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Technical analysis and economic evaluation of a complex shore-to-ship power supply system

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ABSTRACT

In port areas, with the progressive increase in maritime traffic, the problem of pollution is crucial especially when the port is near to an urban area. The cold ironing allows a reduction of pollutants satisfying the power demand of ships while they are at berth, replacing on board diesel engines. In this paper, the methodology of analysis of the electrical loads required by ships concerns the typical week of each month over a one year period. The power is provided by a cogeneration plant powered by natural gas. It is flanked by a Compressed Air Energy Storage system since the energy demand is linked to the presence of ships in port and so very variable over time. The heat waste is recovered in a heating district network for overall optimization. At last, the economical aspect has been evaluated to prove the feasibility of the whole system. The results, for the case of the port of Ancona, show that a 1.5 MW and 2 MW cogenerator covers the 83.05% and 92.5% of the electrical need of ships respectively, and the 61% and 74% of the thermal need of buildings over the period analysed. The coverage of the CAES system is not influenced by the rated power.

1. Introduction

Over the years the continuous increase in maritime traffic of goods and people, both by ferries and cruises (which have the highest growth rate), has highlighted the problem of environmental pollution in port areas, especially when the port is in proximity to an urban area. As reported by the UNCTAD Secretariat in the annual review of maritime transport, the average increase in energy demand for international shipping was about 1.6% per year between 2000 and 2015 [1]. It is estimated that the naval transport sector generates about a billion tons of CO_2, expected to become, according to forecasts, 1.6 billion tons in 2050 [2]. In the third GHG study (2014), the IMO (International Maritime Organization) reports that maritime traffic contributes to approximately 2.2% of CO_2 global emissions [3], a reduction of 0.5% compared to the previous estimate (2009) [4]. In addition, ships contribute to NO_x, SO_x and PM emissions, to different extents depending on the type of engine and fuel used by the ships.

Cold ironing [5] is one possible solution for the reduction in environmental pollution in port areas. This practice consists in an on-shore power supply from the electrical grid or other means, in order to satisfy the energy demand of ships at berth. In fact, ships produce energy through on-board diesel generators and this has a significant impact on the environment. Winkel et al. [6] affirm that if all European ports were to use an on-shore power supply, a potential 800,000 ton reduction in carbon emissions could be obtained. Previous studies confirm the benefits of cold ironing from both an environmental and an economic point of view, as reported for the ports of Los Angeles (US) [7], Oslo (Norway) [8], Aberdeen (Scotland) [9], Copenhagen (Denmark) [10], and Kaohsiung (Taiwan) [11]. Hall [12] estimated that through the cold ironing system CO_2 emission savings could be 29% on average, depending on the type and the port call frequency of the ships, with a peak of 99.5% (Oslo, Norway) and 85% (France), while for the Fort Lauderdale port (US) only 9.4%, as a result of the mixed energy source. The high percentages in northern Europe are a result of renewable sources such as offshore wind farms. There are several possible alternatives to cold ironing. Geng et al. [13] studied the combustion characteristics of an auxiliary engine and obtained a reduction in NOx emission through the use of a blend of waste cooking oil and biodiesel. Çağatay et al. [14] analyse a list of alternatives for operational strategies, technologies and energy management systems for energy efficiency in ports. For example, maritime hybrid energy systems (MHES) have been studied which contain on-ship photovoltaic arrays (PV), battery banks, cold ironing, and on-board diesel generators [15]. Many studies focus on the optimal energy management of MHES, balancing the various components of the

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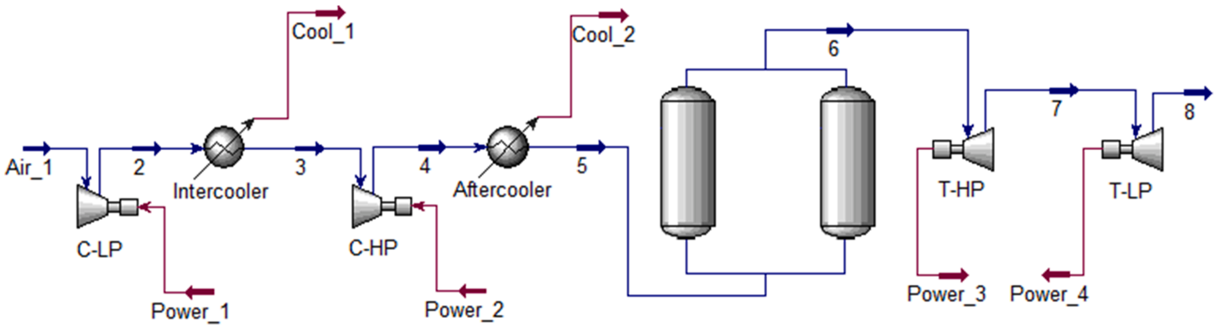


Fig. 1. Plant layout of a CAES system.

