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TECHNICAL-ECONOMICAL ANALYSIS OF COLD-IRONING: CASE STUDY OF VENICE CRUISE TERMINAL

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Abstract. Cold-ironing is the practice that enables to power commercial ships by a link to fixed electricity network, in order to reduce pollutant emissions in the port areas caused by marine fuels in auxiliaries engines feeding on board installations during ships stops at quays. The present paper aims to provide an overview of the most important technical and functional features of the concerned ships power systems and to analyze the technical, economic and financial feasibility of this system. In the first part the main technical-constructive elements for the application of Cold-ironing to different types of ship (such as voltage, frequency, power supply and power demand on the quay) are analyzed. The variety of functional situations does not allow to establish general constructive solutions since the cold-ironing system is depending both on the operational mode and the layout of each terminal. In the second part of the paper it has been analyzed the case study of the cruise terminal in Venice (VTP Spa Venice Passenger Terminal) with the aim of verifying the feasibility of a cold-ironing system for power supply of cruise ships on quays. The analysis was based on ships timetable for the year 2012, which includes the arrivals and the departures of 86 different ships with a global volume of 570 movements. Starting from data on dwell times, following the guidelines of the MEET methodology for estimating emission factors [3] it has been estimated pollutant emissions (nitrogen oxide NOx, sulfur oxides SOx, volatile organic compounds VOC, particulates PM, carbon monoxide CO) as a basis to calculate externalities to be considered for the Cost-Benefit Analysis (CBA). Based on a probabilistic analysis of the terminal occupation by ships (disposal of ship stalls on each quays) five operational scenarios were defined. Each scenario has been defined on the basis of an economic evaluation by means of a cost-benefit parametric analysis with the aim of providing the maximum financial results for assigned budgets. From a comparison of the results of the cost-benefit analysis and an estimate of possible investment costs obtained from USA case studies, it is noticed that the scenario providing coverage of both financial and economic investment includes the minimum number of electrified stalls and a ships journeys reorganization. It was also proposed a sensitivity analysis of CBA for the evaluation of indicators variations according to reference conditions variation.

1 INTRODUCTION

In order to reduce the emissions of a ship during its stop at the dock, a process, called cold-ironing, has been designed and adopted in some regions. It provides the electricity supply for onboard electric generator through a connection to fixed electricity network instead of to use the ship's engines. The power supply is provided through high tension line and a main substation to reduce the voltage. Afterwards, the current is carried out in the different docks, via underground cables, where it is converted into the frequency required for the specific ship. The frequency conversion is an important aspect because the most part of ships' generators use 60 Hz frequency, while the fixed electricity network normally provides 50 Hz standard frequency. The last step of the process is the connection, through the cables, of the dock's station with sockets placed on-board. Furthermore, depending on the voltage of on-board generators, it may be required an additional transformer inside the ship for the end use of electricity. Normally, during navigation the main engines, supported by auxiliary ones, generates the power for the motion and all other services of the ship, but in ports the main engine is switched off and, therefore, all the energy need is normally satisfied by auxiliary engines. Nevertheless some big and modern cruise ships use diesel-electric propulsion systems and are not equipped with auxiliary engines.

2 GENERAL SPECIFICATIONS

The use of cold-ironing on the dock requires the consideration of some basic parameters of the ship, such as the feeding voltage of the generators, the frequency and the power need to ensure the primary functions of the ship during the stop. Depending on the typology of ship these parameters may change relevantly [7]. These parameters are briefly analyzed, as an example, for 4 different typologies of commercial ships: container (deep sea and feeder), Ro-Ro and bulk ships (Table 1).

