Technoeconomic evaluation of energy efficiency retrofits in commercial shipping; a bulk carrier case study

A. Tsereklas-Zafeirakis[1*], K. Aravossis[1], G. Gougoulidis[2], Y. Pavlopoulou[1]
[1]Department of Mechanical Engineering, Sector of Industrial Management and Operational Research, National Technical University of Athens, 15780, Athens, Greece
[2] Department of Naval Architecture and Marine Engineering, Hellenic Naval Academy, 18539, Piraeus, Greece
*Corresponding author: e-mail: a.tsereklas@gmail.com, Tel: +302106197591, Mob: +306978163763

Abstract

The present study approaches the maritime sector from an environmental point of view. In light of the new IMO directives on climate change and the continuous effort to reduce operating costs, this paper investigates the viability of several energy efficiency technologies. The introductory part discusses the environmental problem caused by the gaseous pollutants and describes the existing and future regulatory framework that either has been or will be imposed in order to mitigate the impact of the shipping industry. In the main part, a series of fifteen (15) energy efficiency retrofits, suggested by IMO, are briefly analyzed with a view to applying them on a bulk carrier. This analysis conducts a technoeconomic evaluation of these retrofits as potential investments from an owner's strategic point of view. The assessment, taking into account major uncertainties of the data used, concludes that the vast majority of methods prove to be initially acceptable for investment.

Keywords: IMO; energy efficiency; SEEMP; technoeconomic evaluation; SO_x; bulk carrier; Monte Carlo.

1. INTRODUCTION

The importance of the adverse effects of global warming has been understood by the scientific community since the late sixties. It took more than twenty years till the first adaptation of measures against global warming with the foundation of the Intergovernmental Panel on Climate Change in 1988 and the Kyoto Protocol agreement in 1997. According to the latest updates by the Earth System Research Laboratory in Hawaii, in 2013, CO_2 concentrations for the first time in recorded history exceeded 400 parts per million. International shipping, which accounts for over 90% of global transport, is estimated to have emitted 870 million tonnes, or about 2.7% of the global emissions of CO_2 in 2007 [1]. Today, the International Maritime Organization (IMO) has proposed a plethora of policies that target to the reduction of the gaseous pollutant emissions. The importance of such policies stems from the fact that strict emission limits already imposed, are expected to gradually lower more over the next twenty years. In addition to these measures, the bunker prices reaching an all-time peak in 2012 (Rotterdam 380cst: 712$/t) along with the extremely low hire rates as a consequence of the general economic crisis, make it clear for the shipping companies that new technologies have to be implemented in order to achieve a sustainable future [2].

Several publications have appeared in recent years documenting the potential benefits of implementing innovative energy efficiency improvement methods. The most interesting and comprehensive approach to this issue has been reported in a study by IMO [3], where the economics and cost effectiveness of technical and operational measures to reduce CO_2 emissions from ships are investigated. However, this study is intended primarily to evaluate the cost-benefit relationship of each method, where benefit is defined as the overall anticipated reduction in carbon dioxide. Other studies compare the viability of a limited number of measures in certain types of newbuilds, [4], [5], [6], and [7].

This paper conducts a technoeconomic evaluation of a series of fifteen (15) energy efficiency retrofits, suggested by IMO in SEEMP Annex [8], when applied on an existing vessel. The technoeconomic model developed, takes into account the future regulatory framework, delivers fuel oil price forecasts and assesses the data uncertainty through Monte Carlo simulations. Finally, a multicriteria analysis is proposed where several non-financial factors are also implemented in order to reach a fair and valid classification of the energy efficiency retrofits.

1.1 Measures on CO_2, NO_x, SO_x Emissions

As stated in the aforementioned paragraphs, IMO has proposed a series of measures that aim to reduce the pollutant emissions. More specifically, EEDI (Energy Efficiency Design Index) provides a specific figure for an individual ship design, expressed in grams of carbon dioxide per ship's capacity-mile and is calculated by a formula based on the technical design parameters for a given ship. The CO_2 reduction level (grams of CO_2 per tonne mile) for the first phase is set to 10% and will be tightened every five years to keep pace with technological developments of new efficiency and reduction measures. Moreover, under the revised MARPOL (Marine Pollution) annex VI, progressive reductions in NO_x emissions from marine diesel engines installed on ships are also included. Lastly, since 2006 extended discussions have been made to the possibility of an adoption of a Market Based Measure (MBM), which will place a price on GHG emissions providing an economic incentive to the maritime industry to lower its consumption.