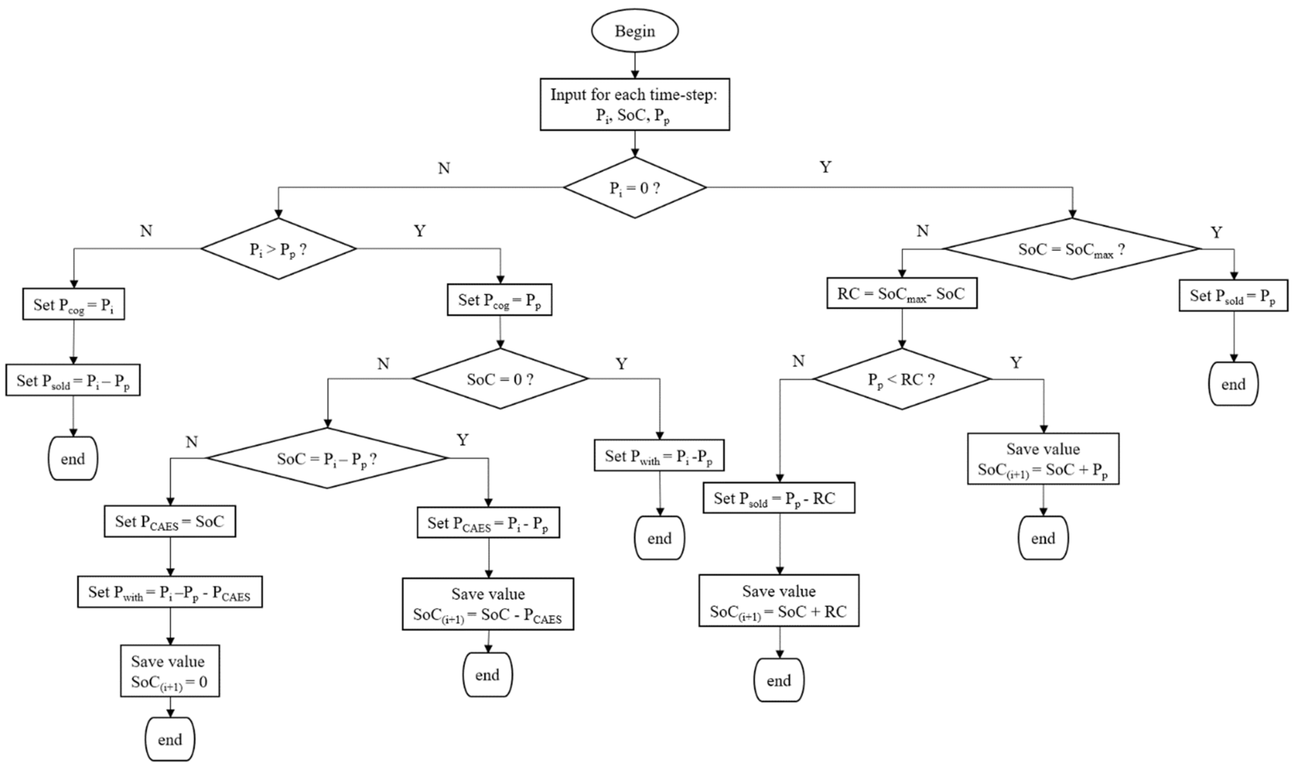


Fig. 2. Flow diagram of control loop.

system and improving the efficiency of the power-flow [16–19]. The improvement in port area efficiency may be related to the electrification of cranes, reducing their peak energy demand [20], and to container refrigeration, to which many studies assign a range between 20% and 45% of the total energy consumption in ports [21,22]. Improved technologies for the energy efficiency of lighting, may have an impact of about 3–5% on the energy required in ports, thereby supporting the use of LED lamps [23]. Piris et al. [24] analyzed the reduction in CO_2 emissions in the port of Santander from the use of automatic mooring systems, that allow an energy saving of around 76% compared to traditional systems. The sea scrubber system [25] is another solution to control the emissions from auxiliary engines while ships are at berth, as well as hybrid plasma-chemical systems for an up to 84% reduction in SO_x and up to 49% drop in NO_x [26].

Cold ironing systems depend on the types of ship and the power required. In January 2000 in the port of Goteborg the world's first high-voltage shore-side connection was inaugurated. This was the first shore-side connection specifically designed for Ro/Ro vessels. The power was distributed via a 10 kV/6.6 kV and 1250 kVA transformer substation on the quay. Since then other projects have been developed in American, European and Asian ports. The cold ironing plant scheme depends on the type of ships to be fed and on the electrical characteristics that they require. In the port of Los Angeles, the project involves container ships that require a voltage of about 400 V and therefore a low voltage connection. The power is provided by the electrical grid at a voltage of 34.5 kV, so a double-step transformation is necessary to reduce the voltage to 400 V. The second step occurs on a barge alongside the ship. The connection is completely different in the port of Oslo, designed as a cruise terminal. These ships require much more power and a connection at a medium voltage (generally 6.6 kV or 11 kV). In this case the energy is distributed at a medium voltage and therefore the connection takes place directly. In both cases the energy is withdrawn from the electrical grid and produced in some way from alternative sources.

In Italy these types of systems have already been studied in Civitavecchia [27], Venice, Livorno [28] and Genoa [29], the latter being the only port where the system has become operational. These projects are all grid-connected despite the fact that in Italy the use of the grid is associated with high costs for electrical energy. For this reason, many studies have highlighted negative results, due to a lack of economic feasibility. This is one of the reasons for choosing on-site energy

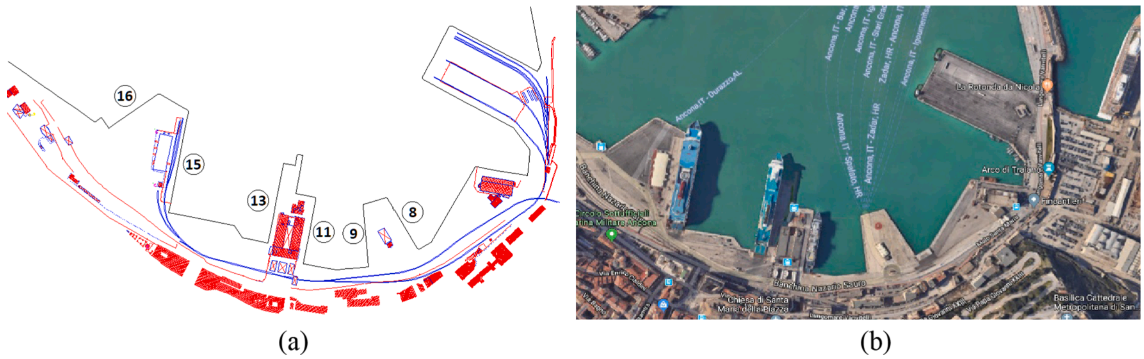


Fig. 3. Area under study in the port of Ancona: CAD reconstruction (a) and satellite view (b).

Table 1
List of ferry ships in the port of Ancona and associated power.

	N° generators	Power each [kW]	Average power [kW]	
			Summer	Winter
Ship 1	3	2100	1600	1600
Ship 2	3	1400	1550	1000
Ship 3	3	1400	1550	1000
Ship 4	3	1900	2200	2200
Ship 5	3	3800	2200	2200
Ship 6	4	850	1200	1200
Ship 7	3	1360	800	800
Ship 8	2	960	500	350
Ship 9	4	783	600	600
Ship 10	3	945	800	800

production. The port of Ancona is taken as a case study. Today the port is classified as a major international port by the European Union, inserted in the Scandinavian Mediterranean corridor of TEN-T networks. Each year more than one million people pass through the port on ferries and cruise ships, heading for the shores of the eastern Adriatic (Croatia, Albania, Greece) and the Aegean. Container traffic has developed in recent years, exceeding 150,000 TEUs per year. Since the port of Ancona is near the urban area, ships at berth are responsible for the increase in environmental pollution in the area, creating a great deal of discontent amongst the population.