Table 1: Example of the construction of one table

	Power	Voltage	Frequency
Container ship deep sea	2 MW÷8 M	380-440 V÷6,6 kV	60÷50 Hz
Container ship feeder	200÷400 kW	Low	50÷60Hz
Ro-Ro ship	700 kW÷2 MW	400-460 kV	60÷50Hz
Bulk ship	1 MW e 2,5 MW	380-440 kV	60÷50 Hz

3 OPERATIONAL CRITICALITY

The variety of ships' technical situations leads to standardization problem for cold-ironing. In addition to different power needs, differences of voltage and frequency supply are problematic. The voltage of current reaching quays is normally variable between 6 and 20 kV. For vessels supplied with lower voltage a further processing is requires. The diagram in Figure 1 shows the situation with the transformer located on-board, but it is also possible a location on the dock. Deciding on the best location of the transformer is a key variable for the optimal process management. The major problems in locating the transformer on-board are the need for additional space and the cost of equipping each ship. It seems more economically viable to install the transformer on the dock to be used by each moored vessel but the presence of handling equipment would limit the availability of space also for this location.

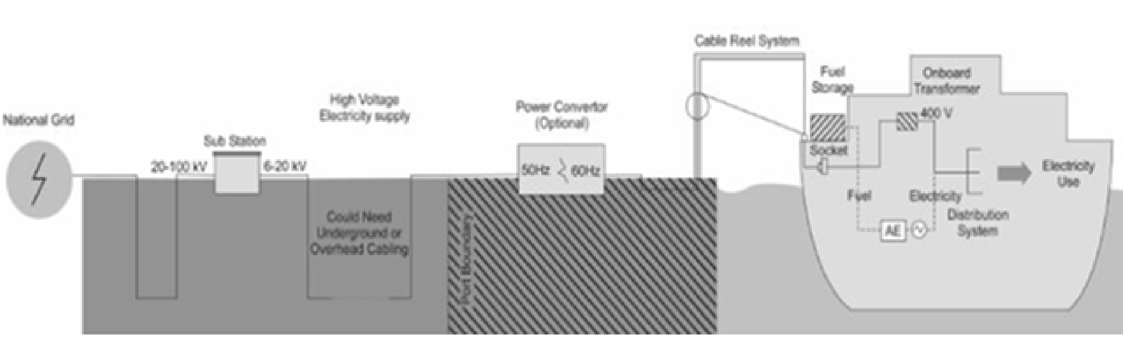

Figure 1: Cold-ironing system components basic scheme

The differences of power supply frequencies require converter on docks and affects the distribution mode from the main substation to the quay substations. The number of connection cables can vary from a few units up to ten, depending upon the type of ship, as well as different types of sockets may be required. All these varieties further complicate the operational aspects of the cold-ironing [7], which would be strongly simplified by unified procedures. For the final connection cables are matched to the ship by a dock crane, which holds them in suspension (Figure 2).

Figure 2: Ship connection

4. CONNECTIONS' SPECIFICATION

It is possible to consider different patterns of connection depending upon the mode of electricity distribution from the main port substation to the ship; normally three different connection systems exist, where the key variable is the allocation of frequency converters:

1. decentralized system: each dock is equipped with a converter;
2. centralized system: a single centralized converter is installed;
3. power distribution system: the current is remotely rectified and converted.

Strengths and weaknesses of the three connections are summarised in Table 2.

Table 2: Strengths and weaknesses of cold-ironing configurations

Configuration	Strengths	Weaknesses
1	Possible failures affect a single dock	High space need. Redundancy in converter use. Converter dimensioning according to maximum power average. Need of many transformers.
2	Limited space need. Converter used under request only.	Vulnerability. High cost of switches.
3	Limited space need. Reduction of losses in cables.	Lack of applications. Vulnerability

5 CASE STUDY: VENICE CRUISE TERMINAL

The cruise terminal in Venice is one of the most important terminal in the Mediterranean, the third in Europe and the eleventh in the world for passengers traffic. A large part of the traffic consist of cruise ships. In 2011 the total number of passengers in Venice reached the record level of 2,248,453, of which 1,777,073 from/to cruise ships. In 1997, operations management and traffic control are assigned to the new corporate Venice Passenger Terminal SpA (VTP), with the aim to improve all aspects of the provided services by reaching an increase of about 218% in 14 years. The facilities are spread over 260,000 square meters of land area in addition to 123,700 square meters of water surface and 3,300 meters of quays. The position is strategic as it allows easy access to the city (just 3 minutes by People Mover connecting the passengers terminal to the train station area). It is also well connected with the Marco Polo International Airport (about 13 km and 200 daily flights). The terminal can accommodate vessels having a maximum length of 340 m and a maximum draft of 8.70 m divided into 7 quays (17 stalls) of different sizes:

- Piave: 549,57 m, 2 stalls;
- Testata Marmi: 203,00 m, unique stall;
- Tagliamento: 726,70 m, 4 stalls;
- Isonzo: 630,00 m, 2 stalls;
- Santa Marta: 465,24 m, 4 stalls;
- San Basilio: 342,57 m, 4 stalls;
- Riva Sette Martiri: 360,40 m, inland cruises only.

5.1 The case-study methodology setting

The envisaged complexity of applications into real contexts has directed the work towards the implementation of a tool for evaluating the feasibility of the cold-ironing system using a technical and economic analysis applied to the case study of the port of Venice. The problem focuses on the sustainability aspects, in particular on the reduction of the emissions, providing inputs to a wide spectrum cost-benefit analysis. The study includes:

- data collection regarding the stay of ships in dock and the use of the terminal;
- estimation of emissions by all ships docked in 2012;
- probabilistic analysis of the terminal to identify the different operating scenarios according to the implementation degree of the cold-ironing;
- parametric cost-benefit and sensitivity analysis of the single scenarios;
- assessments of the economic and financial feasibility of the proposed measures.

5.2 Data collection and analysis

The database used for this work is the timetable (arrivals and departures) of the year 2012: 86 different ships have been handled for a total of 570 calls. The data collected for each ship are:

- name;
- shipping company;
- moorage (Marittima, San Basilio, Santa Marta);
- dock and stall of mooring;
- arrival and departure time.

5.3 Analysis of the staying time

The staying time of the ships have been estimated on the basis of departure and arrival times by stall. The average and maximum values are summarized in Table 3.

Table 3: Average and maximum values of staying time per stall

	Dock										
	Tagliamento		Piave		Isonzo		Santa Marta			San Basilio	
Stall	VE 107	VE 110	VE 117	VE 123	VE 18	VE 20	VE 24	VE 25	VE 27	VE 29	VE 30
Average staying time [hours]	11,3	10,8	12,8	9,2	12,5	9,8	14,9	14,1	10	12,1	12,2
Maximum staying time [hours]	144,5	24,5	72,5	24,5	49	96,5	48,5	49	10	96,5	25

The staying time of the ships in the dock is a key factor, together with the power required to feed all the devices of the ships themselves, to estimate the contribution to energy consumptions and emissions of various pollutants.

5.4 Terminal utilization

It has been estimated the utilization of the terminal by considering the number of daily arrivals and presences of ships in the dock, where the difference is due to multiple days staying of several ships resulting by staying times data. Table 4 contains a summary of docks occupation times.

Table 4: Docks utilization (frequency)

	Docks				
Ships at dock	Tagliamento	Piave	Isonzo	S. Marta	S. Basilio
2	59	10	60	5	4
1	109	115	124	77	114
0	197	240	181	283	247
Total	365	365	365	365	36

This operational analysis is crucial for the identification of the docks to be equipped with cold-ironing devices. Due to different situations considered, it has been developed a more detailed probabilistic study, including the realization of different scenarios depending on the degree of use of the terminal.

5.5 Emissions assessment

To estimate the emissions it has been followed the guidelines proposed in the MEET ("Methodologies for estimating air emissions from transports pollutant") project [3]. This European project is the first presenting a worldwide methodology for estimating the emissions of air pollutants generated by navigation. The methodology was developed by physicist Carlo Trozzi in 1996, was updated in 2008-2009 [4] and is still considered in studies that regard emissions by naval activity [5]. Starting from the staying times data, it has been possible to calculate the quantity of emissions produced as follows:

Emissions (g) = Power required (kW) x Stopping time (h) x Emission factors (g/kWh) (1)

The calculation was performed for all planned ships. The global annual emissions due to the whole traffic of cruise ships in the port of Venice, calculated for a total of 8478 hours, potentially avoidable by cold-ironing implementation, are summarized in Table 5.

