# Fuel saving and reduction of emissions in ports with cold ironing applications

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**ABSTRACT:** It is well known that the progress of economic globalization, the rapid growth of international trade and maritime operation have played an increasingly significant role in providing international cargo and passenger transportation. Consequently, seaports all over the world are suffering from the problem of fuel consumption and exhaust gases coming from ships during their stopover in harbors. Many seaports have taken the necessary precautions to overcome this problem, while others are still suffering from it due to technical, political and financial problems. In Italy, the emissions of the industrial and energy sectors have been declining for years (almost 50% between 1998 and 2012), but the sulfur oxides (SOx) from the maritime sector have almost doubled. The national and international maritime traffic is responsible for 80% of total emissions due to transportation which proves to be a major source of sulfur oxide pollution on a global scale. Clearly, this situation is unsustainable in the long term, especially where the seaports are located, if not integrated, close to the town centers. In prosecution of earlier investigations carried out in our Department, we propose a procedure to compare the cost of various shore-side power sources connections with those obtained by the use of auxiliary engines on board; shore-side power concept, economic and environmental effect analysis are discussed. Finally, two numerical examples will be presented with the aim of applying the proposed procedure; the first refers to a Ro/Ro ship operating on the route between Civitavecchia and Barcelona, the second to a high-speed craft operating in the Mediterranean Sea. The results obtained in terms of costs and reduction of exhaust gas emission, have been discussed in detail.

## 1 INTRODUCTION

Ships at berth generate electricity by means of to their auxiliary engines, and emit air pollutants and noise. As a result, ports become an important and growing source of pollution and can create significant risks for the health of nearby communities. For example, the SISTI (Italian Study on Susceptibility to Temperature and Air Pollution) study conducted on adults of nine Italian cities, in addition to reporting the association between PM10 and mortality, suggests heart failure as a possible mechanism of damage induced by PM10 (M. Stafoggia et alii, 2008). In case of air pollutants coming from the ports, there is a wide range of potential mitigation approaches to this complex problem. Shore-side power has been a hot topic for the port authority in order to promote the protection of the environment and in the hope of finding a way to eliminate the problem (Baily & Solmon, 2004). The main reasons for applying ship-to-shore connection is that the inland power generation in most countries are less polluting as it depends on clean technologies such as natural gas, renewable, and other carbon-free technologies like fuel cell (Ibrahim S. et alii, 2013). This paper gives an overview of shore-side power sources and presents a systematic procedure for shore-side power costs and emission analysis to compare the various costs

of shore-side power sources with those of typical onboard power generation.
Moreover, as numerical examples, it evaluates the environmental and economic benefits of switching from onboard ship auxiliary engines to shore-side power connection for Ro/Ro ship and high-speed crafts operating in the Mediterranean sea area.

## 2 POSSIBLE SHORE-SIDE POWER SOURCES

The term “cold ironing” is used to state a connection with a shore device supplying the electric energy needed for the services onboard. The direct production of the electric power could be thus dramatically reduced together with the emissions from engines powering generators. But while this method is easy to apply when the power required is low, relevant rates of energy imply very complicated connection tools and, upstream, a dedicated and huge system of production, distribution and control of the electric energy (Battistelli et alii, 2012).
Nowadays, some systems of cold ironing are used around the world, generally for low power supply but there are also devices for high powers in ports where huge investments were made to avoid the use of diesel engines when the ship stays at bollard.
Typically, the Californian authority has always been very sensitive to the environmental problem and this resulted in many installations (of various sizes) in those ports where the practice of cold ironing is widespread.
Shore connections for feeding electric energy exist also in Sweden (Goteborg, Stockolm, Helsingborg, Piteå), in Finland (Kotka, Oulu, Kemi), Belgium (Antwerp, Zeebrugge) and in the other US ports like Seattle and Pittsburg. In many other sites medium or small cold ironing connections are installed or studied; in Juneau (Alaska), for example, an important installation for feeding electric energy to cruise ships has been working since 2001. This installation - in addition to supplying a relevant rate of electric power - must resist to the severe wind and sea conditions frequently hitting that port area.
Besides the “classic” cold ironing systems - complex from the economic, technical, managing points of view - and the ones still under development (for example: fuel cells), other systems are used with the aim of supplying electric energy to ships in ports without big investment and stable systems.

