Cost/benefit analysis of alternative systems for feeding electric energy to ships in port from ashore

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Abstract

The development of maritime transportation has increased the territorial role and the socio-economic relevance of harbors. But, at the same time, it has worsened the environmental impact of the maritime operations on ports and surrounding - often highly inhabited - areas, particularly in the Mediterranean. Since ships at berth need a certain amount of electric energy for hull and hotel services, they must keep their auxiliary engines switched on, inevitably generating exhaust emissions and noise. As a consequence, ports become an important and growing source of pollution and can create relevant risks for the health of the communities living nearby. From the economic point of view, it has been assessed that the costs involved in the shore-side power program can vary widely among ports. In this paper a complete cost benefit analysis will be carried out by keeping into account all costs related to the systems capable of supplying electric energy to ships using systems external to it. In particular, cold ironing, LNG power packs and fuel cells will be evaluated; LNG and fuel cells will be considered both as a fixed source of energy, and as a movable one, when fitted in a barge in order to reach the ship to be powered. Additionally, the results obtained in term of the cost of energy from ashore will be compared with the cost of the energy produced onboard, by keeping into account all charges that compose the real price of the electric energy when using the auxiliary engines onboard ships.

Keywords— maritime transportation, environmental pollution, cold ironing

I. Introduction

The exhaust emissions from ships can be evaluated as about 3-5% of the world's air emissions and the share of the industry is increasing. The exposure to toxic emissions is reported to cause cardiovascular and respiratory diseases. It is also well known that the industrial activity is considered as a main contribution to the climate change and to the bad consequences related to it [13], [27]. Legislators, led by the International Maritime Organization, have started to act. Since January 2013, an Energy Efficiency Design Index and a Ship Energy Efficiency Management Plan have been mandatory for all ships of 400 gross tonnage and above. Since 2015, ships operating in Emissions Control Areas have been required to use fuels with 0.1% or less Sulphur content. From 2016, new thresholds have been applied also to nitrogen oxide emissions. In this regard, since January 2010, and limited to the European Union, the 'EU DIRECTIVE 2005/33 / EC " has imposed the use of fuels with 0.1% of sulfur for engines onboard ship (navigation within 12 miles from the coast) and for all diesel generators and fuel boilers of all ships at berth in Community ports.
A number of solutions will enable ship owners to comply with the more stringent regulations. To tackle GHG emissions, fuel-efficient engines and propulsion systems are the most promising technologies. Low-sulphur fuels, liquid natural gas, and scrubbers are three options for complying with regulations aiming at reducing sulphur oxide emissions. Companies offering such solutions will benefit from the push to mitigate impacts from the shipping industry.
An innovative sustainable power supply solution for seaports with the related design and control has become necessary [12]. Ships at berth generate their electricity depending on their own auxiliary engines, therefore emitting air pollutants and creating noise. This makes ports a major and growing source of pollution and could create significant health risks for nearby communities. Notably, the cost of the energy for possible shore side power sources depends both on the port and on the ships at berth; all these considerations show the importance of accurate shore-side power economic analysis and evaluation of the consequent environmental effect.

II. Shore Side Power Source

Ports nowadays are not normally equipped to supply vessels with electricity from the dockside, nor are vessels usually equipped to receive power in this way.
Though, many activities in this direction are now underway and the interest in the technology is rapidly growing, spurred by tougher environmental legislation, greater focus on emissions in ports from shipping and, more recently, rising fuel prices.
Cost-effective implementation of the technology requires collaboration among a wide range of stakeholders at an early stage, for example when planning new quays and ordering new vessels.
An important aspect of this impact is related to the amount of noxious emissions coming from the simultaneous presence of many ships in port, with their diesel generators on to produce the electric power necessary to the ship systems.

