



# Environmental and economical assessment of alternative marine fuels



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## ABSTRACT

Increasing amount of shipboard emissions, and emission regulations entered into force encourage emission reduction technologies to be developed, and new methods to be used. Alternative fuel use as a fuel on marine diesel engines is one of the new methods to reduce shipboard emissions. Methanol and ethanol can be used as a liquid fuel or liquefied natural gas and hydrogen can be used as a gaseous fuel on ships. Aim of this study is to make scientific comparison of alternative fuels which can be used at ships. The environmental and economical performance of methanol, ethanol, liquefied natural gas, and hydrogen were compared. Comparison was made by eleven comparison criterions from different aspects. The most suitable alternative fuel which can be used on ships is determined by defining evaluation scale points for each comparison criterions. Analytic hierarchy process was used to find the weighing of comparison criterions according to given points by five experts to each criterions. Final comparison table is formed including all comparison criterions with given evaluation scale points of each alternative fuels, and weighing for each criterion depend on their importance at maritime sector. Methanol and ethanol, liquefied natural gas, and hydrogen get comparison points of 2.129, 4.092 and 3.796 respectively from the total point of 5.005. Comparison shows that methanol and ethanol do not seem to be preferable to use onboard due to their inadequacy which are investigated in the study. Liquefied natural gas gets the highest total evaluation point in the study, and the most suitable alternative fuel. Hydrogen gets the highest point at safety, bunker capability, durability, adaptability to existing ships, and commercial effects criterions. This study shows that hydrogen can be the alternative to liquefied natural gas used as a fuel at ships, but it requires more studies and improvement on the comply with emission regulations and effect on engine components issues.

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## 1. Introduction

Although renewable energies are started to be used, usage of fossil fuels are in a more dominant position. It is more difficult to apply renewable energy systems on transportation sector than land based facilities. As a consequence, fossil fuel use in the transportation sector has a first priority. It is expected that global energy consumption of liquid fuels in the transportation sector will increase to 131 quadrillion BTU on 2040 from 96 quadrillion BTU on 2010 (EIA, 2013). Sea transportation forms the important part of transportation sector, and 90% of world trade is carried across the world's oceans (Harrould-Kalieb, 2008). So it can be said that most part of the global energy consumption of liquid fuels in transportation sector is created by national and international shipping. International Maritime Organization (IMO) states that all ships

globally consume 300 million tons of fuel annually (IMO, 2014). Consumed fuels generate huge amount of emissions, which are nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and particulate matter (PM). According to Third IMO GHG Study 2014, annual shipboard NO<sub>x</sub> emission on 2012 was 19.002 million tons, SO<sub>x</sub> emission was 10.240 million tons, which are 15% and 13% of global NO<sub>x</sub> and SO<sub>x</sub> emissions, respectively, and CO, CO<sub>2</sub> and PM emissions were 936 thousand tons, 949 million tons and 1.402 million tons on 2012, respective to emission type.

IMO has worked on mitigation and control of the shipboard emissions by international rules and regulations for shipping sector. Limitations for NO<sub>x</sub> emission has been entered into force, and from January 1st 2011, Tier II emission limit has been applied outside of Emission Control Areas (ECA), and more strict limitation of Tier III has been applied at ECA region. On and after January 1st 2016, Tier III emission limits will be applied at all regions (IMO Web, 2015a).

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Sulfur content of the consumed fuel is the reason of SO<sub>x</sub> emission and sulfate formation which is resulted with PM emissions from ships. IMO has limited sulfur content of the fuels. Out of ECA boarders, sulfur limit of fuels was 4.50% prior to January 1st 2012; on and after January 1st 2012, it is reduced to 3.50% until January 1st 2020; and on and after January 1st 2020 (date is not exactly confirmed yet) it will be 0.50%. Inside ECA, sulfur content was 1.50% prior to January 1st 2010; on and after 1 January 2010, it was 1.00% until January 1st 2015; and on and after January 1st 2015 it is 0.10% (IMO Web, 2015b).

In theory when fuel is burnt, CO<sub>2</sub> is composed, and it cannot be prevented to be formed in principle, but it can be decreased by efficient operation. Regulations On Energy Efficiency for Ships in MARPOL Annex VI was entered into force by IMO on January 1st 2013. This regulation aims to control and decrease CO<sub>2</sub> emissions from ships. In this framework, Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) were defined. New building ships have to comply with Required EEDI levels, and existing ships have to have a SEEMP onboard to control and to decrease their CO<sub>2</sub> emissions (IMO, 2011).

It can be seen that stringent rules and regulations are in force, and more strict limitations at outside and inside ECA regions, include the North Sea, the Baltic, and the coastline of North America, are on the way. Additionally, there are some other regions to be ECA, for instance the Bosphorus Strait and Sea of Marmara, Hong Kong, and ports of the coastline of Guangdong in China (Chrysosakis et al., 2014). These developments force ship owners and operators to apply emission abatement technologies to their ships.

The emission abatement technologies are exhaust gas recirculation, selective catalytic reduction, SO<sub>x</sub> scrubbers, and waste heat recovery systems. Comparison of emission abatement technologies was mentioned in a previous study, and it was stated that these technologies reduces their target emissions, on the other hand they can negatively affect remaining emission types, and also increases fuel consumption (Zincir and Deniz, 2014). In another paper, it was indicated that exhaust gas after treatment systems, such as SO<sub>x</sub> scrubbers and urea-based catalysts, are costly and can increase the fuel consumption by 2–3% (Chrysosakis et al., 2014). Interest on alternative fuels at marine industry increases as an emission abatement method. Alternative fuel use at marine diesel engines is an option to reduce shipboard emissions nowadays.

In this study, alternative fuels which can be used at marine diesel engines are investigated. Comparison criterions are generated, and new comparison method is developed to find the most suitable alternative fuel which can be used on ships. Hydrogen is offered as a new alternative fuel, and found that it is worth to use as a fuel onboard.

## 2. Alternative fuels

Alternative fuels which can be used at marine diesel engines are found in two phase; liquid fuels like methanol (CH<sub>3</sub>OH), ethanol (C<sub>2</sub>H<sub>5</sub>OH), bioliquid fuel, and biodiesel; and gaseous fuels like propane, hydrogen and natural gas (Banawan et al., 2009). Remarkable fuels subject to many previous researches are methanol and ethanol in liquid state, and natural gas and hydrogen in gaseous state. Properties of diesel fuel, methanol, ethanol, liquefied natural gas (LNG) and hydrogen are shown at Table 1. The table shows differences between commonly used fossil fuel and alternative marine fuels.

### 2.1. Liquid alternative fuels

Methanol and ethanol are variety of alcohols which can be produced from renewable sources, by destructive distillation of wood, agriculture products and by reformation process from large quantities of natural gas and coal gas (Yusaf et al., 2013; El Gohary et al., 2014b; Cheng et al., 2008). The characteristics of alcohols are low viscosity, providing easy injection, atomization and better mixture formation with air; less emission due to high stoichiometric fuel–air ratio, high oxygen content, high H/C ratio and sulfur free structure; high evaporative cooling which raises the volumetric efficiency during intake process and compression stroke (Sayin, 2010). On the other hand, it should also be considered that methanol is toxic, corrosive and is twice in volume comparing to marine diesel oil (MDO) (MAN, 2015).

Methanol and ethanol cannot substitute diesel fuel or fuel oil directly, due to their high auto-ignition temperature, low cetane number, high latent heat of vaporization, reduced lubrication potential related to low viscosity (Karabektaş et al., 2013). It is possible to use these fuels in diesel engines utilizing two different ways. One of them is premixed fuel composition of methanol or ethanol with diesel fuel or fuel oil, which does not have any controversial comment in the literature about use with alcohols. The main problem of premixed fuel composition is phase separation of alcohols. The addition of proper solvent is the solution (Karabektaş et al., 2013). The other way is injection of methanol or ethanol separately from diesel fuel or fuel oil. Injection area can change depending on the method applied. At the fumigation method, methanol or ethanol are injected into the intake manifold of the diesel engine; and they are injected into the cylinder from separate injector at the dual-fuel method. Methanol or ethanol ratio is approximately 30–50% at fumigation method, while main fuel is methanol or ethanol, and diesel fuel is used as pilot fuel to ignite main fuel at dual-fuel method (Sarjovaara et al., 2013).