Table 5: Total emissions for the year 2012 generated by all operated ships

Engine emissions [t]				
NOx	SOx	VOC	PM	CO
705,62	30,85	103,76	62,26	114,15

6 PROBABILISTIC ANALYSIS OF SCENARIOS

By a probabilistic analysis carried out on the timetable of cruise ships, it has been identified a minimum number of stalls occupied equal to 4, corresponding to a coverage of 80% of the traffic. The following scenarios (number of stalls to be electrified, served ships and supply energy summarized in Table 6) to be assessed by CBA, have been defined on the basis of the following assumptions:

- number of stalls actually used;
- maximum number of moored ships per day;
- presence of stalls in the same docks, for possible technical installations;
- forecast of more polluting ships in 4 more used quays.

Table 6: Scenarios key parameters

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 4 bis
Number of stalls	11	8	6	4	4
Requested energy [kWh]	69.177.749	68.983.441	62.358.146	46.956.516	58.245.860
Number of ships	86	84	58	54	26

7 COST-BENEFIT ANALYSIS OF PROPOSED SCENARIOS

For a comparison between the various proposed techno-economic scenarios it has been implemented a careful CBA, in order to estimate the most effective scenarios in specific economic contexts [1] [6]. Due to the difficulties to obtain data about the costs to install cold-ironing systems it was decided to perform a parametric study based on preliminary assessments of investment and operational costs. The analysis is based on an initial Net Present Value (NPV) threshold set to 30% of those costs. The investment will be considered convenient insofar as the NPV will be at least 30% of the investment costs (evaluated as a limit value that a possible investor may accept to undertake the investment). It is assumed that the investment will be concentrated in the first year, but amortized over 5 years (5.5% per year for 5 years = 30% approximately) and the project life cycle was assumed at 15 years.

7.1 Financial analysis

The benefits considered in the financial analysis are related to the saving in operational costs due to fuel and electric energy consumptions.

$$B = [C_o - C_{sc}]_{internal} \tag{2}$$

- C_o is the cost of fuel in the present situation (reference scenario);
- C_{sc} represents the cost of electricity consumption in the reference scenario.

7.2 Economic analysis

In the economic analysis additional benefits are due to the difference in external costs related to pollutant emissions.

$$B = [C_o - C_{sc}]_{internal} + [C_o - C_{sc}]_{external} \tag{3}$$

where:

- C_o is the cost of fuel in the present situation (reference scenario);
- C_{sc} represents the cost of electricity consumption in the reference scenario;
- C_o is the external cost of emissions in the reference scenario due to fuel consumption;
- C_{sc} is the external cost of emissions in the reference scenario due to electric energy consumption.

In figure 3 are reported the results obtained in the 5 scenarios.

