in the future. Other alternative options do exist, such as uranium and plutonium reprocessing, full recycling, and fully sealed waste, which can effectively reduce the risk, but certainly with higher cost (Schaffer 2011). Moreover, there is also the possibility to use thorium instead of uranium as the fuel in the reactor. Thorium-based reactors only produces about 3% of the high level radioactive waste and have a lower weapon proliferation risk compared with the conventional uranium-based reactors (Carlton et al. 2013). Furthermore, the transportation of the nuclear wastes from nuclear plants to the disposal sites is also vital. Riddel (2009) pointed out that the route should be carefully

considered and located away from the population in order to minimize the risks. The trucks, trains or ships used to transport the wastes should be specially designed in terms of safety and accident resistance, while an automatic monitoring system should also be in place to ensure regular reporting of the position (Benbow 1997).

On the other hand, the initial capital investment for a nuclear-powered vessel will also be considerably higher than building a conventional ship, due to the expensive reactor and design (Khlopkov & Zotov 1997; Carlton et al. 2013). Professional Engineering (vol. 23, no. 18, p. 7, 2010) states that such drawback can only be solved through standard hull and reactor design and mass production. Mitenkov et al. (2007) also stated that the high capital cost of nuclear propulsion system could be reduced through serial production and standardization, which could be proved by the cost reduction experience from land-based nuclear plant. The serial production can lead to a cost reduction by 30% to 35%, while the standardization may decrease the installation cost at shipyard by 20% to 40%.

International regulation is another issue faced by nuclear propelled ships. Unlike land-based nuclear power plant which can be regulated by its own nation's nuclear administration agency, reactor used on merchant ships must be regulated under the cooperation International Maritime Organization (IMO) and the International Atomic Energy Agency (IAEA) (Carlton et al. 2013). The law or regulation must be accepted by both the flag nations and port authorities, otherwise the effects of the regulation will be very limited, just as the case for the 'Code of Safety for Nuclear Merchant Ships, Resolution A.491 (XII)' set by IMO in 1981 (Khlopkov & Zotov 1997).

Insurance for nuclear-powered vessel is also a major challenge. Carlton et al. (2013) mentioned that there will be fundamental differences of insurance principles between the merchant shipping context and national navies where the government take the major responsibilities in underwriting the risks. But this is unlikely in the conventional shipping industry. According to Carlton et al. (2013), the underwriters

for hull and machinery (H&M) may only offer very limited coverage with strict prerequisite including sufficient salvage services, formal vessel response plan and formal port refuge arrangement. For protection and indemnity insurance (P&I), the member who purchased one nuclear vessel will expose other members in the mutual club to substantial financial liability. Moreover, since P&I is third party rather than first party cover, the problem of cover is even enlarged.

Other barriers related with nuclear propulsion in shipping include lack of expertise in all levels, port infrastructure and support system, crew training, high crew wage and emergency response plans (Carlton et al. 2013). Limited repair capacity is also a problem (Hass 2014) .

Nevertheless, several important advantages can be expected after applying nuclear energy in maritime transport. First, for environmental aspects, nuclear power is widely accepted as the cleanest energy source during operation. The nuclear-powered vessel emits no CO₂, NO_x, SO_x, and particulate matters owing to its power generation principle, which truly achieved zero emission level (Carlton et al. 2013).

Second, according to the data regarding U.S. electricity production costs from 1995 to mid 2008 (Figure 2), nuclear is currently the cheapest energy among the most popular fuel sources and this trend has been stabilized for more than 17 years. Carlton et al. (2013) believes that similar situation can also be expected in terms of marine bunker cost. Furthermore, unlike the cost of conventional marine fuel, which is sensitive to the oil price, the cost of nuclear fuel is more fixed, since one refill can last for a relatively long period (Boer 1959).

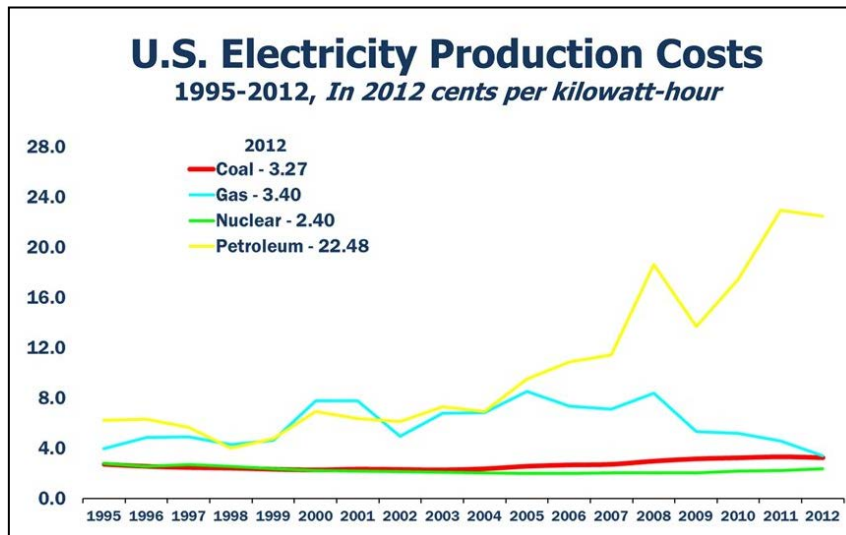


Figure 2: U.S. Electricity Production Costs 1995-2012, source: [NEI \(2013\)](#)

Third, nuclear reactor can provide much stronger propulsion power than the conventional fossil fuel powered engines, which is very suitable for the North Sea route due to the enhanced capability of ice-breaking offered by stronger power ([Khlopin & Zotov 1997](#)). Besides the ice-breaking ability, the stronger power produce by the reactor can also lead to faster speed stated by David Dobson, commercial projects director at Babcock's marine division for integrated technology in [Professional Engineering \(vol. 23, no. 18, p. 7, 2010\)](#). Moreover, since the nuclear fuel has low variable cost, the speed limitation due to economic consideration based on fuel consumption in the conventional propelled ships does not apply in the nuclear power context ([Carlton et al. 2013](#)). Hence, it might become acceptable to operate a container ship at 35 knots or a tanker at 21 knots, which is a significant increase compared with the speed of fossil fuel powered vessels. Furthermore, the maintenance cost of nuclear reactor is low.

Forth, long working period after refill is an vital strength as well ([Khlopin & Zotov 1997](#)). According to the experience from Savannah, the vessel can operate in normal condition for two or three years after refuelling ([Godwin et al. 1959a](#)). [Professional Engineering \(vol. 23, no. 18, p. 7, 2010\)](#) also states that with today's technology, the nuclear reactor can last maximum 10 years after one refill. The low frequency of

refuelling offers the possibility for extra loaded days at sea and opportunities for route optimization (Boer 1959). Therefore, nuclear power is particularly suitable for deep sea shipping which requires long navigation period at sea with no refuelling (WNA 2014).

Last, the bunker size for nuclear fuel is very small (Boer 1959). The amount of nuclear fuel used in a pressurized water reactor (PWR) is significantly less than the quantity of crude oil products, such as HFO or MDO, in conventionally propelled large vessels (Carlton et al. 2013). For instance, the volume of uranium fuel that can propel a 12,500 TEU container ship from Rotterdam to a port located on the east coast of U.S. only amounts to a few kilograms. This quantity of nuclear fuel equals to 1,550 tonnes of HFO for generating the same amount of energy. The development of small modular reactor (SMR) concept further strengthens this advantage. The major improvements of SMR are reduced initial capital cost due to the smaller scale, increased safety level owing to the considerably smaller radioactive inventory and possibility for mass production thanks to the standardization design (Liu & Fan 2014; Vujić et al. 2012; Kessides & Kuznetsov 2012; Waters & Didsbury 2012). Table 2 and Table 3 present the capacity parameters for the proposed SMR design and the typical power requirement for large ships. Through the comparison, it is easily to observe that even though the SMR has much smaller size than the reactors in land-based nuclear power plant, it still can provide sufficient energy to propel all the vessel types in current world fleet.

Table 2: Proposed small modular reactor designs, source: Carlton et al. (2013)

Small reactor designs	Country of manufacture	Power output (MWe)
KLT 40S	Russia OKBM	35
VBER 150	Russia OKBM	110
SMART	South Korea KAERI	100
MRX	JAERI	30
SMR	United States of America Westinghouse	200
mPower	United States of America B+W	125
NuScale	United States of America NuScale Power	45

Table 3: Typical power requirements for large ships, source: [Carlton et al. \(2013\)](#)

Ship type	Size	Typical power requirements (MW)
Bulk carrier	320000 dwt	30
Container ship	12000 TEU	80
Cruise ship	100000 dwt	70

3.2.3 Wind Energy

Wind, as a renewable energy source, can be seen to provide energy to drive ships ([Carlton et al. 2013](#)). [Carlton et al. \(2013\)](#) describes five techniques that could take advantage of wind energy on the ship, including soft sails, flettner rotors, kites, wing sails and wind turbines. Soft sails have the oldest history with some remarkable sailing passages such as tea trade in 19th and early 20th centuries. However the soft sail power was dependent on both wind condition and the skill of the crew on board. The flettner rotor that utilise the Magnus effect of fluid mechanics was appeared in 1920s. The power generated from flettner rotor has a linear relationship with wind speed. Also if there is more than one rotor on the ship, it requires particular ship structure design. Wind sails is a technique that been applied in recent years. Although a propulsive power can be generated, there are still some fluctuations in the loading that require more control system design. Kites also have been explored in recent years and have experimentally on modern merchant shipping. The wind turbines are turbines that equipped on ships to generate electric power. Both kites and wind turbines need a particular design on the ship.

[Carlton et al. \(2013\)](#) describes some advantage and disadvantages of wind energy. The most outstanding advantage is that there are totally no exhaust pollutants from the wind power. The techniques of wind energy have been proved that could attribute to the ship propulsion. However, there are still some disadvantages. It is notable that every wind power systems rely on the wind strength, which means that if there is no wind, the ship will remain becalmed. It also relies on the control system technology that installed on board.

O'Rourke (2006) discussed the wind power techniques including sails and kites mainly from oil reduction and cost aspects. For sail equipped ships, the ships called Usuki Pioneer and Aqua City claimed that with ideal wind condition, they could achieve 30%-40% fuel reduction. However, the fuel saving is marginal and a windship may even consume more fuels than a diesel ship under certain condition. There is no economic benefit for using a windship in current situation. The cost may raise 10% due to the high equipment and maintenance cost. However the Cooke Associates, still believe that wingsails could be used for large commercial ships in the future. The use of kiteship is to against stricter water/air quality regulation and increasing fuel cost. O'Rourke (2006) suggested that a kiteship might become more competitive in cost when the diesel fuel achieve \$1/gal. The ship with skysails system is more economically profitable. The fuel cost can be lowered between 10-35% annually depending on actual wind condition. The investment of skysails system will normally amortise within 3 to 5 years. However some disadvantage of the wind power have also mentioned in the O'Rourke (2006). For example, the sails on ship usually take a large space and the space for cargo will shrink corresponding. Also the loading and unloading is more expensive and adding more time in transaction.

3.2.4 Solar Energy

In 2008, the world's first solar energy powered cargo ship named M/V Auriga Leader has constructed, which marked the solar energy is a kind of renewable energy that feasible for ship propulsion.

Carlton et al. (2013) has talked about the solar energy as photovoltaic methods to generate power on ship. However the solar power was not efficient enough to drive the ship but can be used as supplement. Sometimes the solar energy is combined with wind energy to be an auxiliary power. The solar power has demonstrated to be valid technically and its major advantage is free of emission and pollutants. However Carlton et al. (2013) has mentioned some limits of the solar power. First, the solar energy is weather dependent. The cloud cover will have a significant effect on the

solar energy. Also it is global position dependent. [Lakatos et al. \(2011\)](#) also believe that the most serious problem of solar energy supply is that the energy very low at winter and no energy available at night. Second, the installation of technologies takes a large deck surface area on the ship that will interfere the cargo space. Third, due to the laws of physics, the power that generated from solar energy is low even the efficiency could be 100%, which suggest the solar energy could only be used as auxiliary power for the ship. If use the solar power as a full ship propulsion, then there will be some adverse commercial and financial implications such as voyage times and number of ships.

[Glykas et al. \(2010\)](#) made a cost-benefit analysis of solar hybrid power on merchant marine vessels, using two parameters: solar radiation density and fuel cost. Since the solar radiation density various with the geographical latitude and the season, [Glykas et al. \(2010\)](#) divided the global into six zones with different solar radiation density. The total cost of the solar powered ship includes the cost of solar panels and inverters. There is nearly no salvage value of the investment, because the photovoltaic system only has commercial value for 25-30 years and the removal and relocation cost could be really large. The profit of the solar hybrid power is actually the conventional fuel oil that saved by solar energy, which related with the increasing oil price. The payback time is highly depends on the annual increase rate of the fuel prices and require a minimum of about 10 years. On the other hand, the maintenance cost of solar panel is low while the repair cost of panel or battery could be high. There are various ways of storing the energy such as hydrogen and battery. However the using of hydrogen will reduce the investment profit and the batteries are expensive and hazardous to the environment.