Even with the use of light diesel oil (low content of sulfurs) required by rules, such emissions are still considerable in terms of particulate matters (PM), sulfur oxide (SOx), nitrate oxides (NOx) and greenhouse gases (CO2). Further, noise emissions from generator units have originated complaints from citizens living nearby.
One of the most attractive way to face this problem is the so-called "cold ironing" i.e. a connection between the ship and the shore with the aim of supplying the electric energy needed for the services onboard.
Thus, the production of electric power onboard could be avoided or reduced, together with the inherent emissions from the diesel generation sets.
The shore side power sources depend on various factors as port terminal arrangements, power required onboard, number of ship calls, etc. This report presents the various shore-side power sources, which may be used, as shown in Fig. 1, including three options, namely:

a) new fixed installation, fed by the national electric grid, which is used where high power density is required;
b) installation of one or two fixed fuel cell units for ships as High Speed Craft, tugboats, commercial fishing boats, and crew/supply boats, or ro/ro pax [11];
c) fixed plant powered by dual fuel diesel electric engines using oil and natural gas, (especially where natural gas is available as a fuel source).
d) power supply based on fuel cells or dual fuel diesel electric engines using oil and natural gas system mounted on a barge [29].

The concept, however, is easily applied when the power to be supplied is low; on the contrary, high power supplies require complicated connection tools and dedicated powerful plants for generation, distribution and control of the electric energy.
Several applications of the concept are realized nowadays around the world, often for the supply of a relatively small power (see e.g. pleasure crafts in touristic ports).
Shore connections for supplying electric energy already exist in Sweden (Goteborg, Stockolm, Helsingborg, Piteå), in Finland (Kotka, Oulu, Kemi), Belgium (Antwerp, Zeebrugge) and in other US ports like Seattle and Pittsburg. In Juneau (Alaska), an important installation for supplying electric energy to cruise ships has been working since 2001. This installation was designed for the delivery of large electric power, but also to resist to the severe wind and sea conditions frequently occurring in that area.
Besides the “classic” cold ironing systems, that are complex from the economic, technical and, managerial points of view, other systems are studied with the aim of supplying electric energy to ships in ports without big investments and fixed systems. Among them, the systems mounted on barges are often based on stand-alone movable systems that can be set close to the ship to be fed.

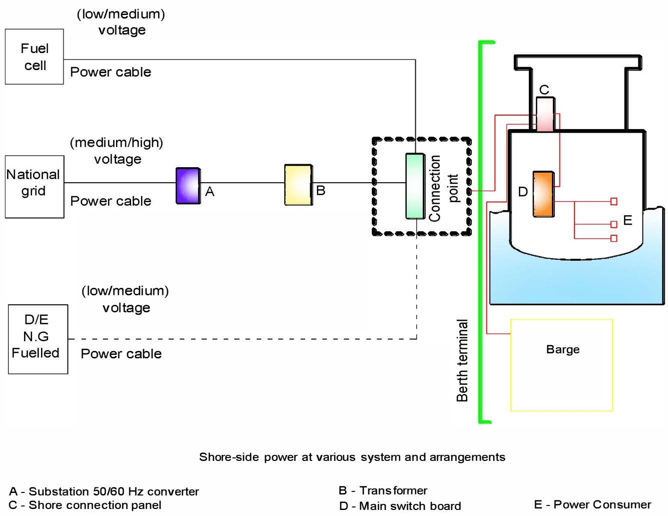

Fig. 1 Shore-side power sources

III. Economic Issue for Shore-Side Power Concept

The purpose of this report is to identify and quantify the benefits coming from the application of shore-to-ship electricity connection systems in ports.
Obviously, it is always possible to use the onboard electric power generation system in case of shore-side power connection problems or in case, the vessel calls a quay without shore electricity connection.
The total cost for onboard generation of electricity will depend on the design of the ship’s power supply system and the fuel used. The fuel prices vary largely over time, place and by fuel quality.
The estimation of onboard Annual Auxiliary Engine Power generation Cost C_{AAEP} – ($/year or €/year) to be basic cost reference, consists of fuel cost, maintenance cost and operating cost (see list of symbols):

$$C_{AAEP} = P_{aux}\, t_p\, s_{fc}\, c_{df}\; 10^{-6} + (\textstyle\sum_m CmMm + + \sum_o CoMo)\, P_{aux}\, t_p \qquad (1)$$

