A COGENERATION POWER PLANT TO INTEGRATE COLD IRONING AND DISTRICT HEATING AND COOLING

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ABSTRACT
As in almost all the major maritime cities, Ancona harbour is very close to the urban area and hosts a multi-purpose port harbouring cruise boats, passenger ferries, commercial liners, and fishing boats. All the ships emit rather high amounts of airborne pollutants including PM10, a toxic mixture of low-diameter solid particles and liquid droplets suspended in the air. A consistent part of the airborne pollutants is due to the vessels' 'hotelling', i.e. their staying within the port. A significant reduction of pollutants emitted by ship engines during their hotelling in harbours can be achieved by applying a ground electrification of the docks to provide the electricity usually produced by the polluting engines of the ships. To check the technical and economic viability of such a technology we have designed a Trigeneration power plant (i.e. a CCHP or Combined Cooling, Heat and Power plant) to be located within Ancona Port. The CCHP plant would be able to provide most of the electricity required during the hoteling of bigger cruisers and ferries and the district heating and/or cooling of most of the buildings nearby. The plant was optimized to achieve the best energy performance by reducing the waste heat/cool and by tuning the electrical loads to those of ships.
Keywords: cogeneration, cold ironing, trigeneration.

1 INTRODUCTION

PM10 (Particulate Matter smaller than 10 microns in diameter) is the term used for a potentially toxic mixture of solid particles and liquid droplets suspended in the air. The EU daily mean limit value set for the protection of human health is 50 µg/m^3, not be exceeded more than 35 days in a calendar year. Furthermore, the annual mean must not exceed 40 µg/m^3. In 2011, PM10 concentrations recorded at the monitoring station 'Ancona-Port', located very close to the wharf, exceeded 97 times this legal limit and, in previous years, the number of exceedings has always been above the legal limits. These data can be compared with those of another environmental monitoring unit, located less than 1 km far and known as 'Ancona–Cittadella'. PM10 values of this unit are lower, both for the annual mean and for the number of exceedings.

To evaluate emissions strictly due to maritime sources, several methodologies can be applied but the cornerstone is represented by a report developed for 'Methodologies for Estimating air pollutant Emissions from Transport' (MEET), namely a set of models to estimate pollutant emissions produced by vessel traffic, through specific emission factors specialized for various types of ships [1–8]. In a paper of 2012 [9], we evaluated ship movements during a typical week in the whole harboring area of Ancona. From these data, we got an estimate of the weakly emissions of particulate produced by vessel traffic, to highlight the impact of this activity on the city and on the whole region. We confronted our results with comparable data, obtained by a branch of Italian National Environmental Agency, ISPRA, using a top-down methodology, i.e. starting from the fuel national consumption and using the percentage of docking in this port among the national total as a disaggregation proxy variable.

As in almost all the major maritime cities, Ancona harbor is very close to the urban area and hosts a multi-purpose port harboring cruise boats, passenger ferries, commercial liners,

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and fishing boats. All the ships emit rather high amounts of airborne pollutants. In particular, they emit high volumes of PM10. A consistent part of the airborne pollutants is due to the vessels' 'hotelling', i.e. their staying within the port.

A significant reduction of pollutants emitted by ship engines during their hotelling in harbors can be achieved by applying a ground electrification of the docks to provide the electricity usually produced by the polluting engines of the ships. This technology, dubbed 'cold ironing', is now widespread in some major ports of the world, mainly in North America and northern Europe. The Port of Los Angeles was the first in the world to implement the cold ironing for container ships in 2004. In Italy, three ports are involved in such a project, namely Civitavecchia (Rome), Genoa and Venice. However, the implementation of cold ironing requires either an important advantage for the freight shipping companies or a proper set of rules to help port authorities to implement and enforce cold ironing.

It must be pointed out that cold ironing involves quite big challenges. Between all, a standard for power supply does not exist and every single ship usually requires electricity with its own non-standard voltage, and sometimes, with its own non-standard frequency. In addition, one of the biggest obstacles to the implementation of cold ironing in Italy is the market price of electricity. In order to push ship owners to implement the rather expensive devices for cold ironing, a competitive price of energy would be a plus. To reduce the cost and the price of electricity, the proximity of many Italian ports to the city centers, while leading to environmental concerns, might become an asset. In fact, the contiguity with densely populated urban areas and commercial activities make easier to implement a power co-generation scheme designed to supply electricity to the docks and heating/cooling to the buildings through district heating/cooling. This would let reduce the price of electricity by selling heat/cooling and also by accessing contributions within energy efficiency improvement schemes.