However, the most important regulation that is going to seriously affect the fuel oil price in the foreseeable future and create a new reality in commercial shipping is the measure on SO_x emissions. IMO has introduced the Emission Control Areas (ECA) to reduce SO_x emissions further in designated sea areas. According to the requirements, in 2015 all vessels sailing in the ECA must reduce the sulphur level in fuel oil to 0.1% from 1%. Similarly in 2020 or 2025, the global requirements will be a reduction of the sulphur content in the fuel to 0.5% from a current 3.5%.

2. METHODOLOGY

2.1 Retrofits and ship presentation

The retrofits under evaluation cover a wide range of existing technologies and are further divided into four (4) main categories:

a. **Main Engine Modifications**
    - **Engine Derating**: lowers the mean ratio between mean effective pressure and maximum pressure in the combustion chambers and increases the thermal efficiency [9]
    - **Waste Heat Recovery System (WHRS)**: utilizes the exhaust gas energy
    - **Autotuning**: automatically optimises and monitors the maximum combustion pressures inside the chamber [4]
    - **LNG Conversion**: liquefied natural gas engine/tanks installation [5]

b. **Propeller flow optimization** [7]
    - **Nozzle**: airfoil shaped rings around the propeller that increase the total thrust
    - **Mewis Duct**: a combination of a vertically offset mounted duct positioned right in front of the propeller and an integrated asymmetric fin arrangement
    - **Costa Bulb:** a bulb attached to the rudder directly behind the propeller boss
    - **Propeller Boss Cap Fins (PBCF):** small fins attached to the propeller hub that reduce the hub vortex generation
    - **Integrated rudder and propulsion manoeuvring system:** e.g. Promas Lite

c. **Improvement of vessels operational profile**

- **Weather Routing:** a procedure to determine an optimum route based on the forecasted environments and seakeeping performance of a particular transit [10]
- **Optimal Trim:** decision support tool designed to provide guidance in selection of the right trim in relation to the loading condition and planned speed [11]
- **Fouling Release Coating (FRC):** reduces average hull roughness, thereby increasing hydrodynamic efficiency [12]
- **Hull and Propeller Cleaning:** underwater maintenance program implementation (it will be evaluated separately as a best practice) [1]

d. **Utilization of renewable energy sources** [3]
   - **Wind (Flettner) Rotors:** aid the ship's propulsion by means of the Magnus effect
   - **Wind Kites:** automatic towing kite propulsion and wind-optimised routeing system

The vessel selected for the evaluation is a Panamax bulk carrier (dwt: 78932 tonnes) named M/V Panamax Sterling. The main engine used is a Mitsui MAN 7S50MC-C operating at a Maximum Continuous Rating (MCR) of 9561kW at 110rpm. The engine is equipped with one MAN turbocharger model B&W TCA66. The overall length of the ship is 225m, the length between perpendiculars 219m, the beam 32.24m and the draught on summer freeboard 14.37m. The service speed of the ship is 13.5 knots and the ships operation profile includes 200 days per year at sea, of which 25 (or 12.5%) are within the ECA. At last, the main engine’s fuel specific consumption at the abovementioned MCR is 169g/kWh, which results in a daily main engine consumption of 27-31 tonnes of Heavy Fuel Oil.

The selection of the Panamax Sterling is based on the wide usage of similarly designed vessels and consequently the generalization we can deduce on the results of the study. More specifically, in 2013 bulk carriers accounted for 42% of the total world’s tonnage with an average vessel size of 68366dwt. In addition, oil tankers, which share technical characteristics with bulk carriers operating at similar service speed, account for another 30.1% of the total tonnage. At last, the age of the ship (built in 2007) was selected so that by the end of the evaluation period in 2030 it will be at the average demolition age of its type, namely 30-32 years [13].

The consumption reduction (CR) as well as the capital expenditure estimation of the above mentioned retrofits for the specific vessel is summarized in Table 1.