3.2.5 Biofuel

[ECOFYS \(2012\)](#) evaluated all the potential aspects of biofuels for shipping industry. The biofuel are refers to “*the liquid or gaseous fuels produced from organic (plant or animal) material, for application in the transport sector*” ([ECOFYS, 2012, page: 5](#)).

Currently there is very less practical experience with using biofuels in shipping. But still some large companies have run some biofuels test both in freight and passenger vessels and get some useful lessons. First, there is market for biofuel in shipping sector. The related policy and regulation show supports for the use of biofuel. Although biofuels are more expensive than fossil fuels, which means there is a high operational cost for ship owner, the biofuels would still be cost-economic beneficial if the emission restriction become more strict or the price of biofuel decrease. Second, the application of biofuels in ship has been proved technically possible. Third, the main biofuel market barrier is market incentives. Biofuel could be an opportunity but also a threat to larger players in conventional market. Also there is very less public information that restraint people access biofuel market. The production cost of biofuels is still higher than fossil fuels which needs technology development to reduce the price.

[Carlton et al. \(2013\)](#) mentioned some advantages and disadvantages of biofuels. The advantage is that biofuel is technically possible to be an alternative to conventional fuels. The disadvantage is that in order to satisfy the demand of the market, large land areas need to devote, while some people question that the land may be more useful for agriculture. The production process is not very efficient but it is already under research. [Carlton et al. \(2013\)](#) also mentioned that one of the major disadvantages of biofuel is the shortage of supply. There is a possible that the total global biomass and biofuels mass would not enough to support the global shipping.

3.3 Other Solutions

Besides using alternative fuel, there are several other possible solutions to solve the two major problems, bunker price and environmental challenge, in this research as well. These solutions can be classified into two categories. One is from industry's perspective, while the other is from legislator's perspective.

3.3.1 From Legislator's Perspective

The solutions from legislator's perspective are usually set by governments or international institutions, such as IMO. The purpose of such measures is to drive the industry to a greener future. Two major methods in this category are regulation and market-based instruments (MBI).

Regulation

Although the allocation of emission from international shipping is not included in Kyoto Protocol ([United Nation 1998](#)), a global regulation is still be set by IMO. MARPOL Annex VI, which entered into force on 19 May 2005, regulated the sulphur oxide (SO_x), nitrogen oxide (NO_x) and particulate matter (PM) from ship exhausts and introduced emission control area (ECA) in order to achieve progressive reduction in specific sea areas ([IMO 2014](#)).

Sulphur emission control area (SECA) has been established in both the Baltic- and the North Sea. The average sulphur content of heavy fuel oils is from 3% to 4.5% required by Annex VI, while Baltic- and North Sea SECA limit the sulphur content in marine fuel to 1.5% or equivalent exhaust gas cleaning technologies must be applied ([Burgel 2007](#)). From 1st January 2015, the maximum allowed sulphur content of the bunker combusted in SECA will decrease significantly to 0.1%, while there are also similar declines for NO_x and PM ([Gilbert 2013](#)). Impressive reductions in emission are expected after implementing SECA in Europe. According to [Kalli et al. \(2013\)](#), the European SECA will lead to a drastic decrease in exhaust of SO_x and PM_{2.5} by 92% and 64% respectively, compared with 2009 level, in 2015. Moreover, if a nitrogen emission control area (NECA) can be established in Baltic Sea, North Sea and English Channel, more significant reduction in NO_x emission (estimated to decrease 11% in 2020 and 79% in 2040 from the 2009 level) will occur ([Kalli et al. 2013](#)). Besides EU, US and Canada have also designated certain coastal areas as ECA, while the ECA in North America includes both sulphur and nitrogen emissions ([Cullinane & Bergqvist in press](#)).

Nevertheless, the implementation of SECA may require switching marine fuel from heavy fuel oil (HFO) which has high sulphur content, to lower sulphur fuel (LSF) which fulfils the requirement under SECA but is much more expensive. [Jalkanen et al. \(2012\)](#) has estimated that fuel switch can probably lead to an extra cost in the range of 3.3 - 4.6 billion USD per year. In order to save fuel cost, the ships coming to and going from SECA may have to carry two different types of fuel, both HFO and LSF ([Burgel 2007](#)). For example, a container vessel from China will likely run on HFO while convert to LSF after entering the North Sea SECA. This kind of operation will require two separate fuel systems, tanks, separators etc. and need to have the capability to safely switch from one fuel to the other ([Burgel 2007](#)). It is correct that the ship can carry only LSF from the very beginning, but such assumption is just theoretical, but not economic, because the fuel cost occupies 40% - 50% of the voyage cost ([Stopford 2009](#)) while the distance requiring LSF only accounts for a very small share compared with the deep sea leg.

Market-Based Instruments (MBI)

The application of market-based instrument (MBI) in solving environmental issues is relatively new. [Stavins \(2001, p.1\)](#) broadly defined MBI as “*the instrument or regulation that encourage behavior through market signal rather than through explicit directives regarding pollution control levels or methods*” . The principle of MBI is to achieve the expected outcomes through self-interest of companies. [Pannell \(2001\)](#) stated that the key interest in MBI application is not only achieving the policy targets but also with a minimized cost and other factors, such as risk. According to [Whitten et al. \(2003\)](#), there are two major advantages for using MBI. First, MBI allows different companies to respond differently based on their unique business structures and opportunities. Second, MBI offers firms incentives to develop cheaper ways to reduce emission which leads to higher dynamic for future improvement and cost reduction.

[Figure 3](#) indicates that there are three types of lever included in MBI. One is

price-based instrument (PBI), one is rights-based instrument (RBI) and the other is market friction instrument (MFI). Regarding PBI, taxation is one of the most widely used practices in emission control. In shipping industry, the purpose of a fuel tax in terms of GHGs emission is to internalize external cost (Kolstad 2000). The advantages of taxation include low administration and monitoring cost, high cost effectiveness in emission reduction, encouraging investment in green technology and certainty to industry due to predictable savings (Mellin & Rydhed 2011). However, the environmental outcomes under taxation instrument are uncertain (Whitten et al. 2003). It will be impossible to apply in an international shipping context due to the high risk of evasion caused by flag of convenience, unless a global standard is implemented and accepted by all flag countries (Mellin & Rydhed 2011). Cap-and-trade scheme is the typical approach among RBIs. In the system, the maximum allowable emissions for the participants are capped and divided into permits that are given to the participants for free or through auctions in the market (Mellin & Rydhed 2011). The cap-and-trade scheme allows companies to trade their permits so that the emitters with high abatement cost can buy permits from those with low emission reduction cost. Cap-and-trade scheme has been applied in both domestic level, such as U.S. SO₂ trading program (Boutabba 2012), and regional level, such as European Union Emission Trading Scheme (EU ETS) (European Union 2013). The advantages of cap-and-trade scheme are obvious. First, environmental outcomes are certain due to the existence of a cap (Whitten et al. 2003). Second, the target of emission reduction can be achieved in the lowest possible cost, while firms will have strong willingness to use all possible methods and invest in new technologies to reduce emission (Mellin & Rydhed 2011). Nevertheless, practical problems, such as over-allocation and emission leakage, may diminish these advantages (Buchner & Ellerman 2007; Mellin & Rydhed 2011). The price of the permit is volatile and can be affected by external facts, such as economic crisis, which brings high uncertainties to firms' benefit in reduction (Bailey 2010). Moreover, high administration cost and problems in building emission inventory due to lack of data are all critical barriers as well (Wang et al. 2007; Wang et al. 2008). It has been discussed that shipping could

become a part of EU ETS, but the failure of involving international aviation into EU ETS demonstrates the difficulties and complexities (Airfinance Journal 2011; Airfinance Journal 2012; Air Transport World 2012). Furthermore, applying cap-and-trade scheme in international shipping at this level would possibly lead to undesired increases in emission due to a reduction of trade transactions based on comparative advantages (Duchin 2005; Strømman & Duchin 2006; Strømman et al. 2009). The MFIs, such as eco-labelling are less commonly used in shipping context.

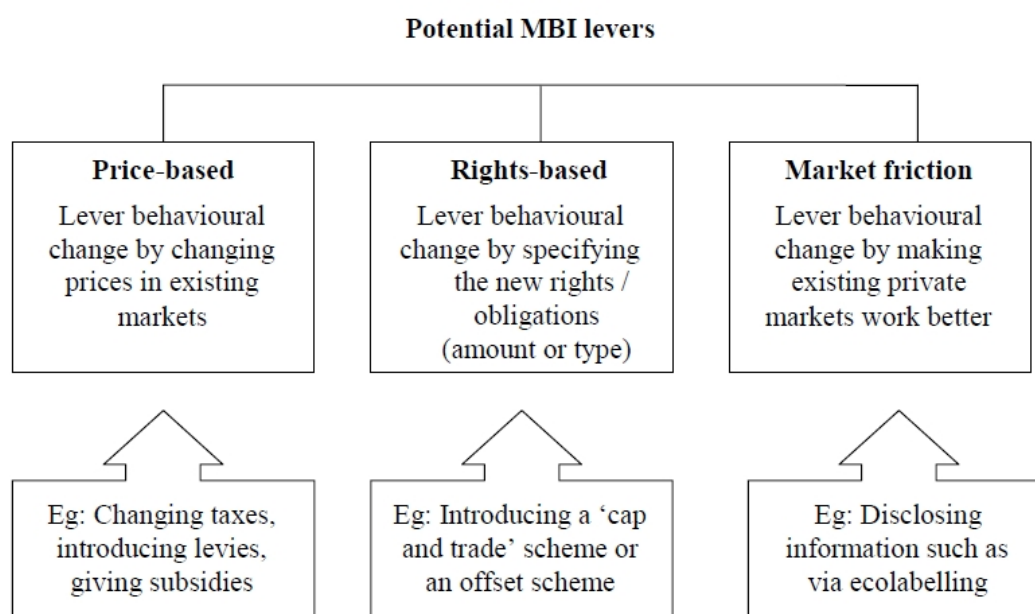


Figure 3: Potential MBI Levers, source: Whitten et al. (2003)

3.3.2 From Industry's Perspective

The solutions from industry's perspective are normally a reaction to the legislator's decision or market situation in order to fulfil the requirement of the policies or overcome the market challenges. The approaches in this category are either operational or technological.

Using Low Sulphur Fuel

Since the average sulphur content in heavy fuel oil (HFO) is from 3% to 4.5%, which obviously cannot meet the requirement under a SECA, many shipping companies start

to use low sulphur fuel (LSF) with only 1.5% sulphur content (Burgel 2007). Although a significant emission of SO_x will be removed after switching from HFO to LSF, many drawbacks still exist in this solution. First, many refineries do not have facilities to produce LSF in large quantities while investing in desulphurization is less attractive than investing in producing more light products (Burgel 2007). Therefore, there will be refinery capacity issues for LSF (Williams et al. 2013). Second, the bunker price for LSF is much higher than that for HFO, which lead to significant negative impacts on shipping economy (Gilbert 2013). Last, switching from HFO to LSF may lead to more CO₂ emissions from the life-cycle perspective, because desulphurization needs considerable energy (Bengtsson et al. 2011; Burgel 2007).

Slow Steaming

Since fuel consumption of a vessel is a cubic function of its sailing speed (e.g. Ronen 1982; Fagerholt et al. 2010), while emissions are proportional to the amount of fuel consumed (e.g. Buhaug et al. 2009; Lindstad et al. 2011), slow steaming becomes a popular strategy accepted by shipping companies to reduce both fuel cost and shipping exhaust. According to Psaraftis & Kontovas (2010), a 10% reduction in vessel's speed can lead to 10% - 15% decrease in emissions. Slow steaming is particularly a suitable operation strategy for container shipping, because it has much higher speed and thus larger share of emission than tanker or bulk carrier (Lindstad et al. 2011; Psaraftis & Kontovas 2009; Psaraftis & Kontovas 2010). According to Corbett et al. (2009), up to 70% reduction in emission can be achieved in container shipping sector if the speed is halved. Slow steaming is popular because it can be easily implemented without investing in any new technology, but it is fragile in long run (Cariou 2011). Wang & Meng (2012) stated that slow steaming could only be acceptable under two prerequisites, high bunker price and surplus container ships. If bunker prices fall while freight rates rise, the incentives for operating the ship at full speed will exceed the motivations for slow steaming in order to reap the profit (Cariou 2011). Moreover, with lower sailing speed, additional vessels are required to maintain the frequency and transport capacity on a specific route (Fagerholt & Lindstad 2000;

Corbet et al. 2009). Actually, besides the cost of hiring additional vessels, slow steaming may also lead to higher inventory cost and risk to lose sales, which is not acceptable especially when the value of the cargo is high (Psaraftis & Kontovas 2010). Other problems, such as engine load issues (Kalli et al. 2013), are also important when slow steam.