**Table 1**  
Properties of diesel fuel and alternative fuels.

|                                        | Diesel                                                                                                                                                                                                             | Methanol | Ethanol | LNG     | Hydrogen |
|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|---------|---------|----------|
| Density (kg m <sup>-3</sup> )          | 833–881                                                                                                                                                                                                            | 798      | 794     | 450     | 0.0838   |
| Auto-ignition temperature (K at 1 bar) | 530                                                                                                                                                                                                                | 743      | 635     | 810     | 858      |
| Flammability limits (vol. % air)       | 0.7–5                                                                                                                                                                                                              | 6–36     | 3–19    | 4–16    | 4–75     |
| Stoich. air–fuel ratio on mass basis   | 14.5                                                                                                                                                                                                               | 6.5      | 9.1     | 17.2    | 34.3     |
| Net heating value (MJ/kg)              | 42.5                                                                                                                                                                                                               | 20.1     | 27.0    | 46–50.2 | 119.9    |
| Flame velocity (cm/s)                  | 30                                                                                                                                                                                                                 | 50       | 41      | 380     | 265–325  |
| Flame temperature (K at 1 bar)         | 2327                                                                                                                                                                                                               | 2163     | 2193    | 2233    | 2318     |
| Octane number                          | 30                                                                                                                                                                                                                 | 109      | 109     | 120     | 130      |
| Cetane number                          | 40–55                                                                                                                                                                                                              | <5       | 8       | –10     | –        |
| Fuel carbon content (wt %)             | 85                                                                                                                                                                                                                 | 38       | 52      | 75      | 0        |
| Fuel hydrogen content (wt %)           | 15                                                                                                                                                                                                                 | 12       | 13      | 25      | 100      |
| Fuel oxygen content (wt %)             | 0                                                                                                                                                                                                                  | 50       | 35      | 0       | 0        |
| Fuel sulfur content (wt %)             | <350 ppm                                                                                                                                                                                                           | 0        | 0       | 0       | 0        |
| References                             | Zincir and Deniz, 2014; MAN, 2015; Yao et al., 2008; Bromberg, 2008; Demirbas, 2010; Heywood, 1988; Huang et al., 2007; FTA, 1994; Sroka, 2007; Herdizik, 2011; Cheenkachorn et al., 2013; El Gohary et al., 2014a |          |         |         |          |

**Table 2**

Effect of alternative fuels on engine performance and emissions.

| Investigation areas                    | Fuel types         |          |          | References                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|----------------------------------------|--------------------|----------|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                        | Methanol & ethanol | LNG      | Hydrogen |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| CO <sub>2</sub> emissions              | Increase           | Decrease | Decrease | Banawan et al., 2009; Bari and Mohammad Esmaeil, 2010; Cheenkachorn et al., 2013; Cheng et al., 2008; Chrysosakis et al., 2014; Einang, 2007; Haraldson, 2014; Levander, 2011; Pan et al., 2014; Poornipatpong and Cheenkachorn, 2011; Popa et al., 2001; Rakopoulos et al., 2008; Samuel and McCormick, 2010; Saravanan and Nagarajan, 2008; Sayin, 2010; Sayin et al., 2009, 2010; Rajaram et al., 2014; Stuer-Lauridsen et al., 2010; Udayakumar et al., 2004; Yao et al., 2008; Zhou et al., 2014 |
| NO <sub>x</sub> emissions              | Decrease           | Decrease | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| SO <sub>x</sub> emissions              | Decrease           | Decrease | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| CO emissions                           | Increase           | Increase | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| PM emissions                           | Decrease           | Decrease | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Total hydrocarbon emissions (THC)      | Increase           | Increase | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Brake specific fuel consumption (BSFC) | Increase           | Decrease | Decrease |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Brake thermal efficiency (BTE)         | Decrease           | Increase | Increase |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |

Table 2 shows effect of methanol and ethanol on engine performance and emissions. There is not any usage of ethanol at commercial vessels in marine engine studies, but there are some studies used ethanol on outboard motors of pleasure boats. Methanol studies at commercial vessels are prevalent. Stena Line, Wärtsilä and MAN B&W are some of the companies working on methanol fuel use at their vessels or diesel engines. Stena Line which has ferry/RoRo lines in ECA area prefers converting their vessel's main engine to methanol–diesel dual fuel engine (Westling, 2013).

## 2.2. Gaseous alternative fuels

Popular fuels in gas state are natural gas and hydrogen. Natural gas consists of paraffinic hydrocarbons such as methane, ethane, propane and butane. It is used in two forms; liquefied natural gas (LNG) which is formed by cooling down the natural gas to  $-162\text{ }^{\circ}\text{C}$  (El Gohary et al., 2014b), and compressed natural gas (CNG) if natural gas is pressurized with 250 bar (Herdzik, 2011). Because of lower densities, occupied volume of LNG is equivalent to 2 for 1 m<sup>3</sup> marine fuel oil; and CNG equals to 4.5 m<sup>3</sup> (El Gohary et al., 2014b). When required spaces for LNG and CNG storage are taken into consideration, LNG is mostly used onboard ships.

Many studies have been carried out about LNG fuel use in land based engines and marine diesel engines for many years. Study results about LNG are shown at Table 2. Marine applications are in considerable amount. According to DNV GL (2015), there are 63 LNG fueled ships in operation, and another 76 new buildings are on the way. Different concepts have been tried at these ships. These concepts are gas-only engines, dual fuel 4-stroke and 2-stroke engines (Chrysosakis et al., 2014).

Hydrogen is a renewable energy carrier which is normally in gas state. It has been attractive for the researchers, due to the clean exhaust of its reaction with oxygen into water (Rajaram et al., 2014). Hydrogen's wide flammability range, high flame speed, high diffusibility, low minimum ignition energy, zero carbon content, and smaller quenching gap which provides more complete combustion are other remarkable characteristics (Zincir and Deniz, 2014; Pan et al., 2014). On the contrary, it has high self-ignition temperature of 858 K, as a result of this hydrogen cannot be used solely in compression ignition engine without a spark plug or glow plug (Saravanan and Nagarajan, 2008). With these properties and high stoichiometric air-to-fuel ratio, hydrogen is an ideal fuel to combine with other fuels (Pan et al., 2014).

Hydrogen can be stored as compressed or liquefied conditions at very low temperatures ( $-253\text{ }^{\circ}\text{C}$ ) (Chrysosakis et al., 2014; Bari and Mohammad Esmaeil, 2010). Compressed hydrogen requires six to seven times more space than same energy content of HFO; and liquefied hydrogen needs cryogenic storage in well insulated tanks with large energy losses (Chrysosakis et al., 2014). Hydrogen storage

onboard is inconvenient due to above mentioned storage properties, so on demand systems should be applied to the ships.

Hydrogen cannot be used effectively as a main fuel in diesel engine due to knocking problems. In addition to this, a study showed that increase in engine efficiency diminished after 5% total diesel equivalent of hydrogen/oxygen gas mixture addition to the diesel fuel, and it did not change after 6% (Bari and Mohammad Esmaeil, 2010). For that reason it is commonly used as additive in diesel engines which is named, fumigation. Fumigation application by alkaline electrolysis system from intake manifold to a ship main engine was mentioned in the previous study (Zincir and Deniz, 2014).

Previous study results with hydrogen use are shown at Table 2. NO<sub>x</sub> emission amount depends on various factors at the engine. These are hydrogen supply rate, equivalence ratio of the engine which should be ultra lean operation for low NO<sub>x</sub> emissions, and engine load. NO<sub>x</sub> emissions were reduced under ultra lean complete combustion with the equivalence ratio between 0.4 and 0.5 (Saravanan and Nagarajan, 2008; White et al., 2006), NO<sub>x</sub> emission reduction can be provided by the correct engine operation. SO<sub>x</sub> emission is not mentioned in the studies, but hydrogen is sulfur free fuel, and the substitution of hydrogen with hydrocarbon fuel is resulted with reduction at SO<sub>x</sub> emission.

## 3. Comparison criterions of alternative fuels

To compare alternative fuels for onboard use, firstly comparison criterions are determined and alternative fuels are evaluated at each criterion. Then matrix table is generated considering the evaluation scales of the comparison criterions. There are five evaluation scales for each comparison criterion, and their denotations are shown at Table 3.