Table 1. Retrofits capital expenditure/ consumption reduction/ estimation of applications

s/n	Description	Capital expenditure ($)	Minimum CR (%)	Estimated CR (%)	Maximum CR (%)	Number of applications
1	Weather Routing	3000	0.1%	2%	4%	>3000
2	Engine Derating	1100000	2%	4%	6%	nk
3	Optimal Trim	150000	1%	2%	5%	800
4	PBCF	80000	2%	4%	5%	2000
5	Nozzle	150000	2%	6%	10%	nk
6	Costa Bulb	270000	2%	3%	4%	300
7	Promas Lite	1000000	6%	7%	9%	30
8	Mewis Duct	350000	4%	6%	9%	400
9	FRC	390000	5%	7%	9%	500
10	Autotuning	40000	1%	2%	3%	nk

11	WHRS	1600000	8%	9%	10%	nk
12	Wind Kites	1400000	4%	8%	12%	10
13	Wind Rotors	1200000	8%	9%	12%	1
14	LNG	7600000	*	*	*	400

*this retrofit will be evaluated by the price difference of HFO and LNG
nk: not known

2.2 Technoeconomical model

The approach used in order to develop the technoeconomical model included the determination of a basic scenario, in which the estimated values of each factor (estimated consumption reduction, fuel oil prices, days within ECA, operational costs et al) were used in order to calculate the expected cash flows for each individual retrofit throughout the investment horizon 2015-2030. The discount rate was then estimated for the basic scenario through the utilization of the Weighted Average Cost of Capital (WACC) formula [14] for seven (7) shipping companies listed on NASDAQ stock market. In the end, the evaluation indicators, namely the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Profitability Index (PI), were calculated. The latter was further used in the sensitivity analysis and the quantitative risk assessment due to its characteristic to evaluate more precisely investments with different initial capital expenditure [15]. PI is the ratio of the Present Value (PV) of the cash flows to the initial investment. A ratio of 1.0 is the lowest acceptable measure on the index.

2.3 Fuel price projections

According to paragraph 1.1, in 2020 or 2025 all vessels sailing outside ECA must reduce the sulphur level in fuel oil to 0.5% from a current 3.5%. Such a measure will automatically mean that the wide usage of Heavy Fuel Oil (HFO) have to be abandoned due to the technical limits that exist when blending different kinds of fuel oils. DNV suggests that by that year the demand for Marine Gas Oil (MGO) will rise to 200-250 million tonnes from a current 30 million tonnes and correspondingly HFO demand will dwindle to 80-90 million tonnes from 290 million tonnes in 2012 [16]. Although a medium to long-term estimation of the fuel oil prices hides an uncertainty that is difficult to gauge, this study approaches this task on a step to step basis and is based on the latest bibliographic data. It is evident that the results of this study cannot be based on a single value. This weakness is equilibrated through Monte Carlo simulations that will be introduced in the following paragraph and can help to further solidify the conclusions on that matter.

The first step takes into account the crude oil price projections reported by the Energy Information Agency (EIA) [17] for the years 2020, 2025 and 2030 and converts them into HFO prices through the diachronic correlation of the West Texas Index ($/barrel) and the HFO180 ($/tonne) of Singapore. This results in a rate of 580, 640 and 700 $/t respectively. The second step includes the estimation of the Low Sulphur Fuel Oil price (LSFO: <0.5% Sulphur Content) that will replace HFO in 2020 or 2025. While several publications have appeared demonstrating a 30-50% difference in HFO (1.5%) and LSFO (0.5%) price [3], [19], [18], others equate the price of LSHO with that of MGO (0.1%) [5]. In general, doubt arises as to attaining the required availability of LSFO (0.5%) in 2020 or 2025, when in 2009 only 0.5% of the fuel used by global marine traffic was heavy fuel oil with a sulphur content of less than 0.5%. For our basic scenario we estimated that LSFO will cost 35% more than HFO resulting in 790, 870 and 950 $/t and MGO will cost 70% more than HFO resulting in a rate of 995, 1100 and 1200 $/t respectively. Finally, a 17% price difference between LNG and HFO is estimated based on the study of the Danish Maritime Authority, which equals to 585$/t (euro to dollar currency: 1.33) in 2030 [20]. For visual representation of the fuel oil prices estimations, the reader is referred to Figure 1.