Other Approaches

Besides slow steaming and using LSF, other measures are also available to the ship owners to solve environmental and bunker price problems. Song & Xu (2011) mentioned that improving port-handling rate and adopting more efficient empty container repositioning could contribute considerable CO₂ emission reduction. Schedule optimization of liner shipping can reduce fuel consumption and thus reduce emission (Song & Qi 2012). Lindstad et al. (2012) stated in his article that economies of scale can also be applied in CO₂ emission. Bigger ships have lower emissions per ton mile than smaller ships. But Lindstad et al. (2012) mentioned that the relationship between vessel size and emission amount is not linear with decreasing marginal emission reduction as ship size increase. Technological methods, such as efficient hull design, energy-saving engine and 'cold ironing' - shore-side power can reduce both fuel consumption and emissions by certain extent as well (Psaraftis & Kontovas 2010; Han 2010). Scrubber can be used to reduce the emission of SO_x, but it may lead to extra CO₂ emission due to the energy required and have installation problem for the old ships (Gilbert 2013). For NO_x emission, technologies including selective catalytic reduction (SCR), direct water injection (DWI) and humid air motor (HAM) are also helpful (Yang et al. 2012).

3.4 Decision-making Tools

When facing the selection, the authors found that there are various decision-making tools that can be used by decision markers. Aguezzoul (2007) has classified all the tools into four categories: linear weighting models, artificial intelligence,

statistical/probabilistic approaches, and mathematical programming models.

3.4.1 Linear Weighting Models

Linear weighting model is the most common approach that usually place a weight on each criterion and calculate the total score of each candidate (Aguezzoul, 2007). Analytic hierarchy process (AHP) is known as an essential tool for management decision making (Cheng et al., 2002). It compares criteria according to their relative importance (Satty, 1994). Cheng et al. (2002, pp.34) summarised six major steps of AHP method:

- *Define the unstructured problem*
- *Decompose the problem into a systematic hierarchical structure*
- *Employ the pair-wise comparison method*
- *Carry out the consistency measure*
- *Estimate the relative weights for the components of each level of the hierarchy*
- *Use the relative weights for different purposes*

Satty (1994) mentioned five benefits for using AHP method. First it encourages people explicit their knowledge and feeling. Second, the hierarchy framework making the prediction more like outcomes. Third, this method makes people be able to incorporate with greater accuracy of understanding. Forth, AHP could involve people's judgements from both emotion and logic.

The analytic network process (ANP) technique is a generic form of AHP. Compare with AHP, it allows more complex and interdependent relationships and feedbacks among elements in the hierarchy (Sipahi & Timor, 2010). The ANP can be seen as a development of AHP and the model in ANP make decisions without assuming about the criteria independency (Jharkhariaa & Shankar, 2007). Both AHP and ANP are widely used in various areas such as manufacturing, construction industry, power and energy industries, transportation industry, and healthcare (Sipahi & Timor, 2010).

3.4.2 Artificial Intelligence

Artificial intelligence is a technique that combines both qualitative factors and human expertise in decision-making process. According to [Aguazzoul \(2007\)](#) there are two main systems in artificial intelligence that are expert system and case-based reasoning (CBR). [Tecuci \(2012, pp.168\)](#) defined artificial intelligence as “*the science and engineering domain concerned with the theory and practice of developing systems that exhibit the characteristics we associate with intelligence in human behaviour*”. Starting as a computer science, artificial intelligence today are widely used in problem solving and planning. [Tecuci \(2012\)](#) described some general methods of artificial intelligence such as resolution, problem reduction, CBR and so on.

[Pomerol \(1997\)](#) compared artificial intelligence with decision theory and found that the artificial intelligence focuses more on diagnosis and human knowledge. The weakness of artificial intelligence is that it disregards the multi-attribute preferences.

3.4.3 Statistical/Probabilistic Approaches

The statistical/probabilistic approaches is to make decision based on the statistical analysis of empirical studies. It deals with mean and standard deviation of data, analyzes the correlation, and finds the probability of data ([Aguazzoul, 2007](#)). The statistical/probabilistic approaches are usually used in performance analysis and prediction. For example, [Grant \(1983\)](#) used statistical and probabilistic approach to assess the mean level, variability and the trend in performance. [Hajiyev & Afandiyev \(2009\)](#) used the statistical and probabilistic approach to find out the optimal computer keyboard layout for Azerbaijani language. [Aguazzoul \(2007\)](#) summarised some disadvantage of statistical/probabilistic approach, such as it can't provide optimal solution and also is sometimes difficult to analyse.

3.4.4 Mathematical Programming Models

The mathematical programming models consists a function objective and a set of constrains that need for modelling, evaluating and planning by mathematical method.

Linear programming modelling is a kind of mathematical programming models. Ipsilandis (2007) used linear programming model to schedule the linear repetitive projects. Chen et al. (2011) applied this model to select the best third party logistics provider. Both of them proved that linear programming model could be used for decision making.

Data Envelopment analysis (DEA) is another common mathematical programming models for making decision. According to Min & Joo (2006, pp.260), DEA has been defined as “*mathematical programming technique that convert multiple incommensurable inputs and outputs of each decision-making unit (DMU) into a scalar measure of operational efficiency*”. For each DMU, the input and output are defined by criteria and weights while a calculation will be used for final decision (Min & Joo, 2006). The DEA is often used in comparative efficiency assessment, not only in respect of individual units but also collective units (Boussofiene et al., 1991).

4. Findings

In this chapter, empirical findings extracted from literature review, questionnaire and interviews are summarized. An alternative fuel or energy for deep sea container shipping (DSCS) in the future is recommended based on the empirical findings.

4.1 Findings from Literature Review

After the review of a large quantity of related literatures, the authors conclude the facts in three aspects in following paragraphs. The three aspects include the necessity of a alternative fuel or energy, the criteria for selecting alternative fuel or energy in DSCS context and the horizontal comparison among selected alternative fuels or energies in terms of these criteria.

4.1.1 Necessity of Alternative Fuel or Energy

Environmental issues have become the major concern in all industries nowadays and

shipping is not an exception. Although there are many other environmental problems such as ballast water and oil spill, the exhausts from shipping are still the most critical challenges with highest priority. This point has been demonstrated by stricter policies and regulations. The emissions from shipping are various and removing one or several of them will not solve the problem. For example, people still have to face the result of global warming caused by the emission of GHGs, if only the SO_x emission has been reduced. Therefore, an effective solution which can totally eliminate all emissions or reduce them to acceptable level is urgently needed. Moreover, the significant achievement of land-based emission reduction leads to higher pressure for shipping industry and increases such urgency.

On the other hand, increasing bunker price is another substantial difficulty for shipping companies. Since fuel cost accounts for more than half of voyage cost of a vessel, high oil price dramatically compresses the profit space of industry. The probable scenario will be higher freight rate which will absolutely bring negative impacts to international trade and global economy. Hence, the shipping industry need to work out a solution to reduce its fuel consumption or dependence on crude oil products so that the industry can remain profitable without transferring high fuel cost to shippers.

Regulation and Market-based Instrument (MBI) are effective methods in emission reduction due to its overwhelming power from governments or regulatory institutions. But the implementation in the shipping context is complex and difficult due to its international characteristic. IMO is an ideal regulator in this case, but there is still a long way to go. Moreover, the solutions from legislator's perspective will not lead to exhausts reduction directly, but only affect shipping companies' strategies and behavior. The final achievement of emission reduction still relies on the solutions from industry's perspective. Another issue is that regulation and MBI measures will not solve the problem of increasing bunker price.

Most of the solutions from industry's perspective also lack the capabilities to fully overcome both environmental and bunker price challenges. Sometimes, a specific solution for one of the problems may even deteriorate the other one. Using low sulphur fuel can significantly reduce the emission of SO_x, but it may lead to higher bunker cost and extra CO₂ emission due to the refinery. Applying equipment, such as scrubber, water injection and humid air motor can reduce the emission of a certain exhaust but have no improvement on others and they may even lead to extra CO₂ emission because the equipment need additional energy to operate. Slow steaming is the most effective operational approach that solves both of the two problems in the biggest extent. Moreover, it does not need any investment in new technologies thus very economical. Nevertheless, the major incentives for companies to slow steam are not environmental concerns but economic concerns. It only happens when bunker price is high and the market is in recession. Once the situation changes, for example freight rate rises, the speed of vessel will possibly increase as well. Therefore, the slow steaming approach is fragile and unreliable and the outcome of slow steaming is unstable. Furthermore, slow steaming in DSCS context will require additional ships and emit more NO_x due to the low engine load.

However, using alternative fuel or energy has potentials to solve both environmental and fuel price problems. No matter, nuclear power, liquefied natural gas (LNG) or renewable energy (solar/wind power) can significantly reduce the emission of all kinds of exhaust. Moreover, the liberation from the dependence of crude oil products can totally solve the problem of increasing oil price, because the reserve of these alternative fuels are sufficient and prices are much lower. Therefore, according to the comparison between applying alternative energy and other solutions based on the information obtained from substantial literatures, it is safe to claim that using alternative energy is the only option which has possibility to solve the two major problems faced by shipping industry in the future.

4.1.2 Fuel Selection Criteria

In this section, several fuel selection criteria for the context of DSCS are listed with explanation and examples. The following is a summary of the reviewed literatures. All the criteria are mentioned by previous researchers when evaluating and discussing alternative fuels.

Safety

Safety of the ship is an important criterion in fuel evaluation. The safety includes the ship operation safety, safety of living and working environment for crews, and safety for port and citizen that living around the port. For example currently used crude oil product is quite safe, while the safety of nuclear power has been questioned for a long time. People fear that nuclear power may have potential threats, although the technology of nuclear is actually matured and the four merchant nuclear ships in history have zero accident and injury record. The transportation of fuel and the disposal of radioactive waste may influence the port citizen as well. The alternative fuel needs to be proved safe before it finally put in use.

GHG emission

Green house emission is an important criterion that is used in fuel evaluation too. Since one of the challenges faced by current fuel is high level of GHG emission, the alternative fuel should have capability to reduce GHG emission as much as possible. For example, using wind or solar power as ship fuel to replace HFO would totally eliminated the CO₂ emission.

Air pollution

The air pollution mainly involves ship emissions of NO_x, SO_x and PM. All of the current crude oil products have air pollution problems. More and more regulations about the emission of nitrogen oxide and sulphur oxide have been issued. For example the SECA area requires the ship fuel to have low sulphur level, which makes air pollution level become an criterion for shipping fuel selection. Biofuel has very low

air pollutant emission. LNG has low NO_x emission and generates no SO_x emission and PM. The nuclear power and solar/wind power have no air pollution. All of them are competitive compared with crude oil products.

Necessary infrastructure and facilities cost

The application of certain shipping fuel needs some necessary infrastructures and facilities to support such as port infrastructure and fuel storage facilities at port. For some fuel, this cost could be very high. For example there are barely any facilities that support nuclear energy in commercial ports or during transportation. Using nuclear power will need a large investment on infrastructure and facilities.

Crew training cost and wage

Certain fuel needs some technique at operation level, which require a crew training. So a crew training cost will be generated and add to the total operational cost. For example nuclear power, wind power and solar power all require people with skills to operate. The skilled crew will also require higher wage than regular crew. In this sense, the crew training cost and crew wage could be criteria for fuel selection.

Shipbuilding or modification cost

The building of ships will vary with the selected fuels. The change of fuel usually needs a ship modification or even building a new ship. When selecting new fuels, the cost of shipbuilding or modification should be considered. For example one type of the wind powered ship require a huge kite on the ship, which will increase the total cost.

Bunker price

The bunker price is directly linked with operational cost. Currently, the bunker cost takes about 60% of the total operational cost. The less sulphur it contains, the more expensive the fuel is. When the price of HFO or IMO increase to a certain level, other alternative fuel may become competitive with their low prices. Especially for solar

and wind power, there is no bunker cost at all. Since the fuel price is really important for total operational cost, it will be seen as a criterion.

Maintenance/repair

The infrastructures and facilities that support the use of fuels will generate maintenance or repair cost. The cost will depend on the complexity of infrastructures or facilities. The maintenance cost of LNG-powered ship will be lower than that of crude oil products. However the maintenance cost of wind power technology is high. The maintenance cost should be a part of operational cost, so that it should be a criterion for fuel evaluation.

Fuel power density and transaction rate

The fuel power density means the power that can be released per unit fuel. And the transaction rate means the percentage of fuel power that becomes ship propulsion power. The nuclear reactor can provide very strong propulsion power that can increase the ship speed to 35 knots. However the transaction rate of wind or solar power is very low.

Reliability

Reliability is very important in deep sea container shipping (DSCS) which means the fuel can propel the ship without being influenced by external factor. The reliability of wind power and solar power is particular low since they highly depend on the position and weather.

Refuelling frequency

Refuel frequency is an important criterion when concerning of the DSCS. If a fuel has a high refuelling frequency, the ship needs to stop at many ports along the route, which will add the voyage time and may lead to detour, hence the operational cost will increase accordingly. For example, LNG has a very high refuelling frequency. It means that the LNG may be competitive in short sea container shipping; while it is

not economic to use LNG during a long voyage.