Compared alternative fuels are methanol, ethanol, LNG and hydrogen. Hydrogen fuel is assumed to be produced by alkaline electrolysis system on demand, and is not stored onboard.

Comparison criterions are determined by taking into consideration of ship safety, global usage, bunker capability, durability, ease of application, rules & regulations, engine performance and emissions, effect on engine components, and commercial issues.

**Table 3**

Evaluation scales and denotations.

| Evaluation scale | Denotation  |
|------------------|-------------|
| 1                | Worst       |
| 2                | Worse       |
| 3                | Moderate    |
| 4                | Fairly well |
| 5                | Best        |

### 3.1. Safety

Safety at ships/sea is important matter, and new technologies for ships are evaluated taking safety into consideration. Safety of alternative fuels can be evaluated by their density, auto-ignition temperature, flammability limits, stoichiometric air–fuel ratio, octane and cetane numbers. Information of these safety measures which are needed for safety evaluation is taken from Table 1. Safety evaluation table is formed by the comparison of the specifications of alternative fuels at Table 4.

If there is a leakage occurred at a storage tank, hydrogen's low density provides it to disappear more quickly in the air, while methanol and ethanol stays due to their high densities. Auto-ignition temperature of hydrogen is the highest, LNG is second, methanol is the third, and ethanol is the lowest. It means hydrogen needs the highest, and ethanol needs the lowest ambient temperature to auto-ignite.

Flammability limits of fuels are the indicator of the needed quantity of the fuel in the air volumetrically to burn fuel. LNG has the narrowest flammability limits of 4–16%, while ethanol has 3–19%, methanol has 6–36%, and hydrogen has the widest with the 4–75%. Hydrogen is easy to burn with different portions of fuel–air mixture.

Stoichiometric air–fuel ratios to burn the fuel completely are 6.5, 9.1, 17.2 and 34.3 for methanol, ethanol, LNG and hydrogen, respectively. Methanol needs the lowest amount of air to burn completely, while hydrogen needs the highest.

Octane number indicates the resistance to auto-ignition and knock; and cetane number indicates the ignition delay and combustion quality. Hydrogen has the highest octane number of 130 and does not have cetane number, while LNG has octane number of 120 and cetane number of –10. Ethanol and methanol have octane number of 109, and cetane number of 8 and lower than 5 for ethanol and methanol respectively. It means again that hydrogen is the hardest to auto-ignite while methanol is the easiest.

These properties of fuels cannot be classified in an evaluation scale of 5. For that reason, fuels are compared with each other and numbered from 1 to 3 for this criterion. Safety evaluation of alternative fuels are made by getting total safety evaluation point ( $SEP_{TOT}$ ) of 24 from multiplication of eight criterions with best numbering of 3. To adapt three evaluation scale comparison of alternative fuels to five scaled evaluation, five evaluation scales are formed according to Table 3 by dividing total 24 point to five intervals. Between 1 and 5, evaluation scale is 1, between 6 and 10, evaluation scale is 2, between 11 and 15, evaluation scale is 3, between 16 and 20, evaluation scale is 4, and between 21 and 24, evaluation scale is 5.

According to safety evaluation of alternative fuels, hydrogen gets 4, LNG gets 3, methanol and ethanol get 1 as evaluation scale point which are fairly well, moderate and the worst respectively.

### 3.2. Global availability

Global availability means usage popularity worldwide. Due to bunker capability and more space is required than HFO or MDO for

storage of methanol or ethanol, only there are few ferry companies which modified their ships engine for methanol fuel. On the other hand, methanol and ethanol usage in diesel engines is a new technology, and this also affects its use on ships. LNG as well requires two times more storage area than HFO, but it is trend nowadays, and bunkering areas are increasing. In addition to that engine manufacturers are interested in LNG fueled diesel engines, and there are fairly well amount of vessels which are in operation and on the way. Use of hydrogen by alkaline electrolysis system requires neither large spaces nor fuel supply. Some companies were applied this system to their ships taking voyage in inland waterways at United Kingdom (IGES, 2015). This is proven technology, it has been used on land based facilities and vehicles for many years, however it does not have certain amount of application for ships. It can be said that LNG is trend and has good amount of applications for ships, so it is 4 (fairly well) at global availability. Hydrogen is 3 (moderate) because it is proven technology, but is newly started to apply on ships; and methanol and ethanol are 2 (worse) because it is a new technology, and does not have enough amount of application.

### 3.3. Bunker capability

Bunker capability is related with global availability. If more ships demand to use a certain fuel type, bunker capability for that fuel type will be high. Use of methanol and ethanol in ships are limited, and this affects the bunker capability. On the other side, LNG use is rising, and it affects bunkering of LNG. Although LNG bunker capability develops, it is not enough for global supply network. Some available bunker ports are Incheon (Korea), Buenos Aires (Argentina), Damietta and Idku (Egypt) and number of ports in Europe (Chryssakis et al., 2014; Banawan et al., 2009). Hydrogen use by alkaline electrolysis system does not need hydrogen supply because it produces hydrogen itself, but system needs pure water. If ship has fresh water generator onboard, pure water supply will not be needed. Moreover, pure water supply can be possible at any port, in case of ship does not have fresh water generator. Hydrogen gets 4 (fairly well), due to its only drawback is fresh water need. LNG gets 3 (moderate), because there are bunkering areas but not enough. Methanol and ethanol get 2 (worse) by the reason of limited bunkering capability.

### 3.4. Durability

Durability term in this study means an alternative fuel's long term usage. It is related with global fuel reserves, global availability, bunker capability, and trends in the future. Global fuel reserves of methanol and ethanol are mostly natural gas and coal, and biomass, because these fuels are produced by them. So, methanol and ethanol production depends on global natural gas and coal reserves, and production rate from biomass. Proven reserves of natural gas is 246,250 trillion  $m^3$  on 2014 (EIA, 2015a). It is huge amount of reserves, and enough for usage of at least 50 years, if calculation is made with annual natural gas consumption (EIA, 2015a). Global fuel reserves affect methanol, ethanol and LNG durability positively. Hydrogen use by alkaline electrolysis system only needs pure water, and pure water reserve is not an issue. As previously, it was mentioned that global availability of LNG is fairly well, hydrogen is the moderate, and methanol and ethanol are worse. It was also found that bunker capability of hydrogen is fairly well, LNG is the moderate, and methanol and ethanol are worse. Trend in the future is clean and renewable energy sources, and hydrogen is the one of them. Methanol and ethanol from biomass are also a renewable energy, however LNG is a fossil fuel.

Numbering is again from 1 to 3 for this criterion. Numberings of each fuel are summed and total durability points ( $DP_{TOT}$ ) are found.

**Table 4**

Safety evaluation table of alternative fuels.

| Safety measures               | Methanol & ethanol | LNG | Hydrogen |
|-------------------------------|--------------------|-----|----------|
| Density                       | 1                  | 2   | 3        |
| Auto-ignition temperature     | 1                  | 2   | 3        |
| Flammability limits           | 2                  | 3   | 1        |
| Stoichiometric air–fuel ratio | 1                  | 2   | 3        |
| Octane number                 | 1                  | 2   | 3        |
| Cetane number                 | 1                  | 2   | 3        |
| $SEP_{TOT}$                   | 7                  | 13  | 16       |

$SEP_{TOT}$ : total safety evaluation point.

**Table 5**  
Durability evaluation of alternative fuels.

| Durability measures  | Methanol & ethanol | LNG | Hydrogen |
|----------------------|--------------------|-----|----------|
| Fuel reserves        | 2                  | 2   | 3        |
| Global availability  | 1                  | 3   | 2        |
| Bunker capability    | 1                  | 2   | 3        |
| Trends in the future | 2                  | 1   | 3        |
| DP <sub>TOT</sub>    | 6                  | 8   | 11       |

DP<sub>TOT</sub>: total durability point.

Durability evaluation of alternative fuels is made by constituting durability evaluation table, which is Table 5. Durability evaluation of alternative fuels is made by getting DP<sub>TOT</sub> of 12 from multiplication of four criterions with best numbering of 3. DP<sub>TOT</sub> is divided to the five for determining evaluation scale intervals. Intervals between 1 and 3, 4 and 5, 6 and 7, 8 and 9, 10 and 12 get 1 to 5 evaluation scale points respectively. According to DP<sub>TOT</sub> of alternative fuels, hydrogen is 5 (best), LNG is 4 (fairly well), methanol and ethanol are 3 (moderate).