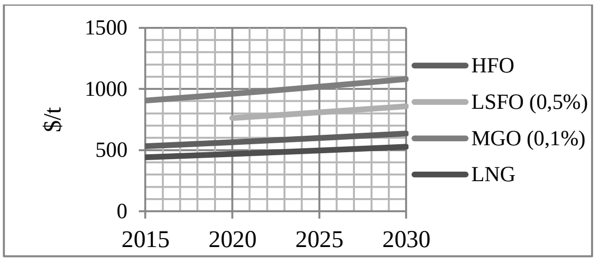

Figure 1. Fuel oil projection 2015-2030

3. RESULTS AND DISCUSSION

3.1 Base scenario results

Calculation of the discount rate with the method described in paragraph 2.2 resulted to an average of 9.22%, which was rounded to 10% for the basic scenario. Table 2 depicts the basic scenario results obtained for the worst case in terms of investing, i.e. Sulphur level requirement outside ECA implemented in 2025.

Table 2. Base scenario results with sulphur level requirement implemented in 2025

s/n	Description	Average annual capital savings ($)	Payback period (years)	NPV ($)	IRR	PI
1	Weather Routing	77304	< 1	573572	2272%	192.2
2	Engine Derating	120070	10	-211844	7%	0.81
3	Optimal Trim	53520	3	248230	32%	2.65
4	PBCF	153076	< 1	1061392	169%	14.27
5	Nozzle	228643	< 1	1554640	135%	11.36
6	Costa Bulb	108011	2	533907	36%	2.98
7	Promas Lite	240054	4	783923	21%	1.78
8	Mewis Duct	222171	1	1304986	56%	4.73
9	FRC	259793	1	1545369	59%	4.96
10	Autotuning	57080	< 1	385539	126%	10.64
11	WHRS	279013	6	470431	14%	1.29
12	Wind Kites	266027	5	574929	16%	1.41
13	Wind Rotors	291957	4	969740	21%	1.81
14	LNG	2681874	7	3016687	15%	1.4

*Hull and Propeller Cleaning presented average annual capital savings of 100 and 130 k$ respectively

The results show that the vast majority of the retrofits, with the exception of the engine derating method, prove to be quite attractive for investing since they manage to lie above the indicators acceptance limits (NPV>0, IRR> discount rate , PI>1). More specifically, six (6) methods return their initial investment in less than one year, while another four (4) demonstrate payback periods of less than four (4) years. In addition, the study showed that the implementation of the sulphur level requirement in 2020 results in higher values of PI of around 8-10%.

3.2 Sensitivity analysis

As stated in the previous paragraphs, the most important component of an investment evaluation is the recognition of all the related factors that can have a positive or negative influence on the objective function (PI in our case) and the monitoring of their impact in a certain range of values. This way a more spherical and comprehensive picture is provided to the decision maker that enables him to weigh the threats and opportunities that may occur during the implementation of a project. In Table 3 those factors are presented and their value range is defined.

Table 3. Factors affecting the objective function (PI)

s/n	Factors description	Lower limit	Basic scenario	Upper limit
1	Price difference of LSFO and HFO	105%	135%	165%
2	Price difference of MGO and HFO	140%	170%	200%
3	Price difference of LNG and HFO	53%	83%	113%
4	Annual HFO price increase	1%	1,19%	2%
5	Annual opex (% of capex)	2%	3%	7%
6	Discount rate	5%	10%	20%
7	Days outside ECA	150	175	200
8	Annual retrofit efficiency decrease	0.1%	1%	2%
9	Annual opex increase	0.1%	1%	2%

It has been found that the value of the discount rate is the factor with the greatest impact on PI, which results in an average 42% increase of PI when selected in its lower limit (5%) and in an average 71% decrease when selected in its upper limit (20%). Moreover, the annual opex returns an 18% decrease of PI when calculated at a rate of 7%. All the other factors seem to influence PI in a scale of 1-8% on average. At last, it should be underlined that the price of LNG related to HFO price has also a strong impact on the evaluation indicators of LNG conversion retrofit resulting in a differentiation of PI between 0.54 and 2.26.