Impact on capacity

It is necessary to consider the criterion of impact on capacity that means the impact of the bunker space on cargo space. For example, in order to reduce LNG refuel frequency, the bunker space of LNG may need to be enlarged. However the large bunker space of LNG will occupy the space originally for containers, so that the cargo carrying capacity will be influenced. Another example is that the installation of solar panel will take a large space on deck, which will influence the cargo space as well.

4.1.3 Horizontal Comparison

When analysing the alternative fuels, biofuel are excluded. Three reasons are summarised according to the literature review. First and the main reason is that the supply of biofuel is from animal fats, vegetable oils, sugar, starch et al.; however the available global resource of biofuels is not enough to supply shipping. In this sense, the biofuels can only be used in a small range but not suitable for generalization in the whole container shipping sector. The second reason is that although some test proved that using biofuel on ship is technically feasible, the practical experience in container shipping are still insufficient. The third reason is that the production cost of biofuel is very high which could not solve the problem of increasing bunker price. These three reasons make biofuel become uncompetitive among all the alternative fuels and will be excluded during the following summary.

For safety aspects, there are not so many literatures mention the safety about crude oil products. But the fact that using crude oil products for lots of years has already proved their level of safety. The public generally have fears regarding nuclear power, considering some well-known nuclear accident such as the Chernobyl disaster. However there is zero accident record when using nuclear power as ship propulsion. It is able to compare the nuclear power with air transport. Both of them have good safety records; but if accidents happen the consequence of accidents may be serious.

The dockers, port staff and crews may be injured. The operation of whole port will be forced to stop for a long time. Moreover, the citizen of port city may need to be evacuated. A unique safety aspect concerning the nuclear power is about the radioactive waste. If using nuclear power as future ship fuel, the radioactive waste needs more appropriate handling method. LNG, as a shipping fuel also has excellent safety record. However there are still some safety issues that need to be addressed. LNG is a combustible fuel so that there may be an accident of fire. Also the LNG fuel has very low temperature which means that frostbite accident may occur when handling the fuel. There are not so many literatures mention the safety about solar and wind power as the propulsion power for shipping. The reason of that is on one aspect, there is no dangerous characteristic for solar and wind energy. On the other aspect, there is still few commercial application of these two energies in maritime transport. More evidences are needed to investigate the safety.

The traditional crude oil product such as HFO has a high GHGs emission level. LNG can decrease the CO₂ emission for 20%-25% in terms of the combustion in engine (Lennerås 2008). While the carbon savings during the whole lifespan may be limited due to the higher energy consumption in liquefaction. Nuclear power, solar power and wind power are competitive since there is no GHGs emission when using them as shipping fuels.

The crude oil products have high level of SO_x, NO_x, and PM emissions. Applying LNG will totally remove SO_x and PM, and also reduced the NO_x for 80%-90% (Lennerås 2008). As the same of GHGs emission, there is no air pollution for nuclear power, solar power and wind power.

Since nowadays crude oil products are the major shipping fuel, the infrastructures and facilities that support the using of crude oil products are well developed and have a relatively low cost. LNG has already been used in some short sea shipping route. Increasing amount of LNG supporting infrastructures and facilities appear in ports,

but more investment are still needed. The infrastructures and facilities for nuclear power in ports are undeveloped. The initial cost of nuclear infrastructures and facilities will be very high. Since the solar and wind power don't require too much facilities in port, there are not so many literatures mention the initial facilities cost of solar and wind power.

There is a particular aspect of nuclear power energy as shipping fuel, which is crew training and crew wage cost. Some literatures have mentioned that the nuclear power needs crews with expertise and skills. Compared with the crews on the ships using other fuel or energy, the crew on a nuclear-powered will need higher training cost and salary.

The ship that use crude oil product as fuel has already had matured design standard with mass production. On the contrary, there is no standard design for ship with nuclear power. The modification or newbuilding costs of nuclear container ship are extremely high. Using LNG may also lead to a modification cost. Regarding newbuildings, it costs 10%-15% more compared with the conventional ship (Levander 2006). For solar power, there are extra costs for solar panels and inverters, as well as the energy storage such as batteries. Wind powered ships also have extra costs for kites, wind sails or wind turbines.

In terms of bunker price, the crude oil products, such as HFO has relatively higher price than other alternative fuels considered in this research. The oil price has an increasing trend in general. Moreover, the bunker price in future for crude oil products may become even higher, because HFO is not capable to meet the stricter requirements of environmental regulations, such as SECA, and shipping companies may have to switch to LSF which is much more expensive than HFO. The price of LNG is almost the same as HFO, but it is lower than MGO and LSF. Therefore, LNG will have bunker cost advantage over crude oil products as marine fuel in the green future. However, the fuel price for nuclear power is even lower than LNG. It is

because the cost of uranium is low while the enrichment and fabrication are also cheap due to the matured technologies. Such cost rank can also be observed in the historical data of electricity production cost with different fuels. Furthermore, the nuclear fuel has low sensitivity to the market price change, because one refill can last for a quite long period of operation. Lastly, since solar power and wind power is generated by the nature and do not rely on any physical fuel matter, there is no bunker cost requirement for these two renewable energies.

Regarding maintenance and repair cost, nuclear reactor has relatively low maintenance cost, but the repair expense is high in case of breakdown due to the expensive price of the reactor itself. Moreover, the maintenance and repair capacity is very limited for nuclear- propelled ship nowadays, because it requires experts with specialized knowledge and skills. LNG-powered vessel has low maintenance cost as well. The cost decreases approximately 40% compared with the cost of conventional ship powered by HFO (Banawan et al. 2010). Solar power ship also has low maintenance cost. The solar panels on the deck do not need too much care but only some simple cleaning increase of dust and dirt. Nevertheless, the repair cost of solar panel is high since it is very vulnerable and it needs to be totally replaced once damaged. Last, wind power ship has high maintenance cost.

Fuel power density and its transaction rate are also important since it will affect propulsion power. For nuclear power, the power density and transaction rate are very high, so it can offer great propulsion power to the vessel. But power density for LNG is lower than HFO which leads to larger space requirement on board for fuel storage. On the other hand, the energy density of solar radiation is changeable and dependent on geographical latitude and the season. Moreover, both solar power and wind power systems have the low transaction rate problem. Hence they are mostly used as assistant power source.

With regard to fuel reliability, crude oil products, nuclear power and LNG all have

outstanding performance, since their performance are not easily affected by external factors. Nevertheless, the reliability of solar and wind power is very low due to their significant dependencies on weather condition and geographical location. Therefore, it is very risky to have solar power or wind power as the sole energy source for propulsion on the sea.

Since LNG has lower energy density than HFO, it has to refuel frequently unless a considerably large room on the ship is left for its storage. Nuclear has overwhelming advantage on this criterion over both LNG and other crude oil products. A nuclear-powered vessel can operate without refill for maximum 10 years with today's technology. For solar and wind power, again, since they do not rely on any physical fuel matter, refueling is also unnecessary.

Last but not least, the selection of fuel for propulsion also affects the carrying capacity of a ship. Since only a small amount of nuclear fuel is enough to propel vessel for a long period, the space requirement of bunker is small. Even if nuclear reactor is considered, the size of the whole system is still much smaller than conventional propulsion system. Therefore, using nuclear power can save room which can be utilized as extra space for cargo. LNG-powered vessel requires 2 to 4 times more volume for bunker when compared with the conventional ship due to its smaller power density ([Herdzik, 2011](#), [Stuer-Lauridsen et al. 2010](#)). Obviously, this drawback will significantly reduce the cargo carrying capability. Similarly, applying solar power and wind power to propel the vessel will also lead to considerable carrying capacity decrease, because the additional equipments, such as solar panels, wind sails and wind turbines, need to be installed and placed on deck, which occupies the space for containers.

According to the summary above, we can easily find that there is no perfect option as fuel for the future. Each alternative energy has its advantages and problems. However, based on these advantages and problems, the authors conclude that nuclear power has

the highest potential as the alternative energy for ship propulsion in DSCS segment in the future because the drawbacks of nuclear power nowadays are mainly operational, hence solvable in the future, while the problems of other alternative energies are fatal and related with their characteristic, thus unsolvable. When talking about nuclear power, public usually have doubts on its safety. The historical nuclear accidents, such as Chernobyl event led to catastrophic results and long lasting psychological trauma for normal people, which finally become public prejudice on nuclear power. But in fact, nuclear power is a safe energy nowadays due to the technology development. The reactor size applied in maritime transport is much smaller than that of a land-based power plant, which reduces the risk and severity in the case of accident. Moreover, the extensive application of nuclear energy in land-based power plants and outstanding safety record of nuclear propulsion in both navy and civil shipping should not be ignored as well. Other barriers, for example high initial capital cost, lack of maintenance capacity and regulation difficulties, are all possible to be overcome through operational methods such as standard design, mass production, specialized training and international legislation, in the future. Solar and wind power have excellent performance in many criteria such as emission and bunker price. Nevertheless, its major drawbacks, for instance dependency on weather and geographical factors, are impossible to improve. Therefore, both solar and wind power are not feasible options as the sole energy source for propulsion in DSCS. The major unsolvable problem for LNG is the GHGs emission. Although using LNG instead of crude oil products can totally remove SO_x emission and almost eliminate NO_x emission, but it can only decrease GHGs emission by 20% (Lennerås 2008). This is not enough to solve the global warming problem since the increasing volume of shipping will offset this reduction. Furthermore, if an international carbon-related market-based instrument (MBI), such as taxation or cap-and-trade scheme, is implemented in the future, LNG will become more uneconomic when compared with nuclear propulsion. Hence, applying LNG as the alternative fuel may lead to lock-in effect (Gilbert 2014). The lock-in effect in shipping refers to the argument that although LNG can help the industry to fulfill the requirement of SECA, the

opportunity of using other carbon-free fuels in the future is locked. Under such condition, twice investments may happen if the co-benefits are not well addressed, which will finally lead to investment wastes. On the other hand, the refuelling frequency and bunker size problems are also unsolvable in the context of DSCS. It is impossible to refuel frequently when the ship is transiting the ocean. It is also unacceptable to sacrifice cargo capacity for more bunker storage space, which significantly decreases the economies of scale. Therefore, LNG might be a good alternative fuel in short sea shipping, but not an ideal choice in DSCS. The summarization of the horizontal comparison is listed in [Table 4](#).

Table 4: Summarization of different fuels'/energies' performance under different criteria.

	<i>Crude Oil Products</i>	<i>Nuclear Power</i>	<i>LNG</i>	<i>Solar Power</i>	<i>Wind Power</i>
Safety	Not mentioned	1. Matured protectiong technology 2. Zero accident record 3. Possible serious concequence 4. Radioactive waste	1. Excellent safety record 2. Combustible 3. Low temperature	Not mentioned	Not mentioned
GHGs emission	High GHGs emission	Zero GHGs emission	20% - 25% emission decrease compared with crude oil products	Zero GHGs emission	Zero GHGs emission
Air pollution	Emissions of SO _x , NO _x and PM	No air pollution	1. Totally removed SO _x and PM. 2. NO _x emission reduced 80% - 90% compared with crude oil products	No air pollution	No air pollution
Necessary infrastructure and facilities cost	Matured, low cost	Undeveloped, high initial investment requirement	Developing, high initial investment requirement	Not mentioned	Not mentioned
Crew training cost and crew wage	Not mentioned	1. Expertise required 2. High crew wage	Not mentioned	Not mentioned	Not mentioned
Shipbuilding or modification cost	1. Matured design standard 2. Mass production 3. Relatively Low capital cost	1. No standard design 2. Expensive reactor 3. High initial capital requirement	1. Modification cost for convectional vessels 2. 10% - 15% more expensive for new buildings compared with conventional vessels	1. Extra cost for solar panels and inverters. 2. Extra cost for storage, such as batteries.	1. Extra cost for kites, wind sails or wind turbines.
Bunker price	1. Relatively high price with increasing trend in general 2. Higher price for special product, such as LSF	1. Relatively low fuel cost 2. Low sensitivity to market price change 3. Stable	1. Almost same price as HFO 2. Cheaper than MGO & LSF	No cost	No cost
Maintenance & repair	Normal Cost	1. Low maintenance cost 2. Limited capacity 3. High repair cost	Lower maintenance cost, 40% decrease compared with oil	1. Low maintenance cost 2. High repair cost	High Maintenance cost
Fuel power density and transaction rate	Normal	High	Low density	Low transaction rate	Low transaction rate
Reliability	High	High	High	Low, rely on lattitude and weather condition	Low, rely on lattitude and weather condition
Refuel frequency	Normal	Low	High	No refuel requirement	No refuel requirement
Impact on capacity	Normal	Increased cargo capacity	Decreased cargo capacity	Decreased cargo capacity	Decreased cargo capacity

4.2 Finding from Questionnaire

The purpose of this questionnaire is to collect empirical data from both academic and industry areas in order to understand their thoughts about different alternative fuels or energies for future DSCS segments. The respondents were asked to do pair-wise comparison among different criteria which will be used to evaluate different alternative fuels or energies later. Then the respondents also compared and ranked every two alternative fuels or energies based on their performance on each criterion. The alternative fuels or energies that were compared in the questionnaire included crude oil products, LNG, nuclear power, solar and wind power, while solar and wind power were combined into the option named renewable energy due to their similarity and the time limitation of the questionnaire. The criteria used in the questionnaire are the same as what the authors have summarized during the literature review, while they were grouped into six new criteria in order to reduce the workload for the respondents. The new criteria are safety, environment, initial cost, operational cost, efficiency & reliability and operational performance. The detailed explanations of each criteria are listed in [Appendix 7](#).

