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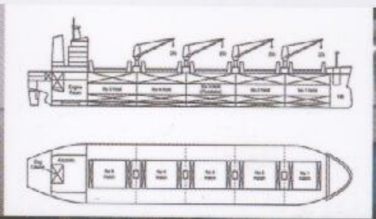

UNA NUOVA FILIERA PER LA VALORIZZAZIONE DEI RIFIUTI: L'USO DEL COMBUSTIBILE DERIVATO DA RIFIUTI NELLA PROPULSIONE NAVALE

Valutazioni tecniche ed economiche

Nino Di Franco, Massimiliano Toppi

USE OF ALTERNATIVE FUELS FOR MARINE PROPULSION

Massimiliano TOPPI
Università Roma Tre, Rome, Italy

Nino DI FRANCO
ENEA Italian National Agency for New Technologies, Energy and Environment, Rome, Italy

ABSTRACT

Owing to the recent dramatic growth of oil price, with the consequential increase of shipping freights, and looking in the same time for new solutions for the problem of wastes management, this work studies the use of Refuse Derived Fuel (RDF) for the propulsion of opportunely mechanically and structurally modified *bulk carrier* ships.

Whereas *bulk carrier* ships are at present all equipped with a classic diesel motorization fed with marine fuel, this work studies the exploitation of a new kind of plant providing the same mechanical power, and consisting essentially of a steam generator with a *Circulating Fluidised Bed Boiler* (*CFBB*) fed with RDF, connected to a system for the treatment of exhaust gases.

This work is based upon the comparison between the current situation and the supposed alternative one; a final estimate of the economy by means of a differential cost-benefits analysis has been carried out; it shows good economic performances with an expected payback time of about 8.5 years.

1 INTRODUCTION

The increasing cost of MFO (Marine Fuel Oil) risks to vanish the profits coming from the ever growing volume of goods shipped by sea at a world level. The present contribution consists in a technological proposal linking together the abatement of costs for marine propulsion and a sustainable-development-oriented approach.

The technological solution carried out in this study doesn't introduce any technical problem, as to until some decades ago the adoption of steam cycles fed with solid fuels (mainly coal) was the standard solution for marine propulsion; even logistic issues both in harbours and on board don't seem insurmountable at present.

The authors focused their attention on the economical assessment of the proposal instead, seen under an entrepreneurial point of view.

The cost-benefit analysis has been based upon the comparison between the two technologies (diesel engine V/s steam turbine), considering the different costs on a differential basis.

2 THE REFUSE DERIVED FUEL

The Refuse Derived Fuel, commonly known as RDF, is in practice the dry part of Solid Urban or Industrial Wastes.

According to the Legislative Decree 1997 feb.5th, n. 22 [1], establishing the reference framework for the integrated management of wastes in Italy, the RDF is part of activities dealing with energy recovery [2]. Furthermore, the Legislative Decree 2003 dec. 29th, n. 387, includes, among the energy sources taking advantage of the favourable regime foreseen for renewable energies, the non-biodegradable fraction of wastes and the refuse derived fuels, RDFs [3].

As far as the use of RDF in dedicated[1] and non-dedicated plants is concerned, its minimal chemical-physic characteristics (shown in table 2.1) are regulated by the Ministry Decree 1998 feb. 5th, which establishes the design-operative criteria for the plants, and the threshold values for the emissions of polluting agents in atmosphere [3].

The RDF is burnt to recover energy, both in the form of electric and/or thermal energy, in dedicated plants or, mixed with common solid fuels, in other kinds of industrial plants; they are normally [3]:

- cement mills
- power plants
- lime production mills
- iron & steel plants
- heating district power plants

In dedicated plants, the RDF is exploited by means of direct combustion, whereas in industrial plants by means of co-combustion (boilers are fed with RDF with other common fuels).

Under a technical point of view the combustion of RDF in dedicated plants doesn't show any problem; at present, the commonly used cleaning technologies of exhaust meet the limits imposed by environmental legislation.

