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# Eco-environmental analysis of ship emission control methods: Case study RO-RO cargo vessel

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ABSTRACT

Air pollution from ships mainly comes from using heavy fuel oils for power generation. Although, these fuels are economical, they produce significant amounts of pollutant emissions. Two methods can be considered to cope with the International Maritime Organization's new emission regulations, either by using diesel fuel or marine gas oil with exhaust gas reduction measures, or by using alternative fuels like Liquefied Natural Gas (LNG). The aim of the current research is to compare between these two methods from environmental and economic points of view. As a case study, medium speed RO-RO cargo vessel operating in the Red Sea area has been investigated. Results show specific environmental benefits of selective catalytic reduction method for reducing $NO_x$ emissions by 90% with cost effectiveness of 873.5 \$/ton and $SO_x$ emissions by 98% with 3115 \$/ton in case of using seawater scrubbing. On the other hand, LNG appears the optimum proposed solution from environmental and economic points of view. It reduces $NO_x$, $SO_x$ and $CO_2$ emissions by about 77.6%, 92.5% and 14.5% with cost effectiveness of 1486 \$/ton, 4084 \$/ton and 160.8 \$/ton, respectively.

## 1. Introduction

Environmental issues such as the increased exhaust gases emissions from shipping are having an increasing impact on the design and operation of ships (Corbett and Koehler, 2003; Eyring et al., 2005; Endresen et al., 2007; Molland et al., 2014). These issues lead the International Marine Organization (IMO) to implement annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1997 (Lawrence and Crutzen, 1999; Fuglestvedt et al., 2009; Song and Shon, 2014). MARPOL convention limits the main air pollutants contained in ships' exhaust gases, especially nitrous oxides ($NO_x$) (Regulation 13) as well as sulfur oxides ($SO_x$) and Particulate Matter (PM) (Regulation 14). Fig. 1 presents emission limits set by MARPOL Annex VI (Welaya et al., 2013; Chorowski et al., 2015; Seddiek, 2016). For reducing $SO_x$ emissions, IMO defines the upper limits of the sulfur content for the fuels used onboard ships sailing inside and outside Emission Control Areas (ECAs). Fuel sulfur content affects $SO_x$ emissions ($SO_2$ is the primary component) and the formation of PM (Capaldo et al., 1999). Presently, the use of marine fuels with up to 0.1% sulfur content is only permitted inside ECAs. For $NO_x$ emissions, three tiers program (Livanos et al., 2014; Aksoyoglu et al., 2016) has been established according to which, both Tiers II and III require 15% and 80% reduction of $NO_x$ emissions compared to Tier I. Both Tiers II and III are currently come into effect.

## 2. Approaches to reduce exhaust gases from ships

To cope with continuously increasing environmental demands, gas emissions from existing ships' engines running on Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) have to be reduced. Combination of cleaner fuels, engine modifications, add-on retrofits and other measures can be used to reduce exhaust gases emissions. Techniques such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) might be required for reducing $NO_x$ emissions. Exhaust scrubbers or alternatively separate low sulfur fuel systems have to be installed onboard for addressing $SO_x$ emissions reduction issue (Burel et al., 2013; Seddiek and Elgohary, 2014).

Natural gas and hydrogen fuels are the most selected alternatives for marine applications (Seddiek et al., 2015; El Gohary et al., 2015). Hydrogen is proven to be efficient and environmental friendly fuel. It has high specific energy, low ignition energy requirement, excellent flame speed and broad flammability range. However, engines run

*Abbreviations:* $CO_2$, Carbon dioxide; DE, Diesel engine; DFDE, Dual-fuel diesel engine; ECM, Emission control method; HC, Hydrocarbon emissions; IMO, International maritime organization; LNG, Liquefied natural gas; MARPOL, International convention for the prevention of pollution from ships; MDO, Marine diesel oil; MGO, Marine gas oil; NGE, Natural gas engine; $NO_x$, Nitrogen oxides emissions; PM, Particulate matter; SCR, Selective catalytic reduction; $SO_x$, Sulfur oxides emissions; SWS, Seawater scrubber

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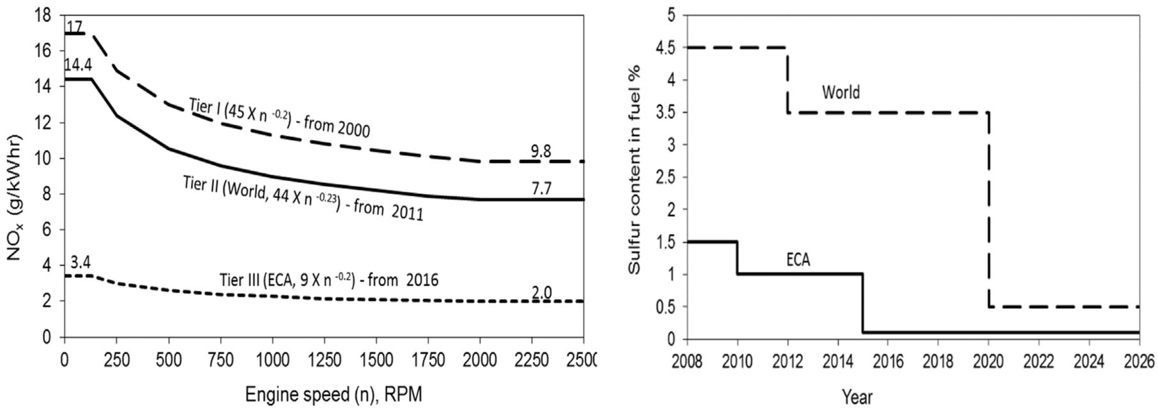


**Fig. 1.** $NO_x$ emissions and fuel sulfur content limits for ships according to MARPOL. Annex VI.

only with hydrogen require expensive hydrogen generation, which limits its use. Therefore, cost of ship-powering by hydrogen fuel is high compared with natural gas (Mukherjee et al., 2015; Bellaby et al., 2016; Mansor et al., 2017). Electric propulsion systems are currently applied in modern ships, including transport ships and warships, but most of them depend on fossil fuels, especially diesel oil which are the main source of the higher emissions rates (Sulligoi et al., 2016).