The basic emission rate from the onboard auxiliary diesel generator Eaux can be estimated as follows:

$$Eaux = Paux\; t_p\; E_{ef} N_{gp} \qquad (2)$$

Fig. 2 is reports the unit cost ($/mt) of the IFO380, MGO (0.1%S) and Brent vs years. Global LNG prices have fallen significantly. In the bunkering market, LNG competes now with oil products (see fig. 3 from www.sundenergy.com). The total cost also depends on costs for investments and maintenance. The investment costs for onboard auxiliaries have been ignored in this report, as the power supply system in most cases has to be installed even if the vessel is using shore-side electricity in all harbors. The maintenance cost will vary with the type of engine (two/four stroke, engine brand, size etc), age and running hours per year.

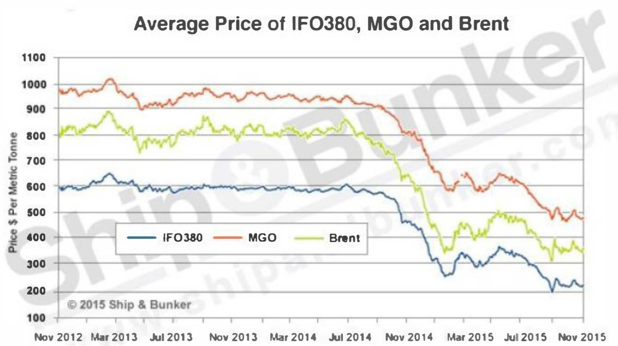

Fig. 2 Average Price of IFO 380, MGO and Brent from www.shipandbunker.com

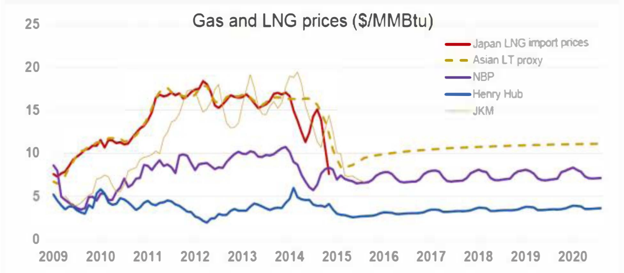

Fig. 3 unit cost ($/MMBtu) versus years; from Montel, Sund Energy analysis, April 2015

A. Using the national electric grid for shore-side applications

The shore power systems use electric power substations that connect berths to the main power grid and allow ships to operate from the grid. It was shown that a typical ship shore-side power system of terminal operator can be divided into several basic elements as follows:

- a transformer for each ship's power supply;
- switchgear equipment such as breaker and disconnector for each ship's power supply;
- an automated shore switch for each ship's power supply;
- a frequency converter to adjust the frequency to the requested value;
- communication equipment between the ship and shore;
- protection relays in order to provide safety for cable-handlers.

Some factors play a role in studying the applicability of the national electric grid for shore-side power, including fuel used for electric energy generated, cost of energy ($/kW·h) and port infrastructures.

The most important advantages of the national electric grid consist in the possibility of supplying high power density, better equipment arrangement, and low maintenance activities.

The estimated cost of electricity from the national electricity grid is composed of the cost of high voltage cable ($/m or €/m), typical harbor canalization ($/m or €/m), cost of frequency transformers ($ or €), cost of ship system modification and electric grid generated price ($/kWh or €/kWh; this parameter depends on the voltage).

The following parameters are usually important when the cost and system requirements are investigated:

- Shore-side frequency (50 Hz in Europe);
- Onboard frequency (60 Hz or 50 Hz);
- Shore side supply of high voltage electricity (voltage, distance to nearest supply point and installation conditions);
- Required power level;
- Available spaces for onboard transformer, and weight restrictions of the vessel.

For some vessels, the extra weight of equipment (transformer) or loss of cargo space may result in reduced profitability or increased fuel consumption. In most cases these costs can be neglected, but for high-speed crafts or other special vessels the factors could be important.