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[1] Dedicated plants are ad-hoc built plants for the thermovalorization of RDF.

2.1 Process production of RDF

The process for the production of RDF provides an enough homogeneous product, without polluting substances and with a good heating value, so that it can be used for power generation instead of common fuels.

Under a legislative point of view, the *production* of RDF is regulated by the Ministry Decree 1998 feb. 5th, concerning the recovery of non-dangerous matter from solid and industrial urban wastes; it allows the use of non-dangerous industrial wastes until 50% (weight in final feed), establishing types and characteristics through the European Wastes Catalogue codex [3]. Such recoverable wastes are:

- Non-chlorinated plastics
- Multilayer matters
- Non-chlorinated synthetic rubbers
- Artificial resins and fibres with Chlorine content under 0.5% (weight)
- Wasted tyres

2.2 Chemical-physic characteristics of RDF

At present, beyond the values imposed by the M.D. 1998 feb. 5th, the UNI 9903 rule foresees two kinds of RDF: the high quality and the standard quality RDF (table 2.1).

Parameter	Unit of Measure	High Quality RDF UNI 9903 rule	Standard Quality RDF UNI 9903 rule and DM 5-2-98
Net Heating Value	kJ/kg as is	> 20.000	> 15.000
Moisture	As is	< 18%	< 25%
Ashes	As is	< 15%	< 20%
Chlorine	As is	< 0,7%	< 0,9%
Sulfur	As is	< 0,3%	< 0,6%
Fly Lead	mg/kg d.s.(*)	< 100	< 200
Chrome	mg/kg d.s.	< 70	< 100
Copper	mg/kg d.s.	< 50	< 300
Manganese	mg/kg d.s.	< 200	< 400
Nikel	mg/kg d.s.	< 30	< 40
Arsenic	mg/kg d.s.	< 5	< 9
Cadmium	mg/kg d.s.	< 3	< 7
Mercury	mg/kg d.s.	< 1	

(*) d.s. = dry substance

Table 2.1: RDF characteristics according to MD 1998 Feb. 5th and UNI 9903 rule (Source: Pirelli Ambiente)

3 USE OF RDF FOR NAVAL PROPULSION

3.1 Bulk carrier ship

The authors chose as the reference ship a bulk carrier, following a series of reasons. They thought that the lower the technical needs of the ship, the easier the installation and the management on board of the power plant fed with RDF should have been. Moreover, a bulk carrier doesn't need technically complex machineries on board as an oil-, chemical- or methane-tanker, and this constitutes a framework quite economic as far as the investment and maintenance costs are concerned.

The main issue influencing the plant size is the cruising speed. Generally, the average speeds of bulk carriers are about 14 ÷ 15 knots (47 ÷ 49 km/h), instead of 26 ÷ 27 knots (47 ÷ 49 km/h) pertaining container vessels. The last kind of ships normally carries valuable goods so it must amortize the technical locking ups getting carrying times shorter. The screws need a quite high power: 60 ÷ 70 MW diesel engines are quite common to meet in *Postpanamax* class container vessels. Bulk carrier ships don't carry loose unperishable materials (but typically iron ore, coke, coal etc.), so they don't need high speeds and consequently high powers. For instance, ships carrying 5,000 dwt are equipped with 1.5 MW engines, and ships carrying 320,000 dwt with 25 MW engines.

Besides that, bulker ships don't need sophisticated safety systems on board like others types of ships, considering that the materials on board are not a great value.

The presence of exhaust gas abatement systems and the arrangement of the fluidised bed boiler, whose overall height is about 30 m, have great influence on the identifying of the optimal size of the ship. The authors chose the Capesize class as the most appropriate size to guarantee an acceptable compromise under an economical point of view, considering the payload loss introduced by the new, larger boiler.