To check the technical and economic viability of such a technology we have designed a Trigeneration power plant (i.e. a CCHP or Combined Cooling, Heat and Power plant) to be located within Ancona Port. The CCHP plant would be able to provide most of the electricity required during the hoteling of bigger cruisers and ferries and the district heating and/or cooling of most of the buildings nearby. The plant was optimized to achieve the best energy performance by reducing the waste heat/cool and by tuning the electrical loads to those of ships.

2 THE PORT OF ANCONA

The port of Ancona is located roughly on the middle of Italy's Adriatic coast and represents the main logistical node of the central Adriatic coast, between Romagna and Puglia. It is one of the port nodes of the so-called Scandinavian-Mediterranean Corridor. This corridor crosses the Baltic Sea from Finland and Sweden, runs through Germany, the Alps and Italy. It connects the main urban centers and ports of Scandinavia and northern Germany to industrialized production centers in southern Germany, Austria and Northern Italy to then reach Southern Italian ports and Malta. Through the 'A14' Highway and the 'Adriatic' railway line, the port of Ancona is connected to the node of Bologna, an integral part of the Baltic-Adriatic Corridor and the Mediterranean Corridor.

In this context, the Ancona port also plays a major role in connecting such corridors and the highways of the south-eastern Mediterranean to Croatia, Albania and Greece. Daily connections with the Greek ports of Igoumenitsa and Patras provide an efficient maritime bridge between Italy and Greece. No other Adriatic port guarantees this frequency, nor does it have such a competitive opportunity, and therefore it represents a pick for customers. The location of the harbor and the peculiarities of the fleet (high-capacity ferries capable of developing remarkable speeds maintaining medium-high comfort for passengers) make the Ancona–Igoumenitsa–Patras line the fast corridor par excellence between Europe and the eastern Mediterranean (Greece, Turkey, Middle Eastern countries). The resulting trips are characterized by the best relationship between total travel time and length of route. This, amongst other things, has a beneficial effect on national and environmental traffic, with a reduction in heavy and light traffic on the road network of central and southern Italy.

For such reasons, the port of Ancona is among the major ones in Italy for international passenger traffic on liner ships, with more than 1 million people passing through the port each year thanks to the vast offer of regular international lines, which are further boosted during the summer season. As already outlined, the port is connected to Greece, Croatia, Albania, as well as Trieste and Istanbul ports (landing only).

The Ancona–Igoumenitsa–Patras line is the main link with at least two daily connections six days a week throughout the year. The geographical location of the port ensures the shortest transit time between South East Europe and the Mediterranean. In particular, the Ancona–Igoumenitsa route is the main maritime ring of the Scandinavian Mediterranean corridor. 61% of flows originate in central-western Europe, 35% in Italy and only 3% come from Scandinavian countries and Eastern Europe. Between all Spain originates 16.1% of transits France (15.7) and Germany(14). Other significant traffic figures come from Holland (7%), Great Britain (3.9%) and Belgium (3%).

2.1 PM10 emissions from Ancona Port

As already mentioned, in a paper published in 2012 [9], total emissions of PM10 due to passenger ships were evaluated as 24.11 tons/year. All the estimates were done considering low-sulfur fuel (0.1%) while emission factors [g/kWh] were the same for PM10 and Total Suspended Particles (TSP). The authors experienced difficulties in calculating the emissions of ships performing service towards Greece since the power of both the main engine and the auxiliary engine were not well estimated by the general models [1–8]. To improve the accuracy of our estimation, a survey on the actual power used by these ships during the hotelling phase is crucial. Comparing our results with the 2005 ISPRA data for the activity 080402, National Sea Traffic Within EMEP Area, we noticed that particulate matter emissions are similar, namely 34.84 tons. ISPRA values were obtained considering the fuel national consumptions and using the number of ships arrived in all the ports of the Province as a proxy variable. ISPRA values are higher also because they consider all the phases of cruising, maneuvering, and hotelling.

The emissions inventory of Marche Region estimates for Ancona a quantity of PM10 coming from all the other activities of about 150 tons. This means that the port accounts for about the 14% of total PM10 emissions.

Regarding cold ironing, in the short period is difficult to intervene on freights terminal to avoid discouraging the activities. Any decision on this sector must be taken by mutual agreement with other ports and/or encouraging the ship owners, because of the high cost for the tuning of the ships. Thus, we support the electrification of the docks destined to cruise and passengers sectors as port authorities of the main Italian ports (Civitavecchia, Venice) currently do. In general, this sector requires high installed powers, namely several MW, so cold ironing is functional in case of high percentage of passenger ships. This is true in Ancona port where most dockings are related to ferry services to the Adriatic East coast countries. Cold ironing applied to this type of ships could save 16.84 ton of PM10 due to the hotelling phase. The cost for this type of traffic is easily amortizable, since these ships carry line service and only the few ones that moor more frequently in the port must be modified.