The onboard frequency and the cost of supplying the quay with high-voltage power are the parameters having a major influence on the installation cost for shore-side electricity connections.

If the vessel is using a frequency of 60Hz, the shore-side power must be transformed from the standard 50Hz to the onboard 60Hz frequency. This is made via a shore-located frequency transformer and does not create any technical problem. The costs for frequency transformers (that converts from 50 Hz to 60 Hz) in the power range suitable for shore-to-ship electric systems can be evaluated between 300.000 and 500.000 euro. One frequency transformer can serve several berths as long there are high-voltage connections between the transformer and the berth connections.

The costs for the power supply of high-voltage at the quayside can vary largely, depending on the distance to the nearest high voltage supply and other local conditions.

If new canalization has to be made for a long distance, the supply costs can be significant.

The Annual National Grid Power Cost (C_{ANGP}) in ($/year or €/year) can be determined as:

$$C_{ANGP} = \frac{i(1+i)^N}{(1+i)^N - 1}\left(Cs + \sum_c CcDc + \sum_y CyDy\right) + \\ + \sum_{mo} CmoMmo + PN.g\,H\,CN.g + \\ + Paux\ td\ sfc\ c_{df}\ \ 10^{-6} + Port_{fees} \qquad (3)$$

B. Fuel cells for shore-side power applications

Fuel Cells (FCs), on the contrary, are electrochemical devices able to convert the chemical energy contained in fuels and in an oxidant directly into electrical energy through an electrochemical process, with high efficiency.

At the present, FCs are the most promising technology in the field of power production. They show several advantages compared to the current technologies:

- energy efficiency higher (typically 0.5 - 0.65) than ICE;
- low emissions especially as regards the release of NOx, CO and PM;
- low noise, since FCs do not have moving components;
- modular operating temperatures (room temperature-r .t.1000°C);
- modular construction that allows to cover different power supplies;

- simpler construction that guarantees greater reliability and easier maintenance.

Currently, two major different types of fuel cells - depending on the fuel type - are available as follows [17]:

- pure H2 based fuel cells, with power capacity of (30W to 1.0MW); they include Proton Exchange Membrane (PEMFC), Alkaline Fuel Cell (AFC) and Phosphoric Acid fuel cells (PAFC).
- hydrocarbons (Natural gas and diesel oil) based fuel cells, with power capacity of (1 kW to 2 MW); they include Molten Carbon (MCFC) and Solid Oxide fuel cells (SOFC).

Usually, three major components are considered in the computation of the cost of electric power for a fuel cell power generation: capital cost, fuel cost, and operation and maintenance costs. Then Annual Fuel Cell Power Cost (C_{AFCP} – $/year or €/year-) can be calculated as:

$$C_{AFCP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(P_{FC}FCC + \sum_y CyDy\right) + P_{FC}H\left(\frac{C_3 f_{CNG}}{\varepsilon} + C_{O\&M}\right) + Paux\ td\ sfc\ c_{df}\ 10^{-6} + Port_{fees} \quad (4)$$

As for the value of the shore-side power emissions Eshore (Kg/year), it can be estimated using the following equation:

$$Eshore = Pshore\,(t_p - t_d)E_{fs} + N_{gp}E_{ef}t_d Paux \quad (5)$$

Eq. (5) will be applied for both cases: the national grid and fuel cell unit (also mounted on barge).

C. Dual fueled engines for shore-side power applications

Shore power from a natural gas fueled mobile generator system offers a flexible solution that can be used today with low infrastructures cost in electrifying the berth. This solution can accelerate the benefits of shore power. In addition, this option may include one or more generators fueled by natural gas, liquefied natural gas (LNG) or compressed natural gas (CNG) to provide electricity to vessels at berth. Switching from diesel to natural gas for internal combustion engines may reduce significantly the exhaust gas emissions. Moreover, this could provide a significant reduction in fuel cost because DF engines have a lower consumption for the same energy release [24].
The Annual Dual Fuel Power Cost (C_{ADFP} – $/year or €/year) is affected by a number of factors such as natural gas price, engine power, maintenance and operation costs. C_{ADFP} can be calculated as:

$$C_{ADFP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(p\ CE + \sum_y CyDy\right) + pH\ \sum_o CoMo + +Paux\ td\ sfc\ c_{df}\ 10^{-6} + H(C_4 f'_{CNG} + pC_2 sfc1\ f_c\ 10^{-6}) + +Port_{fees} \quad (6)$$