In almost all of the cases analysed, cold ironing systems are powered by the national electricity grid while the innovation introduced by the study presented in this paper consists in the proposal of a stand-alone system which is not entirely connected to the electricity network. In fact, the cold ironing system studied in this case has an electrical power supply mainly in the stand-alone phase but, due to energy optimization analysis, it can and must resort to integration with the national electricity grid only in small periods of the year. This is to respond to the characteristic of extreme variability over time in the demand for electricity from the docks of the port for the passenger port. In fact, in the case presented, the passenger ship lines have annual activity, but the frequency of transport is strongly linked to the holiday periods during which the frequency of docking and parking of the ships undergoes a significant increase compared to the remainder of the year. The local electricity production system is a cogeneration plant which in addition to powering electrically, having a thermal residue, produces a hot heat transfer fluid for a building district heating system. To satisfy further the significant variability in the demand for electricity by users also the use of an energy storage systems is considered downstream of the cogeneration system This paper focuses on an energy evaluation of the complex system involving both the electrical energy required by the ships and the air conditioning needed for the buildings nearby the port area and the aim of the study is to illustrate the benefits of on-site energy production, even from an environmental point of view. In fact if the energy from the grid does not come from an efficient and renewable source, the result is simply a displacement of the polluting source, in this case from the ships to the centralized production site. A renewable source such as a photovoltaic system could be exploited, although there is sometimes not enough available surface in the port area. Assuming the installation of panels with a peak power of 230 W, and a size of 170x100 cm in order to obtain 1 MW power, about 4500 panels would be needed, covering an area of about 7.65 km^2. In our energy supply proposal the electrical grid is replaced by a cogeneration plant, flanked by a CAES (Compressed Air Energy Storage) system and the heat waste is recovered in a heating district network for overall optimization. Cogeneration allows for high energy efficiency with a smaller surface, and it ensures energy saving, by producing both thermal and electrical energy simultaneously. This type of production has become widespread in recent years and is likely to continue to be so in the future [30]. Moreover, even if the power plant is in the port area, it is small and for this reason it allows a considerable control of pollutant emissions. For example, cogenerators of a few Megawatts produce NO_x emissions of between 250 and 500 mg/Nm^3 and they do not need specific treatment systems. Another advantage is that there are no transmission losses along the network. The environmental advantages of the installation of a cold ironing system in the port of Ancona have already been studied by G. Passerini et al. [31].

The next sections are organized as follows: Section 2 explains how the methodology of the entire system is analysed. Section 3 presents the port of Ancona (Italy) as a case study. Section 4 summarizes the results from both the energy and the economic point of view, while Section 5 illustrates the conclusions.

2. Methodology

The proposed system consists of a cogeneration plant that produces simultaneously heat and power. Electricity is used to power ships at berth while heat to cover various utilities in port area. The cogenerator is flanked to a CAES system to ensure a major autonomy to the entire plant and avoid continuous power exchange with the grid.

The analysis of the process involves the demand for both electrical and thermal energy. As regards the former, the analysis covers a period of one year. For this period, it is necessary to know the simultaneous presence of ships in port, so as to determine the trend in the electrical power requirements. The power required by the ships present at a given time i [h], P_i, characterizes the electrical energy demand and is calculated as follows (Eq. (1)):

$$P_i = P_{i-1} + P_a - P_d \tag{1}$$

where P_{i-1} is the power required by ships at berth during the previous call, P_a is the power for ships that arrive in the port at time i, and P_d is the power demand for ships that depart from the port. The analysis was carried out considering the typical week, hour by hour, for each month throughout the period.

The choice to use a cogeneration plant, powered by natural gas, is motivated by the possibility to recover the waste heat produced by the

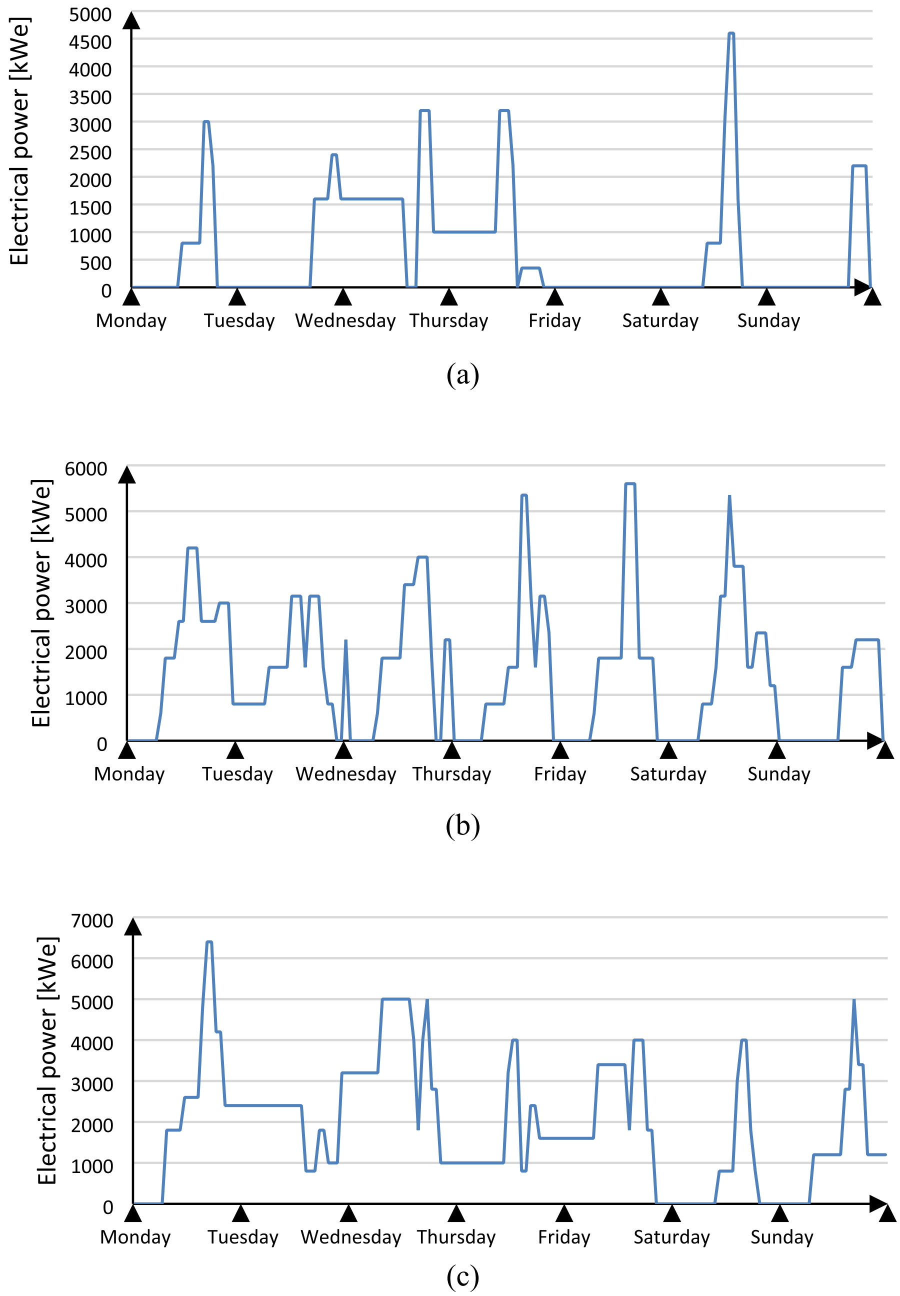


Fig. 4. Trend in electrical energy demand for ships at berth during January (a), July (b) and October (c).

internal combustion engines. This allows the overall efficiency of the plant to be significantly increased and consequently lowers the cost of energy production. Another important aspect is that this energy can be sold to the owners of the utilities concerned thereby representing another source of economic gain for the amortization of the investment costs of the entire project. As regards the thermal energy demand, various needs can be considered in the port area. For example, the presence of industries may require heat for the manufacturing processes, or warehouses for their air conditioning. Alternatively, as illustrated in the case study presented in this paper, the waste heat can be used in a district heating network and feed a number of commercial or residential buildings. This is convenient the closer the urban areas are to the port.