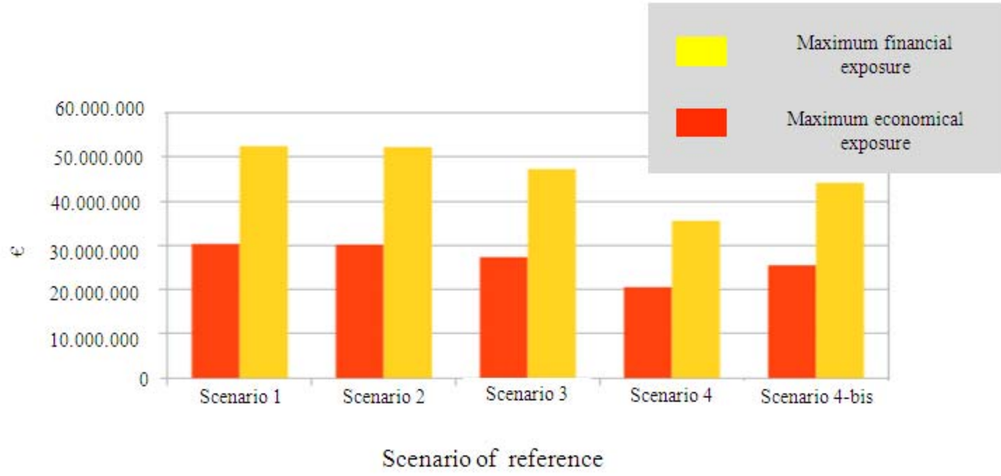

Figure 3: Results of CBA (red: maximum financial exposure – yellow: maximum economic exposure)

The CBA results highlight that the benefits are proportional to the quantity of energy that is provided by means of the cold-ironing system, as well as the financial exposure of the project. On the other hand, the bigger is the number of electrified quays and vessels to be converted to the new supply system the higher is the investment costs to be incurred. Therefore the feasibility of the project is not absolutely granted. In scenario 4-bis, despite the same number of electrified docks and a smaller number of vessels to be converted, there is a relevant increase of the financial and economic exposures. Indeed this scenario achieves larger benefits with lower costs, due to the use of the docks by the most polluting vessels.

7.3 Sensitivity analysis

For the most effective scenario (4-bis) it has been performed a sensitivity analysis based on the variation of fuel and electricity prices used for financial analysis and calculating once more the threshold of maximum financial exposure (Table 7).

Table 7: Threshold of maximum financial exposure related to scenario 4-bis [M€]

Fuel price [€/t]	Electric Energy price [€/Mwh]									
	90	**100**	**110**	**127**	**135**	**145**	**160**	**180**	**195**	**215**
500	10,96	5,86	0,76	-	-	-	-	-	-	-
550	16,65	11,55	6,45	-	-	-	-	-	-	-
605	22,90	17,80	12,70	4,04	-	-	-	-	-	-
670	30,29	25,19	20,09	11,43	7,35	2,25	-	-	-	-
794	44,39	39,29	34,19	25,52	21,45	16,35	8,70	-	-	-
810	46,21	41,11	36,01	27,34	23,26	18,17	10,52	0,32	-	-
890	55,30	50,21	45,11	36,44	32,36	27,26	19,61	9,42	1,77	-
975	64,97	59,87	54,77	46,10	42,03	36,93	29,28	19,08	11,43	1,24
1075	76,34	71,24	66,14	57,47	53,4	48,3	40,65	30,45	22,8	12,61
1180	88,28	83,18	78,08	69,41	65,33	60,23	52,59	42,39	34,74	24,54

The two factors are incremented by 10% steps, starting from the initial value proposed. The empty cells in the table are negative values (high electricity price and low fuel price) with ships powered by fuel. In Figure 4 each value of energy price is associated with a coloured curve versus the maximum financial exposure thresholds.

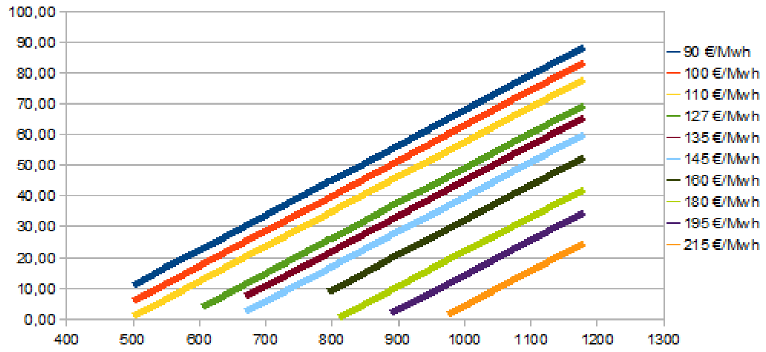

Figure 4: Variation of the threshold maximum financial exposure for the scenario 4-bis according to the prices of fuel and electricity

The relationship between the analysed parameters is linear. On this basis it is possible to estimate the threshold of maximum financial exposure corresponding to the prices of the two parameters (by entering the chart with a certain value of fuel price, intersecting the curve of electricity price curve and then reading the result on the horizontal axis).