### 3.5. Adaptability to existing ships

Adaptability of alternative fuel systems to new building ships is more feasible, however it is difficult to apply new systems to existing ships, due to inadequate space, and required modifications on main engine. Methanol and ethanol fuel systems need additional fuel tanks, or conversion of existing ballast tanks onboard to fuel tanks. Space is required for separate rooms of transfer pumps, and high pressure pumps (Westling, 2013). Double walled pipes are needed for supplying main engine with fuel (MAN, 2015; Westling, 2013). Additional fuel injectors and fuel pumps are needed on main engine for fuel delivery to the cylinders (MAN, 2015; Haraldson, 2014).

LNG fueled ships need special designed LNG tanks as well as tank connection space for conditioning LNG in the tank, and provide the delivery of LNG to the main engine. Also they need gas ventilation space, double wall gas piping, specially protected bunker stations, separation of main engine from engine room by walls and gas safe machinery space (Gumpel, 2012). There are also some modifications on main engine similar to methanol and ethanol fueled ships.

Hydrogen use by alkaline electrolysis system does not require tank for pure water, if ship has fresh water generator; but a fresh water tank can be used for pure water storage if ship does not have it. Space is needed in the engine room for alkaline electrolysis cells and control units. Double wall piping, and minor modifications on the main engine turbocharger is needed to apply on a ship. In addition to this system safety equipment, alarms and adequate ventilation are needed. If the systems are compared, it can be seen that LNG needs more special requirements than methanol, ethanol and hydrogen. Hydrogen has the least special requirements to adapt the system to a existing ship, but still there is need of some arrangements. Because of this reason it gets 4 (fairly well). Methanol and ethanol get 3 (moderate), due to moderate amount of modification, and LNG gets 2 (worse) but does not get 1 (worst), because it needs major modification at existing ships. System can be applied to new building ship with preliminary plan.

### 3.6. Effect on engine performance

Alternative fuels have positive or negative effects on engine performance. Methanol and ethanol decrease BTE, and increase BSFC, because methanol and ethanol fuels have lower LHV (Sayin, 2010). On the other hand, LNG and hydrogen addition to the

diesel engine increase BTE and reduce BSFC, due to their higher heating value and better combustion characteristics (Rajaram et al., 2014; Poornipatpong and Cheenkachorn, 2011). LNG and hydrogen have positive effect on engine performance, while methanol and ethanol have negative effect. Since there is no study about comparison of effect of mentioned alternative fuels on engine performance, weighting cannot be determined. As a result, 1 (worst) is given to methanol and ethanol because of their negative effect, on the other hand 5 (best) is given to LNG and hydrogen by the reason of their positive effect on engine performance.

### 3.7. Effect on engine emissions

Main reason of using alternative fuels onboard is to reduce shipping emissions. The alternative fuels have various effects on different emission types. Lower carbon and sulfur content in the fuel reduce CO<sub>2</sub> and SO<sub>x</sub> emissions. In addition to this, cylinder oil with lower total base number (TBN) can be used with low sulfur fuels, which is the reason of PM formation which has the limits in ECAs. Methanol and ethanol reduce NO<sub>x</sub>, SO<sub>x</sub> and PM emissions, and increase CO<sub>2</sub>, CO, and THC emissions. LNG reduces CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> and PM emissions, but increases CO and THC emissions. Besides with use of LNG fuel, methane slip is occurred and it neutralizes the reduction effect of CO<sub>2</sub> emissions. It was eliminated at two stroke diesel engines, and reduced to minimum levels at four stroke diesel engines with the developing technology (Chrysosakis et al., 2014). For this reason, methane slip is neglected while performing evaluation. Lastly, hydrogen mitigates CO<sub>2</sub>, CO, SO<sub>x</sub> and PM emissions while increasing or decreasing NO<sub>x</sub> emissions depends on engine operating conditions. But it is assumed that hydrogen increases NO<sub>x</sub> emissions as worst scenario at the comparison table.

Different approach is applied to evaluate effect of alternative fuels on onboard emissions. Emission weight points (EWP) are determined for each emission types by a matrix. Table 6 shows the emission matrix points.

Emission global limits are related with international MARPOL regulation, and limits are specified for emissions which are included in the regulation. Emission amount are mentioned previously at introduction section. Emission global limits and emission amount of each emission type are shown at Table 7. Matrix points for each emission type at Table 8 is given according to Table 7.

According to matrix table, value 1 equals to EWP of 1, 2 and 3 is 2, between 4 and 6 is 3, 8 and 9 is 4, and 12 equals to 5. EWP equivalent of emission matrix points of each emission type is shown at Table 8.

Evaluation points of alternative fuels' effect on shipboard emissions are shown at Table 9. Effects of alternative fuels are defined by 0 and 1. 0 means increase effect, and 1 means decrease effect on designated emission types. Calculation was made by using Formula (1) and (2).

$$ERP_{ij} = EWP_i \cdot AFE_{ji} \quad (1)$$

$$ERP_{j,TOT} = \sum ERP_{ij} \quad (2)$$

**Table 6**  
Emission matrix points.

| Global limits          | Emission amount |       |          |      |
|------------------------|-----------------|-------|----------|------|
|                        | Too small       | Small | Moderate | Huge |
| No global limits       | 1               | 2     | 3        | 4    |
| Moderate global limits | 2               | 4     | 6        | 8    |
| Strict global limits   | 3               | 6     | 9        | 12   |

**Table 7**

Emission global limits and emission amount.

| Emission type           | Global limits                                    | Emission amount (tons) |
|-------------------------|--------------------------------------------------|------------------------|
| CO <sub>2</sub>         | MARPOL Annex VI Regulations on Energy Efficiency | 949 million            |
| NO <sub>x</sub>         | MARPOL Annex VI Regulation 13                    | 19.002 million         |
| SO <sub>x</sub>         | MARPOL Annex VI Regulation 14                    | 10.240 million         |
| CO                      | None                                             | 936 thousand           |
| PM                      | MARPOL Annex VI Regulation 14                    | 1.402 million          |
| Total hydrocarbon (THC) | None                                             | Unspecified            |
| Reference               | IMO, 2014                                        |                        |

**Table 8**

Emission weight point equivalent of matrix points.

| Emission type           | Matrix points | Emission weight point (EWP) equivalent |
|-------------------------|---------------|----------------------------------------|
| CO <sub>2</sub>         | 12            | 5                                      |
| NO <sub>x</sub>         | 9             | 4                                      |
| SO <sub>x</sub>         | 9             | 4                                      |
| CO                      | 2             | 2                                      |
| PM                      | 4             | 3                                      |
| Total hydrocarbon (THC) | 1             | 1                                      |

ERP<sub>ij</sub> means 'Emission reduction point for i emission type of j alternative fuel', EWP<sub>i</sub> means 'Emission weight point for i emission type', AFE<sub>ij</sub> means 'Alternative fuel effect of j alternative fuel on i emission type', and ERP<sub>j,TOT</sub> means 'Total emission reduction point for j alternative fuel type'.

ERP<sub>j,TOT</sub> of alternative fuels are evaluated by the sum of EWP of all emission types, and it gets 19. If the ERP<sub>j,TOT</sub> of each alternative fuel systems are between 1 and 3, evaluation scale is 1 (worst), between 4 and 7, it is 2 (worse); between 8 and 11, it is 3 (moderate), between 12 and 15, it is 4 (fairly well), and between 16 and 19, it is 5 (best) according to Table 3. At Table 9, it is found that LNG and hydrogen get 5 (best), methanol and ethanol get 3 (moderate).

### 3.8. Comply with emission regulations

IMO is quite strict about emission regulations, and ships have to comply with the regulations during the application of alternative fuels onboard. Tier II limits for NO<sub>x</sub> emissions are in progress, and Tier III limits will be applied on and after January 1st 2016. Methanol use as a fuel complies with Tier II limits, but technology has to be improved for Tier III limits (Haraldson, 2014). Ethanol does not have a study about the regulations perspective. LNG fuel meets Tier III limits, and suitable fuel for future use (Levander, 2011). Hydrogen's effect on NO<sub>x</sub> emissions is mentioned at engine emissions section, and it is not stable. It can comply with Tier II limits, if

engine operating conditions are ultra lean, hydrogen addition amount to the combustion is adjusted properly, and avoidance from high load engine operation. On the other hand, more marine based studies should be done with hydrogen to reduce NO<sub>x</sub> emissions to Tier III limits.

