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ARTICLE

# Techno-economic study of LNG diesel power (dual fuel) ship

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**Abstract** This article mainly proposed three technically effective alternatives to comply with the emission control regulations and laws in shipping. Liquefied natural gas (LNG)-diesel dual fuel power technology was introduced through feasibility study on several aspects including research development, retrofitting methods, vessel type, safety issues, and other technical characteristics. Based on sample ship and route, economic evaluation was conducted on these three alternatives. Cost-effectiveness of each project was detailed in the calculation of net present value (NPV) and payback time via discount cash flow method. The findings show that LNG-diesel dual fuel power technology performs best among three alternatives. Due to the impact of fuel price, two scenarios were carried out in sensitivity analysis which witnessed a variation of NPV with the fluctuation of fuel price. Further study shows the turning point between project (i) and project (iii) with different discount rate and the interaction between discount rate and fuel price, left project (ii) the least cost-effective solution in three alternatives.

**Keywords** LNG · Dual fuel · Net present value

## 1 Introduction

The recent year has witnessed a growing attention on environment protection. Governments and associations have formulated several measures to reduce air pollution. In shipping industry, particularly, there are EN 2005/33/EC from EU Directive, Marine Agreement Regarding Oil Pollution and Reliability (MARPAL) convention enacted by the International Maritime Organization (IMO) and CARB Title 13/17 in California

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USA, all of which stipulated a detailed schedule and technical guide for emission control in shipping industry (see Table 1)

From Table 1, a stricter emission control on sulfur oxides (SOx) had come into effect last year in the so called emission control area (ECA) where the sulfur content is restricted in 0.1%, while 0.5% is allowed worldwide until 2020. And, the IMO Tier III entered into force this year also put a stringent constraint on nitrous oxide (NOx) emission (see Fig. 1).

Under this circumstance, companies and ship owners usually have three alternative choices to comply with the environment regulations: firstly, to remain current ship situation and reduce SOx and NOx emission respectively through technical methods like equipping a scrubber and selective catalytic reduction (SCR) system; secondly, to change the bunker fuel to lower sulfur content and install an SCR system; and thirdly, adopting new energy like liquefied natural gas (LNG) as marine fuel. All these three alternatives were proved to meet the requirements of emission control policies and regulations (Brynolf, Magnusson, Fridell and Andersson, 2014).

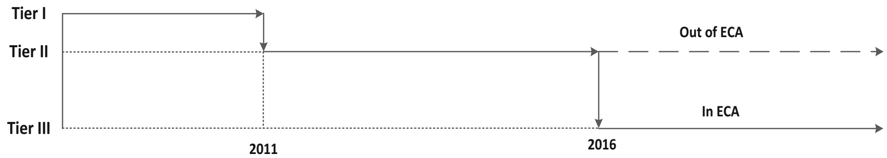
LNG is acknowledged as a clean fuel with no SOx and little NOx emission which is superior to current marine fuels and complies with current and future regulations (Anderson, Salo and Fridell, 2015). Quantitative analysis show that the annual fuel and maintenance cost may decrease by 39 and 30–40% with LNG instead of diesel oil (Banawan, El Gohary and Sadek, 2010; El-Gohary 2012). In contrast with the high fluctuation of heavy fuel oil (HFO) price affected by several factors as political and regional issues, LNG price is more stable from a historic view that implies LNG as a good alternative for traditional fuel (Herdzik, 2011). But, problems occur when it is applied to a normal diesel engine that the so called CH4 slip might increase the pollution of greenhouse gases (Brynolf, Magnusson, Fridell and Andersson, 2014). Jerzy Herdzik's research found that the burning speed is too slow to use LNG in a diesel engine directly. And, with the increment of engine load, risk of energy loss and

**Table 1** Emission control regulations and conventions

| Regulations/convention | S% | Date into execution | Area |
|---|---|---|---|
| MARPOL VI | 3.5 | 1 Jan 2012 | Out of ECA |
| | 0.5 | 1 Jan 2020 | |
| | 1 | 7 Jan 2010 | In ECA |
| | 0.1 | 1 Jan 2015 | |
| EU | 0.1 | 1 Jan 2010 | EU ports |
| CARB | 1.5 | 7 Jan 2009 | 24 nm off California coast and within ports |
| | 0.5 | | |
| | 1 | 8 Jan 2012 | |
| | 0.5 | | |
| | 0.1 | 1 Jan 2014 | |
| | 0.1 | | |

S% of 1.5 and 0.5 aim at MDO and MGO respectively

Source: CCS




Source: IMO

**Fig. 1** Time schedule of IMO regulation for NOx. Source: IMO

self-burning may arise which request the jet system to conduct a retrofitting accordingly (Herdzik, 2011).