The authors finally collected data from 13 valid respondents through the questionnaire. These data was first sorted and cleaned and then inputted into the online analytic hierarchy process (AHP) tool, '[MakeItRational](#)', for calculation. The result of the AHP calculation first shows the weight of different criteria considered by these respondents when selecting the alternative fuels or energies for the future, see [Figure 4](#). Environment and safety concerns are the two most important criteria, while initial cost, operational cost and operational performance are less significant.

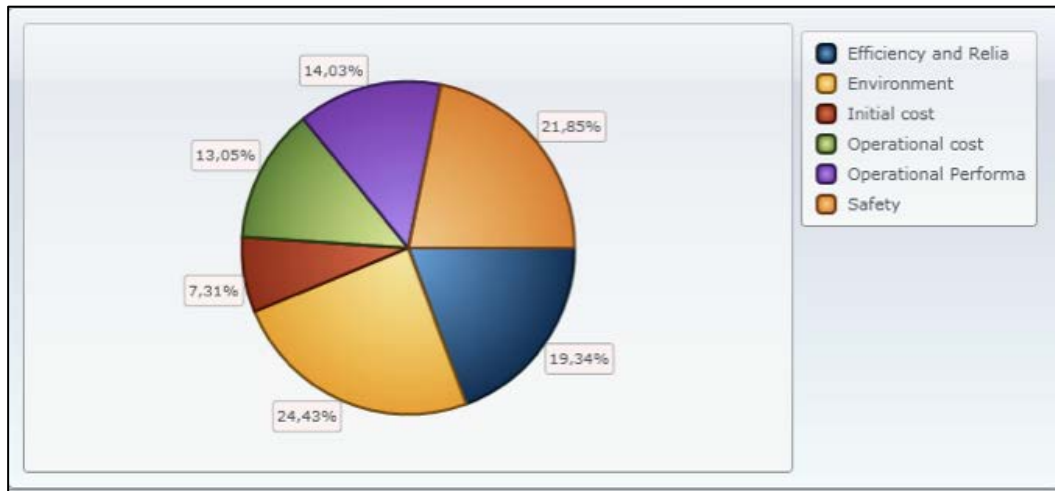


Figure 4: Weight of criteria.

Moreover, AHP tool also calculated the ranking among alternative fuels based on the respondents' scoring between every two fuels on each criterion and the weight of that criterion. The result of ranking is shown in [Figure 5](#). It is quite surprising that the result of AHP calculation based on data from questionnaire is quite different from what has been learnt from the literature review. The ranking shows that renewable energy including solar and wind power has the highest score. LNG and nuclear take the second and third position respectively while crude oil products have the least preference. Several aspects, such as initial cost, operational performance and efficiency and reliability, do match the findings from the literature review. Nevertheless, major differences under the criteria of safety and environment concerns lead to the different results.

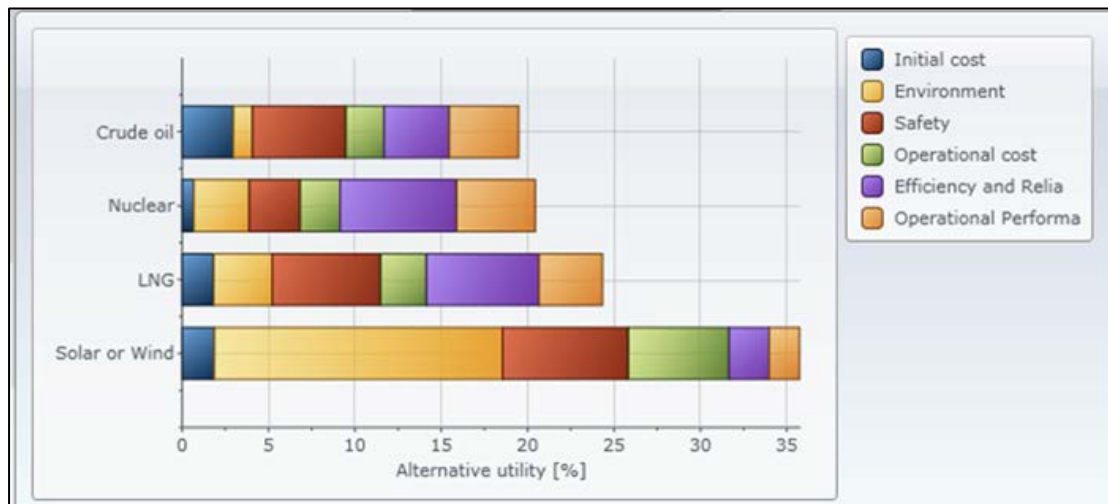


Figure 5: Ranking of alternative fuels.

4.3 Finding from Interviews

The authors eventually made three interviews in this research to collect the empirical data. The three interviewees come from both academic and industry fields. Two of them are professors from Chalmers University of Technology and the other one is the strategic project manager from Wallenius Marine AB.

In the first question of interview, interviewees were required to list out the possible alternative fuels or energies in the future for maritime transportation. The answers are approximately the same as the findings from the literature review, including LNG, methane (main component of LNG), nuclear power and renewable energies.

Then the interviewees were asked about major advantages and disadvantages regarding each alternative fuel or energy they had listed. The answers show that LNG has enormous reserves and contributions in emission reduction. However, the reduction mainly focuses on SO_x , NO_x and PM. Its performance on GHGs reduction is very limited, especially when methane form is applied due to the methane slip. Methane itself is a greenhouse gas and has more significant influences on the climate change than CO_2 . The methane slip can be caused by leak during refueling or incomplete combustion in engine system. Moreover, the liquefaction of nature gas is

also a complex technology which brings difficulties and extra cost for storage and supply of LNG. Currently the facilities supporting LNG refilling are still inadequate in many ports, but the situation is improving. On the other hand, the results of interviews show that the potential of applying solar or wind power as the sole energy in shipping is disappointing. Although they have absolute advantages in environmental aspects and fuel cost savings, the drawbacks such as low conversion efficiency and high dependence on weather condition cannot be overcome. "Thus, they are not commercially reliable", said the project manager from Wallenius Marine AB. All the interviewees agreed that solar and wind powers are better to be used in the hybrid form as the assistant energy sources in ship propulsion. For nuclear power, it is a possible solution to replace crude oil products, but not the first choice, considered by the interviewees. Despite the excellent performance in emission reduction and operational aspects, such as fuel cost savings and smaller space requirements, the major barriers including safety and economic concerns are still outstanding. Interviewees from academic area realize and accept that the nuclear technology is matured and has excellent safety record during its application in land-based power plant, navy and four merchant ships. However, all interviewees raised the viewpoint that the safety concern regarding nuclear power is not technical but more emotional. The historical nuclear accidents, possible serious consequence of a nuclear leak, radioactive waste exposure or overflow and terrorist all lead to the fear of nuclear energy. This kind of emotional factor is enormous and unnegotiable. Furthermore, the economic concern is another challenge for using nuclear power in shipping industry. The biggest problem is the extremely high initial capital investment in buying a new nuclear-powered vessel and this will need long term contracts to support the financing, for instance the loan from banks.

The final question was about the most favourable alternative fuel or energy for DSCS segment in the future. Nevertheless, no clear answer was obtained during the interviews. Interviewees recognized that LNG will be an excellent alternative in short sea shipping, but its limitations in bunker space and refueling frequency may make it

not very promising in DSCS segment. But nuclear power is also not attractive due to the emotional and economic issues.

5. Analysis

In this chapter, an analysis about previous finding is presented. It is related with the literature review concerning characteristics of different fuels, as well as the expert's opinions that collecting from questionnaires and interviews.

When concluding the finding from literature review, it is clear that nuclear power is more feasible than other ship fuel resources in most aspects. However, the result of questionnaire shows a different result that the renewable energy such as solar or wind power become the most popular alternative shipping fuels, with LNG comes second and nuclear takes third place. Three interviews have been conducted to explore reasons behinds the different results between literatures and questionnaires. From the interview content, it is able to see that although people admit that nuclear could be a potential alternative fuel, people still become very emotional when facing the fuel selection. This emotional factor makes people tend to ignore the benefits of nuclear power but enlarge drawbacks. The researches of nuclear power still remain in academia and there is very limit information for public. People usually make judgement by their first impression, which causes biases in the result of questionnaires. For example, the importance of safety and environment criteria are very significant in the surveys that take almost half of the total weight. Renewable power and LNG show strong competitiveness in these fields, while nuclear has low rankings in both safety and environment. However, that fact is that nuclear power has more advantage in GHGs emission than LNG and it has a very good safety record as ship propulsion power. This emotional factor plays an important role when people doing the questionnaire.

Knowing the reason of the difference, the researchers combined the results of literature review, questionnaires and interviews and decided to choose nuclear power as the most feasible future deep-sea container ship fuel for further analysis. First of all,

nuclear power has significant advantages in most aspects except capital cost and safety. For initial capital investment, it is true that the newbuilding price of nuclear ship is much higher than all other types of ship. Nevertheless, this drawback might be offset in the context of specific route, because the total needed number of nuclear ships may be smaller due to higher speed. Furthermore, the huge fuel saving potential cannot be ignored when talking about economic performance. On the other hand, the safety problem is not technical but emotional, thus solvable and can be changed gradually. Once the public perception regarding nuclear safety is improved and the high capital cost can be offset by less ships and fuel cost saving, nuclear power will become promising as the fuel for future DSCS. Secondly, both renewable power and LNG have inevitable problems. For solar or wind power, all the interviewees and most of the literatures have mentioned that they could not be used as the major energy source for ship propulsion but more like supplementary energies to save fuels. The characteristics of either wind or solar energy determine that they are highly dependent on the external factor and have very low reliabilities. For LNG, it is widely recognized as an attractive alternative in shipping industry. However, LNG-powered ship needs a larger bunker space and a higher refill frequency, which makes LNG more suitable for short-sea shipping. Furthermore, the refilling of LNG in port cannot be done during port handling, which leads to time loss. This will need higher speed and more fuel consumption to compensate in order to keep the transport schedule. In deep-sea container shipping, the large bunker space will decrease cargo carrying capacity thus lose economies of scale. The need of refill may cause detour, which will add more transport time and increase total fuel consumption. Also the performance of LNG on GHGs emission is very limit. If LNG is chosen to be the future shipping fuel, there may need a second conversion when GHGs emission is close to the limitation. And this will be a huge waste for the shipping industry.

Now the question turns to whether nuclear power could be appropriate for deep-sea container shipping. When concluding the interviews with experts from both academic and industry area, the authors found that two major concerns about the nuclear power

are pointed out. First, the high capital cost is the biggest barriers for nuclear ship. All the interviewees have mentioned that the cost of building a nuclear ship would be much higher than a conventional ship, which will decrease the profit and make the solution uneconomic. Second, although all the existing nuclear merchant ships have excellent safety records, people still believe that the safety concern would reduce the competitiveness of nuclear power.

5.1 Economic Aspects

It is true that building a nuclear ship may cost several times as a conventional ship. However, it is improper to neglect the economical benefits brought by the characteristics of nuclear power. For instance, the faster speed of nuclear ship could decrease the required number of ships in a fleet. Also the low refill frequency and lower nuclear fuel price would lead to a considerable cost saving compared with conventional ship. The authors believe that looking at only one nuclear ship will enlarge the drawback and lead to biases. Thus it is more reasonable to calculate the economic aspects by counting a fleet on a certain route within a life cycle.

In order to find out whether economic concern is an obstacle for utilising nuclear power on deep sea container shipping, the authors make a rough calculation in terms of shipping companies' point of view. The calculation is shown below.

5.1.1 Assumptions

Since the number and types of nuclear-powered merchant ship are limited and all of them were built several decades ago, it is very difficult for the authors to collect data related with nuclear-powered ship. Therefore, a lot of assumptions have to be made in this research in order to carry on the calculation and these assumptions are all reasonable. The detailed assumptions are listed below.

- The type of container ships for both conventional and nuclear-powered applied in the calculation is post-panamax (10,000 TEU).
- The purchasing expense of the newbuildings in this calculation is paid by cash

rather than financing approaches such as loan from bank.