Latest regulation about sulfur limit is 0.1% at ECAs which entered into force on January 1st 2015. In addition to this sulfur content of fuel will be 0.5% after January 1st 2020. Methanol, ethanol, LNG and hydrogen are sulfur free fuels, so their use as a fuel reduce SO<sub>x</sub>, and PM emissions. Methanol and LNG can be used at ECAs due to nearly zero SO<sub>x</sub> emissions, and lower PM emissions (MAN, 2015; Levander, 2011). Hydrogen reduces SO<sub>x</sub> emissions, however there are not any detailed studies to see the compliance with rules and regulations.

EEDI and SEEMP are the CO<sub>2</sub> emission reduction, and energy efficiency practices for new building and existing ships. Methanol and ethanol use as a fuel increase CO<sub>2</sub> emissions, so these fuels are not energy efficiency compliant. CO<sub>2</sub> emissions are reduced by LNG and hydrogen use as a fuel. These fuels can be one of the energy efficiency measures.

LNG meets with Tier III limits, and reduce all type of emissions related to regulations for this reason it gets 5 (best) point. Methanol and ethanol meet with Tier II limits, and however they do not reduce CO<sub>2</sub> emissions. These fuels get 3 (moderate) point. However hydrogen meets with Tier II limits, NO<sub>x</sub> reduction capability is unstable and SO<sub>x</sub> reduction limit is unknown, so it gets 2 (worse) point.

### 3.9. Effect on engine combustion chamber components

Effect of alternative fuels on engine combustion chamber components is important, because repair and maintenance intervals are shortened, and spare part expenses are increased with the negative effect. Fuel effect on engine components is related with calorific value and elementary composition of the fuels (Sroka, 2007). Methanol and ethanol have nearly half of the net heating value of diesel fuel, however methanol deteriorates lubricating oil structure and increase viscosity (Totten, 2003). Ethanol has close structure

**Table 9**

Comparison of alternative fuels effect on shipboard emissions.

| Fuel types         |     | Methanol & ethanol    |                   | LNG                    |                    | Hydrogen               |                    |
|--------------------|-----|-----------------------|-------------------|------------------------|--------------------|------------------------|--------------------|
| Emission types (i) | EWP | AFE <sub>ME</sub>     | ERP <sub>ME</sub> | AFE <sub>LNG</sub>     | ERP <sub>LNG</sub> | AFE <sub>HYD</sub>     | ERP <sub>HYD</sub> |
| CO <sub>2</sub>    | 5   | 0                     | 0                 | 1                      | 5                  | 1                      | 5                  |
| NO <sub>x</sub>    | 4   | 1                     | 4                 | 1                      | 4                  | 0                      | 0                  |
| SO <sub>x</sub>    | 4   | 1                     | 4                 | 1                      | 4                  | 1                      | 4                  |
| CO                 | 2   | 0                     | 0                 | 0                      | 0                  | 1                      | 2                  |
| PM                 | 3   | 1                     | 3                 | 1                      | 3                  | 1                      | 3                  |
| THC                | 1   | 0                     | 0                 | 0                      | 0                  | 1                      | 1                  |
| EWP <sub>TOT</sub> | 19  | ERP <sub>ME,TOT</sub> | 11                | ERP <sub>LNG,TOT</sub> | 16                 | ERP <sub>HYD,TOT</sub> | 15                 |

EWP: emission weight point.

AFE<sub>j</sub>: alternative fuel effect of j type of alternative fuel.ERP<sub>j</sub>: emission reduction point of j type of alternative fuel.EWP<sub>TOT</sub>: total emission weight point.ERP<sub>j,TOT</sub>: total emission reduction point for j type of alternative fuel.

with methanol, and also it has negative effect on lubricating oil. Their use on a diesel engine reduce life time of exhaust valves and seats, piston ring, and liner wear may occur due to inadequate lubrication (Haraldson, 2014).

LNG has close net heating value to diesel fuel, composes around same level of heat release, so it does not affect engine combustion chamber components negatively. In addition to this, sulfur free structure of LNG prevents sulfuric acid ( $H_2SO_4$ ) formation in engine cylinders.

Hydrogen has three times bigger net heating value than diesel fuel, and has high flame speed. These properties of hydrogen provide quick heat release rate in combustion chamber, and shorten the life time of the combustion chamber components.

There have not been any comparative research about these fuels effect on engine combustion chamber components, as a consequence it is impossible to do numbering of their effects. 5 (best) point is given to LNG for its positive effect, and 1 (worst) point is given to methanol, ethanol and hydrogen for their negative effect.

### 3.10. Commercial effects

The commercial effects of alternative fuels are reduction at cargo loading capacity, fuel amount for voyage, and bunker capability of fuel. Methanol and ethanol can be stored either in a new separate fuel tank or existing suitable tank onboard, for instance, ballast water tanks. If separate tank has to be used, space is needed for additional tank; and these space can be provided from cargo loading space. Furthermore methanol and ethanol system need separate pumping room space which can occupy space at cargo area. As it mentioned at adaptability to existing ships section, LNG fuel has to be stored at special designed tanks, and these tanks occupy large spaces either on deck or under deck. Adachi et al. (2014), made a study on a container ship, and they stated that ship length has to be longer for carrying same number of container at a ship using LNG fuel. Another study stated that cargo capacity of a feeder container vessel reduced by 4% due to LNG tank (Gullberg and Gahnström, 2011). Actual occupied space of methanol and LNG tanks will vary from ship to ship (Brynolf et al., 2014). Hydrogen does not require tank, because it is produced onboard on demand. Only pure water tank is needed, if there is not fresh water generator

onboard. System equipment parts for hydrogen are less, and they occupy small space which can be provided at the engine room.

Due to the density and lower heating value differences between fuels, fuel amount need for the same voyage is variable. Methanol and ethanol have about the same density with diesel fuel, however they have half of diesel fuel lower heating value. Twice amount of methanol and ethanol are needed to substitute diesel fuel to produce same amount of heat release. Twofold tank space is required for same voyage. LNG has about the same level of lower heating value, but it has half value of density of diesel fuel. As a consequence, twice tank space is needed for same voyage. A study was made on a Ro-Ro ship, with application of LNG fuel. Daily consumption of LNG is 19 tons, and for two day voyage it was 38 tons (Levander, 2011). The required tank volume is 84 m<sup>3</sup> for 38 tons of LNG fuel. It would around 38 m<sup>3</sup>, if consumed fuel was HFO or MGO. Hydrogen is not stored onboard, and produced on demand by alkaline electrolysis system. So no additional space is needed for hydrogen fuel use at ships.

Bunker capability of fuel affects the route of a ship. If a port does not have enough bunker available, ship has to change her route, and sail to the port or area, which has bunker capability. This situation increases voyage expenses of ship owner. Hydrogen is the most bunker capable, LNG is the moderate; methanol and ethanol are the worst bunker capable. So voyage expenses are the highest at the methanol and ethanol use, moderate at LNG use, and the least at the hydrogen use. Sum of all, 5 (best) point is given to hydrogen, 3 (moderate) point is given to methanol, ethanol and LNG for their drawbacks.

### 3.11. Costs

Costs include capital expenditures (CapEx) and operational expenditures (OpEx) of application of alternative fuel systems onboard. All costs related to CapEx and OpEx are described at Table 10.