Even if major roadblocks still exist as lack of bunkering supply system and loss of cargo space occupied by LNG tanks, the application of LNG as a hybrid fuel on board is on its way in non-LNG carriers (Herdzik, 2012). GL and MAN jointly conducted a cost-effectiveness analysis of LNG as fuel on container ships from 2500TEU to 18,000TEU. Four technical solutions were proposed as scrubber, scrubber and waste heat recovery (WHR) system, LNG system, and LNG with WHR system. The findings show that the difference in price between LNG and oil and retrofitting cost were two main factors affecting companies' decision making. And, when the price of LNG became lower or the same as HFO, 2500TEU container ship would have a better economic scenario. Transport Research Board's (TRB, 2013 (http://www.lngbunkering.org/sites/default/files/2013%20HEC%20lng%20effect%20on%20ship%20design.pdf)) report about LNG as marine fuel made an elaboration of the ship type, propulsion options, LNG fuel system and bunkering, operation, and design of LNG-fueled container ships. It indicated that suitable ship types for LNG power were restricted in tug, ferry, and other short route or coast sailing ships. Further, construction and equipment costs as economic analysis factors were compared between two container ships around 1000TEU, one in LNG fuel and the other in marine gas oil (MGO). Statistics show that the construction cost of LNG powered ship was 20% higher than its counterpart but could be covered by its savings on fuel cost and other environmental value; for example, LNG did not have to pay the carbon tax and had tax concession in some ports as an incentive (Burel, Taccani and Zuliani, 2013). Recent studies also focus on LNG storage on board the ship, Japan Marine United Corporation (JMU) has developed an LNG fuel gas system employing an IHI-SPB gas fuel tank for LNG-fueled ship, and the case study demonstrate that it fits well on large container ships (Yoshinori, 2015).

Above all, researches about LNG as marine fuel have made progress. LNG-diesel dual fuel was accepted by the industry and expounded and proved in reality which showed better environmental protection and cost-efficiency. Nevertheless, thanks to the low price of oil fuel at present, environmental regulation under formulation, and extra cost for new technology, LNG is only a regional solution especially in north Europe; nearly 81% of the LNG fueled fleet was in Norway (DNV GL, 2015 (https://www.dnvgl.com/Images/DNV%20GL_LNG%20Report%202015_tcm8-24903.pdf)). At the same time, few studies have focused on the effect of price fluctuation on cost-efficiency of LNG diesel fuel ship as well as in bigger ships. Based on these situations, this article trise to make a further step on the techno-economic analysis on ocean transport LNG diesel dual fuel power ships and other technical alternatives complying with present and future emission regulations including the effect of price factor in these alternatives.

## 2 Method

In order to highlight the cost-efficiency of new technologies, three common alternatives complying with current and future emission control regulations talked above are introduced hereunder:

i. IFO + Scrubber + SCR
ii. Diesel + SCR
iii. LNG-diesel dual fuel

For project (i), it means the remaining current ship situation in intermediate fuel oil (IFO) and reducing SOx and NOx emission respectively through technical proposals by retrofitting a scrubber and selective catalytic reduction (SCR) system. Project (ii) suggests to change the bunker fuel refined to lower sulfur content, MGO (0.1%S), or marine diesel oil (MDO, 0.5%S), with an SCR system. Project (iii) takes LNG as the main power fuel and diesel as auxiliary fuel in a dual fuel engine like Wärtsilä X92DF.