3.3 Quantitative risk assessment

In order to observe the results within the whole value spectrum of the factors and reach a valid classification of the retrofits in terms of acceptance probabilities, a Monte Carlo simulation was developed. To achieve this, one thousand (1000) triangle distributed random values were generated within the factors' ranges, and in turn resulted in each retrofit Gaussian probability density and cumulative distribution functions (in terms of PI) [21]. Figure 2 depicts the histogram and cumulative distribution function for the method of LNG conversion.

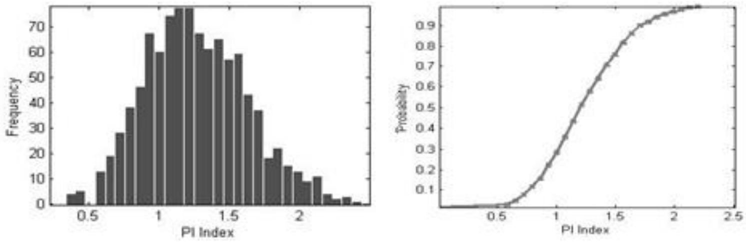

Figure 2. PI histogram and cumulative distribution function for LNG conversion with sulphur level requirement implemented in 2025

From this figure it can be seen that there is a 28% cumulative probability that the method will present PI<1. Following the same procedure for all retrofits, they were classified based on their cumulative probability of rejection. Table 4 demonstrates this classification.

Table 4. Retrofits classification

s/n	Description	Cumulative probability of rejection (PI<1)	Minimum PI value
2	Engine Derating	91.0%	0.12
12	Wind Kites	24.0%	0.31
14	LNG	28.0%	0.37
11	WHRS	20.0%	0.64

7	Promas Lite	0.4%	0.89
13	Wind Rotors	0.2%	0.98
3	Optimal Trim	0.0%	1.21
6	Costa Bulb	0.0%	1.24
8	Mewis Duct	0.0%	2.09
9	FRC	0.0%	2.27
5	Nozzle	0.0%	3.19
4	PBCF	0.0%	5.36
10	Autotuning	0.0%	5.42
1	Weather Routing	0.0%	18.12

3.4 Multicriteria analysis

Up to this paragraph the evaluation is based uniquely on financial indicators. Nonetheless there is a plethora of factors that should also be taken under consideration by the decision maker before investing in an option [22]. In this paper we explore the probability of rearrangements in our retrofit initial classification when non-financial factors, such as the technological maturity (TM) and CO_2 reduction, are involved in the evaluation procedure. The former has been assessed in a scale of 1 to 5 based on the number of applications and the current market knowledge, whereas the latter has been calculated utilizing the data of the basic scenario. Different scenarios of the factors' weigh distribution were investigated. Table 5 presents the results when PI, TM and CO_2 reduction account for 60, 35 and 5% respectively.

Table 5. Multicriteria retrofits classification

s/n	Description	PI	TM	CO2 reduction (t)	Classification
12	Wind Kites	1.41	1	2304	1.73%
13	Wind Rotors	1.80	1	2304	1.81%
2	Engine Derating	0.80	2	1152	2.53%
11	WHRS	1.29	2	1920	2.75%
7	Promas Lite	1.78	2	1728	2.82%
6	Costa Bulb	2.97	3	768	4.00%
9	FRC	4.96	3	1728	4.54%
3	Optimal Trim	2.65	4	960	5.07%
10	Autotuning	10.63	3	576	5.49%
8	Mewis Duct	4.72	4	1728	5.59%
14	LNG	1.39	3	13475	5.66%
5	Nozzle	11.36	4	1920	6.94%
4	PBCF	14.26	5	960	8.46%
1	Weather Routing	192.19	4	768	42.60%

4. CONCLUSIONS

This paper is a contribution to the ongoing discussions on the future technologies of the maritime sector. The originality of the proposed solution lies in the fact that a holistic evaluation approach has been used, where the risks of the investments have been recognized and measured in order to present a quantitative probabilistic result. Moreover, this paper has addressed the importance of the multicriteria decision making process. The main limitation of our study stems from the fact that although our reference vessel covers a wide range of similar cases, the results cannot be generalized for every case due to the build design and type differences between vessel types. From the outcome of this investigation it can be concluded that the majority of the retrofit systems (10/14) prove to be attractively and suitably eligible for the investor. Nevertheless, the investment selection criteria always remain at the discretion of the decision makers, who will finally set the methodological framework of optimal classification.