As reference, the Dunkirkmax-Capesize Cape Victory bulk carrier ship has been chosen; it has been recently built and at present it is engaged on international courses, able to carry about 177,000 dwt, with a mechanical power of 16.8 MW (table 3.1) [4].

class: Capesize-Dunkirkmax	
capacity [dwt]	177.359
dimensions:	
lenght overall [m]	288,97
lenght p.p. [m]	280,45
breadth [m]	45,00
draught [m]	17,955
Main technical features:	
power [kW]	16.800[2]
speed knots]	14,8

Table 3.1: *Cape Victory's* main technical features [4]

4 STEAM PLANT FOR NAVAL PROPULSION

Steam plants for naval propulsion are quite different from those designed for power plants. As a matter of fact, more complex schemes and thermodynamic cycles surely produce benefits in terms of overall energy efficiency; on the other

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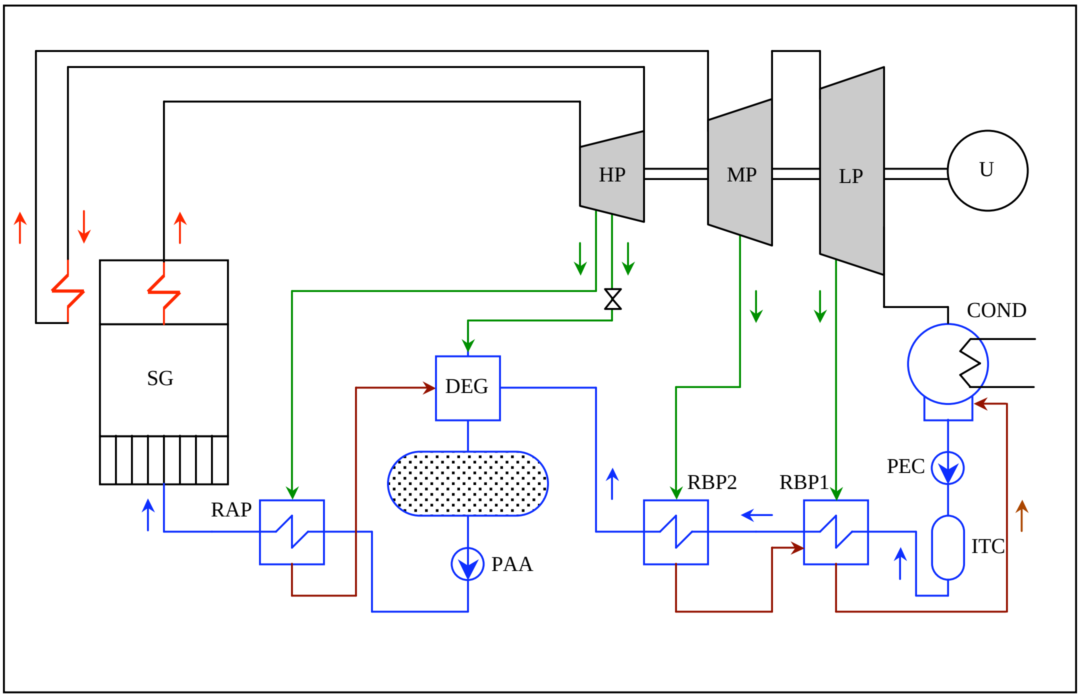
[2] Such a power value is not related to the Cape Victory itself but it must be considered as a reference value for a Capesize-Dunkirkmax class bulk carrier.

side this means structural complications with a subsequent increase of investment costs and, as far as ships are concerned, a heavier structure. In power plants the trend to carry out high power concentrations (more than 1000 MW) justifies and makes these extra-costs acceptable and sustainable under an economical point of view. Nevertheless in naval field powers are by far lower, and such convenience doesn't exist; for instance, the biggest bulk carrier in the world, carrying more than 300,000 dwt, doesn't exceeds 25 MW.

Reliability reasons impose the implementation of simple plants, with always subcritical operating pressures and peak temperatures not exceeding 500 °C; normally, technical configurations foresee only a single reheat stage and at most five steam extractions [5].