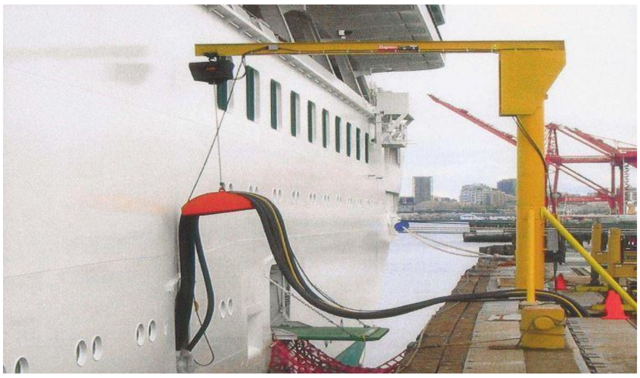

**Fig. 1** Cold ironing arrangement in the port of Seattle (US)

**Fig. 2** Cold ironing arrangement in Juneau (Alaska)-1-

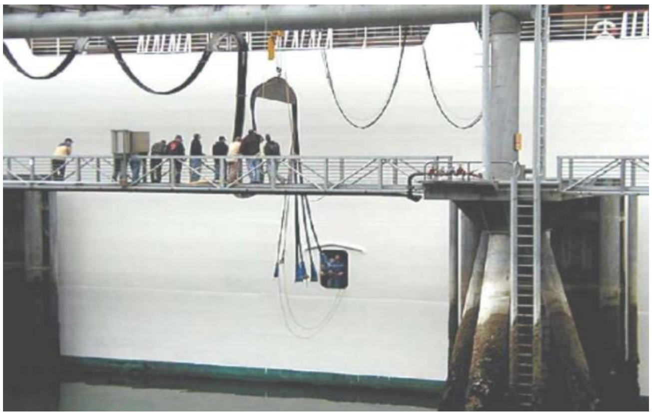

**Fig. 3** Cold ironing arrangement in Juneau (Alaska)-2-

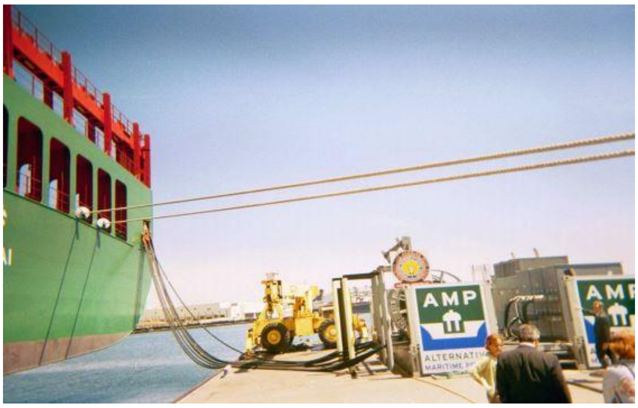


**Fig. 4** Cold ironing arrangement in a Chinese port

One of these is a container fitted with a prime engine, an alternator and the control and distribution devices needed for supplying the electric energy directly to ships.

Generally, the prime mover is a gas turbine or a diesel engine fueled by gas; if LNG is used, this results in a relatively high energy rate available for ships and a low environmental impact due to good emission qualities of gases.
This paper presents a systematic procedure and two numerical examples to the various shore-side power source applications, which may be used, including three options, namely:
a) new fixed installation, supplied from national electric grid, which is used where high power density is required;
b) installation of one or two fixed fuel cell units (200 to 250 kW or 1500 to 2000 kW) at berths where some ships HSC, tugboats, commercial fishing boats, and crew/supply boats, or Ro/ro pax, for example, are hoteling;
c) fixed plant of dual fuel diesel electric engines using oil and natural gas, especially where natural gas is available as a fuel source.
d) power barge unit equipped with fuel cells that can maneuver within a port to supply power in various locations.

## 3 SYSTEMATIC PROCEDURE FOR SHORE-SIDE POWER COST AND EMISSION ANALYSIS

The economic issue of shore-side power concept will vary from case to case depending on two main factors: the total costs of onboard electricity generation and the total costs of shore-side power supply. Generally, the total costs of onboard generation of electricity will depend on the ship's power supply system, maintenance activities and price of fuels. Moreover, it may increase if local or global emissions taxes are implemented.
On the other hand, the total costs of shore-side power depend mainly on the source of shore power electricity, which will include the following items (Ibrahim S. et alii 2013):

- -capital cost of power source unit, such as fuel cell or dual fuel engine;
- -typical harbor canalization;
- -costs of high voltage cable, where the distance between the needed berth supply point and the nearest high voltage access point can be typically between 30 meters to 500 meters in port;
- -the costs of frequency converters (from 50 Hz to 60 Hz);
- -any other modification cost required onboard, which can vary from ship to ship.