References

1. Buhaug, Ø., Corbett, J. J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., ... & Yoshida, K., 2009. *Second IMO GHG Study*. International Maritime Organization (IMO), London, UK.
2. Aravossis, K., Pavlopoulou, Y., 2013. Creating Shared Value with Eco-Efficient and Green Chemical Systems in Ship Operations and In Ballast Water Management. Fresenius Environmental Bulletin, **22(12 C)**, 3880-3888
3. Faber, J., Nelissen, D., St Amand, D., Consulting, N., Balon, T., Baylor, M., & Kane, D., 2011. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures. *Document MEPC 61/INF. 18.* London UK: International Maritime Organization (IMO).
4. Schnack, S., 2009. 35.000 DWT Bulk Carrier Exhaust Gas Emission Reduction Concept Study by Grontmij/Carl Bro. Green Ship of the Future.
5. Andersen, M., Clausen, N., Sames, P., 2012. Costs and benefits of LNG as ship fuel for container vessels. Germanischer Lloyd, Hamburg, Germany.
6. Nielsen, C., Schack, C., 2012. Vessel Emission Study: Comparison of various abatement technologies to meet emission levels for ECA's. *9th annual Green Ship Technology Conference*, Copenhagen
7. SNAME, DNV, 2011. Guideline for fuel saving measures on bulk carriers
8. IMO, 2012. MEPC.213 (63)-Guidelines for the development of a ship energy management plan (SEEMP). International Maritime Organization, Marine Environment Protection Committee, London.
9. Wettstein, R., & Brown, D., 2008. Derating: a solution for high fuel savings and lower emissions. Switzerland, Wärtsilä.
10. Hagiwara, H., 1989. Weather routing of (sail-assisted) motor vessels (Doctoral dissertation). Technische Universiteit Delft.
11. Sherbaz, S., & Duan, W., 2012. Operational options for green ships. *Journal of Marine Science and Application*, **11(3)**, 335-340.
12. Corbett, J. J., Winebrake, P. J. J., Green, E., & Comer, B., 2010. Energy and GHG emissions savings analysis of fluoropolymer foul release hull coating. *Energy and Environmental Research Associates*: Pittsford, NY, 10, 21.
13. Asariotis, R., Benamara, H., Finkenbrink, H., Hoffman, J., Jaimurzina, A., Premti, A., Rubiato J. & Youssef, F., 2013. Review of Maritime Transport, 2013. *Review of Maritime Transport*.
14. Benninga, S., & Czaczkes, B., 2000. Financial modeling. *MIT press*.
15. Aravossis, K., Karmperis, A., Sotirhos, A., 2012. Techno-economical Evaluation of Investments. *Law Library*. Athens, Greece.
16. Det Norske Veritas, 2012. Report: Shipping 2020. Oslo, Norway.
17. Outlook, U. A. E., 2013. US Energy Information Administration (EIA): Washington, DC, 2013.
18. Kalli, J., Karvonen, T., & Makkonen, T., 2009. Sulphur content in ships bunker fuel in 2015: A study on the impacts of the new IMO regulations and transportation costs. *Ministry of Transport and Communications,* **(31)**.
19. Notteboom, T., 2011. The impact of low sulphur fuel requirements in shipping on the competitiveness of roro shipping in Northern Europe. *WMU Journal of Maritime Affairs,* **10(1)**, 63-95.
20. Authority, D. M., 2012. North European LNG Infrastructure Project: A feasibility study for an LNG filling station infrastructure and test of recommendations. Final Report, March.
21. European Commission, 2008. Project Performance Indicators: Annex C- Guide to Cost Benefit Analysis of Investment Projects
22. Saaty, T. L., 1988. What is the analytic hierarchy process? (pp. 109-121). *Springer Berlin Heidelberg.*