The authors chose a configuration inspired from Kawasaki steam plants (the latest installed for naval propulsion), where four steam extractions and a single reheat stage are present (figure 4.1).



Steam Plant Scheme

SG: Steam generator
MP: Medium pressure turbine
U: User
CP: Condensate pump
CTP: Condensate treatment pant
LPH: Low pressure heater

HP: High pressure turbine
LP: Low pressure turbine
CON: Condenser
FWT: Feed water tank
FP: Feed pump
HPH: High pressure heater

Figure 4.1: Simplified scheme of *Kawasaki* steam plant

The peak efficiency of this cycle is surely lower than the efficiency of a similar scheme designed for electricity generation. Furthermore, marine steam generators can't reach the output of 'on soil' generators due to weight and volume limitations imposed by the ship structure.

Finally, considering the scale effect, even the mechanical output shows sensibly lower values, since it is well known that when powers (and sizes) decrease the losses increase: all that causes a higher specific fuel consumption and a lower efficiency.

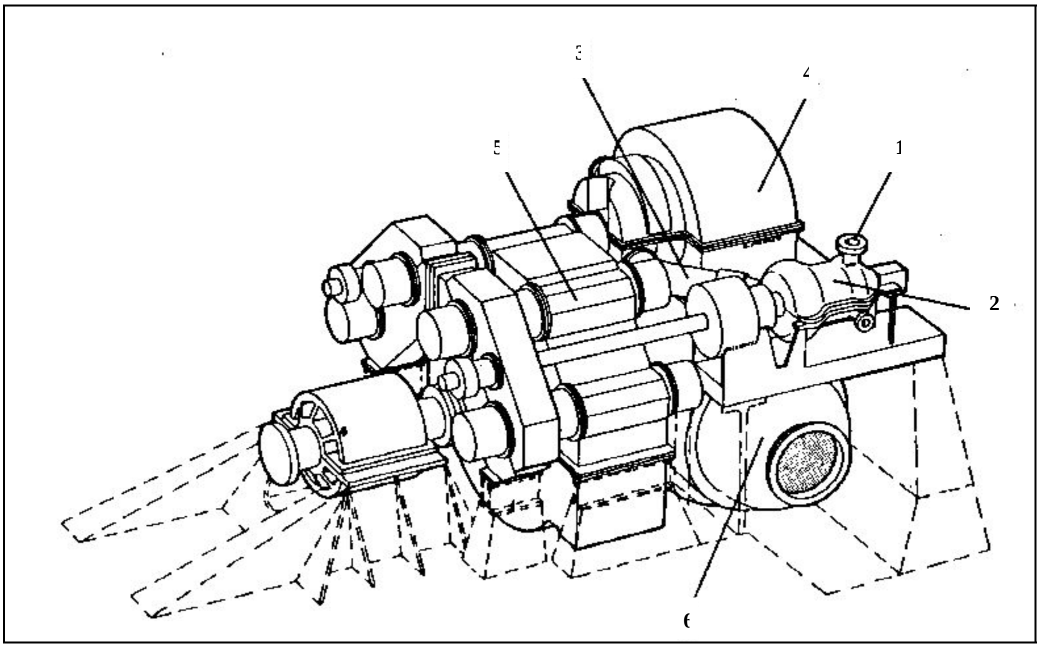
The foreseen plant is further limited by the use of RDF in the boiler: the presence of the circulated fluidised bed boiler sets the highest operating temperatures at 900 ÷ 950 °C. In these conditions, the corrosive action of chlorine compounds in exhaust (amplified by temperatures exceeding 1000 °C) is limited. For all these reasons thermodynamic steam parameters can't exceed 60 ÷ 65 bars with an operating temperature of about 450 °C [6].