A real vessel operating on Asia-Europe route was selected as the sample ship, COSCO VIETNAM, to conduct the cost-efficiency analysis. COSCO VIETNAM is an 8501TEU container ship operated by COSCO (COSCO SHIPPING Holdings Co., Ltd) on its Line NE6 start from port of QINGDAO to Port of HAMBURG at north Europe via the Suez Canal with a round voyage in 77 days. Particular parameters can be found in Tables 2 and 3.

Table 4 lists the engine output, fuel consumption rate, and switch of fuel on each project. (i) and (ii) remain the diesel engine while (iii) is retrofitted to a two-stroke dual fuel (DF) engine with a load decline to 58,400 kw. Given a 10 years' evaluation time,

**Table 2** Voyage schedule of COSCO VIETNAM

| Port of call | ETA | Time | ETD | Time |
|---|---|---|---|---|
| Qingdao | Sat | 0 | Sun | 1 |
| Gwangyang | Tue | 3 | Thu | 3 |
| Pusan | Wed | 4 | Tue | 5 |
| Shanghai | Fri | 6 | Sat | 7 |
| Yantian | Mon | 9 | Tue | 10 |
| Singapore | Fri | 13 | Sat | 14 |
| Algeciras | Wed | 32 | Thu | 33 |
| Hamburg | Mon | 37 | Wed | 39 |
| Roterdam | Thu | 40 | Sat | 42 |
| Le Havre | Sun | 43 | Mon | 44 |
| Algeciras | Thu | 47 | Fri | 48 |
| Singapore | Thu | 68 | Thu | 68 |
| Yantian | Tue | 73 | Tue | 73 |
| Qingdao | Sat | 77 | | |

ETA/ETD: estimated time of arrival/departure

Source: www.cosco.com

**Table 3** Ship parameters

| Capacity | 8501TEU |
|---|---|
| LOA | 334 m |
| Lpp | 319 m |
| B | 42.8 m |
| D | 14.61 |
| Main engine output (total) | 68,530 mkW (97 rpm) |
| Auxiliary output (total) | 11,000 ekW(60 Hz) |
| Fuel consumption | 250 t/day(24.5knot) |
| Chartering rate of sister ships | $24,000/day |

Source: Clarkson

the operation program is divided into two phases, 5 years each, mainly on the different fuel decision out of ECA due to the upcoming emission regulation in 2020. The first phase is shown as “out of ECA (Acciaro, 2014)” which represent the years 2015 to 2020 and 2021 to 2025 on behalf of out of ECA (Adachi et al., 2014) in Table 4. As described above, project (i) still use the bunker fuel of present quality, mostly IFO380 in practice, whatsoever, in or out of ECA during the whole time schedule. With regard to projects (ii) and (iii), IFO will be applied out of ECA during the first phase and MDO will take its position as the component of dual fuel in ECA.

Moreover, attention should be put on that LNG as marine fuel has special requirement for storage. As per IMO’s regulation, type C storage tank needs to be used to reduce the percolation of heat and thus vaporization of LNG. Due to the fact of inevitable vaporization when LNG bunkering, 100% bunkering cannot be promised and a ratio of bunkering at 93.6% was seen according to Masaki Adachi’s study

**Table 4** Engine parameter and fuel choice

| Project | i | ii | iii |
|---|---|---|---|
| Main engine | | | |
| Type | Two-stroke diesel | Two-stroke diesel | Two-stroke DF |
| Total output | 68,530KW | 68,530KW | 58,400KW |
| Fuel rate (g/kwh) | 152 | 152 | 174 |
| Auxiliary | | | |
| Type | Diesel | Diesel | Dual fuel |
| Units | 4 | 4 | 4 |
| Per output | 2750 KW | 2750 KW | 2700 KW |
| Fuel rate (g/kwh) | 197 | 197 | 217 |
| Fuel | | | |
| In ECA | IFO | MGO(0.1%S) | LNG + MGO |
| Out of ECA (Acciaro, 2014) | IFO380 | IFO380 | LNG + IFO380 |
| Out of ECA (Adachi et al., 2014) | IFO380 | MDO (0.5%S) | LNG + MDO |

Source: Author and Masaki Adachi etc.