The estimation of dual fuel engines annual emission (E_{dual} – Kg/year-) will change as a consequence of the effect of natural gas and diesel fuel oil percentages, as shown in the following equation:

$$E_{dual} = P\,(t_p - t_d)(C_1 E_{fNG} + C_2 E_{ef}) + N_{gp}E_f t_d Paux \quad (7)$$

D. Power supply based on fuel cells fueled by LNG/Hydrogen or dual fuel diesel electric engines on a barge

Besides the “classic” cold ironing systems, complex from the economic, technical and, management points of view, other systems are studied with the aim of supplying electric energy to ship in ports without big investments and fixed systems. These are often based on stand-alone movable systems that can be set near the ship to be supplied (systems mounted on barges). In this case, alternative sources of energy, with a lower environmental impact than the one from diesel engines running on oil are used. For instance, Becker Marine Systems and AIDA Cruises have come together with other partners to develop a LNG hybrid Barge for the energy-saving and emissions-reducing supply of power to cruise ships during layovers at the Hamburg port. In this case, the use of LNG prevents most of the noxious emissions, but the prime mover is still a conventional internal combustion engine, with standard performances in terms of noise, efficiency and CO2 emissions.
In case of Power supply based on Molten Carbon or Solid Oxide fuel cells fueled by LNG, the Annual Fuel Cell Power Barge Cost (C_{AFCPB} – $/year or €/year-) can be calculated as:

$$C_{AFCPB} = \frac{i(1+i)^N}{(1+i)^N-1}\left(P_{FC}FCC + \sum_b CbDb\right) + P_{FC}H\left(\frac{C_3 f_{CNG}}{\varepsilon} + C_{O\&M}\right) + Paux\ td\ sfc\ c_{df}\ 10^{-6} \quad (8)$$

In case of Dual fueled engines for shore-side power applications, the Annual Dual Fuel Barge Power Cost (C_{ADFBP} – $/year or €/year) can be calculated as:

$$C_{ADFBP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(p\ CE + \sum_b CbDb\right) + pH\ \sum_o CoMo + Paux\ td\ sfc\ c_{df}\ 10^{-6} + H(C_4 f'_{CNG} + +pC_2 sfc1\ f_c\ 10^{-6}) \quad (9)$$

IV. CASE STUDY: SHORE-SIDE POWER FOR RO/RO PAX

The RO/RO (roll on/roll off) PAX is a vessel built for freight vehicle transport with passenger accommodation. The vessels with facilities for more than 500 passengers are often referred to as cruise ferries.
A ro-ro pax ship offers a number of advantages over traditional ships. This kind of ship became extremely popular among holidaymakers and private car owners and contributed to the growth of tourism.
In this study, calculations will be carried out using the preview equations for ports in order to compare the various costs of shore-side power sources with those of onboard power generation systems, in case of RO/RO Pax.
Due to the probability of having political or economic changes in ports, as reference period T, a range of thirteen years will be considered through the primary economic study.
The previous parameters were estimated by using the provided ship's documents and port authority's data, listed in Table 1.