In addition, the cost for supplying a terminal with high-voltage power (variable from one country to another) plays an important role in this process. To cope with the international emissions regulation, ports around the world have adopted approaches which can significantly reduce their contribution to air pollution, such as using cleaner fuels while ship is berthed.
The amount of emissions released in the port's area depends mainly on emissions factors of the fuel used, which vary largely among different engines and fuels. On the other side, the emissions released by the use of shore-side power will vary from country-to-country and maybe from port-to-port within the same country due to variations in the fuel mixture in different regions.

### *3.1 The systematic procedure for shore side cost analysis*

In this study, a systematic procedure will be applied to compare the various costs of shore-side power sources with those of normal onboard power generation. Due to the medium probability of having political or economic changes at the reference ports, a range of ten years, as reference period (T), has been taken through the primary economic study.
The systematic procedure is based on the following steps:

a) The first step includes the estimation of onboard Annual Auxiliary Engine Power generation Cost ($\mathrm{C_{AAEP}}$ – \$/year or €/year) to be basic cost reference, which consists of fuel cost, maintenance cost and operating cost. It can be written as (see list of symbols):

$$\mathrm{C_{AAEP}} = \mathrm{P_{aux}}\, \mathrm{t_p}\, \mathrm{s_{fc}}\, \mathrm{c_{df}}\ 10^{-6} + \sum_m \mathrm{CmMm} + \sum_o \mathrm{CoMo} \qquad (3.1.1)$$

Remarkably, a good estimation of the annual onboard auxiliary engines maintenance cost (\$/annual or €/year) and annual onboard auxiliary engines operating cost, in ten years, is about 25% of $\mathrm{C_{AAEP}}$.

b) The second step is the estimation cost of electricity from the national electricity grid. It consists of 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 (\$/kW or €/kW), which varies according to the voltage level.
The Annual National Grid Power Cost ($\mathrm{C_{ANGP}}$) in (\$/year or €/year ) may be determined as:

$$C_{ANGP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(Cs + \sum_c CcDc + \sum_y CyDy\right) + \\ + \sum_n CnMn + PN.g\,H\,CN.g + \\ + Paux\ td\ sfc\ c_{df}\ \ 10^{-6} + Port_{fees} \qquad (3.1.2)$$

c) The third step is the estimation cost of electricity from fuel cell unit. The optimal selection of fuel cell type for specific applications may be affected by some criteria such as fuel type, power capacity, efficiency and installation. Currently, two major different types of fuel cells - depending on the fuel type - are available as follows (Ibrahim S. et alii, 2013):
a)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). Among them, PEMFC seems to be at a mature stage and it can be considered the best selection for moderate electric load, especially from the point of view of the installation cost.
b)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). Draw-back of start/up operation of this type is considered the main disadvantage, but this may be compensated by its high electric generation efficiency in comparison to H2 fuel based type.

Usually, three major components are considered in the computation of the cost of electricity 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:

$$C_{AFCP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(P_{FC}FCC + \sum_y CyDy\right) + \\ + P_{FC}H\left(\frac{C_3 f_{CNG}}{\varepsilon} + C_{O\&M}\right) + Paux\ td\ sfc\ c_{df}\ \ 10^{-6} + \\ + Port_{fees} \qquad (3.1.3)$$

d) Finally, the systematic procedure for shore side cost analysis requires the estimation cost of electricity from dual fuel engine.
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 cost. $C_{ADFP}$ may be calculated as:

$$C_{ADFP} = \frac{i(1+i)^N}{(1+i)^N-1}\left(p\ CE + \sum_y CyDy\right) + \\ + pH\ \sum_o CoMo + Paux\ td\ sfc\ c_{df}\ \ 10^{-6} + \\ + H(C_4 f_{CNG} + + pC_2 sfc1\ f_{c\ 10^{-6}}) + Port_{fees} \qquad (3.1.4)$$

e) A comparison between various costs of shore-side power sources, $C_{ANGP}$ , $C_{AFCP}$ , $C_{ADFP}$ with those of typical onboard power generation $C_{AAEP}$, underlines the economic benefits due to switching from onboard ship auxiliary engines to shore-side power connections.

### *3.2 Emissions analysis of shore-side power sources*

To evaluate the impact of the switch from onboard auxiliary diesel engines to shore-side power concept, it is essential to estimate the level of gases emitted by each proposed shore-side power source, and then compare it with that emitted by onboard auxiliary diesel engines. The basic emissions quantity which is emitted from the onboard auxiliary diesel generator (Eaux) can be estimated as follows:

$$Eaux = Paux\ t_p\ E_{ef} N_{gp}\ (Kg/year) \qquad (3.2.1)$$

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

$$Eshore = Pshore\left(t_p - t_d\right)E_{fs} + N_{gp}E_{ef}t_d Paux \qquad (3.2.2)$$

Eq. (3.2.2) will be applied for both cases: the national grid and fuel cell unit, while estimation of dual fuel engines annual emissions quantity ($E_{dual}$) will change as a consequence of the effect of natural gas and diesel fuel oil percentages, as shown in the following equation:

$$E_{dual} = \\ P\left(t_p - t_d\right)(C_1 E_{fNG} + C_2 E_{ef}) + N_{gp}E_f t_d Paux \qquad (3.2.3)$$

The equations (3.2.1), (3.2.2) and (3.2.3) give the annual emissions rate for the basic onboard power generation and the various shore-side power options.