CapEx are the investment costs including system components, engine retrofit and engine room modifications of the mentioned alternative fuel systems. Engine conversion costs depend on ship type and dimensions. Methanol dual fuel system CapEx costs are comprised by engine conversion costs, and engine room safety modifications. The majority of the conversion cost of LNG system consists of LNG storage tanks and its safety systems (El Gohary

**Table 10**  
Cost descriptions of alternative fuels.

| Fuel types        |                       | Methanol & ethanol                                                                                                                                                                                                                                                                                                                                 | LNG                             | Hydrogen                                                      |
|-------------------|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------|
| <b>CAPEX</b>      |                       |                                                                                                                                                                                                                                                                                                                                                    |                                 |                                                               |
| Investment costs  |                       | 350 Euro/kWh (Stefenson, 2014)                                                                                                                                                                                                                                                                                                                     | 1000 Euro/kWh (Stefenson, 2014) | 100 USD/kWh (Bourgeois, 2006)                                 |
| <b>OPEX</b>       |                       |                                                                                                                                                                                                                                                                                                                                                    |                                 |                                                               |
| Maintenance costs | Maintenance intervals | Related with the effect of fuels on engine components. Methanol, ethanol and hydrogen have negative effect on combustion chamber components, and LNG has positive effect. Maintenance intervals will be shorten by using methanol, ethanol and hydrogen as a fuel, and will be wider by using LNG.                                                 |                                 |                                                               |
|                   | System complexity     | With the increment of system complexity more system components are involved in operation, and it means more failure possibility and special spare parts need. Hydrogen use by alkaline electrolysis system has the least system components and most portable one. Methanol and ethanol system is the moderate, and LNG is the most complex system. |                                 |                                                               |
| Consumable costs  | Lubricating oil       | Methanol and ethanol have negative effect on lubricating oil, and reduce the lubrication property of the oil. It should be changed within close intervals, and lubricating oil costs will raise. LNG and hydrogen are sulfur free fuels, and do not deteriorate lubricating oil.                                                                   |                                 |                                                               |
|                   | Spare parts           | Related with the effect of fuels on engine components, and maintenance intervals. LNG has less spare parts usage than methanol, ethanol and hydrogen.                                                                                                                                                                                              |                                 |                                                               |
|                   | Additional costs      | Operational additive and chemical costs.                                                                                                                                                                                                                                                                                                           |                                 |                                                               |
| Fuel price        |                       | Methanol Europe                                                                                                                                                                                                                                                                                                                                    | 518 USD/mt (Fagerlund, 2014)    | Hydrogen is produced onboard by alkaline electrolysis system. |
|                   |                       | 371 USD/mt<br>N. America<br>416 USD/mt<br>Asia<br>330 USD/mt (Methanex, 2015)                                                                                                                                                                                                                                                                      |                                 |                                                               |
|                   |                       | Ethanol                                                                                                                                                                                                                                                                                                                                            | 502 USD/mt (EIA, 2015b)         |                                                               |

**Table 11**

Ranking of alternative fuels at each cost items.

| Cost items            |  | Methanol & ethanol                                                                                                      | LNG                    | Hydrogen                                                                      |
|-----------------------|--|-------------------------------------------------------------------------------------------------------------------------|------------------------|-------------------------------------------------------------------------------|
| <b>CAPEX</b>          |  |                                                                                                                         |                        |                                                                               |
| Investment costs      |  | 3                                                                                                                       | 1                      | 5                                                                             |
| Ranking reason        |  | Ballast tanks can be used                                                                                               | Separate, special tank | No tank need                                                                  |
|                       |  | Moderate component number                                                                                               | High component number  | Low component number                                                          |
|                       |  | Moderate price                                                                                                          | High price             | Lower price                                                                   |
| <b>OPEX</b>           |  |                                                                                                                         |                        |                                                                               |
| Maintenance costs     |  | 1                                                                                                                       | 5                      | 1                                                                             |
| Maintenance intervals |  | It cannot be ranked. 5 is given for extending maintenance intervals, and 1 is given for reducing maintenance intervals. |                        |                                                                               |
| Ranking reason        |  |                                                                                                                         |                        |                                                                               |
| System complexity     |  | 3                                                                                                                       | 2                      | 4                                                                             |
| Ranking reason        |  | Same numbering with the adaptability to existing ships section is used.                                                 |                        |                                                                               |
| Consumable costs      |  | 1                                                                                                                       | 5                      | 5                                                                             |
| Lubricating oil       |  | It cannot be ranked. 5 is given for positive effect on lubricating oil, and 1 is given for negative effect.             |                        |                                                                               |
| Ranking reason        |  |                                                                                                                         |                        |                                                                               |
| Spare parts           |  | 1                                                                                                                       | 5                      | 1                                                                             |
| Ranking reason        |  | It cannot be ranked. Same numbering with effect on engine combustion chamber components is used.                        |                        |                                                                               |
| Additional costs      |  | 4                                                                                                                       | 5                      | 3                                                                             |
| Ranking reason        |  | Solvent need                                                                                                            | No additional costs    | Potassium hydroxide need Fresh water need if no fresh water generator onboard |
| Fuel price            |  | 4                                                                                                                       | 3                      | 5                                                                             |
| Ranking reason        |  | Ranking is done according to fuel prices at Table 8                                                                     |                        |                                                                               |

et al., 2014b). Special designed LNG storage tank cost is above 3000 USD/m<sup>3</sup> (Anderson et al., 2011). Hydrogen use by alkaline electrolysis system has less system component which are electrolysis cell unit, pumps, piping and safety systems, and there is no need of major engine modification.

OpEx are operational costs consist of maintenance costs, consumable costs and fuel price. Maintenance costs are related with engine maintenance intervals and system complexity. It can be expected that maintenance intervals will be shorten with using methanol, ethanol and hydrogen as a fuel, and maintenance intervals will be wider with using LNG. It is stated in a study that using natural gas as a fuel at diesel engines increases maintenance intervals threefold to fourfold in comparison with diesel fuel operation (Tawfek et al., 2007). System complexity is another factor affecting maintenance costs.

Consumable costs are lubricating oil costs, spare parts costs and additional costs for the system working. Cheaper lubricating oils with lower total base number (TBN) can be used due to lack of sulfur content in the LNG and hydrogen, and does not need to change lubricating oil within closer intervals than HFO operation. Spare parts using frequency is related with effect of alternative fuels on engine combustion chamber components and maintenance costs.

Additional cost for methanol and ethanol is solvent additive. If they are pre-mixed with diesel or HFO fuels in a tank, solvent has to be added to prevent phase separation of methanol and ethanol from mixed fuel composition. Fumigation method does not need pre-mixed fuel composition. Methanol and ethanol are stored in a separate tank, so system does not need solvents. Hydrogen use by alkaline electrolysis system has additional costs of pure water costs, and potassium hydroxide (KOH) costs. Ship with fresh water generator onboard does not need to supply pure water, but if there is not fresh water generator onboard, pure water costs are added to OpEx. Pure water price is between 35 and 55 USD/mt in Turkey (Saf Su, 2015; Birlik Su, 2015). KOH chemical is used to turn pure water to alkaline water for electrical conductivity. KOH in the solution should be 25–30% mass of total solution to get best conductivity (Mazlooni and Sulaiman, 2012). KOH price changes between 900 and 1200 USD/mt at various manufacturers (Alibaba, 2015). LNG does not have any additional costs for the operation of the fuel system.

Fuel price is an important factor at commercial business. LNG price is higher than methanol and ethanol. Hydrogen use by

alkaline electrolysis system is a fuel production system by consuming pure water, so fuel price is not considered for this system. Table 11 shows ranking of alternative fuels at each cost items.

To evaluate costs of alternative fuels, total costs of each alternative fuels are found from Formula (3) and (4). Formula (5) is used to find the total evaluation point, and determine the evaluation scale intervals.

$$CEP_{ji} = CWP_i \cdot ESP_{ji} \quad (3)$$

$$CEP_{j,TOT} = \sum CEP_{ji} \quad (4)$$

$$CWP_{TOT} = \sum (CWP_i \cdot 5) \quad (5)$$

$CEP_{ji}$  is cost evaluation point of  $j$  type of alternative fuel of  $i$  type of expenditure item,  $CWP_i$  is cost weight point of  $i$  type of expenditure item, and  $ESP_{ji}$  is evaluation scale point of  $j$  type of alternative fuel at  $i$  type of expenditure item at Formula (3).  $CEP_{j,TOT}$  is total cost evaluation point of  $j$  type of alternative fuel at Formula (4), and  $CWP_{TOT}$  is total cost weight point at Formula (5).  $CWP_{TOT}$  is calculated by the sum of all  $CWP_i$ 's multiplied by the highest point of 5.  $CWP_i$  are found by formed frequency-cost proportion matrix table, Table 12.