### 2.1. Reducing $SO_x$ emissions

As fuel sulfur content was lowered to 1000 ppm in ECAs by 2015, shipping companies have to install one of the exhaust gas scrubber technologies in order to use the lower-cost higher-sulfur fuel types or to use the lower-sulfur fuels like Marine Gas Oil (MGO) of 0.1% sulfur content (Carr and Corbett, 2015). For this reason, the first approach towards reducing $SO_x$ emissions is to decrease its fuel sulfur content. The reduction of sulfur levels from 2.7% to 0.5% would reduce $SO_x$ emissions by about 80%. Furthermore, as most of the PM emissions from marine engines are related to fuel sulfate contents, sulfur fuel reduction leads to lower sulfate formations and consequently minor PM emissions (Doudnikoff et al., 2014; Contini et al., 2015). Conventional after-treatment methods of removing sulfur oxides from exhaust gas, often referred to as flue gas desulfurization (FGD), usually involves scrubbing either by dry or wet methods. The wet method is the most popular, (Srivastava et al., 2001) and usually a slurry of limestone is used as sorbent (Andreasen and Mayer, 2007). The open loop seawater scrubbers are the commonly used method where seawater is taken onboard to clean the exhaust gases and then discharged as a warm acidic scrubber discharges into the sea, changing its pH. These discharges need to comply with the IMO marine environment protection committee regulation that requires the wash water to reach a pH greater than 6.5 at a distance of 4.0 m from the point of discharge (MEPC, 2009). This can be achieved by neutralizing wash water's discharge by an alkali and filtering sludge created by carbon particles and other particulate fuel impurities before discharging it into the sea (Ülpre and Eames, 2014).

The use of seawater for wet scrubbing (SWS) in order to reduce sulfur oxides emissions is a competitive method for FGD from its capital and operational costs (Oikawa et al., 2003). So, seawater scrubbing can be considered as a well-established control methodology that can achieve $SO_x$ emission removal level in compliance with MARPOL limits.

### 2.2. Reducing $NO_x$ emissions

$NO_x$ emissions reduction for marine diesel engines can be achieved either with engine modifications or with after-treatment devices. The $NO_x$ limits of ECA zones will require engine after-treatment technologies, whereas previous $NO_x$ reductions were achieved with engine based controls (Burgard and Bria, 2016). Engine modifications include exhaust gas recirculation, internal engine modifications, humid air motors and direct water injection. The most common after-treatment system is SCR which allows for 80% $NO_x$ emissions reduction. It involves the treatment of exhaust gases using ammonia or urea with catalysts (Wik, 2010; Feng et al., 2016). These catalysts are expected to be operational for thousands of hours, with defined replacement intervals that can be scheduled during ship maintenance periods. Moreover, disposal requirements are now available for land-based industries. These provisions can also be used to marine applications by which the spent catalysts can be regenerated and re-introduced into the supply chain again (Azzara et al., 2014; Kairis, 2016).

### 2.3. LNG for ship propulsion

In order to comply with IMO rules, Liquefied Natural Gas (LNG) is becoming an interesting option for merchant ships (Burel et al., 2013). LNG is a competitive fuel in comparison to low sulfur MDO and MGO, from both technical and economical points of view (Bengtsson et al., 2011). LNG is stored in vacuum insulated tanks at – 163 °C temperature and 1.7 bar fulfilling the requirements of marine regulations (Bortnowska, 2009). After liquefaction process, its volume is reduced to about 600 times against its initial state, which constitutes its main advantage for shipping and storing. LNG must be vaporized and pressurized to the pressure which is compatible with the engine requirements. The boil-off must be controlled to avoid the occasional gas release to the atmosphere (Livanos et al., 2014; Chorowski et al., 2015). In addition, $CH_4$ emissions, sometimes called "methane slip" is one of the disadvantages of natural gas-operated marine engines which in majority work according to Diesel or Otto cycles. Diesel engines produce lower methane slip rates compared with Otto cycle engines (Thomson et al., 2015). Moreover, new dual-fuel engines with thermal efficiency ranges from 40% to 50% will greatly reduce these rates (Wärtsilä, 2014). Although these rates are considered one of the contributors of total world greenhouse gas emissions, their effect is negligible compared with direct methane emissions from industry and natural seepage (Rolls-Royce, 2012; Corbett et al., 2014).

LNG was initially used as propulsion fuel in LNG carriers where the boiled-off gas produced inside the LNG tanks were used for propulsion in a traditional boiler or steam turbine systems and, at a later stage, in dual-fuel diesel engines (DFDE) (Sattler, 2000; Banawan et al., 2010). LNG propulsion system seems as an economically interesting solution for ship types spending a long period of their sailing time in ECA zones like handy size tankers and medium size RO-RO vessels (Leo et al., 2010).

The aim of the current paper is to study both the environmental and economic effects of the use of SCR, SWS, MGO and LNG options for reducing exhaust gases emissions from ships to comply with IMO new

**Table 1**
Main technical data of Al Hurreya RO-RO ship.

| Ship name | Al Hurreya |
|---|---|
| Type | RO-RO cargo |
| IMO number | 9266487 |
| Year of built | 2005 |
| Length (LOA), m | 139.5 |
| Length (BPP), m | 123 |
| Breadth, m | 23.6 |
| Depth, m | 16.5 (to upper deck) |
| Port of registration | Alexandria |
| Gross tonnage, GT | 13569 |
| Service speed, knots | 17 |
| Main engine type | MAN B & W |
| Number of cylinders | 9 L 32/40 |
| Power (MCR) | 2 × 4320 kW at 750 RPM |
| Diesel generators | 2 × 250 kW at 1200 RPM |
| Number of trips per year | 200 |
| Trip time, hrs. | 14 |

regulations. As a case study for application, a medium speed RO-RO cargo vessel operated in the Red Sea is investigated.