The cogenerator is flanked by a CAES system [32–34], since the electrical energy demand is very variable over days and seasons, because it is linked to the presence of ships. This system allows energy to be accumulated when the required energy is less than the amount produced and this surplus can then be exploited when the potential of the cogenerator is insufficient to satisfy the demand, on occasions when more ships are present in port. The plant scheme has been modelled using the Aspen Hysys software and is depicted in Fig. 1. It is made up of three parts.

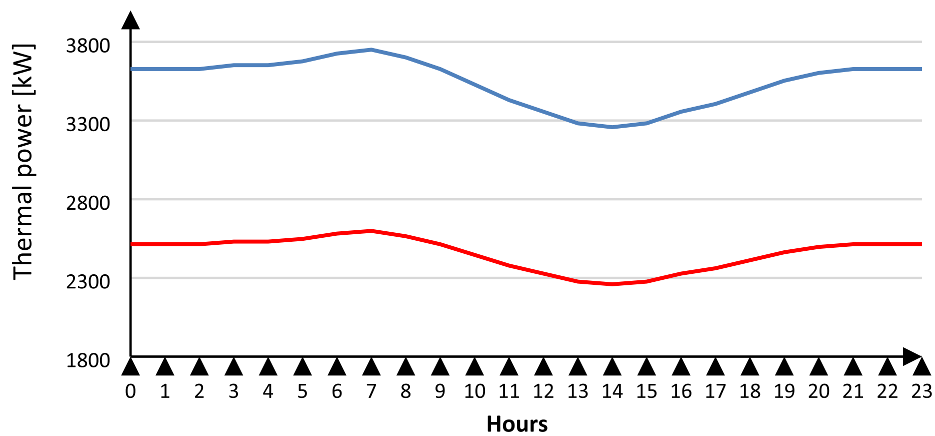
In the figure a low-pressure compressor (1–2) and a high-pressure compressor (3–4) are depicted, between which an intercooler (2–3) is interposed to prevent the air from reaching temperatures which are too high. For the same reason an aftercooler (4–5) is inserted before the tanks because storage at high temperatures can damage the walls of the tank itself. The air is then stored in two or more tanks placed in parallel. The choice to divide the necessary volume is due to the fact that smaller

Table 2
Thermal energy demand [kW] of buildings in winter and summer.

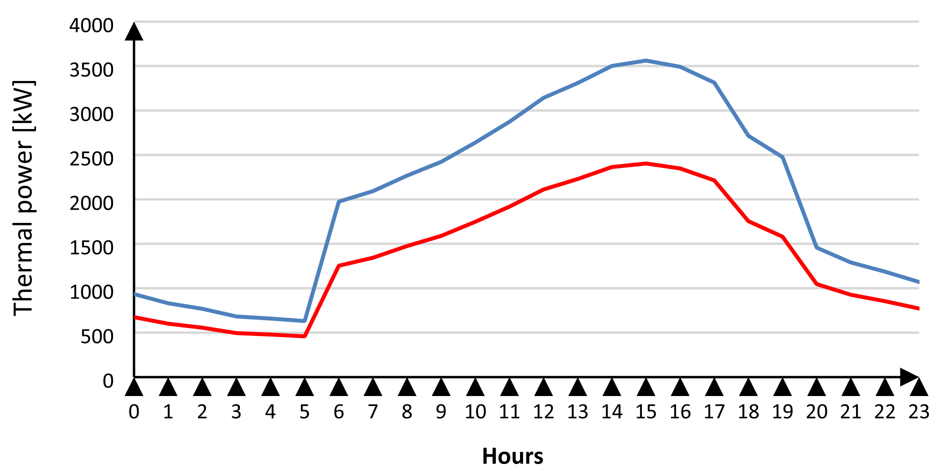
Buildings		Winter	Summer
1	Non-commissioned officers club	338	–
2	Finance police HQ Tommaso Mariani	238	–
3	Former Fincantieri administrative offices	132	145
4	Port authorities	469	480
5	Current maritime station	632	599
6	Port authorities 2	168	–
7	Border police	247	350
8	Coast Guard	214	–
9	Administrative court	427	436
10	ITN Elia	612	–
11	INAIL	351	417
12	Fincantieri canteen	565	–
13	Finance police HQ Carlo Grassi	150	176
14	New port authority headquarters	877	945
		5474	**3604**

The sizing of a CAES system is based on the choice of a set parameter, which can be the storage pressure, the tank volume or the charging or discharging time, which determines the stored energy. As one of the parameters increases, the investment costs of the system also increase. The effect of the increase in storage pressure is manifested on the thickness of the tank which must contain the pressure, while the volume influences the quantity of material necessary for its construction [32]. The chosen parameter for the sizing is the tank charging time. It can be evaluated through the average of the times in which there is no demand for energy due to the absence of ships in port. This time can be used to charge the storage system.

Once the vector [Pi] has been determined for the electrical demand over the year considered and the parameter has been chosen for the storage system, a control model to investigate the energy flow-chart can be implemented, for a given power of the cogenerator. This is needed in order to establish how the demand is satisfied at each time step distributed between the cogenerator, the network and the storage system. The model returns the total annual revenue provided by the cogenerator, the storage system and the network, considering both the sold and withdrawn energy. The control model has been implemented



(a)



(b)

Fig. 5. Trend in thermal demand of buildings in January (a) and July (b). The blue line is associated with weekdays, the red one with holidays.

tanks are more readily available on the market and more manageable as regards transport and installation. Expansion also takes place in multiple stages (6–7 and 7–8), to limit the expansion ratio and consequently increase the efficiency of the process.