- The opportunity cost of capital is alternative saving interest. The average saving interest rate of capital is 6% per year and maintains stable during the calculation period.
- The available working days per ship per year for both nuclear and conventional ships are 350 days.
- The relationship between round trip cycle time and sailing speed is approximately a negative linear correlation.
- The number of crews and their wages on nuclear-powered vessel are higher than those on conventional vessel. It is assumed that total manning cost of nuclear ship is as twice as that of conventional vessel.
- The lifespan of the hull and other main machineries of the nuclear ship are same as that of a conventional ship.
- When the lifespan of the hull and other main machineries of the nuclear ship are expired, the reactor can be removed and installed into another new ship as long as the reactor's lifespan is still enough for another cycle.
- The insurance cost of the reactor on the vessel is similar to that of land-based nuclear power plant, while other insurance costs of a nuclear ship are similar to the conventional ship.
- The cost structure of marine nuclear reactor disposal is similar to that of land-based reactor and has linear relationship with the reactor's capability.
- The administration cost of a nuclear-powered ship is similar to that of a conventional ship.
- The cost of stores and consumables of a nuclear-powered ship is same as that of a conventional ship.
- The price of intermediate fuel oil (IFO) 380 keeps stable in the calculation period.
- The price of marine nuclear fuel and nuclear waste disposal are same as those of the land-based nuclear plants.

5.1.2 Formula

The formula is based on shipping companies' point of view. The total cost in this calculation involves initial capital cost, operation cost and fuel cost.

$$\mathbf{TC = C + O + F + R}$$

TC: total cost of a specific route during the entire calculation period with a certain type of ship and sailing speed

C: total capital cost during the entire calculation period

O: total operation cost during the entire calculation period

F: total fuel cost during the entire calculation period

R: total reactor disposal cost during the entire calculation period, only applied for nuclear-powered ships.

Total capital cost if the nuclear-powered ships are used:

$$C_N = P_N * n * \left[\alpha * \frac{T}{t_R} + (1 - \alpha) * \frac{T}{t_N} \right] + OC$$

P_N : price of a new nuclear ship

n : number of ships needed on the specific route

α : share of the reactor's cost in the total nuclear ship price

t_R : life cycle time of the reactor

t_N : life cycle time of the hull and other main machineries of the nuclear ship

T : time period for calculation

OC: total opportunity cost of capital

Total capital cost for if the conventional ships are used:

$$C_C = P_C * n * \frac{T}{t_C} + OC$$

P_C : price of a new conventional ship;

t_C : life cycle time of the conventional ship;

T : time period for calculation.

Total number of ships needed on the specific route:

$$n = \frac{CT * \frac{365}{f_d}}{350}$$

CT: cycle time for a single round trip on the specific route;

f_d : frequency of departure on the specific route;

Total opportunity cost of capital:

$$OC = P_{N/C} * n * i * T$$

i : average saving interest rate of capital

Total operation cost:

$$O = (W + I + M + A + S) * n * T$$

W: total crew wages per ship per year

I: total insurance cost per ship per year

M: total maintenance cost per ship per year

A: total administration cost per ship per year

S: total cost for stores and consumables per ship per year

Total fuel cost if the nuclear-powered ships are used:

$$F_N = (E_N + WD) * n * \frac{T}{f_r}$$

E_N : nuclear fuel expense per refill;

WD: nuclear waste disposal cost per refill;

f_r : refueling frequency of nuclear-powered ship.

Total fuel cost if the conventional ships are used:

$$F_C = p_o * w * n * 350 * T$$

p_o : oil price

w: fuel consumption quantity per day of a conventional ship

5.1.3 Calculation

First of all, the capital cost on a specific route during the calculation period depends on ship price (P_C & P_N), number of ships needed (n) and lifespan of the ship and reactor (t_R , t_N & t_C). According to [Maersk Broker \(2014\)](#), the latest newbuilding price for a post-panamax (10,000 TEU) is about \$90 million (P_C). However, there is no existing nuclear-powered post-panamax as the example to offer the data of newbuilding cost. Hence, the researchers have to estimate based on building price of the latest nuclear container ship, Sevmorput. The initial capital cost for building Sevmorput was about \$265 million, while the price of a newbuilding conventional ship with similar size in that year (1988) was \$33 million ([Thalenius & Rehnström 2002](#)). The authors utilize this relationship (eight times) to estimate the possible newbuilding price of a nuclear-powered post-panamax (10,000 TEU). Moreover, the cost reduction, about 40% ([Mitenkov et al. 2007](#)), after standard design and mass production should also be considered to get a reasonable price. Therefore, the estimated price for a nuclear-powered post panamax (10,000 TEU) is \$432 million (P_N).

In this research, the calculations of the economic performance regarding conventional and nuclear-powered ships are done on three specific routes including Asia-Europe route, transpacific route and transatlantic route. The data of frequency and transit time are based on the information obtained from Maersk Line's database through its website. The Maersk Line's AE10 (roundtrip) is selected as the sample for Asia-Europe route. The detailed information of this route can be found in [Appendix 8](#). The route TP2 (westbound & eastbound) of Maersk is chosen for the transpacific line. [Appendix 9](#) lists the detailed information of this route. For transatlantic path, route TA5 can be used as the example. Related information of this route is shown in [Appendix 10](#). According to the departure schedules, the frequencies for all the three routes are approximately weekly ($f_d = 7$). The cycle time of a round trip by using conventional ships on the Asia-Europe route is 83 days, while the cycle times for transpacific and transatlantic route are 37 days and 33 days respectively. Therefore,

the number of conventional vessel needed on Asia-Europe route is 13, while the numbers for transpacific and transatlantic route are 6 and 5 respectively. The designed speed for nuclear-powered vessel could reach 35 knot (Carlton et al. 2013; Sawyer et al. 2008) while the current operating speed of conventional ship is close to 18 knot due to slow steaming. The designed speed for the conventional post-panamax is 25 knot (MAN 2009). Since slower speed requires more ships on a specific route in order to maintain the departure frequency, the number of vessels required on the same route for conventional ship under designed speed and nuclear-powered ship will be smaller. Based on this assumption, the number of conventional vessels under designed speed on the three routes will be 9 for Asia-Europe route, 4 for transpacific route and 4 for transatlantic route. Similarly, the number of nuclear-powered ships needed on the three routes will be 7 (Asia-Europe), 3 (transpacific) and 3 (transatlantic).

The average life cycle of a container vessel (t_C & t_N) is about 25 years (MAN 2009), while the lifetime of a reactor (t_R) can reach 50 years (WNA 2013a), so the researchers applied 50 years as the calculation period (T) in this research. The share of the reactor's cost in the total nuclear ship price (α) is about 60% according to the experience from four merchant nuclear ships ever built.

Based on the above inputs and assumptions, capital cost under different situations on a specific route during 50 years can be calculated. The results are listed in Table 5.

Table 5: Result of calculation regarding total capital cost.

Route Ship Type	Asia-Europe	Transpacific	Transatlantic
Conventional (slow steaming)	\$5850million	\$2700 million	\$2250 million
Conventional (designed speed)	\$4050 million	\$1800 million	\$1800 million
Nuclear-powered	\$13217 million	\$5720 million	\$5720 million

The second part of the total costs on a specific route is the operation cost comprising manning, insurance, maintenance, administration and stores costs. [Notteboom \(2006\)](#) has summarized all these costs per year for post-panamax (10,000 TEU) in his research. Detailed data are listed in [Table 6](#). However, the nuclear-powered ship will have extra insurance cost for its reactor, which is about \$0.86 million per year ([NEI 2014a](#)).

Table 6: Operating costs of post-panamax ships. Source: [Notteboom \(2006\)](#).

	Post-panamax (10,000 TEU)
Manning	\$0.85 million per year
Repair and maintenance	\$1.15 million per year
Insurance	\$1.70 million per year
Stores and lupes	\$0.35 million per year
Administration	\$0.175 million per year

Based on the data above, the total operation cost for different ships on different routes during the calculation period can be calculated. The results are shown in [Table 7](#).

Table 7: Result of calculation regarding total operation cost.

Route Ship Type	Asia-Europe	Transpacific	Transatlantic
Conventional (slow steaming)	\$2746 million	\$1268 million	\$1056 million
Conventional (designed speed)	\$1901 million	\$845 million	\$845 million
Nuclear-powered	\$2087 million	\$1150 million	\$1150 million

The last major part on a shipping company's cost list is fuel cost. For nuclear vessel, the fuel price of uranium is about 0.75 cents / kWh ([NEI 2014b](#)), while the output

power requirement for a nuclear reactor to propel a post-panamax (10,000 TEU) is about 80 MW (Carlton et al. 2013). The nuclear waste disposal cost may differ in different countries, but slightly. The authors applied the U.S. rate in this research, which is about 0.1 cents / kWh (WNA 2013b). According to Professional Engineering (vol. 23, no. 18, p. 7, 2010) and the experience from the 4 built merchant nuclear ships, the refueling frequency varies from 3 to 10 years. The authors use 5 years as the refill frequency in this research for calculation. Hence the nuclear fuel expense per refill (E_N) is \$25.2 million and the waste disposal cost per refill (WD) is \$3.4 million. On the other hand, the latest oil price for IFO 380 (p_o) is about \$600 per metric tonne (Bunkerworld 2014). Moreover, the fuel consumption amounts for a post-panamax under different speeds are 98.8 tonnes per day (18 knot) and 292 tonnes per day (25 knot) (Notteboom & Carriou 2009). With these data, then the total fuel cost on the three routes during the life cycle can be calculated, see Table 8.

Table 8: Result of calculation regarding total fuel cost.

Route Ship Type	Asia-Europe	Transpacific	Transatlantic
Conventional (slow steaming)	\$13486 million	\$6244 million	\$5187 million
Conventional (designed speed)	\$39858 million	\$12264 million	\$12264 million
Nuclear-powered	\$2002 million	\$858 million	\$858 million

Eventually, after summing the three main costs, capital, operation, fuel costs and adding the reactor disposal cost, which is estimated to be about 5 million per reactor (NEI 2014b), the total costs of different applications on the three selected routes during the 50 years can be obtained, see Table 9.

Table 9: Result of calculation about the total costs.

Route Ship Type	Asia-Europe	Transpacific	Transatlantic
Conventional (slow steaming)	\$22.08 billion	\$10.21 billion	\$8.49 billion
Conventional (designed speed)	\$45.81 billion	\$14.91 billion	\$14.91 billion
Nuclear-powered	\$17.31 billion	\$7.73 billion	\$7.73 billion

5.1.4 Results

The final result is surprising and interesting compared with the data collected through questionnaire and interviews which shows that economic factor is a major barrier for applying nuclear-powered ship. It is correct that the initial capital cost of building a nuclear-powered ship is significantly higher than that of a conventional ship, about five times. Nevertheless, this gap is partly offset since the total number of nuclear vessels required is smaller than the conventional vessel on the same route due to the higher sailing speed. However, the opportunity cost of capital for nuclear ships is dramatically higher than that of purchasing conventional ships. Although there will be extra insurance cost for reactors and higher crew wages, the operation costs between nuclear-powered ships and conventional ships on the same route is still similar because of the fewer ships needed. The major advantage of applying nuclear power is huge fuel cost savings, even if there will be additional expense for radioactive waste disposal. Therefore, the final output of the calculation shows that applying nuclear power on all the three routes are more cost effective than using conventional ships, no matter under slow steaming or designed speed. Furthermore, the shipping companies do not need to sacrifice the speed which may lead to revenue loss if they use nuclear vessels. On the other hand, the result also shows that the economic benefit in terms of total lifespan cost is largest on the transpacific route (24.3% total cost saving at least) while smallest on the transatlantic route (9% total cost saving at least). Therefore, it

will be more promising to apply nuclear ships on the transpacific route.

The authors realize that the results may not be enough accurate, since a lot of assumptions are made and many data used in the calculation are estimated. For example, it is not common that the purchasing of newbuilding is fully paid by cash. In the real business context, the capital needed may be financed through various approaches, such as mortgage-backed loan, private investment, public offering, bond issuing and finance leasing. All these methods will lead to additional financing cost, such as dividend or interest payment, which surely decreases the cost advantage of applying nuclear ships. However, to what extent will total cost be affected by the financing is uncertain. It highly depends on the detail terms, such as interest rate or financing period, in the financing plan. On the other hand, considering the financing cost will bring great complexity in the calculation as well. For instance, the capital for purchasing the ships may be financed through a combination of several different financing methods. The financing strategy may also affect the opportunity cost of capital. Therefore, the financing aspect is not considered in the mathematical model in this research. Moreover, shipping company would have much higher pressures on cash flow management if nuclear power technology was applied. Nevertheless, this calculation can still offer a rough picture of the economic performance comparison between nuclear-powered ships and conventional ships. Furthermore, if the possibilities of reactor price decrease due to the development of small modular reactor (SMR), oil price increase and carbon emission expense are considered, the cost situation will become more advantageous to nuclear-powered vessel. On the other hand, compared with conventional bunker space, the reactor is very small. With a much smaller bunker space, the ship can either be built smaller to save capital cost, or have more cargo space to increase the commercial benefits. Both ways could make nuclear power more competitive in shipping economy.