Investment costs under the CapEx costs are only at the application of the alternative systems with high costs. So, its frequency is the least, and cost proportion is the highest. As a result, investment costs get 4 points. Under the OpEx costs, maintenance costs are assumed as with the frequency of moderate, and cost proportion of moderate, and consumable costs are assumed as with the moderate frequency and the lowest cost proportion. These expenditure items get 4 and 2 points at the matrix table, respectively. Lastly, fuel price

**Table 12**

Frequency-cost proportion matrix table.

| Frequency   | Cost proportion |          |             |             |
|-------------|-----------------|----------|-------------|-------------|
|             | The lowest      | Moderate | Fairly high | The highest |
| The least   | 1               | 2        | 3           | 4           |
| Moderate    | 2               | 4        | 6           | 8           |
| The highest | 3               | 6        | 9           | 12          |

**Table 13**  
CapEx & OpEx comparison of alternative fuels.

| Fuel types         |                       |     | Methanol & ethanol    |                   | LNG                    |                    | Hydrogen               |                    |
|--------------------|-----------------------|-----|-----------------------|-------------------|------------------------|--------------------|------------------------|--------------------|
| CAPEX              |                       | CWP | ESP <sub>ME</sub>     | CEP <sub>ME</sub> | ESP <sub>LNG</sub>     | CEP <sub>LNG</sub> | ESP <sub>HYD</sub>     | CEP <sub>HYD</sub> |
| Investment costs   |                       | 3   | 1                     | 3                 | 3                      | 9                  | 5                      | 15                 |
| OPEX               |                       |     |                       |                   |                        |                    |                        |                    |
| Maintenance costs  | Maintenance intervals | 3   | 1                     | 3                 | 5                      | 15                 | 1                      | 3                  |
|                    | System complexity     | 3   | 3                     | 9                 | 2                      | 6                  | 4                      | 12                 |
| Consumable costs   | Lubricating oil       | 2   | 1                     | 2                 | 5                      | 10                 | 5                      | 10                 |
|                    | Spare parts           | 2   | 1                     | 2                 | 5                      | 10                 | 1                      | 2                  |
|                    | Additional costs      | 2   | 4                     | 8                 | 5                      | 10                 | 3                      | 6                  |
| Fuel price         |                       | 4   | 4                     | 16                | 3                      | 12                 | 5                      | 20                 |
| CWP <sub>TOT</sub> |                       | 95  | CEP <sub>ME,TOT</sub> | 43                | CEP <sub>LNG,TOT</sub> | 72                 | CEP <sub>HYD,TOT</sub> | 68                 |

CWP: cost weight point.

ESP<sub>j</sub>: evaluation scale point of j type of alternative fuel.

CEP<sub>j</sub>: cost evaluation point of j type of alternative fuel.

CWP<sub>TOT</sub>: total cost weight point.

CEP<sub>j,TOT</sub>: total cost evaluation point of j type of alternative fuel.

is assumed that it has the highest frequency and fairly high cost proportion, so it get 9 points at the matrix table.

At the matrix table it is assumed that 1 equals to CWP of 1, 2 and 3 are 2, 4 and 6 is 3, 8 and 9 is 4, and 12 equals to 5. According to this, investment costs and maintenance costs get CWP of 3, consumable costs get 2 and fuel price gets CWP of 4.

CEP<sub>j,TOT</sub> of methanol and ethanol, LNG and hydrogen are found as 43, 72 and 68, respectively at Table 13. Evaluation scale points of Table 3 for each alternative fuels are determined by CWP<sub>TOT</sub> of 95. It is assumed that evaluation scale points are 1 (worst) between 1 and 19, 2 (worse) between 20 and 38, 3 (moderate) between 39 and 57, 4 (fairly well) between 58 and 76, and 5 (best) between 77 and 95. Thus, LNG and hydrogen are 4 (fairly well), methanol and ethanol are 3 (moderate).

#### 4. Results & discussions

The aim of this study is to find the best suitable alternative fuel to use onboard. For this purpose detailed evaluation in various criterions of aforesaid alternative fuels is made. Final comparison table of alternative fuels, Table 18, is formed to find total points of alternative fuels at the end of the comparison. Weight point for each criterion has to be determined at the table, thus ranking of the criterions according to their importance at maritime sector is wanted from five experts who are worked at ships more than 8 years, and has chief engineer license. Ranking is made as from 11 to 1 point. Safety is at the top of the ranking and global availability is at the bottom of the ranking according to answers of the experts. Expert ranking of comparison criterions are shown at Table 14.

**Table 14**  
Expert rankings of comparison criterions.

| Criterion notation | Comparison criterions                          | Expert ranking |
|--------------------|------------------------------------------------|----------------|
| C1                 | Safety                                         | 11             |
| C2                 | Global availability                            | 1              |
| C3                 | Bunker capability                              | 2              |
| C4                 | Durability                                     | 3              |
| C5                 | Adaptability to existing ships                 | 4              |
| C6                 | Effect on engine performance                   | 8              |
| C7                 | Effect on engine emissions                     | 9              |
| C8                 | Comply with emission regulations               | 10             |
| C9                 | Effect on engine combustion chamber components | 5              |
| C10                | Commercial effects                             | 6              |
| C11                | Costs                                          | 7              |

Analytic Hierarchy Process (AHP) is used to calculate weight points of criterions at Table 18. There is scale of relative importance at AHP, which is shown at Table 15. Relative importance of criterions is found by using expert ranking differences of each two criterions. Table 16 shows equivalent relative importance scale of expert ranking difference intervals. Highest expert ranking difference is 10, which is obtained between the difference of 11 and 1.

Comparison matrix is formed with given expert points for all comparison criterions at Table 17. Weighing of every criterions are calculated, maximum eigenvalue ( $\lambda_{\max}$ ) and consistency index (CI) is found for doing consistency check. Average random index is taken as 1.52 (Ren and Sovacool, 2015). Consistency ratio (CR) is 0.093 which is lower than 0.1, and complies with the rule.

Total comparison points of methanol and ethanol, LNG, and hydrogen are 2.129, 4.092 and 3.796 respectively by calculation from Formula (6) and (7). Maximum total comparison point, 5.005, is found by Formula (8) at Table 18.

$$CP_{ij} = WP_i \cdot RP_{ji} \quad (6)$$

$$CP_{j,TOT} = \sum CP_{ij} \quad (7)$$

$$CP_{TOT} = \sum (WP_i \cdot 5) \quad (8)$$

CP<sub>ij</sub> is comparison point for i comparison criterion of j alternative fuel. WP<sub>i</sub> is weight point for i comparison criterion, and RP<sub>ji</sub> is ranking point of j alternative fuel at i comparison criterion in Formula (6). CP<sub>j,TOT</sub> is total comparison point of j alternative fuel in Formula (7). CP<sub>TOT</sub> is maximum total comparison point in Formula (8).

**Table 15**  
Scale of relative importance (Ren and Sovacool, 2015).

| Scales     | Definition             | Note                                                              |
|------------|------------------------|-------------------------------------------------------------------|
| 1          | Equal importance       | i is equally important to j                                       |
| 3          | Moderate importance    | i is moderately important to j                                    |
| 5          | Essential importance   | i is essentially important to j                                   |
| 7          | Very strong importance | i is very strongly important to j                                 |
| 9          | Absolute importance    | i is very absolutely important to j                               |
| 2, 4, 6, 8 | Intermediate value     | The relative importance of i to j is between to adjacent judgment |

**Table 16**

Relative importance scale equivalent of expert ranking difference intervals.

| Scales | Expert ranking difference intervals |
|--------|-------------------------------------|
| 1      | 0                                   |
| 2      | 0–1.25                              |
| 3      | 1.25–2.50                           |
| 4      | 2.50–3.75                           |
| 5      | 3.75–5.00                           |
| 6      | 5.00–6.25                           |
| 7      | 6.25–7.50                           |
| 8      | 7.50–8.75                           |
| 9      | 8.75–10.00                          |

Inferences from the final comparison table are;

- Structural and combustion properties of alternative fuels are taken into consideration. Hydrogen is found to be the safest alternative fuel which can be used onboard,
- LNG fuel usage is a trend nowadays, for that reason it has the most global availability. On the other hand, hydrogen has more bunker capability than any other alternative fuels, because it is produced by alkaline electrolysis system onboard, and only supply need is pure water at ships which does not have fresh water generator. Durability evaluation depends on global fuel reserves, global availability, bunker capability and trends in the

future. Hydrogen use by alkaline electrolysis system uses pure water for hydrogen production, and pure water can be easily found worldwide. Bunker capability of hydrogen is the highest, and trends in the future shows that renewable energies like hydrogen will be in demand in the future. Only defect of hydrogen is lack of global availability, but it does not affect the final result of durability evaluation of hydrogen.