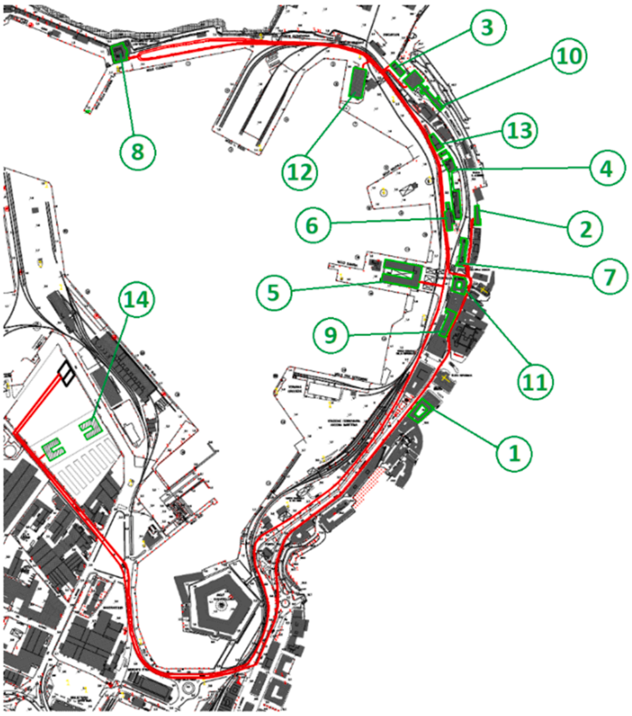


Fig. 6. Heating district network and position of buildings on the map.

in port, it is necessary to know the powers of the auxiliary motors installed on each vessel and the number in use during docking. To evaluate the power and the other electrical characteristics required by each ship at berth, a series of meetings were organized with the ship's masters. The data collected are summarized in Table 1 (the ships are numbered rather than named).

For Ancona, the data were found on the PMIS portal (Port Management Information System), that contains all the information regarding the length of stay for each ship on the quay, registered according to the day and time of arrival and departure and the number of the quay.

The following figures report the trend for only one winter month, one summer month and one mid-season month (Fig. 4).

As can be observed, the winter months are characterized by a low frequency of calls which determines a low average demand for electrical energy. The summer months have a higher frequency of calls with stays mainly concentrated during the daytime and for short periods of time due to the greater seasonal traffic. On the contrary, the mid-season months (March and October) are characterized by longer stays, even for several days and this determines the maximum demand in these months.

As regards the thermal energy demand, since the buildings are close to the port area a district heating system [35] was chosen. The number of buildings to be supplied, on the other hand, was chosen based on the amount of energy required by each of them, trying to maximize the heat that can be used in relation to the electrical energy required. The design conditions (external and internal temperature and relative humidity) are those established by the European standard. For the calculation of the

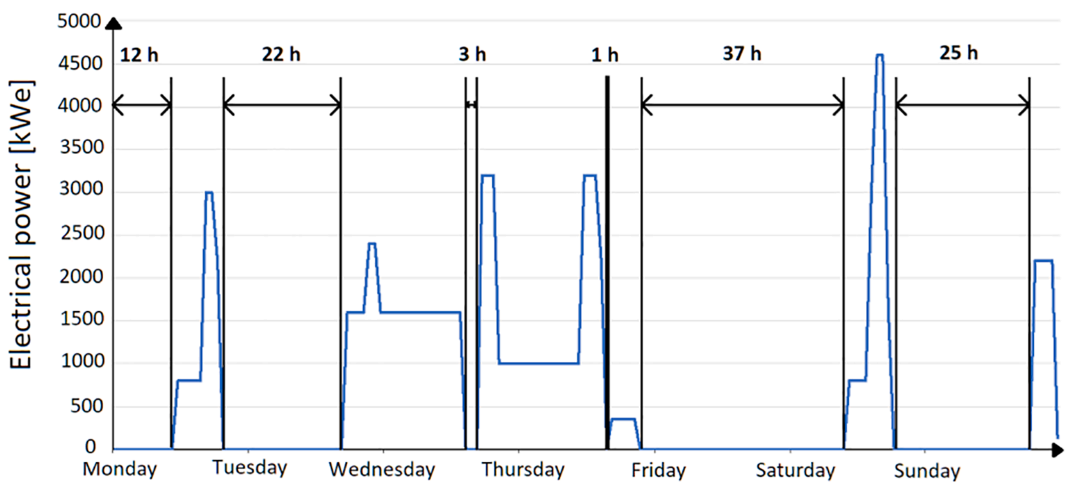


Fig. 7. Electrical demand gaps during January.

on MATLAB software, and the flow diagram is depicted in Fig. 2. Pi indicates the power required by ships at time i, Pp is the power produced by the cogenerator, SoC and SoC(i + 1) indicate the charge level of the storage system at the present time step and at the following one, respectively. SoCmax is the parameter set at the beginning to size the storage, Psold is the power sold to the network. Pcog, PCAES and Pwith are the power supplied to utilities by the cogenerator, by the CAES system and by the network respectively.

3. Case study

The energy analysis, over a one year period (in this case from 01-08-2018 to 31-07-2019) concerns only the ferry docks since they have a fairly regular call frequency, and they do not require as much power as cruise ships. In the case of the port of Ancona the ferry docks are numbered 8–9–11–13–15–16, as depicted in Fig. 3.

Before determining the trend in the electricity required by the ships overall heat transfer coefficients of the walls, roofs, floors and glazed surfaces, stratifications have been assumed for each building based on the best characteristics related to the year of construction, that ensure a good approximation in the absence of more detailed data. The results obtained are summarized in Table 2.

The calculation of thermal losses in the extreme conditions considered to be the "worst scenario" is useful for sizing the equipment, such as heat generators for the winter regime and refrigeration machines for the summer, as well as all the auxiliary devices. To carry out an analysis of real consumption, for example on an annual scale in order to obtain a more complete dataset, it is necessary to carry out a dynamic calculation, continuously varying the external conditions in a suitable manner. Therefore, it was necessary to trace the climate data hour by hour for each month, thus defining the "average monthly day" for this dynamic analysis. As regards the winter months, that is from October to April, it is sufficient to know the temperatures, while in the summer months relative humidity and solar radiation must also be considered.