## 3. Medium speed RO-RO cargo ship case study

Short sea shipping voyages are the main characteristics of the Red Sea area. The exhaust gas emissions from these voyages affect adversely on the environment in the Red Sea area (Seddiek et al., 2012). Al Hurreya is a RO-RO cargo ship which operates between Hurghada port in Egypt and Duba port in Saudi Arabia. The ship is sailing under the Egyptian flag. Its technical data can be summarized in Table 1.

Egypt is characterized by being one of the largest oil and gas infrastructures in the continent of Africa, especially in the segment of transportation. In addition, the country is considered as a vital natural gas exporter due to its transmission pipeline systems as well as LNG facilities situated on the coast of the Mediterranean Sea. This infrastructure has been extended and upgraded on regular basis to serve the national plan of expanding gas utilization in the residential sector. There are two LNG stations (Damietta and Alexandria) which can be used for natural gas bunkering through transferring LNG from one of these stations to Hurghada or Safaga ports (Oilandgas, 2016).

### *3.1. Environmental analysis for emission control methods*

Many studies have been carried out to estimate the quantity of emissions from ships. One of these was conducted by the US Environmental Protection Agency (EPA) and the Canadian inventory efforts (Farooqui et al., 2013). For a single trip, emission quantity ($m_{e,trip}$) can be calculated for standby (sb), maneuvering (m) and cruise (c) modes of the ship as follows:

$$m_{e,trip} = m_{e,sb} + m_{e,m} + m_{e,c} \tag{1}$$

Two different methods can be used to estimate ship emissions. They are based either on fuel consumption or engine power. When fuel consumption for each phase of trip is known, $m_{e,trip}$ can be computed by:

$$m_{e,trip} = \sum_{Ph} (m_{f,i,j} \cdot EF_{i,j} \cdot ER) \tag{2}$$

where, ($m_f$) is the fuel consumption, (EF) is the fuel emission factor in kg/kg$_f$, (i) is the pollutant type, (j) is the fuel type (MDO, MGO and LNG), and (Ph) is the phase of trip. It includes cruise, maneuvering, and standby with engine load percentages of 80 per cent, 20 per cent, and 5 per cent, respectively (SENES, 2004). (ER) is emissions reduction percentage in case of using emission control method.

When running time (T), power (P), load (L), and emission factor (E) in kg/kWh of an engine for a specific trip are known, $m_{e,trip}$ can be calculated using Eq. (3).

$$m_{e,trip} = \sum_{Ph} (T \cdot P_{i,j} \cdot L_{i,j} \cdot E_{i,j} \cdot ER) \tag{3}$$

When considering the use of DFDE with 95% natural gas and 5% diesel oil, ($E_{DFDE}$) can be calculated using Eq. (4).

$$E_{DFDE} = x_{DF}E_{DE} + x_{NG}E_{NGE} \tag{4}$$

where, $E_{DE}$ and $E_{NGE}$ are emission factors for diesel and natural gas engines, $x_D$ and $x_{NG}$ are percentage of MDO and natural gas in case of using DFDE.

Diesel engine emission factors at low loads increase as the load decreases because of the increased specific fuel consumption and consequently, the reduced efficiency. Energy and Environmental Analysis Inc. (EEA) demonstrated this effect in a study prepared for EPA in 2000 (EEA, 2000). EEA developed Eq. (5) for specific fuel consumption (be) in g/kWh for loads below 20%:

$$b_e = \frac{14.1205}{\%\text{load}} + 205.7169 \tag{5}$$

In addition, based upon test data, EEA developed algorithms to calculate emission factors (E) in g/kWh at reduced load. Eq. (6) calculates the $NO_x$, PM and $CO_2$ emission factors. For $SO_2$ emissions, however, emission factor can be calculated using Eq. (7). The coefficients for the two equations are given in Table 2 (ICF, 2009a).

$$E = a(\%\text{load})^{-z} + b \tag{6}$$

$$E_{SO_2} = a(b_e \times \text{Fuel sulfur fraction}) + b \tag{7}$$

According to the data obtained from local-port authorities, the average time for each trip is 14 h in total. It is divided into 12 h for cruise, 1.17 h for maneuvering and 0.83 h for standby. For the Al Hurreya RO-RO ship, the speed of main engine is 750 rpm. It operates with MDO of 1.0% sulfur. The values of medium-speed diesel engine emission factors can be shown in Table 3 (ICF, 2009a; Seddiek and Elgohary, 2014). Emission factors are increased in maneuvering modes as engine load decreases. This trend results because at low loads specific fuel consumption of diesel engines is increased with reduced engine power and efficiency. Thus, mass emissions (grams per hour) will be decreased at low loads while emission factor in grams per kW will be increased.

Emission factors of $NO_x$, $SO_x$, PM, $CO_2$, CO and HC for natural gas engine in cruise mode are 2.16 g/kWh, 0 g/kWh, 0 g/kWh, 548.2 g/kWh, 0.54 g/kWh and 0.9205 g/kWh, respectively (Banawan et al., 2010; Seddiek and Elgohary, 2014). DFDE emission factors can be calculated from that of diesel and natural gas engines. Table 4 presents the average emission factors for DFDE operated at cruise and maneuvering modes. It can be noticed that, HC emissions will be increased when using DFDE since the converted diesel engine works at a much leaner mixture than natural gas engine does, and this agrees with (Chanchaona and Chaioranan, 1997). In addition, at maneuvering conditions, dual-fuel engines will have higher $NO_x$ and PM emissions as these emissions will be produced by natural gas engines at higher rates than that of diesel engines.