4.1 Multistage turbine

Steam turbines for naval purposes are normally divided in different stages, generally two, one at high pressure (HP) and one at low pressure (LP), each one at the appropriate thermodynamic and cinematic conditions depending on the characteristics of the expanding steam. Frequently a third stage at medium pressure (MP) is added, and the authors focused just this last solution in this study, considering that last technological developments have been concerning the three stages arrangement since 1980.

In naval propulsion the turbine is normally divided into two groups in a cross-compound scheme (groups mounted on two separated shafts). The HP group (with the MP group in the three stages solution) rotates at a 6,000 ÷ 7,000 rpm speed, whereas the LP one rotates at about 3,000 ÷ 4,500 rpm speed.

Technically speaking, since the screw rotates normally at about 80 ÷ 130 rpm, with the trend to get this speed lower and lower, the designing of the reduction gear is assuming more and more importance.



1) Steam inlet in HP turbine
2) HP turbine
3) Link between HP turbine outlet and LP turbine inlet
4) LP turbine
5) Reduction gear
6) Condenser

Figure 4.1: Simplified scheme of a cross-compound reduction-gear-turbine

Modern reduction gears at double and treble reduction provide a high output and a good reliability, with reduction ratios of 60 ÷ 1 and more. In fig. 4.1 the simplified scheme of a cross-compound-type reduction gear-turbine is shown.

4.2 Fluidised bed boiler

The hypothesis related to a fluidised bed on board is not completely innovative. In 1978 the Swedish company Stal Laval, in order to relaunch the steam turbine technology, proposed the VAP (Very Advanced Propulsion), a project aiming at: 1) improving the thermodynamic cycle, 2) improving the reduction gear and hull of ships, 3) providing the thermal production by means of a fluidised bed boiler [5]. However, afterwards Stal Laval dropped the project.

Fluidised bed boilers are made of a combustion chamber where the bed (a certain quantity of inert material, normally sand) is fluidised by an ascendent airflow injected through a grid placed in the bottom; such an air flow constitutes also the comburent agent. The circulation assures a deep contact between fuel and comburent air and a good uniformity of temperature and mixture, necessary conditions for a complete combustion.

In the beginning, the fluidised bed technology was studied and tuned for the petrochemical industry; then it has been recognized as the natural solution for the combustion of rather homogeneous small-sized solid fuels, as the RDF.

The fluidised bed boilers, depending on the flow rate speed, are classified in *bubbling beds* and *circulating beds*. In first ones the bed stays suspended under the opposing actions of weight and ascending thrust of the air; in second ones the bed is driven by the airflow and ricirculated, while a heavy-duty cyclone section separates it from the exhaust gases (figure 4.2).

In bubbling beds the air is injected with a speed of about 3 m/s, while in circulating beds speeds are higher, until 8 ÷10 m/s.

Design parameters	
Air speed (bubbling beds)	1 ÷ 3 [m/s]
Air speed (circulating beds)	5 ÷ 8 [m/s]
Thermal load (bubbling beds)	10 ÷ 50 [MW]
Thermal load (circulating beds)	40 ÷ 80 [MW]
Volumetric thermal load	175 ÷ 235 [MW/m^3]
Residence time of material in boiler	50 ÷ 90 [min]
Residence time of gas	10 [s]
Operating Conditions	
Operating temperature	850 ÷ 900 [°C]
Air excess	30 ÷ 40 [%]
Typical energy output	25%

Table 4.1: Main design parameters and operating conditions for fluidised bed boilers

Under an environmental point of view, since temperatures are of about 900 °C and residence time is quite long, the burnout of the fuel is rather complete, and therefore the related polluting emissions are relatively low.

The use of RDF involves a reduction of the boiler efficiency, caused mainly by the chemical-physic characteristics of fuel and exhaust. The output of the studied steam generator has been supposed 85%; consider that Italian operating fluidised bed boilers for the combustion of RDF are normally working with an efficiency of 83 ÷ 85%.