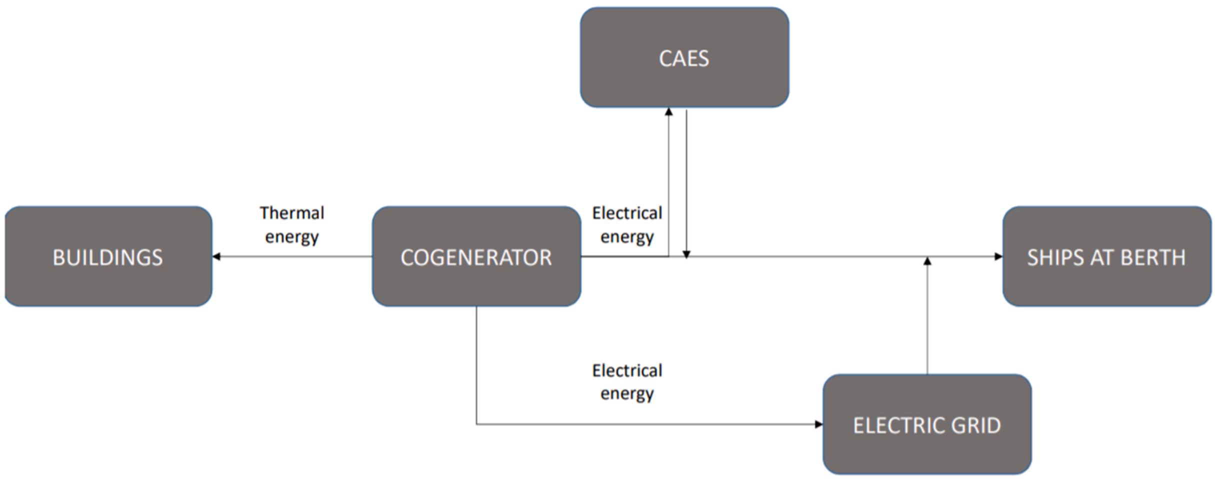


Fig. 8. Cold ironing, district heating and CAES system scheme.

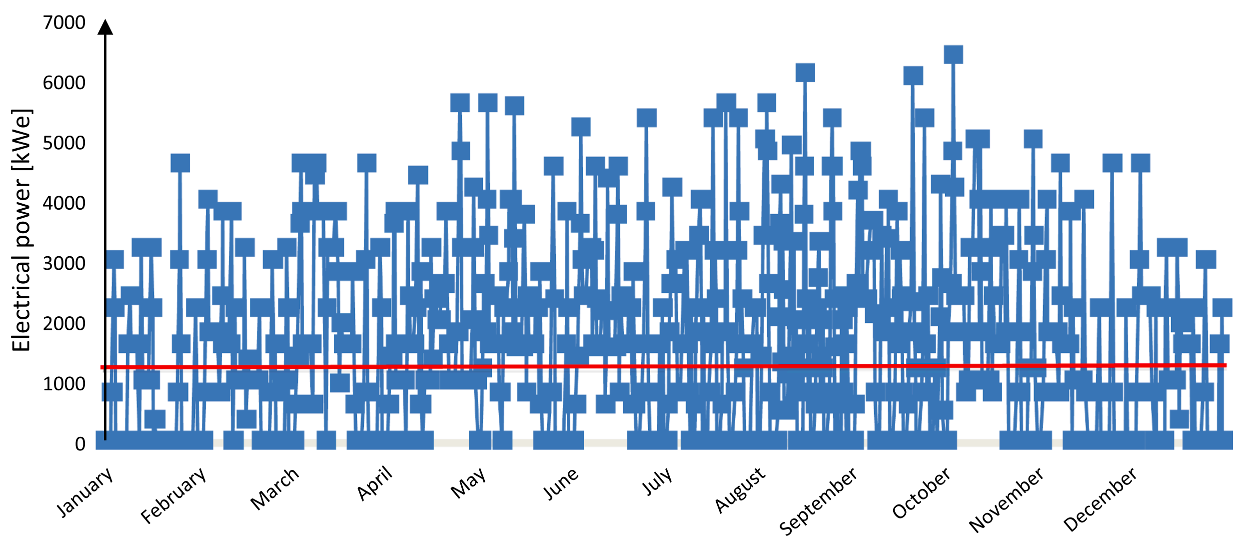


Fig. 9. Annual trend in electrical energy required by ships at berth. The red line indicates the average over the year analysed.

Table 3
Simulations carried out.

	Power [kW]	Thermal efficiency [%]	Electrical efficiency [%]	Overall efficiency [%]
Scenario A	1560	43.8	43.2	87
Scenario B	2000	43.2	43.7	86.9

Furthermore, in order to have a more complete energy analysis, working days need to be separated from holidays. On the latter, in fact, some buildings, such as those used as offices, are closed and are therefore not involved in the calculation.

In Fig. 5a the trend in the thermal demand of the buildings in a winter month is depicted, taking January as an example. For the winter months it is sufficient to adapt the calculation to the outside temperature, taken from the CNR (National Research Centre) databases [36].

The minimum value occurs during the hottest hours of the day, as shown in the figure. In a summer month, the relative humidity and the variation in solar radiation must also be considered. The temperature values for the calculation of the transmitted power through the building envelope and the incident solar radiation on the surfaces (both opaque and transparent surfaces) are reported in an Italian standard. The trend appears as in Fig. 5b (July is taken as an example) and presents a peak in the hours with the maximum solar radiation.

The buildings are all in proximity to the port area. Fig. 6 depicts the ring district heating network with the position of the buildings chosen for the Ancona case study.

For the sizing of the CAES system, Fig. 7 highlights the moments in which the energy demand is zero, due to the absence of ships at berth, for a typical week in January. The procedure was repeated for each month and an average was calculated.

A final representation of the system, for the case of the port of Ancona, is shown in Fig. 8.

4. Results and discussion

The sizing of the thermal power plant is based on the average of the annual demand for electricity, which is around 1394 kW, as shown in Fig. 9.

The aim of this sizing is to create a constant production of energy in order to balance the moments of no energy demand with the moments of maximum demand, leaving the task of “load tracking“ to the storage system. Two different scenarios are hypothesized. The first simulation