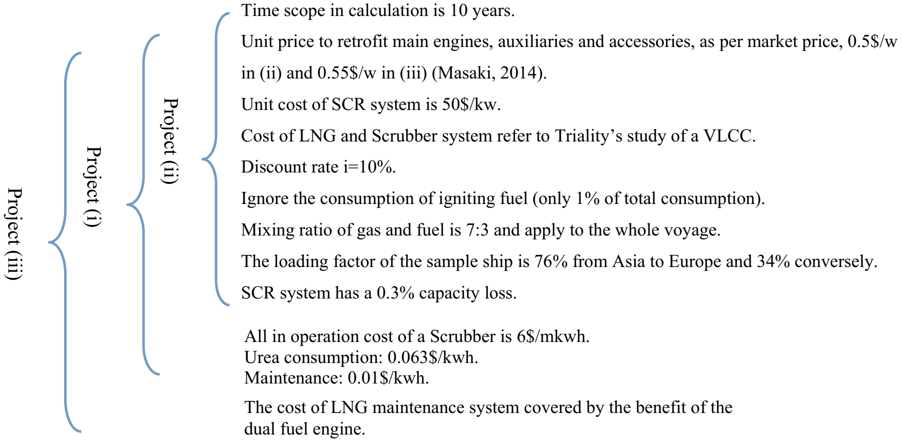



**Fig. 2** Assumptions of each project

(Adachi et al., 2014). So, the capacity of the tank should be 14,583 $m^3$ at least since 1.2 $m^3$ LNG is equivalent to 1 kg of oil fuel due to the statistics from Tables 3 and 4.

In order to simplify the calculation process, the boil off gas is supposed to be completely consumed in the boiler and SCR burning system.

## 3 Cost-efficiency analysis

Cost-efficiency analysis are adapted to measure the difference among three alternatives and divided into three parts: retrofitting cost, operation situation, and fuel cost. Figure 2 shows the assumptions of each project:

### 3.1 Retrofitting cost

Based on the statistics of Table 3 and 4 and the assumptions above, the retrofitting cost of main engines; auxiliaries; and scrubber, SCR and LNG systems are calculated in Table 5; the price gap between projects (i) and (ii) is 440 m$ and 1131.6 m$ for (ii) and (iii). The retrofitting cost of the LNG system seems to be far higher than of the other two alternatives.

**Table 5** Retrofitting cost of each project

| Million $ | IFO + scrubber + SCR | MGO + SCR | LNG + MGO |
|---|---|---|---|
| Main engine | 34.265 | 34.265 | 32.120 |
| Auxiliary | 1.375 | 1.375 | 2.700 |
| Scrubber | 4.400 | 0.000 | 0.000 |
| SCR system | 3.564 | 3.564 | 0.000 |
| LNG system | 0.000 | 0.000 | 15.700 |
| Total | 43.604 | 39.204 | 50.520 |

**Table 6** Freight price form Shanghai to North Europe

| $/TEU | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|
| SH-NE | 1395 | 1789 | 881 | 1353 | 1084 | 1172 | 1056 |

## 3.2 Operation situation

Operation situation in this article include the annual revenue and operating cost of the emission control system. With regard to liner shipping practice, income mainly comes from the freight revenue while the cost contains shipping maintenance, harbor dues, crew fee, insurance, so on and so forth. For the reason given above that this article focuses on project evaluation, this study hereby takes only the operating cost of the retrofitting systems into account.

As freight revenue is the function of freight rate and freight volume (in TEU), freight rate and volume on the Asia-Europe route should be input as dependent variables. According to the latest report of UNCTAD and Clarkson, the annual container freight rate from Shanghai to north Europe is listed in Table 6 (2015 only include the first quarter). Excluding the unusual value in 2010 and 2011, taking average of the remaning 5 years, the average annual freight revenue is 1212$/TEU. And, the rate from north Europe to Shanghai is set at two thirds of it, which is approximately 800$/TEU based on market experience.