## 4 CASE STUDIES: APPLICABILITY OF SHORE-SIDE POWER FOR RO/RO PAX AND HIGH-SPEED CRAFT FOR CIVITAVECCHIA AND ANCONA PORTS

The port of Civitavecchia is one of the main Italian ports for passenger traffic, with over 2 million travelers in transit each year. The port of Civitavecchia, excluding cruise ships, permanently connects the peninsula with Sardinia (Cagliari, Olbia, Porto Torres and Arbatax), Sicily (Palermo, Trapani, Catania), Malta, Spain (Barcelona) and North Western Africa. In recent years, the port of Civitavecchia has increased the services of Short Sea Shipping, also called "Motorways" of the sea, connecting the countries facing the Mediterranean Sea with the islands, so as to move to the sea the traditional on-land traffic (TIR and passengers). In this regard, in July 2012 an agreement was signed between the Civitavecchia and Barcelona Port Authorities, in order to facilitate the sea traffic. The motor seaways of the Sea Terminal is located in the space behind the dock 18, in a central position, in the heart of the area dedicated to traffic Ro-Ro cargo and passengers. The property is spread over an area of about 2000 m². The structure itself has tripled in size and expanded services since 2006, in order to facilitate embarkation and disembarkation. The northern area of the port of Civitavecchia is dedicated to the traffic of cargoes and logistic systems.

**Fig. 5** coal-fired power plant near Civitavecchia Port

Near the Civitavecchia port there is the ENEL Torrevaldaliga North (Fig.5), a coal-fired power plant with a total capacity of 1980 MW installed. Since 2003, when the conversion started, the new coal system has replaced the old one, a fuel oil thermal power plant with a total capacity of 2640 MW.

The port of Ancona is the first Italian port for international traffic of vehicles and passengers, with over 1.5 million passengers and 200,000 trucks each year, and one of the first of the Adriatic ports for goods; as for fishing, the fish markets of Ancona together hold the second position in the Adriatic fish markets and the sixth position at national level. In this study, calculations will be carried out using the preview procedure for both of Civitavecchia and Ancona ports to compare the various costs of shore-side power sources with those of normal onboard power generation.

The first application regarding Cruise Barcelona ship, launched on 16 February 2008 at the shipyard of Castellammare di Stabia in Naples (Fig. 6).


**Fig. 6** Cruise Barcelona Ro/ro

The ship, second in a series of four, was commissioned by the Grimaldi Group to reinforce the Mediterranean lines. Technically, it is very similar to the Cruise Roma, with a maximum speed of 28 knots and a capacity of 3050 line meters of cargo load which corresponds to about 220 trailers. Cruise Barcelona is capable of carrying 251 cars and 2300 passengers, with 19 suites and about 400 cabins. The ship entered service in September 2008 on the route Civitavecchia – Barcelona (Fig.7).

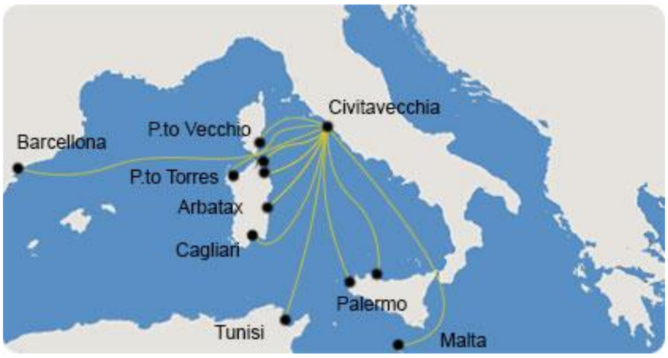


**Fig. 7** Route Civitavecchia-Barcelona

The second application regards the Croazia Jet fast ferry Fig. 8.


**Fig. 8** Croazia Jet High Speed

The Croatia Jet is one of the means of super-fast SNAV (Società Navigazione Alta Velocità). Built in 1996, with a gross tonnage of 3012 tons, 74 meters long and 26 meters wide is moving at more than 37 knots at full load and is capable of carrying 100 cars and 500 passengers (Fig. 8). The ship entered service in June to October on the route Ancona-Split Fig. 9.