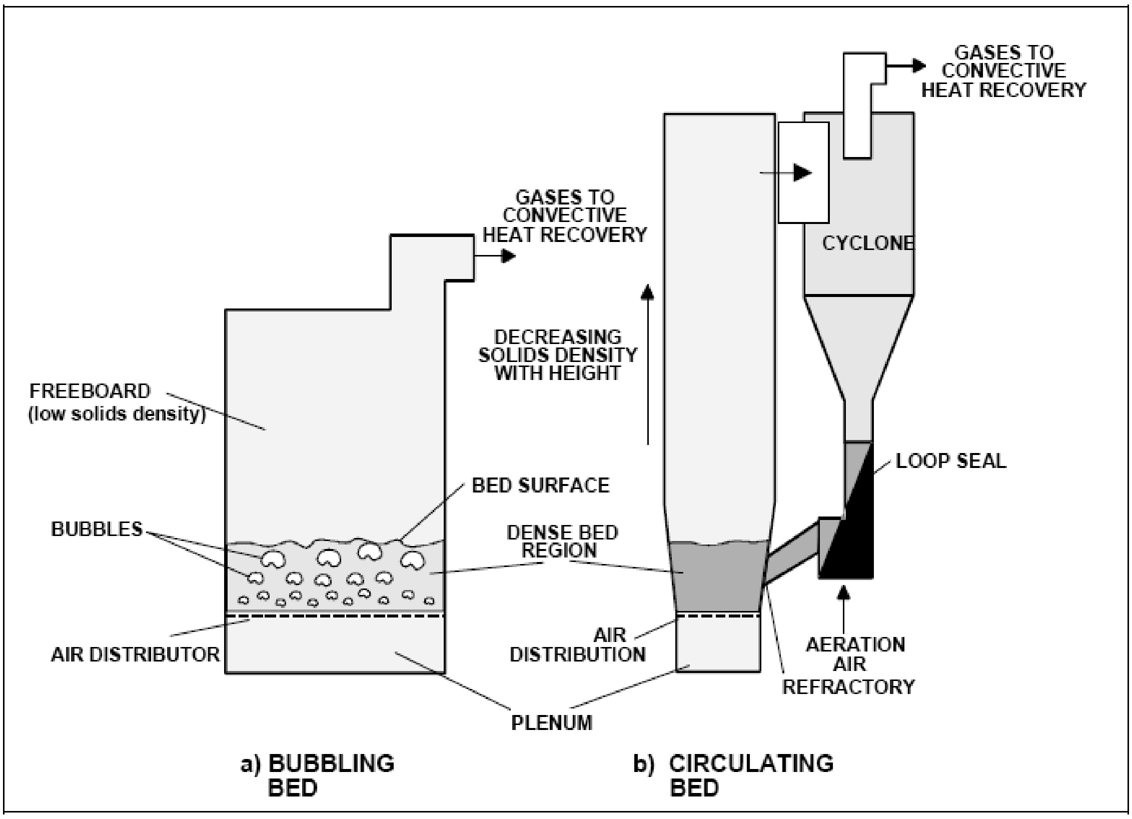


Figure 4.2: Schemes of bubbling fluidised bed boiler and circulating fluidised bed boiler [9]

5 COST BENEFIT ANALYSIS

5.1 Plant

The analysis started from the detection, depending on dwt to move, of the diesel engine mostly fit for the propulsion, able to allow a cruising speed of 14 ÷ 15 knots (25 ÷ 27 km/h). MAN B&W data have been used, indicating a power value of about 16.8 MW for a class Dunkirkmax-Capesize ship as the Cape Victory (175,000 dwt) [7]. A global output value of 25% has been supposed [8], giving a thermal power of 67.2 MW_{th} at the boiler. The mass flow rate of RDF has been calculated as 13.44 t/h considering a calorific value for the RDF of 18.000 kJ/kg. For a working time of 6,000 h/y, the global amount of RDF needed is about 80,640 t/y.