### *3.2. Economic analysis for emission control methods*

The annualized capital cost recovery (ACC) due to applying emission control method (ECM) depends on the capital cost value (CC), the

**Table 2**
Emission factor algorithm coefficients for main engine of ocean going vessels.

| Coefficient | $NO_x$ | $SO_2$ | PM | $CO_2$ | CO | HC |
|---|---|---|---|---|---|---|
| a | 0.1255 | 2.3735 | 0.0059 | 44.1 | 0.8378 | 0.0667 |
| z | 1.5 | n/a | 1.5 | 1.0 | 1.0 | 1.5 |
| b | 10.4496 | −0.4792 | 0.2551 | 648.6 | 0.1548 | 0.3859 |

 

**Table 3**
Medium-speed diesel engine emission factors.

| Fuel type | Emission factor (g/kWh) | $NO_x$ | $SO_x$ | PM | $CO_2$ | CO | HC |
|---|---|---|---|---|---|---|---|
| MDO (1.0% S) | At cruise | 13.2 | 3.97 | 0.47 | 646.08 | 1.1 | 0.5 |
| | At maneuvering | 11.85 | 6.079 | 0.3211 | 869.1 | 4.344 | 1.132 |

**Table 4**
Calculated medium-speed dual-fuel engine emission factors.

| Fuel type | Emission factor (g/kWh) | $NO_x$ | $SO_x$ | PM | $CO_2$ | CO | HC |
|---|---|---|---|---|---|---|---|
| 95% NG 5% M-DO | At cruise | 2.712 | 0.1985 | 0.0235 | 553.1 | 0.568 | 0.8995 |
| | At maneuvering | 12.66 | 4.579 | 0.8711 | 718 | unknown | unknown |

average expected ship age after conversion (n), and the interest rate (r) (Hunt and Butman, 1995). ACC can be calculated using Eq. (8).

$$ACC = CC \times \frac{r(1+r)^n}{(1+r)^n - 1} \tag{8}$$

Economically, applying either SCR or SWS systems will add extra annual installation costs (AIS) for the ship. These costs include ACC, annual maintenance and running costs (MC), fuel cost increment (ΔMGO) in case of using marine gas oil instead of SWS for $SO_x$ reduction. So, AIS can be calculated using Eq. (9).

$$AIS = \sum_{ECM} ACC + \sum_{ECM} MC + \Delta MGO \tag{9}$$

Finally, annual cost effectiveness for each ECM ($ACE_{ECM}$) can be calculated separately for each pollutant. This involves calculating ACC, annual operating and maintenance costs (MC) and annual emission reduction (AR) in tons/year (ICF, 2009b). $ACE_{ECM}$ can be calculated using Eq. (10).

$$ACE_{ECM} = \frac{ACC + MC}{AR} \tag{10}$$

## 4. Results and discussion

In this section, the economic and environmental results of four emission control methods are presented. Firstly, the eco-environmental benefits for using LNG conversion system are discussed. Secondly, the results for using SCR, SWS and MGO systems are compared with LNG results from environmental and cost effectiveness points of view.

### *4.1. LNG eco-environmental results*

Technically, brake specific fuel consumption of a converted diesel to dual-fuel engine will be increased by 23% compared with that of the conventional diesel (Zbaraza, 2004). This is because these engines were initially designed for diesel fuel. So, natural gas fuel consumption can be determined by diesel fuel consumption and by knowing that each one cubic meter of diesel oil is equivalent to 1197 $m^3$ of natural gas. Hence, natural gas storage volumes will depend on the percent of natural gas used in the engine. The proposed dual-fuel engine will operate with a mixture of 95 per cent natural gas and 5 per cent diesel fuel in maneuvering and cruise modes. In addition, Al Hurreya RO-RO vessel carries out 200 trips per year. Table 5 shows diesel oil and natural gas fuel consumptions for the case study.

**Table 5**
Al Hurreya RO-RO ship fuel consumptions.

| Engine type | Fuel type | Fuel consumption ($m^3$) | |
|---|---|---|---|
| DFDE | Diesel oil | Per trip | 2.101 |
| | | Per year | 420.2 |
| | Natural gas | Per trip | 26501 |
| | | Per year | 5.30E+06 |
| DE | Diesel oil | Per trip | 23.97 |
| | | Per year | 4794 |

Emission rates in kg/min during one trip using DE and DFDE can be obtained from emission factors in Tables 4–6. These values can be compared with that of IMO emission rates as shown in Fig. 2. For the Al Hurreya RO-RO ship, $SO_x$ emission rates are 0.4573 kg/min and 0.02287 kg/min for DE and DFDE in cruise modes, respectively. It should be compared with IMO 2020 rates of 0.288 kg/min. On the other hand, $NO_x$ emission rates are 1.521 kg/min and 0.3124 kg/min for DE and DFDE in cruise modes, respectively. These values are compared with IMO 2016 (Tier III) rate of 0.34 kg/min. Fig. 2 shows that $SO_x$ and $NO_x$ emissions of DFDE will be compliant with the new IMO emission limits in cruise mode, while $NO_x$ emissions in maneuvering mode and diesel engine will not. So, converting diesel engines to dual-fuel engines in cruise mode will comply with not only the current IMO emission rates but also with the future ones.