7.4 Cost-benefit analysis summary

The analysis (summarised in Table 8) showed that the cold-ironing can offer benefits both financially (electricity cost lower than fuel cost) and economically, thanks to relevant emissions reductions. The sensitivity analysis showed that Scenarios 1 to 4 are almost invariant with respect to the combination of parameters, as well as Scenario 4-bis lets achieve significantly better results.

8 ECONOMIC-FINANCIAL FEASIBILITY OF PROPOSED SCENARIOS

Starting from the proposed scenarios, some assumptions about electrification docks equipment based on USA studies on cold-ironing have been taken and the corresponding costs items have been estimated to define an order of magnitude of the global costs [2]. In Table 9 a comparison among scenarios in terms of economic indicators is showed. Scenario 4-bis turns out to be the most efficient because it is the only one that ensures financial coverage of the investments. The remaining scenarios only provide economical coverage. The efficiency of scenario 4-bis is conditioned by the docking of the 26 most polluting ships on Isonzo and Tagliamento docks, which should be ensured by the reorganization of ship moorage aside the stalls organization for year 2012.

Table 8: Summary of CBA parameters and results

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 4-bis
Number of stalls to be electrified		11	8	6	4	4
Required energy [kwh]		69,177,749	68,923,441	62,358,146	46,956,516	58,245,860
Number of ships to be converted		86	84	58	54	26
Reduction of emissions [t/year]	NOx	674.23	671.76	607.77	457.66	567.69
	SOx	-12.98	-12.93	-11.70	-8.81	-10.93
	VOC	103.52	103.14	93.31	70.27	87.16
	PM	60.52	60.29	54.55	41.08	50.95
	CO	100.71	100.34	90.78	68.36	84.79
Maximum financial exposure [€]		30,315,203	30,203,760	27,326,704	20,577,373	25,524,610
Maximum economic exposure [€]		52,424,178	52,231,459	47,256,157	35,584,517	44,139,791

Table 9: Comparison among scenarios

	Possible investment cost	Maximum financial exposure	Investment coverage	Maximum economic exposure	Investment coverage
Scenario 1	57,000,000	30,315,203	NO	52,424,178	YES
Scenario 2	55,200,000	30,203,760	NO	52,231,459	YES
Scenario 3	38,900,000	27,326,704	NO	47,256,157	YES
Scenario 4	35,800,000	20,577,373	NO	35,584,517	YES
Scenario 4-bis	19,000,000	25,524,610	YES	44,139,791	YES

9 CONCLUSIONS

The use of the cold-ironing system is characterised by a very high level of complexity for the wide range of aspects and for the great number of stakeholders, whose primary goals are sometime different. Therefore the adoption of joint decisions meeting the needs of all operators is rather complicated. In the analysed case study are mainly faced the technical and economic aspects of the project, with a focus on the reduction of the emissions, without considering all technical details concerning the equipment required for the implementation of the cold-ironing. The cold-ironing system provides an important contribution for the reduction of emissions, mainly because the energy consumption of the cruise ships is high in comparison with other typologies of commercial ships. This high consumption is due to the energy need of a wide range of on-board equipment, in order to satisfy the passengers' needs. Different implementation scenarios have been proposed. The most efficient scenario (4-bis) requires additionally a change into the assignment of ships to docks in comparison with the present situation. The other scenarios lead to a further reductions of the emissions, since they consider a higher amount of equipped ships and docks, but the economic and financial indicators proposed are lower due to higher investment costs. Only the 4-bis scenario ensures both financial and economic coverage. The other scenarios reach the economic coverage only, therefore their feasibility depends on the adoption of incentive schemes to cover the total investment.

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