**Fig. 9** Route Ancona-Spalato

Due to the probability of having political or economic changes in the ports of Civitavecchia and Ancona, as reference period T, a range of ten years will be taken through the primary economic study.

### *4.1 Applicability of shore-side power for ro/ro pax and high speed crafts*

The previous parameters were estimated by using the provided ship's documents and port authority's data, listed in Table 1. Using Eq. (3.1.1), Annual Auxiliary Engine Power generation Cost ($C_{AAEP}$ – $/year or €/year) the total electricity cost was estimated (respectively) to be about **1.340.000** and **415.000** ($/year - refereed to the case of shore connection for 10 years-).

| Item | Ro/ro | Fast/ship |
|---|---|---|
| Shore connection years (N-years-) | 10 | 10 |
| Annual shore connection time (tp-h-) | 2300 | 5000 |
| Annual shore connect and disconnect time (td-h-) | 230 | 500 |
| sfc Specific fuel consumption (g/kW•h) | 250 | 250 |
| fc Diesel fuel cost, ($/ton) | 1000 | 1000 |
| Paux Onboard auxiliary engines power (kW); | 1750 | 250 |
| Partial Annual Auxiliary Engine Power generation Cost ($C_{AAEP}$) in ($/year) | 1.006E6 | 3.125E5 |
| Total Annual Auxiliary Engine Power generation Cost ($C_{AAEP}$) in ($/year) | **1.342E6** | **4.167E5** |

**Table 1** Shore-side general data for Cruise Ship Ro-ro Pax and Croazia Jet Fast ferry

As far as the estimation cost of electricity from the national electricity grid eq. (3.1.2), the effect of increasing the expected ship working years (N) on the value of annual electricity cost at various CN.g must be taken into account. The values obtained are showed in tables 2.1 and 2.2.

| N | CNg | $C_{ANGP}$ **($/year)** | CNg | $C_{ANGP}$ **($/year)** | CNg | $C_{ANGP}$ **($/year)** |
|---|---|---|---|---|---|---|
| 1 | 0.10 | 1.314E6 | 0.12 | 1.474E6 | 0.14 | 1.636E6 |
| 2 | 0.10 | 1.070 E6 | 0.12 | 1.231E6 | 0.14 | 1.392E6 |
| 3 | 0.10 | 9.894 E5 | 0.12 | 1.150E6 | 0.14 | 1.311E6 |
| 4 | 0.10 | 9.489 E5 | 0.12 | 1.110E6 | 0.14 | 1.271E6 |
| 5 | 0.10 | 9.247 E5 | 0.12 | 1.086E6 | 0.14 | 1.247E6 |
| 6 | 0.10 | 9.085E5 | 0.12 | 1.070E6 | 0.14 | 1.231E6 |
| 7 | 0.10 | 8.970E5 | 0.12 | 1.058E6 | 0.14 | 1.219E6 |
| 8 | 0.10 | 8.884E5 | 0.12 | 1.049E6 | 0.14 | 1.210E6 |
| 9 | 0.10 | 8.818E5 | 0.12 | 1.043E6 | 0.14 | 1.204E6 |
| 10 | 0.10 | 8.765E5 | 0.12 | 1.037E6 | 0.14 | 1.198E6 |

**Table 2.1** Cost of electricity from the national electricity grid Cruise Ship RoRo Pax

| N | CNg | $C_{ANGP}$ **($/year)** | CNg | $C_{ANGP}$ **($/year)** | CNg | $C_{ANGP}$ **($/year)** |
|---|---|---|---|---|---|---|
| 1 | 0.10 | 6.487E5 | 0.12 | 6.987E5 | 0.14 | 7.487E5 |
| 2 | 0.10 | 4.566E5 | 0.12 | 5.066E5 | 0.14 | 5.567E5 |
| 3 | 0.10 | 3.937E5 | 0.12 | 4.427E5 | 0.14 | 4.927E5 |
| 4 | 0.10 | 3.608E5 | 0.12 | 4.107E5 | 0.14 | 4.607E5 |
| 5 | 0.10 | 3.416E5 | 0.12 | 3.916E5 | 0.14 | 4.416E5 |
| 6 | 0.10 | 3.289E5 | 0.12 | 3.789E5 | 0.14 | 4.289E5 |
| 7 | 0.10 | 3.198E5 | 0.12 | 3.698E5 | 0.14 | 4.198E5 |
| 8 | 0.10 | 3.130E5 | 0.12 | 3.630E5 | 0.14 | 4.130E5 |
| 9 | 0.10 | 3.077E5 | 0.12 | 3.578E5 | 0.14 | 4.077E5 |
| 10 | 0.10 | 3.036E5 | 0.12 | 3.536E5 | 0.14 | 4.036E5 |