Table 1: PM10 emissions from ships in 2011 [9].

TO/FROM	Total arrivals	Manoeuvring [tonn PM10 per year]	Hotelling [tonn PM10 per year]
Croatia and Albania	748	1.01	7.16
Greece	805	4.52	9.68
Total ferry	**1553**	**5.53**	**16.84**
Cruise	62	0.33	1.41
Total (ferry+cruise)	**1615**	**5.86**	**18.25**
Bulk + container	797	0.70	3.54
Total	**2412**	**6.56**	**21.79**

3 A PROPOSAL FOR COLD IRONING THROUGH CO-GENERATION

We evaluated a proposal for electrification of docks dedicated to passenger ferries. The quays under investigation are nos. 8 and 9 of Wojtyla dock, no. 11, 12 and 13 of the Santa Maria dock and no. 15 and 16 of the pier XXIX September.

To offer electricity to moored berth at a competitive price we conceived an unconventional solution. This solution involves the assembly of a Trigeneration CCHP plant combined with a district heating network. In Fig. 1, we can observe the quays that are the object of the electrification proposal, the central power plant (in green), the underground electricity grid (in blue), the buildings served by the district heating network (in black), and the district heating network (in red).

This electrification hypothesis for the passenger ferries only derives from their high frequency and regularity of transit and also because of the need for the plant to work at an annual overall efficiency of at least 75% to benefit from the possible economic incentives.

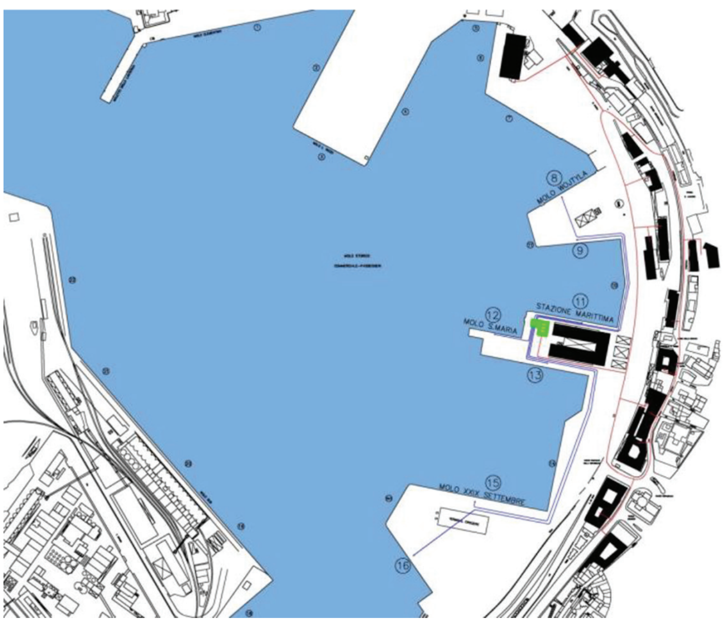

Figure 1: Layout of electrification and district heating/cooling.

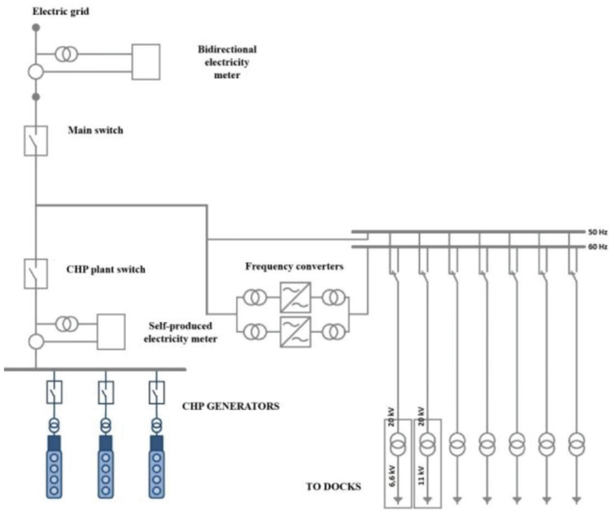

Figure 2: Schematic of the cold ironing system.

The CCHP power plant is placed inside the dismissed old palace of port authority, as a retrenchment hypothesis and for the barycentric position with regard to piers and building.

The Trigeneration Unit shall employ internal combustion engines powered by natural gas. This choice derives from the overall power to be installed, which is less than 10 MW, and from the high electrical efficiency, these units can guarantee.