Bulk carrier class: ***Capesize***	
Power [kW]	16.800
Plant output	0,25
Thermal power [kW_t]	67.200
RDF caloric value [kJ/kg]	18.000
Feed: RDF [t/h]	13,44

Table 5.1: Steam plant data

5.2 Investment cost

As regards the investment cost, the authors started from considering the specific investment cost indexes pertaining specific technologies.

The authors searched for data of *diesel engines* from different companies: a cost index of 0,273 M€/MW has been considered in the end, resulting as an average from different source data costs. Such datum gives a global investment of € 4,586,400 (0.273 M€/MW x 16.8 MW).

As for the *steam plant*, the present operating technology in Italian RDF combustion plants has been considered, with a cost index of 4.0 M€/(t_{RDF}/h): the global investment cost is € 53,760,000 (4.0 M€/(t/h) x 13.44 t/h).

The difference between the two preceding investments is € 49,173,600.

Bulk carrier class: Capesize	
Power [kW]	16.800
Steam plant cost index [M€/(t/h)]	4,0
Steam plant investment [k€]	53.760
Unit cost for diesel engine [M€/MW]	0,273
Diesel engine investment [k€]	4.586
Differential investment cost [k€]	**- 49.174**

Table 5.2: Investment costs

5.3 Operating costs

The assessment of the operating costs, meaning those costs occurring every year and different from the investment cost, has been carried out in two ways:

1) Comparison and differential analysis of different operating cost items pertaining both technologies, starting from the breakdown of the costs as follows:
   - personnel

Propulsive Technology	**Annual cost [€/year]**
Diesel engine	241.534
Steam turbine	277.764
Differential cost	**-36.203**

Table 5.3: Cost of personnel [9]

   - maintenance

Propulsive Technology	**Annual cost [€/year]**
Diesel engine	117.065
Steam turbine	1.075.200
Differential cost	**-958.135**

Table 5.4: Cost of maintenance

2) detection and estimate of costs arising from the adoption of the steam turbine technology instead of the current diesel motorization. When passing from the previous technology to the supposed new one, following cost variations have to be taken into account:

- MFO fuel

Diesel engine power [kW]	16.800
Working hours [h/year]	6.000
Specific consumption index [g/kWh]	170
MFO specific cost [k€/t]	300
MFO cost [€/year]	**5.140.800**

Table 5.5: MFO Cost (Source: Staffetta Quotidiana Petrolifera)

- RDF

  At present the RDF use introduces a benefit of 30 €/t

Steam plant power [kW]	16.800
Working hours [h/year]	6.000
RDF Specific consumption [t/h]	13,44
RDF annual consumption [t/year]	80.640
RDF cost [€/year]	**2.419.200**

Table 5.6: RDF Cost (Source: ENEA)

- Auxiliary materials cost (lubricants, chemical additives, etc.)

Auxiliary material cost (with respect to MFO annual cost)	3,2% [7]
MFO cost [€/year]	5.140.800
Lubrificating oil cost [€/year]	**164.506**

Table 5.7: Lubrificating oil cost

Steam plant power [kW]	16.800
Lime specific cost [€/t]	60 (1)
Lime specific consumption for ton of RDF [kg/t]	15 (1)
RDF annual consumption [t/year]	80.640
Lime annual consumption [t/year]	1.209,60
Lime cost [€/year]	**72.576**

(1) Data provided by ENEA

Table 5.8: Auxiliary materials cost

- Payload loss cost

Estimated payload loss [%]	4,63
Economic loss [€/year]	**1.223.180**

Table 5.9: Payload loss cost

The global cash flow is given by the algebraic sum of all operating costs so far reckoned:

Economic Evaluation		
NPV calculation		**Capesize**
Differential investment cost	[k€]	**-49.173,60**
Cost estimation		
MFO cost	[k€/year]	**+5.140,80**
RDF cost	[k€/year]	**+2.419,20**