5.1.5 Sensitivity Analysis

Sensitivity analysis is a methodology often used to check how the output of a

mathematical model is affected by different sources of uncertainties in its inputs. The one-factor-at-a-time method (OFAT) was applied in this analysis. The OFAT method means that researchers would only change one variable and keep other variables unchanged at a time when they do the sensitivity analysis. The outputs in this sensitivity analysis are the differences between the total cost of conventional ships and nuclear-powered ships on the three routes ($\text{Output} = \text{TC}_C - \text{TC}_N$), while the inputs include all independent variables. However, the authors only picked from independent variables to do the sensitivity analysis in this research. They are average oil price (IFO 380) during the calculation period, average saving interest rate of capital in the whole lifespan, newbuilding price of a conventional post-panamax (10,000 TEU) when purchased, namely P_c , and newbuilding price of a nuclear-powered post-panamax (10,000 TEU) when purchased, namely P_n . The reason behind the choice is that these four independent variables are most volatile and have the largest influences on the outputs, while other independent variables are more stable and have slighter impacts on the total cost. We assume the reasonable range that oil price, P_c and P_n may vary during the 50 years is between $\pm 50\%$, while similar range for saving interest rate is $\pm 33\%$. The results of the sensitivity analysis on three routes regarding the difference between the total cost of conventional ships under slow steaming and nuclear ships are listed in [Table 10](#), while the results regarding the cost difference between conventional ships under designed speed and nuclear ships are offered in [Table 11](#).

Table 10: Sensitivity analysis - conventional ships under slow steaming vs nuclear ships

Asia - Europe	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	4.77	-1.97	11.51	6.62	2.92	1.84	7.70	11.38	-1.84
Variation		-6.74	+6.74	+1.85	-1.85	-2.93	+2.93	+6.61	-6.61
Unit variation (1%)		-0.129	+0.129	+0.056	-0.056	-0.059	+0.059	+0.132	-0.132
Transpacific	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	2.48	-0.64	5.60	3.24	1.72	1.13	3.83	5.34	-0.38
Variation		-3.12	+3.12	+0.76	-0.76	-1.35	+1.35	+2.86	-2.86
Unit variation (1%)		-0.062	+0.062	+0.023	-0.023	-0.027	+0.027	+0.057	-0.057
Transatlantic	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	0.76	-1.83	3.35	1.61	-0.09	-0.37	1.89	3.62	-2.10
Variation		-2.59	+2.59	+0.85	-0.85	-1.13	+1.13	+2.86	-2.86
Unit variation (1%)		-0.052	+0.052	+0.026	-0.026	-0.023	+0.023	+0.057	-0.057

The unit in this table is \$ billion

Output: the difference between total cost of conventional ships under slow steaming and nuclear ships.

Variation: the difference between the original output value and the new output value after one variable changed.

Unit variation (1%): the variation of 1 percent change.

Table 11: Sensitivity analysis - conventional ships under designed speed vs nuclear ships

Asia - Europe	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	28.50	8.57	48.43	30.71	26.29	26.47	30.53	35.11	21.89
Variation		-19.93	+19.93	+2.21	-2.21	-2.03	+2.03	+6.61	-6.61
Unit variation (1%)		-0.399	+0.399	+0.067	-0.067	-0.041	+0.041	+0.132	-0.132
Transpacific	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	7.18	1.05	13.31	8.12	6.24	6.28	8.08	10.04	4.32
Variation		-6.13	+6.13	+0.94	-0.94	-0.90	+0.90	+2.86	-2.86
Unit variation (1%)		-0.123	+0.123	+0.028	-0.028	-0.018	+0.018	+0.057	-0.057
Transatlantic	Original Value	Oil Price		Interest Rate		P _c		P _n	
		-50%	+50%	-33%	+33%	-50%	+50%	-50%	+50%
Output	7.18	1.05	13.31	8.12	6.24	6.28	8.08	10.04	4.32
Variation		-6.13	+6.13	+0.94	-0.94	-0.90	+0.90	+2.86	-2.86
Unit variation (1%)		-0.123	+0.123	+0.028	-0.028	-0.018	+0.018	+0.057	-0.057

The unit in this table is \$ billion

Output: the difference between total cost of conventional ships with designed speed and nuclear ships.

Variation: the difference between the original output value and the new output value after one variable changed.

Unit variation (1%): the variation of 1 percent change.

The results of the sensitivity analysis show that the correlations between output and variables including oil price and conventional ship building price are positive, while the correlations between output and factors comprising interest rate and nuclear ship price are negative. This means that when the average oil price or conventional ship price increases, the cost advantages of nuclear ships over conventional ships will enlarge. For saving interest rate and newbuilding price of nuclear ships, the situation is contrary. Moreover, the outputs in all conditions are most sensitive to changes of the oil price and the newbuilding price of the nuclear-powered panamax (10,000 TEU) in general. However, the detailed situation is slightly different when the conventional ships' sailing speeds are different. If the conventional ships operate under slow steaming, the sensitivity of the outputs to the change of nuclear ship price is slightly higher than that of oil price, only except on the transpacific route. Meanwhile, the outputs are most sensitive to the change of oil price when the conventional ships sail with designed speed on all the three routes. This sensitivity to oil price change is much bigger than that to the change of nuclear ship price in this situation. Therefore, the major determinants in terms of cost consideration for the shipping companies to decide whether to use conventional ships or apply nuclear technology on the three routes under slow steaming are oil price and the newbuilding price of nuclear ships. The significance of these two factors is approximately equal. But if the shipping company's operation strategy is to sail the ships under designed speed, then oil price change is the most important risk that needs to be considered if the nuclear-powered ships are going to be used.

Compared with conventional ships under slow steaming, nuclear-powered ships have the possibilities to become less cost effective on both Asia-Europe and transpacific routes owing to the change of oil price and nuclear ship price. However, nuclear ships will always be more cost effective than conventional ships on these two routes as long as only one of the two variables, interest rate and conventional ship price, change within the assumed range while other variables remain steady. The breakeven points for oil price here are \$378 per metric tonne (37% decrease) on Asia-Europe

route and \$360 per metric tonne (40% decrease) on transpacific route. Once the average oil price during the calculation period declines lower than the breakeven point while other factors keep unchanged, nuclear-powered ships will no longer have the benefit on total cost savings. Similarly, if the newbuilding prices of nuclear ships at the purchasing point are higher than \$588 million (36% increase) on Asia-Europe route and higher than \$662 million (44% increase) on the transpacific route, the conventional ships under slow steaming will become more economic in terms of total cost. On the transatlantic route, the cost advantage obtained from application of nuclear ships is vulnerable to all the four variables when compared with conventional ships under slow steaming. Nuclear-powered ships will lose their cost advantages on that route if the average oil price during the whole lifespan is lower than \$510 per metric tonne (15% decrease), the average saving interest rate in the 50 years is higher than 7.74% per year (29% increase), the price of a new conventional post panamax (10,000) TEU is lower than \$60 million (33% decrease) and the newbuilding price for the nuclear ship is higher than \$488 million (13% increase) when they are purchased. On the other hand, the tolerances of cost benefit offered by nuclear ships to variation of the four variables are much stronger when the conventional ships are sailing with designed speed on all the three routes. The economic advantage in terms of total cost for nuclear-powered ships will always exist as long as the four variables change within the assumed scope. Hence, it can be concluded that applying nuclear ships to replace the conventional ships sailing with designed speed will have much lower risks than to replace the conventional ships under slow steaming regarding the reasonable changes of all the four variables. Within the situation of slow steaming, it will be most risky to apply nuclear ships on the transatlantic routes. The cost advantage brought by nuclear ships is very fragile. Nevertheless, it will be much safer to use nuclear ships on the transpacific route.

5.2 Safety aspects

Besides the shipping economic aspects, safety is another major concern and obstacle

for utilising nuclear power. However, this is not an unsolved problem but can be improved by several ways.

First, nuclear power has a very outstanding safety record on ship propulsion. What people concern is not the operation but the serious consequences that bring by nuclear accident. There are two directions in order to solve this problem. One is to improve the maturity of nuclear technology, which needs to take more effort on the researches and experiments for example to reduce the reactor size as well as improve the protective measures. Another direction is to control the consequence into a small range and minimize the personal injury. A designed solution is to build an island-based deep water port such as Yangshan Port that isolate the ship port with citizen. With deep water ports built in each continent, nuclear ships could be only used on deep-sea and transocean transportation while using ships with LNG or renewable energy for transportation between deep water port and seaport city. However, this solution may lead to extra transshipment that will increase the cost for the shipping company. In such approach, the leading role is not shipping lines but governmental authorities, since it is not economic for shipping lines to invest and build a such deep water port by themselves. Nevertheless, the shipping lines can still foster such development through offering collective proposals and active cooperation with the government in the planning.

Second, influencing by several major nuclear accidents people become very emotional when talking about the nuclear power. For example, Germany has dismantled several nuclear power plants quickly after the Fukushima nuclear accident. These nuclear-fear emotions make people focus less on the study of nuclear power. However these emotional thought can be influenced by national policies, media campaigns and public information. When dig the root of these emotions, there involve several reasons. One is lack of national policies on the management and utilization of nuclear power thus sometimes cause confuses among shipping companies, shipper, and other characters. Also medias should take major responsibility on nuclear-fear

emotion, since they may exaggerate the serious consequence of nuclear power but ignore the benefit parts. Another reason is that researches about nuclear power still spread around the academia, while the public could access very limit information about nuclear power. The lack of knowledge making people becomes impulsive and conservative when facing the fuel selection. Thus as long as the reality regarding the nuclear safety can be passed to the public through media and academia, and comprehensive laws and regulations can be delivered by policy makers, the nuclear-fear emotion could be reduced by a large degree. Also the building of island-based deep water port that mentioned before will isolated citizen with nuclear ships, which may ease the nuclear fear emotion.

Third, ownership would play a significant part on the safety management. The privatization of nuclear energy may have some potential problem such as individual terrorism. In this sense a certain macro-control by nation is necessary and could solve this problem. For example, the government could supervise the production and utilisation of nuclear energy, and take the ownership of nuclear reactors, nuclear ship ports or even nuclear ships. There would be a limit numbers of nuclear reactor that exist at the shipping company at the same time. Although the ownership needs further discussion regarding the change of shipping market, it is still a feasible solution for safety concern.

Forth, international shipping regulations could be changed and improved in order to make the application of nuclear energy under control and more organized. For example the IMO could make new regulation concerning the nuclear safety. Different ports of countries could increase the cooperation within each other so that the protection measures will be enhanced.

Together with these methods, it is able to see that the safety concern can be gradually solved.

6. Conclusions

In the beginning of this thesis, two major problems, increasing fuel price and environmental concern, faced by the shipping industry were concluded, while deep sea container shipping (DSCS) was selected as the focus of this thesis. Three research questions were developed based on these two problems and the academic research was carried out to answer these research questions. Both qualitative and quantitative methods were applied during the research process. The results showed that other solutions, such as slow steaming, could not thoroughly resolve but partly or temporarily relieve the main challenges. Using alternative fuel or energy to replace crude oil products could be the possible solution for both problems.

According to the literature review, the authors had summarized the feasible alternative fuels or energies for ship propulsion, including liquefied natural gas (LNG), nuclear energy, bio fuel, solar and wind power. On the other hand, the main criteria used to evaluate the feasibility of alternative fuels and energies comprise safety, environmental sustainability, initial cost, operation cost, efficiency & reliability and operational performance. Based on these criteria, related data for each alternative fuel or energy were collected through literature review, questionnaire and interviews. The findings from literature review showed that, bio fuel has the resource limitation to support the shipping industry and may occupy massive farmlands and lead to food supply problems. LNG could be a good solution for short sea segment, while it still has significant GHGs emissions and is not promising for deep sea shipping due to its own characteristics. Solar and wind power can only be utilized as supportive energy in a hybrid propulsion system due to its low conversion efficiency and reliability. Nuclear power can fulfill all the requirements of deep sea shipping and overcome the two main problems by its advantages in emission reduction and fuel cost savings. But high initial cost and radioactive waste disposal could be the barriers. Nevertheless, the results obtained from questionnaire and interviews showed that nuclear power is not preferred as expected based on the finding from literatures. The major concerns raised

by the respondents and interviewees are safety and economic issues. However, all the interviewees mentioned that the safety issue regarding nuclear power was rather emotional concerns of public than technical problems. Moreover, the high initial cost of buying a new nuclear-powered vessel makes this option uneconomic.