The ring configuration has been adopted for the district heating/cooling network due to its ability to distribute evenly it in both directions, to the flexibility of the system and to the ease of development.

The configuration chosen for the power grid is illustrated in a simplified functional diagram in Fig. 2. It consists of a connection to the national medium voltage network, a bidirectional energy measuring device, a general device, a medium voltage supply to the service of the quay power supply, an interface device and a medium voltage bus powered by the electric generators.

The quay power system is based on a centralized frequency conversion plant with corresponding double-bus bars (one at 50 Hz and one at 60 Hz). The frequency converters are connected in parallel and operate depending on the power required at 60 Hz. The panels are completed with a general switch and another switch for each power line. The centralized switching system allows choosing the frequency at each quay, thus ensuring maximum flexibility of system use. A further advantage of this configuration is the smaller space required for each quay since most of the site equipment is located in the central station.

3.1 Evaluation of electrical and thermal loads

This section analyzes the energy needs to be met. As mentioned, we took into account only regular passenger ships, the so-called ‘Ro-pax’. Passenger service is carried out by seven companies, four of which operate through two joint services. Table 2 lists these companies, the ships they operate in Ancona and the number of dockings in 2016.

Table 2: Overall dockings of passenger ferries in 2016.

Company	Ship	Calls per year
Minoan Lines	*Cruise Europa*	183
	Cruise Olympia	183
Anek Lines & Superfast	*Superfast XI*	123
	Olympic Champion	114
	Hellenic Spirit	114
	Asterion	42
Jadrolinjia	*Marko Polo*	137
	Zadar	62
Adria ferries	*Af Marina*	157
	Bidge	54
Blue line & Snav	*Regina Della Pace*	92
	Aurelia	104

The district heating network has been designed to serve a number of buildings located near the port area and therefore suitable for efficient supply of heating and cooling.

3.1.1 Electrical loads

For the determination of electric loads, the electrical power required by each ship during hotelling was calculated first. To do this, we used data provided by the Port Authority for the previous study of pollutant emissions [9] for larger ferries, while for smaller ferries we applied the procedure proposed by Entec corrected by scale factors as proposed in many studies carried out over the years [10, 11]. The results of this step are summarized in Fig. 3. Then, the reconstruction of Ro-pax vessels' traffic was carried out for the whole 2016. For each ship, information was collected such as date and time of arrival, date and time of departure and, thus, hotelling time. Four standard weeks have been identified for different periods of the year and the related instantaneous electrical power required for the hotelling was determined.

3.1.2 Thermal loads

After detecting the buildings, the related thermal analysis has been performed on the basis of building characteristics. The peak winter thermal loads were calculated according to UNI 12831 using UNI 10349 for climatic data reference. Summer loads were determined following the RTS of ASHRAE [12].

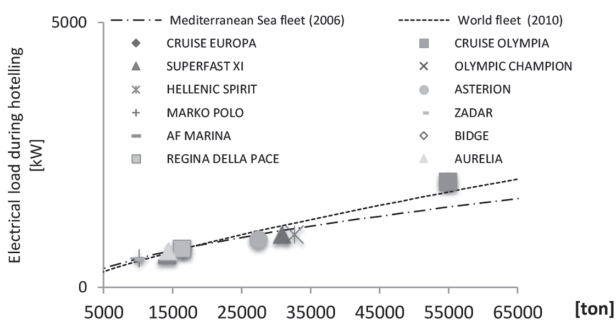

Figure 3: Electrical power requirement during hotelling.

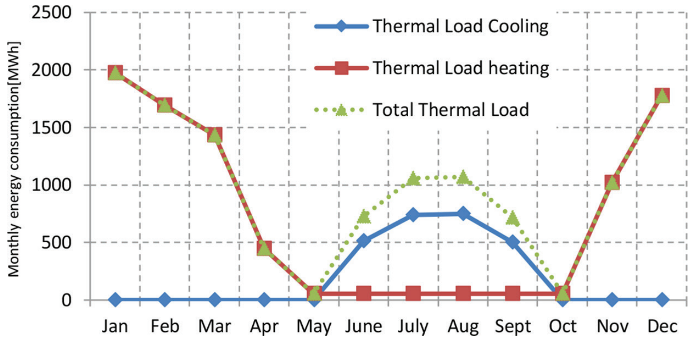

Figure 4: Total average monthly thermal loads for heating and cooling.