Differential personnel cost	[k€/year]	**-36,23**
Differential maintenance cost	[k€/year]	**-958,20**
Differential auxiliary material cost	[k€/year]	**+91,93**
Payload loss cost	[k€/year]	**-1.223,18**
Subtotal cash flow	[k€/year]	**+5.434,32**
Amortization (13 years)	[k€/year]	**-3.782,58**
Duties (30%)	[k€/year]	**-495,52**
Cash Flow	[k€/year]	**+4.938,80**
Net Present Value	[k€]	**+52,030,39**

Table 5.10: Cash flow estimate

5.4 Net Present Value

The relationship between the NPV and the life years, over 20 years, is shown in figure 5.1.
Assuming a discount rate of 5% a NPV value of 111 M€ is obtained, with a Payback Time of 8.5 years and an Internal Rate of Return of about 12.3%.
An inflation rate of 2%, a freights growth of 4% and a MFO cost growth of 12% have been assumed (this last value takes into account the historical series of MFO prices in last 20 years).

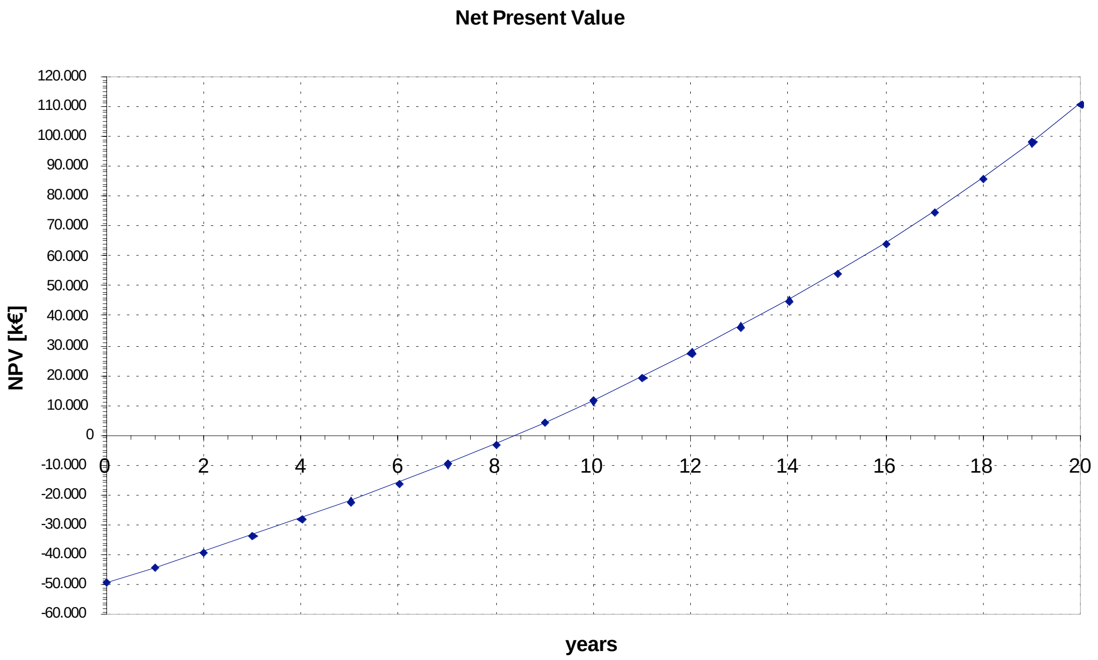


Figure 5.1: Relationship between NPV and life years

6 CONCLUSIONS

The cost-benefit analysis has shown a good economic performance for the investigated hypothesis. However some issues should deserve further widenings, above all: the RDF production chain, the harbour logistics at an oceanic level, the installation of more thermodynamically performing plants on board.

The analysis on NPV shows a strong relationship with the MFO cost trends. It is easy to suppose that, in case of future energetic recessions, the use of renewable energy sources like the RDF could become a strategic choice both under an economic and an environmental point of view.

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