- LNG and hydrogen are the best effective alternative fuels on engine performance by the increasing at BTE, and decreasing at BSFC, in addition to this LNG is considered to be the best effective alternative fuel on engine emissions. LNG is also complies with all emission regulations.
- Hydrogen is placed in front of other alternative fuels in terms of the adaptability to existing ships criterion, due to less system components, simple system structure, no need of large space, and no special tank need for hydrogen storage. Otherwise, LNG use as a fuel has the most positive effect on engine combustion chamber components, because it does not have negative effect on engine components, in addition to this sulfur free structure of the fuel prevents sulfur oxide formation in the engine cylinder. These criteria are related with commercial effects and costs criteria. Commercial effects are associated with cargo loading capacity, fuel amount need for same voyage and bunker capability. Hydrogen does not need storage tank, because it is produced on demand. This does not affect cargo loading capacity. Hydrogen is only use as additive to diesel or HFO, so it cannot be evaluated in

**Table 17**

Comparison matrix of criterions.

| Comparison criterions | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  | C11  | Weighing |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|----------|
| C1                    | 1.00 | 9.00 | 9.00 | 8.00 | 7.00 | 4.00 | 3.00 | 2.00 | 6.00 | 5.00 | 5.00 | 0.265    |
| C2                    | 0.11 | 1.00 | 0.50 | 0.33 | 0.25 | 0.14 | 0.13 | 0.11 | 0.20 | 0.20 | 0.17 | 0.014    |
| C3                    | 0.11 | 2.00 | 1.00 | 0.50 | 0.33 | 0.17 | 0.14 | 0.13 | 0.25 | 0.20 | 0.20 | 0.018    |
| C4                    | 0.13 | 3.00 | 2.00 | 1.00 | 0.50 | 0.20 | 0.17 | 0.14 | 0.33 | 0.25 | 0.20 | 0.025    |
| C5                    | 0.14 | 4.00 | 3.00 | 2.00 | 1.00 | 0.20 | 0.20 | 0.17 | 0.50 | 0.33 | 0.25 | 0.034    |
| C6                    | 0.25 | 7.00 | 6.00 | 5.00 | 5.00 | 1.00 | 0.50 | 0.33 | 4.00 | 3.00 | 2.00 | 0.109    |
| C7                    | 0.33 | 8.00 | 7.00 | 6.00 | 5.00 | 2.00 | 1.00 | 0.50 | 5.00 | 4.00 | 3.00 | 0.147    |
| C8                    | 0.50 | 9.00 | 8.00 | 7.00 | 6.00 | 3.00 | 2.00 | 1.00 | 5.00 | 5.00 | 4.00 | 0.198    |
| C9                    | 0.17 | 5.00 | 4.00 | 3.00 | 2.00 | 0.25 | 0.20 | 0.20 | 1.00 | 0.50 | 0.33 | 0.047    |
| C10                   | 0.20 | 5.00 | 5.00 | 4.00 | 3.00 | 0.33 | 0.25 | 0.20 | 2.00 | 1.00 | 0.50 | 0.062    |
| C11                   | 0.20 | 6.00 | 5.00 | 5.00 | 4.00 | 0.50 | 0.33 | 0.25 | 3.00 | 2.00 | 1.00 | 0.082    |

 $\lambda_{\max} = 12.420$ ,  $CI = 0.142$ ,  $CR = 0.093 < 0.1$ 
 $\lambda_{\max}$ : maximum eigenvalue.

CI: consistency index.

CR: consistency ratio.

**Table 18**

Final comparison table of alternative fuels.

| Comparison criterions                          | Weighing | Methanol & ethanol   |                  | LNG                   |                   | Hydrogen              |                   |
|------------------------------------------------|----------|----------------------|------------------|-----------------------|-------------------|-----------------------|-------------------|
|                                                |          | RP <sub>ME</sub>     | CP <sub>ME</sub> | RP <sub>LNG</sub>     | CP <sub>LNG</sub> | RP <sub>HYD</sub>     | CP <sub>HYD</sub> |
| Safety                                         | 0.265    | 1                    | 0.265            | 3                     | 0.795             | 4                     | 1.060             |
| Global availability                            | 0.014    | 2                    | 0.028            | 4                     | 0.056             | 3                     | 0.042             |
| Bunker capability                              | 0.018    | 2                    | 0.036            | 3                     | 0.054             | 4                     | 0.072             |
| Durability                                     | 0.025    | 3                    | 0.075            | 4                     | 0.100             | 5                     | 0.125             |
| Adaptability to existing ships                 | 0.034    | 3                    | 0.102            | 2                     | 0.068             | 4                     | 0.136             |
| Effect on engine performance                   | 0.109    | 1                    | 0.109            | 5                     | 0.545             | 5                     | 0.545             |
| Effect on engine emissions                     | 0.147    | 3                    | 0.441            | 5                     | 0.735             | 5                     | 0.735             |
| Comply with emission regulations               | 0.198    | 3                    | 0.594            | 5                     | 0.990             | 2                     | 0.396             |
| Effect on engine combustion chamber components | 0.047    | 1                    | 0.047            | 5                     | 0.235             | 1                     | 0.047             |
| Commercial effects                             | 0.062    | 3                    | 0.186            | 3                     | 0.186             | 5                     | 0.310             |
| Costs                                          | 0.082    | 3                    | 0.246            | 4                     | 0.328             | 4                     | 0.328             |
| CP <sub>TOT</sub>                              | 5.005    | CP <sub>ME,TOT</sub> | 2.129            | CP <sub>LNG,TOT</sub> | 4.092             | CP <sub>HYD,TOT</sub> | 3.796             |

RP<sub>j</sub>: ranking point of j type of alternative fuel.CP<sub>j</sub>: comparison point of j type of alternative fuel.CP<sub>j,TOT</sub>: total comparison point of j type of alternative fuel.CP<sub>TOT</sub>: maximum total comparison point.

fuel for same voyage topic. It was mentioned that hydrogen is the most bunker capable fuel. As a result, hydrogen is the most commercially effective alternative fuel. Costs are investigated in two sub-topics as CapEx and OpEx. Hydrogen has the least investment costs, due to less and simple system components. On the other hand, LNG has the least operating costs related to lubricating oil, spare parts and additional costs. At the total costs, LNG and hydrogen are found as the best alternative fuel.

## 5. Conclusion

Aim of this study is to make scientific comparison of alternative fuels which can be used at ships. In this purpose possible alternative fuels which can be used were investigated. Methanol and ethanol are selected from liquid alternative fuels while LNG and hydrogen are selected from gaseous alternative fuels. Because more studies on these fuels were made for both land and marine based applications. Their structural and combustion properties were studied, and various comparison criterions were designated to evaluate these fuels. Lastly, analytic hierarchy process was made to find weighing of each criterion in maritime sector, and calculate the success of alternative fuels.

In spite of there are marine engine studies on methanol and ethanol known by marine engine manufacturers, these fuels have defects such as safety concerns, bunker capability problems, engine performance reduction issues, negative effect on engine combustion chamber components, and lower cost effectiveness. For these reasons methanol and ethanol get the lowest evaluation points at the final comparison table from these criterions, and currently they do not seem to be preferable for use onboard.

LNG has application difficulties to the existing ships due to complex system structure, special designed tanks which occupies large space, and system safety precaution. As a consequence, LNG get the lowest points at the adaptability to existing ships criterion of final comparison table. Although its application difficulties, LNG is a trend at maritime sector nowadays, and it is applied mostly to the new building ships.

Hydrogen use by alkaline electrolysis system has been being used at land based industry to produce hydrogen for many years, but its application on ships is limited. Final comparison table shows that it has inadequacy at compliance with emission regulations, and negative effect on engine combustion chamber components. But this study proves that hydrogen can be used as a fuel at merchant ships, and it is better than LNG fuel at many sides. More studies should be carried out on hydrogen fuel application on marine diesel engines to eliminate the inadequacy of the hydrogen at marine applications. By the improvement of the hydrogen use as a fuel at ships, it can cope with strict emission and energy efficiency regulations, and create an alternative to nowadays trend.

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