Depending on the study of MAN Diesel and Turbo, the SCR system has a 0.3% capacity loss (MAN, 2012 (http://www.ngva.eu/images/MAN-Rene-Sejer.pdf)). When it comes to project (iii), the LNG tank may occupy the cargo capacity directly by 471TEU converting from 14,583 $m^3$. And, Fig. 2 shows the capacity loss on the annual revenue (see Fig. 3).

With respect to the operation cost including the consumption of material and maintenance, each system has its own factors needed to be considered. A scrubber is equipped to filtrate the sulfur in the exhaust gas in project (i) whose operation relies heavily on the sodium hydroxide consumption, pumping, and water consumption. Considering its working hour in ECA, this article adopts the starting and end point at port of Algeciras, namely, 42.66 days in ECA. And, the main engine is set to be fully

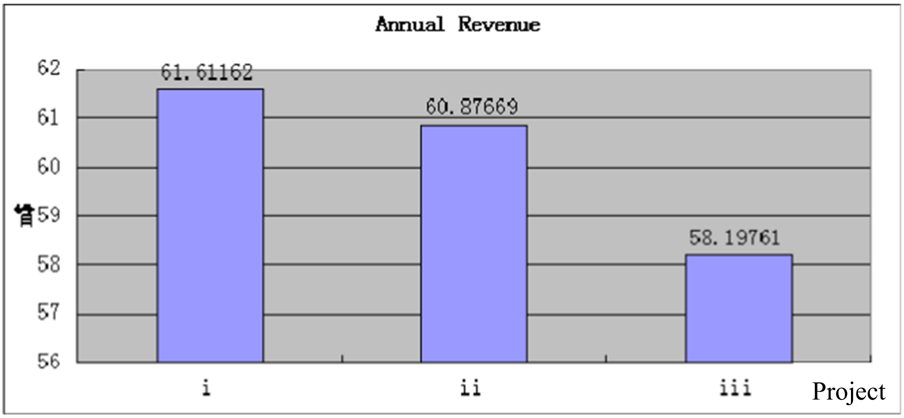



**Fig. 3** Annual revenue

**Table 7** Annual cost

| Cost/$ | Fuel | Scrubber | SCR | Total |
|---|---|---|---|---|
| Annual cost 2015–2020 | | | | |
| i | 26,517,309.25 | 437,876 | 5,327,490 | 32,282,675.25 |
| ii | 29,035,987.01 | 0 | 5,327,490 | 34,363,477.01 |
| iii | 21,967,462.91 | 0 | 0 | 21,967,462.91 |
| Annual cost 2021–2025 | | | | |
| i | 26,517,309.25 | 3,746,477.73 | 5,327,490 | 35,591,276.98 |
| ii | 44,050,759.74 | 0 | 5,327,490 | 49,378,249.74 |
| iii | 22,917,712.91 | 0 | 0 | 22,917,712.91 |

loaded with one auxiliary while the scrubber is under operation, so the output should be 71280 kw according to Table 4; thus, the annual cost of the scrubber system is US$437,876. The International Association for Catalytic Control of Ship Emissions to Air (IACCSEA) has lucubrated the efficiency and cost of the SCR system, so as the calculation of scrubber system, the annual cost of the SCR system is US$5,327,490 in projects (i) and (ii). In addition, Meike Baumgart found that the LNG diesel dual fuel engine had a longer life time than do other ordinary diesel engines which had a potential benefit for future utility that could cover the maintenance cost of the whole lifetime, so this calculation did not take the maintenance cost of the LNG system into consideration. (Baumgart and Olsen, 2010).

## 3.3 Fuel cost

Shipping companies always choose Singapore and Rotterdam as port of bunkering because of the comparatively low fuel price in Asia and Europe. Since shipping companies always have fuel hedging to lock their fuel cost, the fuel price is set as the average price in December 2014. From the report of Bunkerworld and Clarkson, the price of different kinds of fuel in Singapore were IFO380 = 366$/t, MDO = 592.5$/t, MGO = 602.5$/t and, in Rotterdam were IFO380 = 322.5$/t, MDO = 548.5$/t, MGO = 558.3$/t.

The price of LNG is estimated from the local market of Rotterdam which has finished the construction of the LNG bunkering system invested by Shell and Singapore on Jurong Island in 2013. As per ICIC's report, the corresponding price of LNG in those two ports are US$332.8 and US$249.6 per cubic meter, respectively.