**Table 2.2** Cost of electricity from the national electricity grid Croazia Jet fast ferry

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 showed in table 3.1 and 3.2.

| Item | Cost |
|---|---|
| Frequency transformer (if required) Convert from 50 to 60 Hz; $/set (1) | 600000 |
| Harbor canalization operation $/m (2) | 160-250 |
| High voltage cable (10 kV) $/m (3) | 16-25 |
| Flexible cable $/m (4) | 28-42 |
| Typical onboard cost installation (including the transformer), $ (5) | 147000-372000 |
| Maintenance cost (5% of installation cost),$ (6) | - |
| H Annual running hours, h/years (7) | - |
| PN.g National grid electricity power, kW (8) | - |
| i (9) | - |
| Harbor canalization, High voltage cable and Flexible cable, m (10) | - |
| Portfees, ($) (11) | 100% PN.g *H* CN.g |

**Table 3.1** Average for other costs of national electric grid as shore side power

| Item | Average Barcelona | Average Croazia Jet |
|---|---|---|
| (1) | 600000 | 600000 |
| (2) | 205 | 205 |
| (3) | 20.5 | 20.5 |
| (4) | 35 | 35 |
| (5) | 200000 | 100000 |
| (6) | 10000 | 7500 |
| (7) | 2300 | 5000 |
| (8) | 1750 | 250 |
| (9) | 5% | 5% |
| (10) | 300 | 300 |
| (11) | 100% PN.g *H* CN.g | 100% PN.g *H* CN.g |

**Table 3.2** Average for other costs of national electric grid as shore side power

As far as the Annual Fuel Cell Power Cost ($C_{AFCP}$ – $/year) it may be calculated by using the (3.1.3) equation on the basis of the date of table 4.

| Item | RoRo Pax Barcelona | Fast ferry Croazia Jet |
|---|---|---|
| Power Output (kW) | 1750 | 250 |
| Capital Cost CC ($/kW) | 3000 | 5000 |
| Fuel cost fC.N.G ($/kW h) | 0.0136 | 0.0136 |
| C3 Theoretical heat rate | 1 | 1 |
| ε Fractional efficiency | 0.5 | 0.5 |
| CO&M Operating & Maintenance costs ($/kW·h) | 0.035 | 0.035 |
| H Annual running hours, h/years | 2300 | 5000 |
| N (Year) | 10 | 10 |
| i (%) | 5% | 5% |
| cfc Diesel fuel cost, ($/ton) | 940 | 940 |
| Annual shore connect and disconnect time (td-h-) | 230 | 500 |
| sfc Specific fuel consumption (g/kW•h) | 250 | 250 |
| Paux*sfc *td* $c_{df}$ *10^-6 ($) | 9.459E4 | 2.94E4 |
| Portfees ($) | 9.459E4 | 2.94E4 |
| $C_{AFCP}$ **($/year)** | **1.129E6** | **3.081E5** |

**Table 4** summarizes the main specification of the proposed unit, using natural gas as fuel that could provide the required electricity load.

The estimation of $C_{AFCP}$ ($/year) results in about **1.130.000 $/year** for ro/ro pax Barcelona and about **300.000 $/year** for Croazia Jet, on the basis of an accepted economical concept; the fuel cell may be considered as an economic solution for the shore-side power source, especially with the current development of fuel cells design and manufacture.
Finally, as far as the estimation cost of electricity from dual fuel engine the Annual Dual Fuel Power Cost ($C_{ADFP}$) in ($/year), obtained by the (3.1.4) equation, can be estimated on the basis of the Dual Fuel engine, operating and maintenance costs synthesized in table 5.1 and 5.2.

| Item | RoRo Pax Barcelona | | |
|---|---|---|---|
| Power (kw) | 1500 | 1750 | 2000 |
| Capital cost CE ($/kw) | 1520 | 1400 | 1350 |
| Natural gas fuel consumption C4(m^3/h) | 0.318 | 0.390 | 0.435 |

| | | | |
|---|---|---|---|
| Natural gas fuel cost fcng($/kW h) | 1.36E-2 | 1.36E-2 | 1.36E-2 |
| Diesel oil consumption sfc1(g/kW h) | 250 | 250 | 250 |
| Diesel Oil percent C2 % | 30% | 30% | 30% |
| Variable service contract ( $/Kw h) | 0.010 | 0.008 | 0.007 |
| Variable consumables ( $/Kw h) | 1.5E-4 | 1.5E-4 | 1.5E-4 |
| Fixed Maintenance ( $/Kw h) | 0.0019 | 0.0011 | 0.009 |
| Net Cost O&M ( $/Kw h) | 0.022 | 0.0175 | 0.016 |
| i | 5% | 5% | 5% |
| H annual running hours | 2300 | 2300 | 2300 |