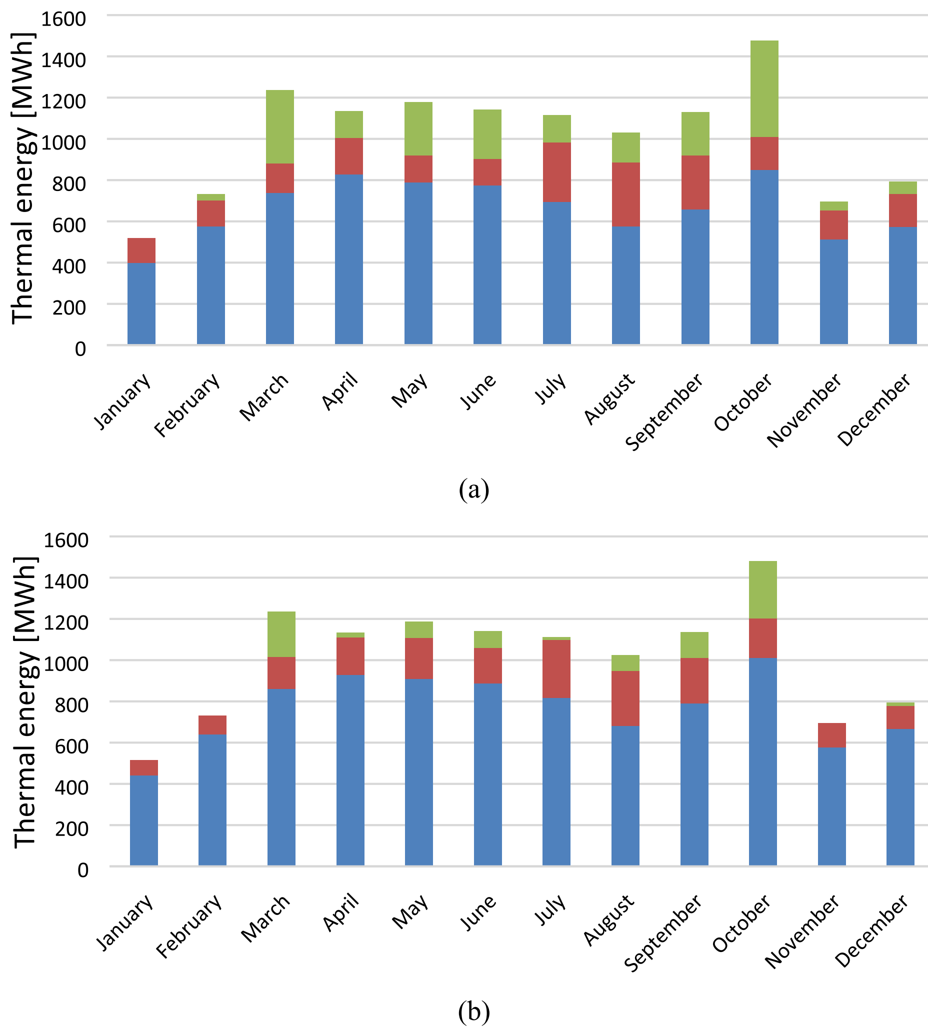


Fig. 10. Coverage of electrical power demand for the 1560 kW scenario (a) and the 2000 kW scenario (b). Blue indicates the portion covered directly by the cogenerator, red by the CAES system and green by the electrical grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

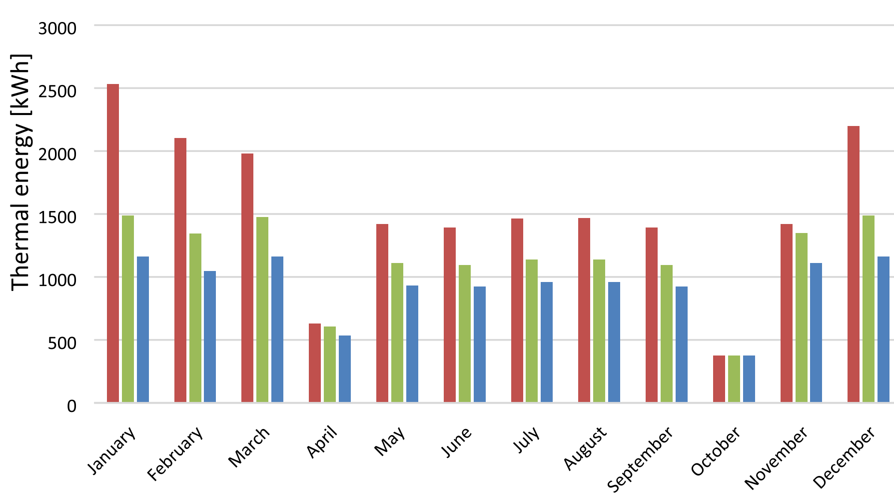


Fig. 11. Coverage of thermal demand. Red indicates the thermal energy demand, green the energy provided by scenario B, while blue indicates scenario A.

Table 4
Percentages covered.

	Scenario A	Scenario B
January	45.82%	58.74%
February	49.83%	63.88%
March	58.58%	74.54%
April	84.70%	96.50%
May	65.56%	78.20%
June	66.21%	78.42%
July	65.51%	77.77%
August	65.41%	77.65%
September	66.28%	78.46%
October	100.00%	100.00%
November	78.15%	94.87%
December	52.79%	67.66%
Average	**61,18%**	**74,55%**

Table 5
Capital costs and operational and maintenance costs.

Capital costs	
Specific cogenerator [€/kW$_e$]	650
Specific district heating [€/m]	300
Specific heat exchangers [€/kW]	50
Grid connection [€]	190,000
Inverter [€]	600,000
Cost of underground Mt line [€/km]	40,000
Electric transformer [€/cad]	70,000
Cable handling system [€/cad]	30,000
Berth terminal [€/cad]	40,000
CAES system [€/kW]	700
Operational and maintenance costs	
Pumping [€/MWh$_{th}$]	1.6
O&m district heating [€/MWhth]	1.9
CHP maintenance [€/kWanno]	52
CAES maintenance [€/kWanno]	25

Table 6
Economic results.

	PB	NPV	IRR
Scenario A	5 years, 7 months	€ 5.640.003,24	13.4%
Scenario B	4 years, 5 months	€ 10.348.968,00	18.9%

was designed trying to stay as close as possible to the average annual demand. The objective was to minimize exchanges with the electrical grid and therefore to design a power plant that is as self-sufficient as possible. The available catalogue value is 1560 kW (scenario A). On the contrary, for the second simulation a 2000 kW (scenario B) plant was chosen, with the aim to increase the autonomy of the plant and supply a greater amount of thermal energy to the buildings, so as to increase the percentage coverage of their needs (Table 3).

The two histograms (Fig. 10) show how the demand for electricity is satisfied. They illustrate how the power required by ships at berth is supplied, whether by a cogenerator, a network or a storage system.

As regards the first simulation (Fig. 10a), even if the energy produced by the plant corresponds to 105.04% of the demand, it is unable to directly meet the needs of the ships without exchanges with the external network. Of this amount, in fact, 83.05% arrives directly at the utilities. The remaining 21.98% is sold to the network, because in some periods it is produced when the demand is low, and 16.95% (that is 43.53% of the amount sold) is again withdrawn at times of high demand. These exchanges are due to the dynamic trend in energy demand. On the contrary, (Fig. 10b) higher power (2000 kW) produces an amount of energy equal to 136.41% of the demand. The energy directly used by the utilities is 92.5% while the remaining 43.90% is sold on the network because it is not necessary when it is produced. 14.58% of the quantity sold to the network (7.5% of the total) is then withdrawn at times of high demand. In both cases the storage system covers about 17% of the total energy demand thereby eliminating the need for continuous exchanges with the network. Overall scenario B allows for greater autonomy as it is self-sufficient for electricity supply for three months a year, compared with only one month for scenario A.