Using various natural gas percentages, the emissions reduction percentages for $NO_x$, $SO_x$, PM and $CO_2$ can be obtained from Fig. 3. As diesel oil percent increases, emission rates increase for DFDE. So, it is preferred to reduce diesel oil percent as much as possible during ship cruise at sea to reduce exhaust-gas emissions. The highest emission reduction of dual-fuel engine can be achieved at 5% diesel oil and 95% natural gas.

Environmental benefits of the DFDE are clear when compared with those of the diesel engine as shown in Fig. 4. For the case study, $NO_x$, $SO_x$, $CO_2$ and PM emission rates are 1.119 t/trip, 0.342 t/trip, 55.43 t/trip and 0.034 t/trip, respectively. The converted engine has lowered these rates by 77.6%, 92.5%, 14.5% and 90.7%, respectively.

Converting the main engine of a ship to run on natural gas fuel will include some modifications. These modifications include engine conversion for dual-fuel, LNG fuel storage containers, piping, and related safety systems. As the required natural gas volume for the case study is very high compared to that of diesel fuels, the suitable storage form is LNG as it requires lower space than compressed phase. Table 6 shows the pressure, dimensions, weight and capacity of ASME coded LNG container models which are used for LNG storage onboard (CHART, 2016; SEFIC, 2016). The 20 foot ASME coded vessels come in a variety of working pressures from 6.9 bars to 15.9 bar. The 40 foot intermodal container comes in the pressure of 10 bars for EN coded vessels and 6.9 bar for ASME coded vessels. These containers are designed and optimized for liquid natural gas services.

For the Al Hurreya RO-RO ship, models ICC-54-P-100 and ICC-115-P-100 will be suitable regarding pressure and capacity for the required 44.17 $m^3$ of LNG during one trip. This means that, to provide the ship with necessary fuel, it will need four LNG containers if the bunkering is only at one port and two containers if the bunkering infrastructure is established at both ports. The available LNG storage ports in Egypt are in Damietta and Idku. So, LNG can be transferred from these two ports to the ship port by LNG containers specified in Table 6.

The annual fuel cost split for both diesel and dual-fuel engines are shown in Fig. 5. The prices of diesel oil and natural gas fuels are 150 $/$m^3$ and 0.0917 $/$m^3$, respectively, according to the local prices in Egypt. These prices are 408 $/$m^3$ and 0.1009 $/$m^3$, respectively, according to the worldwide prices (Bunkerworld, 2016). The bunkering prices for diesel oil and natural gas fuels are 8 $/$m^3$ and 0.009 $/$m^3$,

**Table 6**
Specifications of the LNG containers.

| Model | Pressure (bar) | Dimensions (m) L*W*H | Weight (kg) | Capacity ($m^3$) | Hold Time Days (LNG) | Evaporation LNG%/day |
|---|---|---|---|---|---|---|
| ICC-54-P-100 | 6.9 | 6.058*2.438*2.591 | 34,000 | 20.380 | 44 | 0.25 |
| ICC-54-P-150 | 10.3 | 6.058*2.438*2.591 | 34,000 | 20.360 | 54 | 0.25 |
| ICC-53-P-230 | 15.9 | 6.058*2.438*2.591 | 34,000 | 20.160 | 65 | 0.25 |
| TVS-43-PB-10 | 10 | 12.200*2.438*2.591 | 11,500 | 43.5 | 65 | 0.25 |
| ICC-115-P-100 | 6.9 | 12.200*2.438*2.591 | 11,500 | 43.5 | 53 | 0.20 |