TABLE 1 RANGE SHORE-SIDE GENERAL DATA FOR SHIP RO-RO PAX- IN PARENTHESIS THE AVERAGE VALUES-

Item	
Reference Shore connection years (N-years-)	10-16 (13)
Annual shore connection time (tp-h-)	1400-3000 (2200)
Annual shore connect and disconnect time (td-h-)	140-300 (220)
sfc Specific fuel consumption (g/kW•h)	220
fc Diesel fuel cost, ($/ton)	400-1000 (700)
Paux Onboard auxiliary engines power (kW);	1250-2500
$\sum_m$ CmMm specific onboard auxiliary engines maintenance cost, ($/kW•h)	2.00*10^-3- 2.50*10^-3 (2.250*10^-3)
$\sum_o$ CoMo specific onboard auxiliary engines operating cost, ($/kW•h)	5.00*10^-3- 5.16*10^-3 (5.08*10^-3)

Using Eq. (1), Annual Auxiliary Engine Power generation Cost (C_{AAEP} – $/year) the total cost for electric power was estimated and shown in table 2 ($/year - refereed to the case of shore connection for 13 years-).

TABLE 2 ANNUAL COST OF ELECTRICITY C_{AAEP} – $/YEAR VERSUS PAUX AND CDF (RO-RO PAX)

Paux\cdf	400	500	600	700	800	900	1000
1250	2.62E+05	3.23E+05	3.83E+05	4.44E+05	5.04E+05	5.65E+05	6.25E+05
1500	3.15E+05	3.87E+05	4.60E+05	5.32E+05	6.05E+05	6.78E+05	7.50E+05
1750	3.67E+05	4.52E+05	5.36E+05	6.21E+05	7.06E+05	7.91E+05	8.75E+05
2000	4.19E+05	5.16E+05	6.13E+05	7.10E+05	8.07E+05	9.03E+05	1.00E+06
2250	4.72E+05	5.81E+05	6.90E+05	7.99E+05	9.07E+05	1.02E+06	1.13E+06
2500	5.24E+05	6.45E+05	7.66E+05	8.87E+05	1.01E+06	1.13E+06	1.25E+06
2750	5.77E+05	7.10E+05	8.43E+05	9.76E+05	1.11E+06	1.24E+06	1.38E+06
3000	6.29E+05	7.74E+05	9.20E+05	1.06E+06	1.21E+06	1.36E+06	1.50E+06

In table 3 the estimated cost of electricity from the national electricity grid (C_{ANGP} - eq. 3) and the national grid electricity cost (CN.g) vs national electric power (PN.g) are reported.

TABLE 3 COST OF ELECTRICITY FROM THE NATIONAL ELECTRICITY GRID -SHIPS RORO PAX-

PN.g (kW)	CN.g ($/kWh)	CANGP ($/year)	CN.g ($/kWh)	CANGP ($/year)	CN.g ($/kWh)	CANGP ($/year)
1250	0.10	6.05E+05	0.12	7.15E+05	0.14	8.25E+05
1500	0.10	7.15E+05	0.12	8.47E+05	0.14	9.79E+05
1750	0.10	8.25E+05	0.12	9.79E+05	0.14	1.13E+06
2000	0.10	9.35E+05	0.12	1.11E+06	0.14	1.29E+06
2250	0.10	1.04E+06	0.12	1.24E+06	0.14	1.44E+06
2500	0.10	1.15E+06	0.12	1.37E+06	0.14	1.59E+06
2750	0.10	1.26E+06	0.12	1.51E+06	0.14	1.75E+06
3000	0.10	1.37E+06	0.12	1.64E+06	0.14	1.90E+06

The values of C_{ANGP} ($/year) have been obtained on the basis of the average for other costs of national electric grid as shore side power shown in table 4 [21].

TABLE 4 OTHER COSTS OF NATIONAL ELECTRIC GRID AS SHORE SIDE POWER -IN PARENTHESIS THE AVERAGE VALUES-

Item	Cost
Frequency transformer (if required) Convert from 50 to 60 Hz; $/set for 3 Ships	460000-758000 (600000)
Harbor canalization operation $/m	160-250
High voltage cable (10 kV) $/m	16-25
Flexible cable $/m	28-42
Typical onboard cost installation (including the transformer), $	147000-372000
Maintenance cost (5% of installation cost),$	7350-18600
H Annual running hours, h/years	2200
i	3%
Harbor canalization, High voltage cable and Flexible cable, m	200
Portfees, ($)	100% PN.g *H* CN.g

The Annual Fuel Cell Power Cost (C_{AFCP} – $/year) can be evaluated by using the equation (4) based on the data in table 5.