**Table 5.1** Dual Fuel engine, Operating and maintenance costs hypothesis for RoRo Pax Barcelona

| **Item** | **Fast ferry Croazia Jet** | | |
|---|---|---|---|
| Power (kw) | 100 | 250 | 300 |
| Capital cost CE ($/kw) | 2100 | 2010 | 1940 |
| Natural gas fuel consumption C4 (m^3/h) | 0.042 | 0.141 | 0.174 |
| Natural gas fuel cost fcng($/kW h) | 1.36E-2 | 1.36E-2 | 1.36E-2 |
| Diesel oil consumption sfc1(g/kW h) | 250 | 250 | 250 |
| Diesel Oil percent C2 % | 30% | 30% | 30% |
| Variable service contract ( $/Kw h) | 0.02 | 0.016 | 0.015 |
| Variable consumables ( $/Kw h) | 1.5E-4 | 1.5E-4 | 1.5E-4 |
| Fixed Maintenance ( $/Kw h) | 0.0019 | 0.0011 | 0.009 |
| Net Cost O&M ( $/Kw h) | 0.022 | 0.0175 | 0.016 |
| i | 5% | 5% | 5% |
| H annual running hours | 5000 | 5000 | 5000 |

**Table 5.2** Dual Fuel engine, Operating and maintenance costs hypothesis for Fast ferry Croazia Jet

Table 6 shows the results obtained of the Annual Dual Fuel Power Cost ($C_{ADFP}$ – $/year) versus the number of year N and the power (respect. 1500, 1750 and 2000 kW for RoRo Pax Barcelona and 100, 250 and 300 kW for Fast ferry Croazia Jet ).

| | **RoRo Pax Barcelona** | | | **Fast ferry Croazia Jet** | | |
|---|---|---|---|---|---|---|
| **N** | $C_{ADFP}$ **(1500)** | $C_{ADFP}$ **(1750)** | $C_{ADFP}$ **(2000)** | $C_{ADFP}$ **(100)** | $C_{ADFP}$ **(250)** | $C_{ADFP}$ **(300)** |
| 1 | 2.84E6 | 3.06E6 | 3.42E6 | 2.95E5 | 6.74E5 | 7.82E5 |
| 2 | 1.65E6 | 1.79E6 | 2.00E6 | 1.76E5 | 4.05E5 | 4.73E5 |
| 3 | 1.25E6 | 1.36E6 | 1.52E6 | 1.37E5 | 3.16E5 | 3.69E5 |
| 4 | 1.05E6 | 1.15E6 | 1.29E6 | 1.17E5 | 2.71E5 | 3.17E5 |
| 5 | 9.36E5 | 1.02E6 | 1.15E6 | 1.05E5 | 2.45E5 | 2.86E5 |
| 6 | 8.58E5 | 9.39E5 | 1.052E6 | 9.737E4 | 2.268E5 | 2.654E5 |
| 7 | 8.01E5 | 8.79E5 | 9.85E5 | 9.18E4 | 2.14E5 | 2.51E5 |
| 8 | 7.59E5 | 8.34E5 | 9.35E5 | 8.76E4 | 2.05E5 | 2.40E5 |
| 9 | 7.27E5 | 7.99E5 | 8.96E5 | 8.43E4 | 1.97E5 | 2.31E5 |
| 10 | 7.01E5 | 7.71E5 | 8.65E5 | 8.17E4 | 1.91E5 | 2.24E5 |
| 11 | 6.80E5 | 7.48E5 | 8.40E5 | 7.96E4 | 1.87E5 | 2.19E5 |
| 12 | 6.62E5 | 7.29E5 | 8.19E5 | 7.78E4 | 1.83E5 | 2.14E5 |
| 13 | 6.47E5 | 7.13E5 | 8.01E5 | 7.64E4 | 1.79E5 | 2.10E5 |
| 14 | 6.35E5 | 7.00E5 | 7.86 E5 | 7.51E4 | 1.76E5 | 2.07E5 |
| 15 | 6.24E5 | 6.88E5 | 7.73E5 | 7.40E4 | 1.74E5 | 2.04E5 |

**Table 6** Annual Dual Fuel Power Cost ($C_{ADFP}$) in ($/year) versus the number of year N and the power (respect. 1500, 1750 and 2000 kW for RoRo Pax Barcelona and 100, 250 and 300 kW for Fast ferry Croazia Jet ).)- without $\mathrm{Port_{fees}}$-