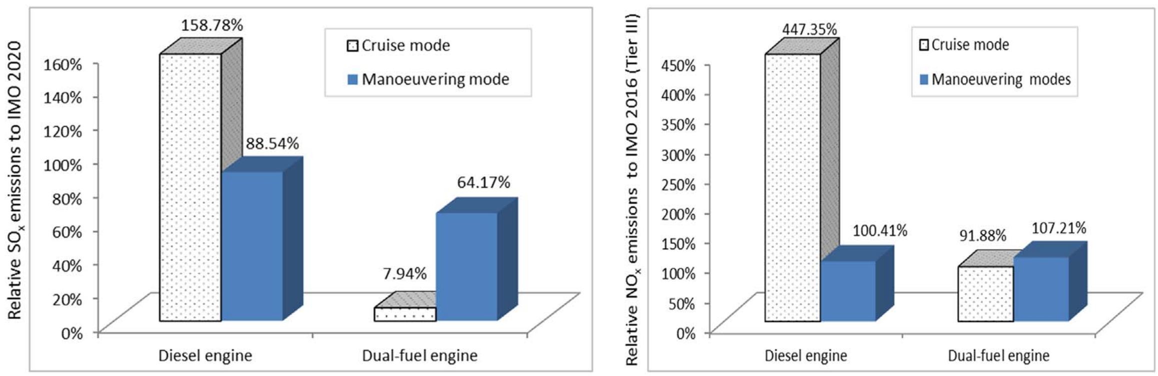


**Fig. 2.** Comparison of the IMO emissions limits for DE and DFDE for the Al Hurreya RO-RO vessel.

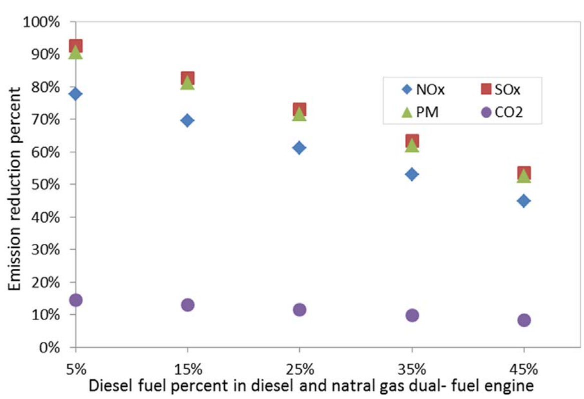


**Fig. 3.** Emission reduction percentages for DFDE.

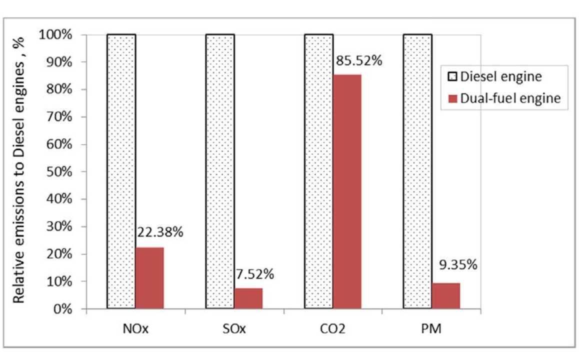


**Fig. 4.** Relative emissions of DE and DFDE for the Al Hurreya RO-RO ship.

respectively. The cost of LNG container transferring from Damietta to Hurghada is 0.275 $/m^3$.

The total annual fuel cost for diesel and dual-fuel engines varied from $ 757,523 and $ 690,526, respectively (according to local prices) to $1.994 million and $ 849,103, respectively (according to worldwide prices). For a diesel engine, 95% of the total fuel cost is for diesel oil and 5% is for bunkering. On the other hand, the cost of diesel oil and natural gas fuels are $63,024 and $486,027 with percentages of 70% and 9%, respectively of the total dual-fuel costs. Although, LNG bunkering and container transferring costs are higher than diesel oil bunkering cost by 15%, the total natural gas fuel cost is less than that of diesel oil by 8.8% according to the local prices. This can reduce the annual ship costs after the conversion process. Therefore, preliminary analysis for natural gas conversions can be justified from fuel saving alone.

The time required for money recovery is very important in the economic decision for the converted DE to DFDE. Fig. 6 shows the annual cost for capital cost recovery with payback periods. These periods should be compared with the expected working years for the ship after the conversion process. For the case study, the annual capital cost recovery is 431,132 $/year. At interest rate of 10%, the minimum payback period is 12 years. Assuming the average ship age is 28 years (Mikelis, 2008), the conversion process will be economical if the ship age is less than 16 years. Moreover, the change of fuel cost has to be taken into consideration in order to calculate the economic benefits for engine conversion process.

In addition to fuel costs, maintenance cost highly affects engine total annual running costs. The mean time between maintenance periods for DFDE increased threefold in comparison with DE (Zbaraza, 2004; Banawan et al., 2010). Therefore, the annual cost saving due to shifting to natural gas ($ACS_{DFDE}$) can be calculated as follows:

$$ACS_{DFDE} = \Delta FC + \Delta MC - \Delta BC - ACC_{DFDE} \quad (11)$$

where, ($\Delta FC$) is the summation of diesel and natural gas fuels cost difference. ($\Delta MC$) is the difference between maintenance and operating costs of DE and DFDE. ($\Delta BC$) is the difference between ship bunkering process costs of diesel oil and natural gas. ($ACC_{DFDE}$) is the capital cost of conversion from DE to DFDE.

Moreover, annual fuel cost difference ($\Delta FC$) can be estimated as follows:

$$\Delta FC = PT[(b_e \cdot C_f)_{DE} - (xb_e \cdot C_f)_{NGE} - (xb_e \cdot C_f)_{DE}] \quad (12)$$

where, ($b_{eDE}$) and ($C_{fDFDE}$) are MDO specific fuel consumption and cost for DE. ($b_{eNGE}$) and ($C_{fNGE}$) are natural gas specific fuel consumption and fuel cost for DFDE.

For the Al Hurreya RO-RO ship, the annual maintenance cost saving will be 173,102 $/year. In addition, the total annual saving costs