TABLE 5 SUMMARIZES THE MAIN SPECIFICATIONS FOR FCS USING NATURAL GAS

Item	Value
Capital Cost CC ($/kW)	3000
C3 Theoretical heat rate	1
ε Fractional efficiency	0.5
CO&M Operating & Maintenance costs ($/kW·h)	0.035
H Annual running hours, h/years	2300
N (Year)	13
i (%)	3%
cfc Diesel fuel cost, ($/ton)	600
Annual shore connect and disconnect time (td - h)	230
sfc Specific fuel consumption (g/kWh)	220
Paux*sfc *td* c_{df} *10^-6 ($)	9.459E4
Portfees ($)	9.459E4
C_{AFCP} ($/year)	1.129E6

All the results obtained are based on an evaluation of 50 MJ/kg for the lower calorific value.
The estimation of C_{AFCP} ($/year) is shown in table 6.
The Annual Dual Fuel Power Cost (C_{ADFP}) can be evaluated by the equation (6) with the parameters obtained in table 7 [30].
The results obtained for C_{ADFP} are shown in table 8 and they confirm an accepted economical concept; the dual fuel can be considered as an economic solution for the shore-side power, especially in areas where the LNG cost is lower.

TABLE 6 C_{AFCP} ($/YEAR) VERSUS f_{CNG} AND P_{FC}

PFC\fcng	0.017	0.024	0.031	0.038	0.044	0.051
1250	4.81E+05	5.18E+05	5.56E+05	5.93E+05	6.31E+05	6.68E+05
1500	5.75E+05	6.20E+05	6.65E+05	7.10E+05	7.55E+05	8.01E+05
1750	6.70E+05	7.23E+05	7.75E+05	8.28E+05	8.80E+05	9.33E+05
2000	7.65E+05	8.25E+05	8.85E+05	9.45E+05	1.00E+06	1.07E+06
2250	8.59E+05	9.27E+05	9.95E+05	1.06E+06	1.13E+06	1.20E+06
2500	9.54E+05	1.03E+06	1.10E+06	1.18E+06	1.25E+06	1.33E+06
2750	1.05E+06	1.13E+06	1.21E+06	1.30E+06	1.38E+06	1.46E+06
3000	1.14E+06	1.23E+06	1.32E+06	1.41E+06	1.50E+06	1.59E+06

TABLE7 PARAMETERS OF DUAL FUEL ENGINE AS SHORE SIDE POWER

Item	Value
Capital Cost CE($/kW)	310-380 (345)
Diesel Oil percent C2 %	1%
$\sum_o$ CoMo Dual fuel operation & maintenance cost, ($/kW·h)	0.00733
H Annual running hours, h/years	2300
N (Year)	13
i (%)	3%
C4 natural gas specific fuel consumption, m^3/h	-
f'_{CNG} Natural gas specific cost, ($/m^3 or €/m^3)	-
$\sum_y$ CyDy infrastructure cost (for one ship), $	

TABLE 8 ANNUAL DUAL FUEL POWER COST (C_{ADFP}) IN ($/YEAR) VS POWER AND NATURAL GAS COST FOR RORO PAX -WITHOUT THE FIXED ANNUAL COST OF PORT ($PORT_{FEES}$)-

p\f'CNG	1,07E+02	1,49E+02	1,92E+02	2,35E+02	2,77E+02	3,20E+02
1250	1,79E+05	2,24E+05	2,69E+05	3,13E+05	3,58E+05	4,03E+05
1500	2,15E+05	2,69E+05	3,22E+05	3,76E+05	4,30E+05	4,84E+05
1750	2,51E+05	3,14E+05	3,76E+05	4,39E+05	5,02E+05	5,65E+05
2000	2,86E+05	3,58E+05	4,30E+05	5,02E+05	5,73E+05	6,45E+05
2250	3,22E+05	4,03E+05	4,84E+05	5,64E+05	6,45E+05	7,26E+05
2500	3,58E+05	4,48E+05	5,37E+05	6,27E+05	7,16E+05	8,06E+05
2750	3,94E+05	4,93E+05	5,91E+05	6,90E+05	7,88E+05	8,87E+05
3000	4,30E+05	5,37E+05	6,45E+05	7,52E+05	8,60E+05	9,67E+05