Since LNG and renewable (solar/wind) energy have the restriction caused by their own characteristics, the authors believe that nuclear power is still the most feasible solution for deep sea container shipping sector, in spite of the negative feedback from respondents and interviewees. Therefore, the authors did deeper analysis regarding the two major barriers for application of nuclear power separately. For safety issue, several possible approaches, such as deep water port and government's ownership, to reduce the negative emotional effects about the nuclear safety concerns were proposed and discussed. Furthermore, a life cycle analysis was applied in order to compare the total lifespan cost between nuclear-powered and conventional fleet (under designed speed and slow steaming) on three specific routes. The result of the calculation showed that although the initial capital investment of a single nuclear-powered ship is much higher than the conventional one, the number of nuclear-powered ships required on the route is smaller due to the high speed, which diminishes the gap in the total capital cost of the whole fleet. The application of nuclear technology will finally lead to considerable cost savings in the end of the life cycle due to the impressive fuel cost savings. Furthermore, smaller bunker space and zero emission may lead to further economic benefits, such as increasing revenue and environmental tax savings. Nevertheless, the high initial capital cost is still a significant challenge which will lead to strong cash flow and mortgage problems for the shipping company.

Through this research, the authors conclude that developing alternative fuels to replace crude oil products in shipping industry will become an unavoidable topic due to the two major challenges faced by the industry. However, not like the crude oil era, the coming future will not be dominated by a sole fuel or energy, but a combination of

different alternative fuels. For example, LNG will be the good option for short sea segment, while solar and wind power can be applied in both short and deep sea shipping as assistant energy source in order to save fuel. Nuclear power can possibly be the most feasible solution for DSCS because of its various advantages. On the other hand, DSCS is also the best place to pilot nuclear technology in maritime transport. The economies of scale can offset the drawback of high initial cost. Moreover, fewer ships needed in DSCS compared to feeder segments means fewer reactors, while the fixed route of liner shipping makes the management and monitoring simpler and easier as well. These two points will reduce the safety risks.

7. Limitations

Although the authors tried the best to improve the research, there are still some limitations. First, the calculation in the analysis has too many assumptions and the most of the data is not accurate, which will lower the reliability of the calculation and could only provide a rough assessment. The reason for this limitation is that there is no commercial nuclear ship still operating today so that it will be very hard to have related figures. Second, the sample size of questionnaire and interview is very small. The questions require some professional knowledge of container shipping and fuels, which determines that the population of the research could not be large. The cost of research and time limit also restrict the sample size. Third, since this thesis is focus on shipping, there are not so many focuses on the technical issue of alternative fuels. But the technical issue could not be ignored and needs more research in reality. Forth, there are not so many thoughts on law and regulation concerning the alternative fuels. The thesis focuses more on the characteristics of fuel itself, and the law or regulation could be improved to adapt the most appropriate fuels.

8. Future Study

This thesis gives an approximate picture that shows nuclear power has potential possibility to be applied on deep-sea container shipping. So for future analysis, the calculation of the economic performance of nuclear ship could be more accurate for

example to analysis the annual cash flow of the shipping company. Also, since the emotional factor could not be neglect when facing the fuel selection, the analysis about how to balance people's emotion with nuclear ship could be further developed. Moreover, this thesis is more like providing a concept of the possibility of nuclear ship, so there could be more analysis about the actual application of nuclear power on a specific route in the future.

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Appendix

Appendix 1: Name list of the interviewees

Name	Title	Comapny
Bengt Ramne	Professor	Chalmers Shipping and marine technology
Magnus Blinge	Senior Lecturer	Logistics & Transportation Chalmers
Carl Fagergren	Strategic Projects	Wallenius Marine AB

Appendix 2: Detailed information of the respondents. Source: Authors.

Name of organization	Number of respondents
Lighthouse Maritime Competence Center	1
UN - Economic Commission for Latin America (ECLA)	1
University of Gothenburg	2
Göteborgs Hamn Ab	1
Chalmers University of Technology	4
Port of Gothenburg	1
Norwegian Marine Technology Research Institute (MARINTEK)	1
Swedish Transport Agency	2

Appendix 3: Parameters of N.S. Savannah. Source: [Godwin et al. \(1959b\)](#).

Ship Type:	Nuclear-powered cargo-passenger ship
Tonnage:	13,599 gross register tons
Fully loaded displacement:	21,800 tons
Length:	596 ft (181.66 m)
Beam:	78 ft (23.77 m)
Propulsion:	20,000 hp - 22,000 hp
Speed:	21 knots (service speed), 23 knots (maximum speed)
Capacity:	60 passengers, 8,500 ton cargo capacity (18,000 m ³)
Crew:	124
Service period:	1964 - 1972

Appendix 4: Parameters of Otto Hahn. Source: [RadiationWorks \(2009\)](#).

Ship Type:	Cargo ship
Overall length:	172.05 meters
Width:	23.40 meters
Freeboard:	5.33 meters
Displacement:	25,790 tons
Load carrying capacity:	14,040 tons
Loading spaces:	6
Crew:	63
Research personnel:	35 max
Top speed:	17 knots
Reactor:	38 MW
Reactor volume:	35 m ³
Design pressure/temperature:	85 kp/cm ² - 300°C

Appendix 5: Parameters of Mutsu. Source: [Sasaki \(1969\)](#).

Ship Type:	Nuclear-powered freighter
Gross tonnage:	8300 tons
Length:	130 m (430 ft)
Beam:	19 m (62 ft)
Draught:	6.9 m (23 ft)
Depth:	13.2 m (43 ft)
Reactor type:	Pressurized light water reactor
Reactor thermal output:	36MW
Propulsion:	10,000 hp
Service speed:	16.5 knots
Crew:	80

Appendix 6: Parameters of Sevmorput. Source: RS (2012).

Ship Type:	Container ship
Gross tonnage:	38226 tons
Net tonnage:	11468 tons
Deadweight (tonn):	33240 tons
Displacement:	61880 tons
Length:	260.30 m (854.0 ft)
Draught:	11.80 m (38.7 ft)
Speed:	20.5 knots
Capacity:	1324 TEU

Appendix 7: Detailed explanation of the criteria in the questionnaire

- **Safety:** Please consider following possible safety impacts on 1) ship operation, 2) living and working environment of crew, 3) ports and citizens.
- **Environment:** Please consider following possible environmental impacts on 1) Greenhouse gases (GHGs) emission, 2) Air pollutions (SO_x, NO_x, etc.) and 3) Water pollution (both from accident and operation).
- **Initial Cost:** Please consider following possible initial cost impacts on 1) fuel production, 2) necessary infrastructure and facilities, 3) crew training, 4) ship building or modification.
- **Operational Costs:** The operational costs that should be considered in this survey comprise: 1) Bunker fuel, 2) Crew wage, 3) Maintenance / repair.
- **Efficiency & Reliability:** Efficiency involves two aspects. 1) fuel power density, 2) fuel power transaction rate. The reliability of the fuel means that to what extent the performance of the fuel would be affected by external factors, such as weather and climate.
- **Operational Performance:** Please consider the refuel frequency and the impact on capacity due to the characteristics of fuel, such as space requirement for engine, solar battery, windmill, bunker, etc.

Appendix 8: Asia - Europe Route, source: [Maersk Line](#)

Asia - Europe (AE10) - Roundtrip



Port	Arrives	Departs	Transit
Busan, Korea	MON	TUE	--
Kwangyang, Korea	TUE	WED	1
Ningbo, China	THU	FRI	3
Shanghai, China	SAT	SUN	4
Yantian, China	WED	WED	8
Tanjung Pelepas, Malaysia	SUN	MON	12
Suez Canal, Egypt	FRI	FRI	24
Rotterdam, Netherlands	FRI	SAT	32
Bremerhaven, Germany	SUN	MON	34
Gdansk, Poland	WED	SAT	37
Aarhus, Denmark	MON	MON	41
Gothenburg, Sweden	TUE	WED	42
Bremerhaven, Germany	THU	FRI	45
Rotterdam, Netherlands	SAT	SUN	47
Port Tangier, Morocco	THU	FRI	51
Suez Canal, Egypt	WED	THU	58
Singapore, Singapore	FRI	SAT	73
Yantian, China	WED	FRI	79
Hong Kong, Hong Kong	FRI	FRI	80
Busan, Korea	MON	TUE	84

Appendix 9: Transpacific Route, source: [Maersk Line](#)

Transpacific 2 (TP2) - Westbound



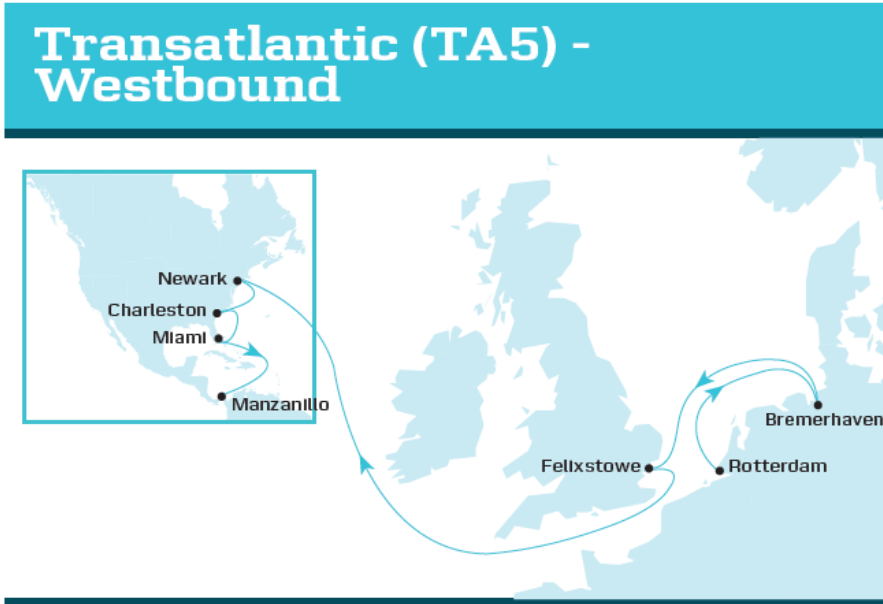
Port	Arrives	Departs	Transit
Long Beach, USA	TUE	FRI	--
Kaohsiung, Taiwan	MON	TUE	17
Hong Kong, Hong Kong	WED	WED	19
Xiamen, China	THU	FRI	20
Shanghai, China	SUN	MON	23
Ningbo, China	MON	TUE	24

Transpacific 2 (TP2) - Eastbound

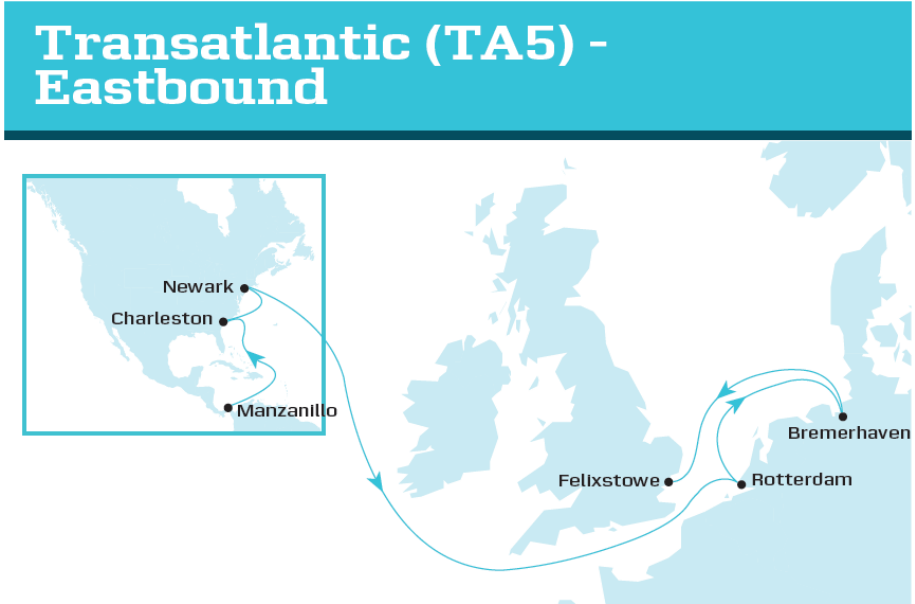


Port	Arrives	Departs	Transit
Kaohsiung, Taiwan	MON	TUE	--
Hong Kong, Hong Kong	WED	WED	1
Xiamen, China	THU	FRI	2
Shanghai, China	SUN	MON	5
Ningbo, China	MON	TUE	6
Long Beach, CA, USA	TUE	FRI	20

Appendix 10: Transatlantic Route, source: [Maersk Line](#)



Port	Arrives	Departs	Transit
Rotterdam, Netherlands	WED	THU	--
Bremerhaven, Germany	THU	FRI	1
Felixstowe, United Kingdom	SAT	SUN	2
Newark, USA	MON	MON	11
Charleston, USA	WED	THU	13
Miami, USA	THU	FRI	15
Manzanillo (Panama), Panama	MON	TUE	18



Port	Arrives	Departs	Transit
Manzanillo (Panama), Panama	MON	TUE	--
Charleston, USA	FRI	SAT	4
Newark, USA	MON	MON	6
Rotterdam, Netherlands	WED	THU	15
Bremerhaven, Germany	THU	FRI	17
Felixstowe, United Kingdom	SAT	SUN	19