Above all, the annual cost of each alternative is calculated in Table 7.

**Table 8** NPV and NPV rate

| Project | NPV | NPV rate |
|---|---|---|
| i | 145.63 m$ | 3.34 |
| ii | 103.48 m$ | 2.64 |
| iii | 189.34 m$ | 3.75 |

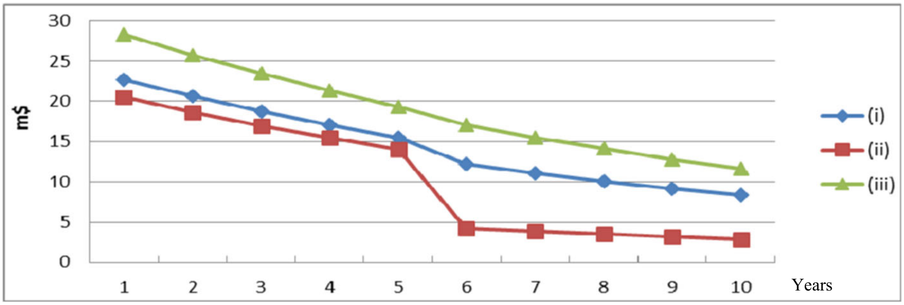



**Fig. 4** NPV year by year

## 4 Net present value

Net present value (NPV) is defined as the sum of the present values (PVs) of incoming and outgoing cash flows over a period of time. Incoming and outgoing cash flows can also be described as benefit and cost cash flows, respectively (Acciaro, 2014). NPV is used as a financial indicator to make comparison with each project so as to decide which one is the best choice. The formula is

$$\mathrm{NPV} = \sum_{j=o}^{n} \frac{C_j}{(1+i)^j} = \sum_{j=1}^{n} A_j(P/\mathrm{A}, i, j) + R(P/F, i, n) - P \quad (1)$$

where $j$ is the number of year; A$j$ and C$j$ stand for the revenue and net cash flow, respectively, in year $j$; $n$ is its life time, set as 10 years in this article; $i$ represents the discount rate, 10%; $R$ as scrap value, 0 at year 10; and $P$ is the initial investment of each project.

Statistics show that project (iii) is the highest, either in NPV or NPV rate, (see Table 8):

The value seems to be high due to the excluding of construction cost and other operating cost. Meanwhile, project (iii) performs best among these alternatives while (ii) beyond the expectation which indicate that changing fuel is not a good idea in the game between cost-efficiency and emission control. In details, year by year, from Fig. 4, the curve of project (i) is smooth while the other two have a drop after 5 years because of fuel switching. This means projects (ii) and (iii) are more vulnerable to the fluctuation of fuel price.

The pay back time (PBT) of each alternative, depending on the formula, indicate the risk of projects:

$$\mathrm{PBP} = \frac{\lg\left(\frac{A}{A-Pi}\right)}{\lg(1+i)} \quad (2)$$

where $A$ is annual revenue; $Pi$ is the same in the formula above. So, the PBT of projects (i), (ii), and (iii) are 2.07, 2.06, and 2.01, respectively, which means project (iii) have