V. CONCLUSIONS

The study of alternative systems to supply electric energy to ships moored in ports is a very complex matter requiring a thorough analysis of all the relevant aspects, in order to define its feasibility.

After an accurate determination of the parameters involved and of their influence on the proposed solutions some indications have been provided to help decisions regarding the adoption of the shore power systems and consequent advantages.

Specifically, the results obtained indicate a better technical end economic efficiency of dual fuel engines fed by LNG; most of all, this is due to the cost of capital and of infrastructures needed to build alternative systems for the feeding of electric power from ashore.

On the contrary, with the raise of the cost of fuels, the connection with the electric national grid provides the higher efficiency, especially when this kind of energy is cheap (ref. 0.10 $/kWh).

In any case, the technical and economical analyses do not take into account the environmental impact of the presence of a number of ships close to very inhabited areas. In other words, a solution that seems convenient from the technical point of view, could become unacceptable once “anthropic” aspects come into consideration such as the impact on human health of consistent emissions in the atmosphere from the engines of the ships in port.

The next development of such work should therefore be to study a criterion introducing a “global” parameter of the effects of the environmental pollution on the calculations that should help evaluating the real, global benefit of any solution proposed.

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LIST OF SYMBOLS

Paux onboard auxiliary engines power (kW);
t_p berthed time (h);
s_{fc} specific fuel consumption (g/kW·h);
c_{df} diesel fuel cost, ($/ton or €/ton);
$\sum_m$ CmMm annual onboard auxiliary engines maintenance cost, ($/kWh or €/ kWh);
$\sum_o$ CoMo annual onboard auxiliary engines operating cost, ($/kWh or €/ kWh).
i annual interest, %;
N ship working years, year;
Cs ship modification cost, $ or €;
$\sum_c$ CcDc infrastructure cost (port), $ or €;
$\sum_y$ CyDy infrastructure cost (for one ship), $ or €;
$\sum_{mo}$ CmoMmo annual maintenance cost modification onboard ship, $/year or €/year;
PN.g national grid electricity power, kW;
CN.g national grid electricity cost; $/kW h or €/kW h;
H annual running hours, h/years;
td connection& disconnection time, h;
$Port_{fees}$ is the fixed annual cost of port, $/year or €/year.
C3 Theoretical heat rate; %;
FCC fuel cell Capital Cost, $/kW or €/kW;
P_{FC} is the power fuel cell required, (kW);
ε Fractional efficiency;
CO&M Operating & Maintenance costs ($/kW·h or €/kW h);
CE engine capital cost, $/kW or €/kW;
p dual fuel power , (kW);
C2 diesel fuel oil/%;
C4 natural gas specific fuel consumption, m^3/h;
f_{CNG} Fuel cell Natural gas cost, ($/kW·h or €/ kW·h);
f'_{CNG} Dual fuel natural gas cost, ($/m^3 or €/m^3);
sfc1 dual fuel diesel oil specific fuel consumption, g/kW·h;
fc diesel fuel cost, ($/ton or €/ton);

$\sum_o$ CoMo Dual fuel operation & maintenance cost, \$/kW h;
N_{gp}number of working diesel generator;
E_{ef}engine emission factor, g/kW·h;
Pshore shore side power generation;
E_{fs} shore connection emission factor, g/kW·h ;
E_{fNG}Natural gas emissions factor, g/kW·h;
C1 Natural gas fuel/%
$\sum_b$ CbDb Barge cost (for one ship), \$ or €;
$\sum_n$ CnMn annual maintenance cost modification onboard ship, \$/year or €/year;

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