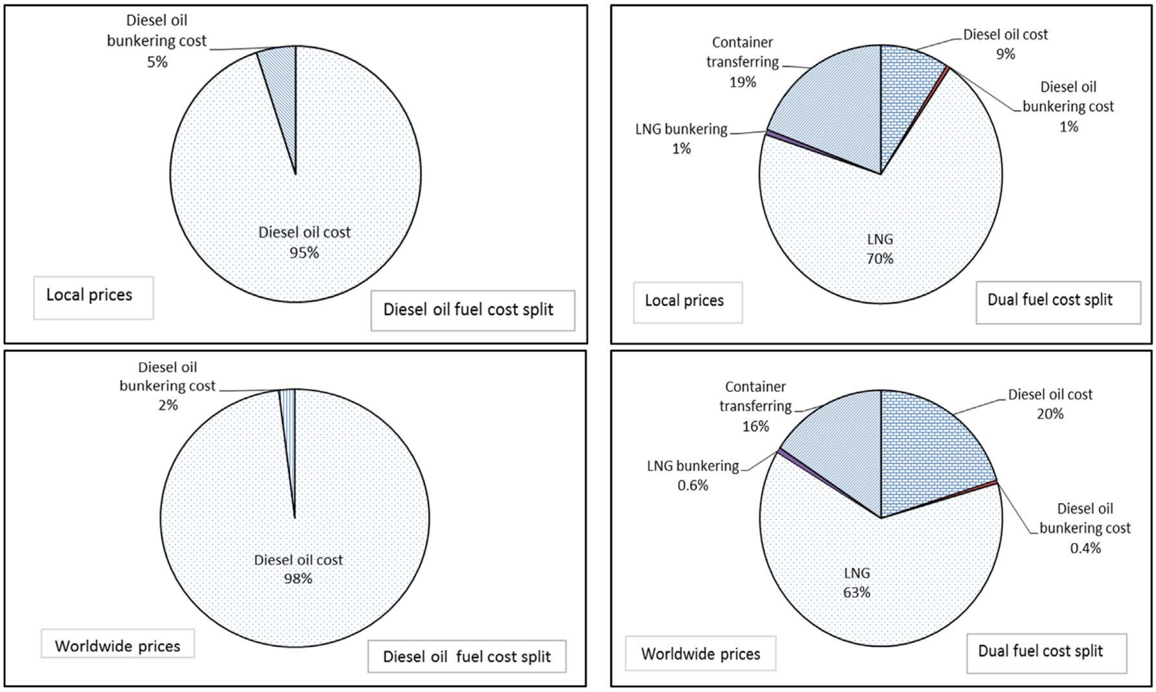


**Fig. 5.** Cost split for diesel oil and dual fuels based on local and worldwide prices for the Al Hurreya RO-RO ship.

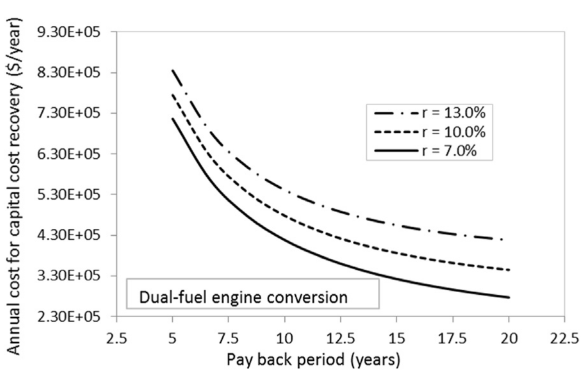


**Fig. 6.** Annual cost recovery and payback periods for dual-fuel engine.

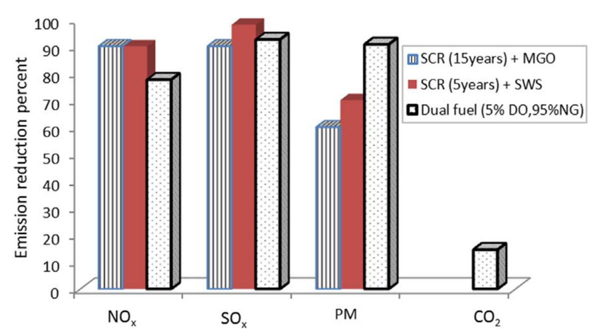


**Fig. 7.** Ship emission reduction with various strategies.

in the case of changing to DFDE is $240,099. So, annual maintenance cost saving will be 72% of the total cost saved for the converted engine.

### *4.2. SCR, SWS and MGO eco-environmental results*

The aim of SCR and SWS is to reduce exhaust gases emissions especially $SO_x$, $NO_x$ and PM emissions. SCR reduces $NO_x$ emissions by 90%, which would comply with required IMO emission levels. It depends on injecting urea solution into the exhaust gas stream in combination with catalyst housing in the exhaust channel. Compact SCR system consists of a reactor, which contains several catalyst layers, a treating and storage system for the reagent, and a control system. It has an average volume of 1.0 $m^3$/MW and a weight of 1.0 kg/kW, including: urea storage tanks, pumps, injection and control system (Wärtsilä, 2016). Urea consumption rate for SCR system is 0.025 $m^3$/MWh onboard ships. On the other hand, both SWS and MGO reduce $SO_x$ emissions. The use of SWS system will reduce $SO_x$ and PM emissions by 98% and 70%, respectively, while the use of MGO (0.1% sulfur) will reduce sulfur emission rates from 3.97 g/kWh to 0.4 g/kWh with a reduction percentage of 90%. In addition, PM emissions will be changed from 0.47 g/kWh to 0.19 g/kWh with a reduction percentage of 60%. Nitrogen oxides and $CO_2$ emissions are unchanged.

In order to reduce both $NO_x$ and $SO_x$ emissions, a combined system of SCR, SWS and MGO can be used as shown in Fig. 7. MGO mainly used to reduce $SO_x$ emissions. From the case study, the yearly diesel engine $NO_x$, $SO_x$, $CO_2$, and PM emissions are 223.8 t/ year, 68.31 t/ year, 11086 t/year and 7.926 t/year, respectively. A combined system of SCR and MGO leads to a reduction of $NO_x$, $SO_x$ and PM emissions with percentages of 90%, 90% and 60%, respectively. These emissions can be reduced using SCR and SWS systems by 90%, 98%, and 70%, respectively. Dual-fuel engine with 5% diesel oil and 95% natural gas can be compared with other ECMs. The highest $CO_2$ emission reduction is achieved by dual-fuel engines. This is due to lower carbon content in natural gas compared with diesel oil.

Economically, the ECM can be judged from average installation cost per kW of engine power, annual cost for capital cost recovery and annual cost effectiveness for ECM. For this study, fuel costs were examined in terms of their cost-efficiency. According to local prices, MGO cost is 193.5 \$/$m^3$ at the end of the year 2016. The capital cost of installing SWS onboard ship is 160 $/kW with operating costs about 3% from this (Wang and Corbett, 2007). In addition, initial SCR investment cost rate is 50,000 $/MW with 3.75 $/MWh and 0.9 $/MWh for running and maintenance costs, respectively (INTERTANKO, 2007). According to literature, the main SCR component, the catalyst, requires rebuilding depending on the sulfur content (%S) by weight in fuel during operation. The reactor requires rebuilding in 15–20 years for $S < 0.2$ and in 5 years for $0.2 < S \leq 1.5$ (Nikopoulou, 2008). For the