The results from a thermal point of view are analysed by looking at the percentage covered by the demand of the buildings. The trend is variable, with a minimum in January where the demand is higher and a maximum in October where both scenarios can satisfy 100% of the requirements. Overall, the 2 MW plant covers almost 15% more, as it recovers a greater amount of thermal energy. The results are shown in detail in Fig. 11, and the percentages covered, obtained from the ratio between the energy supplied and the demand, are summarized in Table 4.

The index used to evaluate the performance from the energy point of view is the PES (Primary Energy Saving) [37]. It is calculated as follows (eq. (2)):

$$PES = 1 - \frac{1}{\frac{\eta_{th,CHP}}{\eta_{th,s}} + \frac{\eta_{el,CHP}}{\eta_{el,s}}} \quad (2)$$

where $\eta_{th,CHP}$ is the thermal efficiency of the cogenerator, defined as the ratio between the useful heat and the fuel supply used to produce the

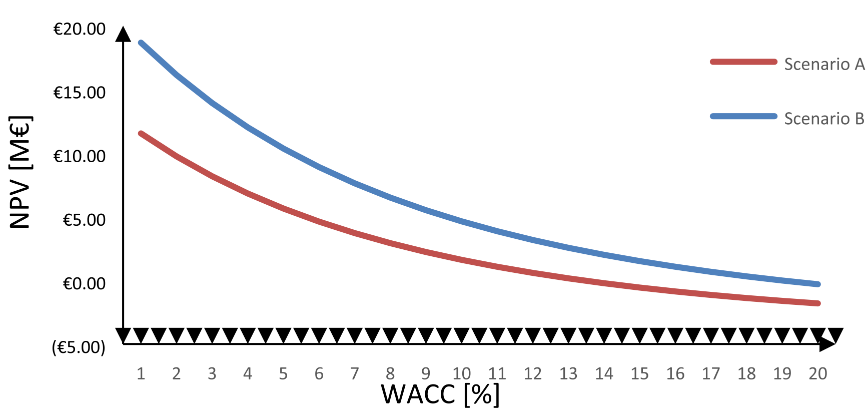


Fig. 12. NPV performance as a function of the weighted average cost of capital.

sum of useful heat output and electricity from cogeneration, $\eta_{th,s}$ is the reference thermal efficiency of separate production, $\eta_{el,CHP}$ is defined as "annual electricity from cogeneration" divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration and $\eta_{el,s}$ is the reference electrical efficiency of separate production. The calculation shows that scenario A has a value of 17.89 while B results in a value of 17.5. Therefore the first solution is slightly better since this configuration determines a greater PES, thereby minimizing the waste of energy.

Economic analysis is essential to assess the feasibility of the investment. The NPV (Net Present Value), the IRR (Internal Rate of Return) and the PB (Pay-back) were chosen as evaluation indices. A cost and benefit analysis was used for the calculation. The costs related to the investment have been estimated, and can be classified in two categories, the capital costs and the operational and maintenance costs throughout the useful life of the plant. These analyses are summarized in Table 5.

The sources of income derive from the sale of thermal energy to buildings, from the sale of electricity to the national network and from the incentives provided by Italian legislation. The economic life of the system is 20 years, and over the entire period the discount rate is 5%, as suggested by the GSE (Italian electricity services manager) in the development plan for cogeneration combined with district heating.

The results of the considered indices are summarized in Table 6 and Fig. 12. The best investment is therefore the one associated with scenario B because it produces a lower PB with a higher associated NPV and IRR. The main reason for this is due to the higher revenues from the sale of thermal energy from the district heating network and the greater revenue from the incentives linked to the increased sale of electricity to the grid.

Finally, savings are analysed from the point of view of the shipowners in the transition from internal energy production from diesel generators to on-shore supply. The costs of generating electricity from diesel engines were compared with consumption data taken from Sciutto and Pinceti [29] and the cost of energy from the cold ironing system. The total savings over the year is around 850 thousand euros, or about 59% of the current cost. Fig. 13 shows the trend in the two costs during the period analysed.

5. Conclusions

This paper, taking as a case study the port of Ancona, provides a methodology to evaluate the energy demand of ships at berth and to produce electricity through a highly efficient cogeneration plant. In this way ships can shut down their auxiliary engines, which are a great cause of pollution due to the sulphur content of fuels, with a consequent important reduction in the emission of pollutants in the port area. Considering a cogenerator as a power source, the heat recovered can be exploited and this allows the overall efficiency of the plant to be increased and consequently the cost of energy production to be lowered, making a stand-alone power supply system more convenient than traditional cold ironing which is entirely dependent on the electricity grid. In addition, a CAES system allows a further increase in autonomy and reduces the amount of energy which has to be withdrawn from the grid.

For the case of the port of Ancona, the analysis lasted over a one year period. The waste heat has been exploited in a ring district heating network, allowing a number of buildings to be connected and supplied with useful heat. In this way these buildings can reduce the impact of their traditional boilers and thereby further improve the benefits as regards the reduction in pollutants emitted. The results can be summarized as follows:

- As regards energy, scenario A (1560 kW) allows a greater PES than scenario B (2000 kW), because it minimizes the amount of fuel used (natural gas);
- Scenario B is self-sufficient for electricity supply for three months a year, compared to only one month for scenario A, thanks to the greater amount of electricity produced;
- Scenario B (74.55%) better satisfies the thermal demand of the buildings compared to scenario A (61.18%);
- From the economic point of view, scenario B allows a greater NPV and associated IRR, with a lower PB.

Furthermore, the feasibility from the shipping companies' point of view has been demonstrated, with yearly savings of about 850 thousand euros, or about 59% of the current costs.

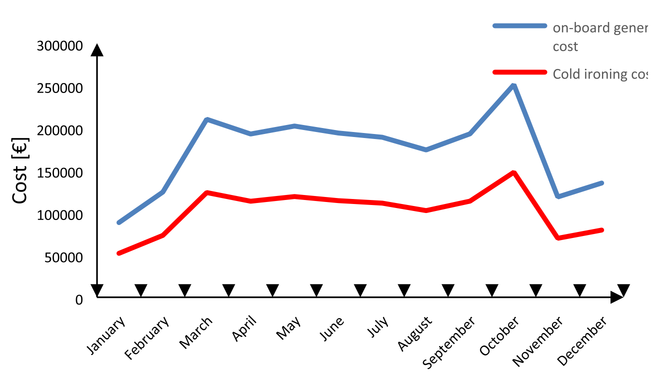


Fig. 13. Savings trend obtained from the production of electricity from cold ironing and on board diesel generators.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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