### *4.1.1 Emissions analysis of shore-side power sources for ro/ro pax and high speed crafts*

Generally, the value of emissions rates depends mainly on emission factors, electric consumed load and working hours. Table 7 summarizes a comparison among the main emission factors of various electric energy sources (Banawan A. et alii 2010, Altmann M. et alii 2004, Papagiannakis R, et alii 2010); evidently that there was a shortage in obtaining the exact value of (HC) for both fuel cell and national grid.

| **Shore power source** | **CO2** | **CO** | **NOx** | **PM 10** | **SOx** | **HC** |
|---|---|---|---|---|---|---|
| Onboard engine | 698 | 1.68 | 13.4 | 0.55 | 2.56 | 0.53 |
| Dual-fuel engine | 553 | 0.597 | 2.59 | 0.015 | 0.2 | 0.90 |
| Fuel cell unit* | 520 | 0.18 | 0.15 | 0 | 0 | - |
| National grid | 514 | 0.133 | 0.85 | 0 | 0 | - |

**Table 7** Various energy source emissions factors (g/kW·h)
* Fuel cell emissions using natural gas fuel

The basic emissions quantity which is emitted from the onboard auxiliary diesel generator (*Eaux*) could be estimated on the basis of the parameters synthesized in the following table 8:

| Parameter | RoRo Pax Barcelona | Fast ferry Croazia Jet |
|---|---|---|
| C2 | 30% | 30% |
| C1 | 70% | 70% |
| td(h) | 230 | 500 |
| tp(h) | 2300 | 5000 |
| Paux (kW) | 1750 | 250 |
| Ngp | 1 | 1 |

**Table 8** Parameters for basic emissions quantity

The use of equations (3.2.1, 3.2.2, 3.2.3 and 3.2.4) gives the annual emissions quantity for the basic onboard power generation and the various shore-side power options for RoRo Pax Barcelona for Fast ferry Croazia Jet, Table 9 and Table 10.

| Shore power source | CO2 | CO | NOx | PM10 | SOx | HC |
|---|---|---|---|---|---|---|
| **Onboard engine** | **2.81E6** | **6762** | **5.41E3** | **2214** | **1.03E4** | **2133** |
| Dual-fuel engine | 2.44E6 | 4015 | 2.65E4 | 857 | 4323 | 3074 |
| Fuel cell unit* | 2.16E6 | 1328 | 5949 | 221 | 1031 | - |
| National grid | 2.14E6 | 1158 | 8485 | 221 | 1031 | - |

**Table 9** Onboard ship and shore side power sources emissions quantity (kg/year) for Ro-Ro Pax Barcelona

| Shore power source | CO2 | CO | NOx | PM10 | SOx | HC |
|---|---|---|---|---|---|---|
| **Onboard engine** | **8.72E5** | **2100** | **1.68E4** | **687** | **3202** | **662** |
| Dual-fuel engine | 7.58E5 | 1247 | 8251 | 266 | 1342 | 954 |
| Fuel cell unit* | 6.72E5 | 412 | 1847 | 69 | 320 | - |
| National grid | 6.65E5 | 360 | 2635 | 69 | 320 | - |

**Table10** Onboard ship and shore side power sources emissions quantity (kg/year) for Fast ferry Croazia Jet

## 6 Conclusion

The various shore-side power systems and their barriers were introduced. The direct annual cost for onboard generation of electricity was compared to that from the shore-side electricity systems. Ro/ro pax and High Speed Craft were also investigated as cases study for the applicability of shore-side power concept while berthed at Civitavecchia and at Ancona ports. The results prove the national electricity grid concept as the best possible option from the economic point of view.

Furthermore, the study shows that emissions factors of the proposed shore-side power systems were much lower than those onboard the ship. The estimated exhaust gas emissions released from onboard power generation at berth were compared with previous data emitted from the various shore-side electricity concepts. The outcome of that comparison proves that the national grid concept is the best possible choice as a shore-side power source, from the point of view of the environment safety.

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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, ($/annual or €/year); $\sum_o$ CoMo annual onboard auxiliary engines operating cost, ($/year or €/year).
i annual interest, %;
N ship working years, year;
Cs annual ship modification cost, $/year or €/year;
$\sum_c$ CcDc infrastructure cost (port), $ or €;
$\sum_y$ CyDy infrastructure cost (for one ship), $ or €;
$\sum_n$ CnMn 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);
fuel cost fC.N.G ($/kW·h or €/kW h);
ε Fractional efficiency;

CO&M Operating & Maintenance costs ($/kW·h or €/kW h);
CE fuel engine capital cost, $/kW or €/kW;
p dual fuel power , (kW);
C2 diesel fuel oil/%;
C4 natural gas specific fuel consumption, m^3/h;
$f_{CNG}$ 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/%

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