**Table 9** IRR of each project

| Project | i | ii | iii |
|---|---|---|---|
| IRR | 41% | 38% | 46% |

Source: Author's research

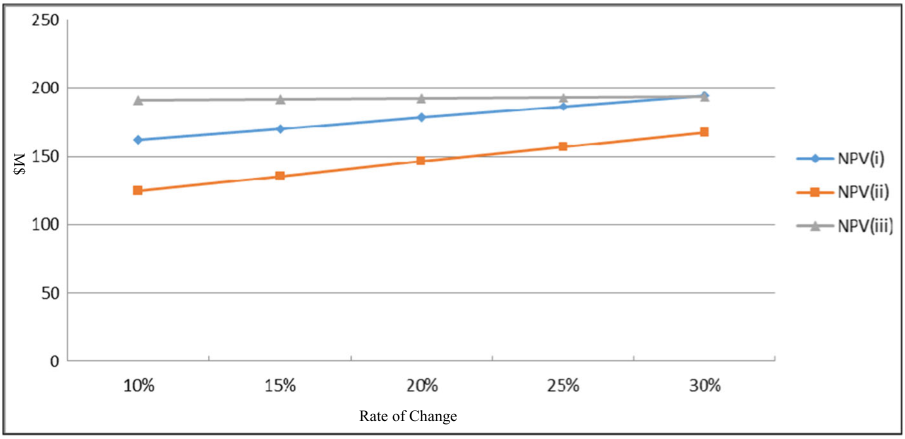



**Fig. 5** Situation under steady LNG and droping oil price

the lowest risk in the three alternatives.

In addition, internal rate of return (IRR) is calculated below that also tells project (iii) is the best performer followed by project (i) (Table 9).

## 5 Sensitivity analysis

In the last 2 years since 2008, the fuel price fluctuated between 250 and 664$/t (IFO380) and 479.5–958.3$/t (MGO) where sensitivity analysis was conducted. The analysis concentrated on the rise of LNG price and slump of oil. Rate of change was set by 10, 15, 20, 25, and 30%. Figure 5 is the situation where oil price dropped while LNG price was kept steady. The intersection of curve, projects (i) and (iii) are at nearly 30%, precisely 29.31%, where (i) catches up to (iii), becoming the most profitable project. And, Fig. 6 shows the scenario of rising LNG price and steady oil. The intersection also expresses that when LNG price rises by 35%, project (i) will be the best performer.