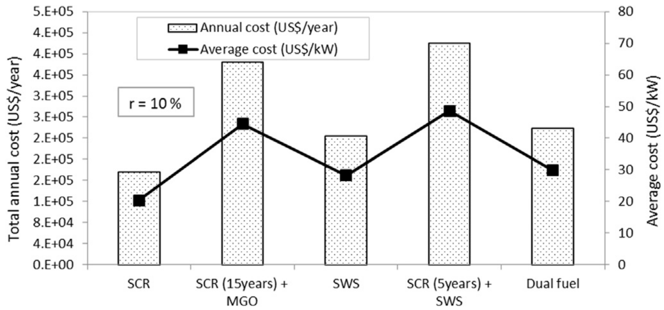


**Fig. 8.** Average and annual costs for applying different ECMs.

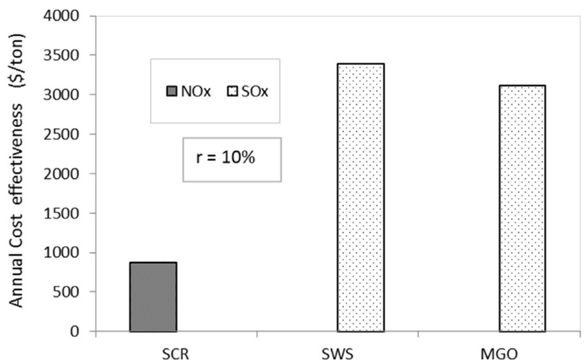


**Fig. 9.** Annual cost effectiveness for $NO_x$ and $SO_x$ emission reduction measures.

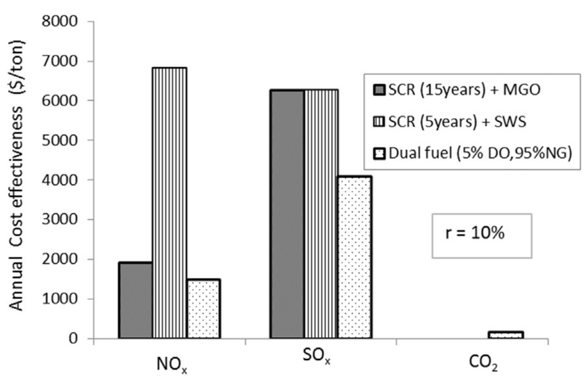


**Fig. 10.** Annual cost effe.

case study, catalyst reactor has to be rebuilt every five years when used in (SCR+SWS) system where MDO contains 1.0% sulfur. It needs rebuilding after 15 years when MGO with 0.1% sulfur content is used.

Fig. 8 shows the annual and average installation costs for ECMs. The installation costs for SCR and SWS are 175895 $/year and 244358 $/year, respectively with average engine output power cost of 20.35 $/kW and 28.28 $/kW, respectively. In addition, applying combined (SCR+SWS) and (SCR+MGO) will increase the ship annual operating costs by 420,252 $/year and 384,453 $/year with average installation costs of 48.6 $/kW and 44.5 $/kW, respectively. In addition, the total installation and maintenance costs for dual-fuel engine is 258030 $/year with 29.9 $/kW average cost per output power. From Fig. 8, the most economical solution proposed for the case study is using dual-fuel engine with 5% diesel oil and 95% natural gas.

On the other hand, annualized cost-effectiveness of each ERM can be used for choosing the suitable method for emission reduction. It compares the total annual capital and maintenance costs with the amount of emission reduction after applying exhaust reduction method. Fig. 9 shows the cost effectiveness for the reduction of $NO_x$ and $SO_x$ emissions using SCR, SWS and MGO. The cost effectiveness for reducing $NO_x$ emissions using SCR is 873.5 $/ton for the reduced 201.4 t annually. $SO_x$ emissions can be reduced by 61.48 t/year and 66.94 t/year with cost effectiveness of 3392 $/ton and 3115 $/ton using MGO and SWS, respectively.

In addition, combined systems of SCR, SWS and MGO can be used to reduce exhaust gas emissions in order to comply with new IMO regulations. Fig. 10 shows the proposed two combined system compared with dual-fuel engines. Using (SCR+MGO) system would reduce $NO_x$ and $SO_x$ for the case study with cost effectiveness of 1909 $/ton and 6254 $/ton, respectively. The reduction of these emissions can be achieved using (SCR+SWS) with cost effectiveness of 6836 $/ton and 6278 $/ton, respectively. The most economic option for reducing $NO_x$, $SO_x$ and $CO_2$ emissions is using dual-fuel engine with cost effectiveness of 1486 $/ton, 4084 $/ton and 160.8 $/ton, respectively.

## 5. Conclusions

The eco-environmental analysis of four exhaust-gas reduction methods were investigated for RO-RO cargo ship operated in the Red Sea. These methods include selective catalytic reduction (SCR), seawater scrubbing (SWS), marine gas oil (MGO) and LNG conversion. The main conclusions from this paper can be summarized as follows:

- $SO_x$ and $NO_x$ emissions are the main components of ship emissions. Using LNG conversion or a combined system of (SCR+SWS) or (SCR+MGO) can be applied onboard the ship in order to reduce these emissions. High $NO_x$ and $SO_x$ emission reduction percentages can be achieved using combined (SCR+SWS) system. It reduces $NO_x$ and $SO_x$ emissions by 90% and 98%, respectively. In addition, LNG conversion process achieves the highest PM emission reduction of 14.5%. It is the only method which reduces $CO_2$ emissions by 14.5%.
- From an economical point of view, using a combined system of (SCR+MGO) is more economical than the system (SCR+SWC) with average installation costs of 48.6 $/kW and 44.5 $/kW, respectively. The most economical of the studied systems is LNG dual- fuel engine conversion system with an average installation cost of 29.9 $/kW and emission reduction cost effectiveness factors of 1486 $/ton, 4084 $/ton and 160.8 $/ton for reducing $NO_x$, $SO_x$ and $CO_2$ emissions, respectively.
- Finally, using LNG conversion can economically achieve the required emission levels for international regulations. In addition, it can be considered as an economic solution for the newly built ships or currently operated ships with age less than 16 years.

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