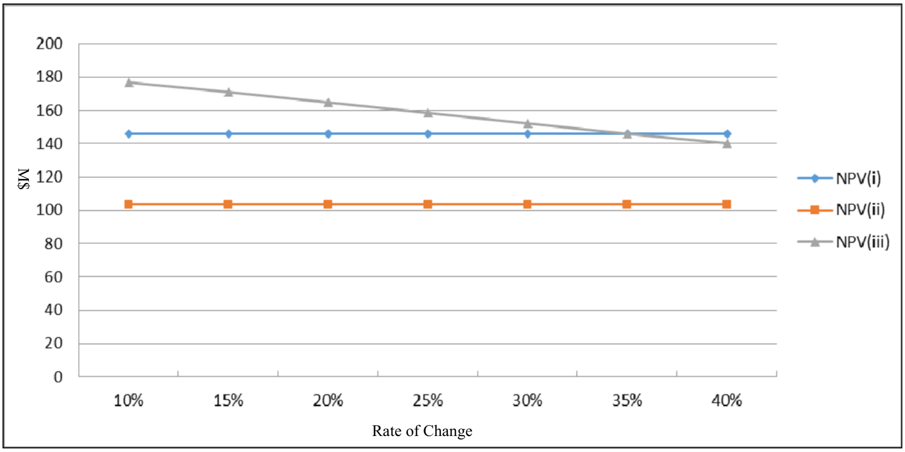



**Fig. 6** Situation under steady oil and rising LNG price

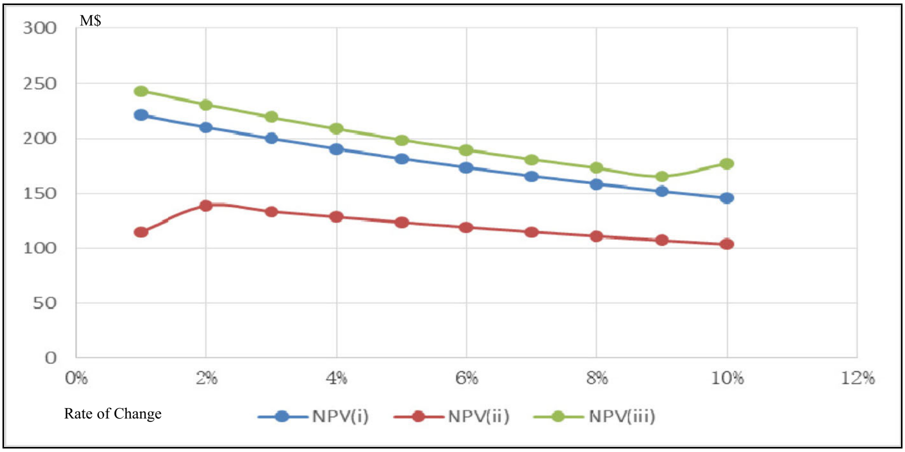



**Fig. 7** NPV change with discount rate

What is more, the result may also be affected by the discount rate. Discount rate, as variable here, was selected according to Weitzman's finding (Weitzman, 1998) and company practice. As per Weitzman, social discount rate declines over time due to many uncertainty factors, and when it comes to company, the discount rate is affected by the social discount rate; however, companies have to lock their benefit, so it is not simply the same and should be adjusted on the basis of social discount rate. So, in this article, comparison was made among different discount rates, from 10 to 1% (see Fig. 7).

Last but not least, the joint influence of fuel price and discount rate was analyzed. In Fig. 8, scenario 1 means the turning point between projects (i) and (iii) at different rates of dropping oil price with the changing discount rate. In contrast, scenario 2 shows the condition of increasing LNG price. Take 1% discount rate for example, when the discount rate is 1% and oil price drop by 29.92%, or LNG price rises by 27.83%, project (i) is prior to project (iii), so on and so forth. The trend of the curve can draw the conclusion that discount rate does affect the result of this study and higher rate may decline the turning point between projects (i) and (iii); however, there is no signal for

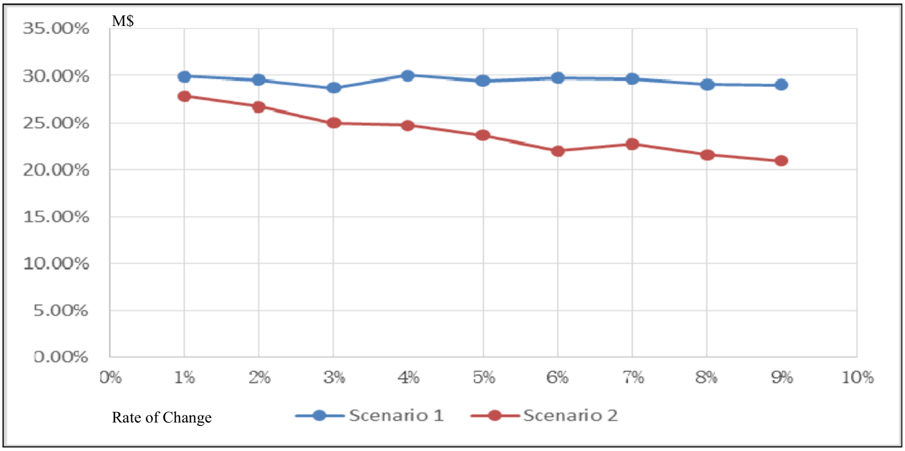



**Fig. 8** Turning point between projects (i) and (iii)

the influence of project (ii) since it is the last choice between these alternatives when the discount rate is under 10%. The point of intersection exists when the discount rate reaches 20%, but this point is too theoretical and does not comply with the real situation according to Weitzman (1998).

## 6 Conclusion

This article mainly proposed three technically effective alternatives to comply with the present and future emission control regulations in shipping industry. The findings show that LNG-diesel dual fuel power technology performs best among the three alternatives. Due to the impact of fuel price on the conclusion, two scenarios were carried out in sensitivity analysis which witnessed a variation of NPV with the fluctuation of fuel price. Further studies show the turning point between project (i) and project (iii) with different discount rates, and the interaction between discount rate and fuel price made project (ii) the least cost-effective method in three alternatives. The superiority of LNG technology was foreseen as the industry is reacting step by step and factors like ship size, load distance, route choice, stricter regulation, and technology breakthrough will have an impact on the outcome and further affect the decision of shipping companies. On the other hand, the usage of LNG technology on board the ship will change the development of policy. Policy makers may react on not only the social and environmental benefit but also on the reaction of shipping companies. That is, if the trend of LNG as marine fuel becomes popular thanks to overcoming technical shortcomings, stricter regulations and schedules might appear on the stage and vise versa. So, future study is recommended on these factors.

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