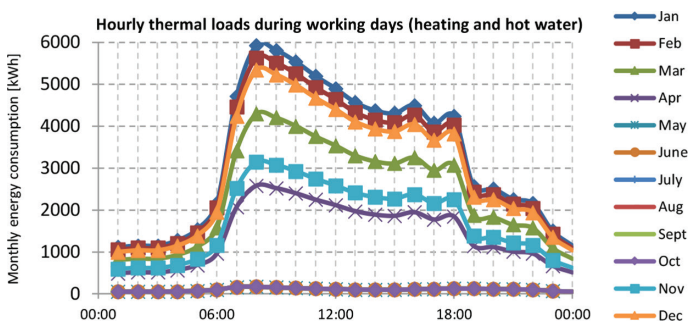

Figure 5: An example of daily thermal load behaviour: typical working day.

The power required per volume unit is perfectly in line with the suggestions provided by the Italian Electrical Services Manager 'GSE' for district heating systems located in Climate Zone D (23.3 W/m^3). The average monthly heat requirement was calculated according to UNI TS 11300 standards introducing again UNI 10349 data. The thermal energy requirements for refrigerators have been increased by assuming the COP of absorption refrigerator equal to 0.7. The heating period is from 1 November to 15 April. This is because, according to Italian Legislation district heating systems are exempted from compliance with the daily time limit, but must adhere to heating period. Figure 4 shows the results obtained.

In order to better characterize the operation of the plant and therefore to carry out a realistic energetic simulation, a model proposed by the ENEA [13] has been employed to evaluate the hourly heat demand for a standard day of each month of the year. This model is different depending on whether the buildings are residential or for office use. As a result, the resulting load against time was calculated by adding all the individual loads. The residential model has been applied to all barracks, as they host permanent housing, while the remaining buildings have been considered as offices. As an example, Fig. 5 shows the hourly heat demand for a working day of each month.

3.2 Choice and design of trigeneration systems

After determining the electrical and thermal loads, we have carried out a series of simulations, assuming different plant configurations. Simulations have been conducted over an entire year taking into account holidays and different seasonal periods.

For the CCHP system, internal combustion engines powered by natural gas have been chosen, thanks to the high electricity/heat ratio they are able to supply. In fact, being the electric loads of the same order of magnitude of the thermal loads, gas turbines have been discarded a priori. To ensure an energy production as close as possible to the rated load, the power generator has been divided into several units to avoid the heavy partial-load performance decay of most commercial systems.

The hypothesized conduction mode is thermal-driven, so it is the thermal demand of the utilities to determine the operating regime of the cogeneration system, which follows the demand trend up to the maximum load over which the auxiliary boiler runs. All this is necessary to achieve a near 100% heat recovery in cogeneration units, a prerequisite for working with a total annual output of more than 75% and accessing economic incentive schemes.

Three different scenarios were analyzed, all of which were made up of several eight-cycle internal combustion engines fueled with natural gas:

1. Cogeneration unit consisting of three CHPs 'MWM TCG 2016 V16' of 800 kW (electricity) each;
2. Cogeneration unit consisting of three CHPs 'MWM TCG 2020 V12' of 1200 kW (electricity) each;
3. Cogeneration unit consisting of four CHPs 'MWM TCG 2020 V12' of 1200 kW (electricity) each.

All three solutions include the installation of one or more auxiliary boilers, suitably dimensioned to cope with malfunctions of one or more units, thus ensuring continuous district heating service. For the network, as mentioned, a ring solution was chosen. Energy losses for systems with such high thermal density are usually less than 10%, so a precautionary value of just 10% was chosen.

4 RESULTS

The first scenario, consisting of three CHPs capable of 800 kW of electrical power, resulted to be the best choice to match the needs of Ancona port. The other ones resulted to be slightly oversized leading to poorer overall performance. Due to the limited number of pages, we can only show the numerical results of the first scenario.

The cogeneration unit consists of three internal combustion engines MWM TCG 2016 V16 of 800 kW each. The manufacturer declares the following data: Electrical power = 800 kW; Thermal power = 854 kW; Electrical efficiency = 42.5; Thermal efficiency = 45.3.

Results obtained through simulations assume hourly values. The months of May and October were excluded from the simulation because they were not subject to heating or cooling. For the simulation related to the first scenario (the solution with the smallest CHP units), Fig. 6 shows thermal loads, while Fig. 7 shows electric loads. We can easily notice that the generators can never cover the electrical load alone, even during periods of minor traffic, corresponding to the winter months. On the other hand, 80% of thermal loads are supplied by the generators and the remaining 20% by the auxiliary boilers.

More in deep, primary energy saving is 19.11% and the heat supplied by the generators is 80.9% of the total heat. Due to the fact that design and conduction are thermal-driven, the annual complex yield of the cogeneration unit is over 85%. For all these reasons, access to incentive schemes is guaranteed.

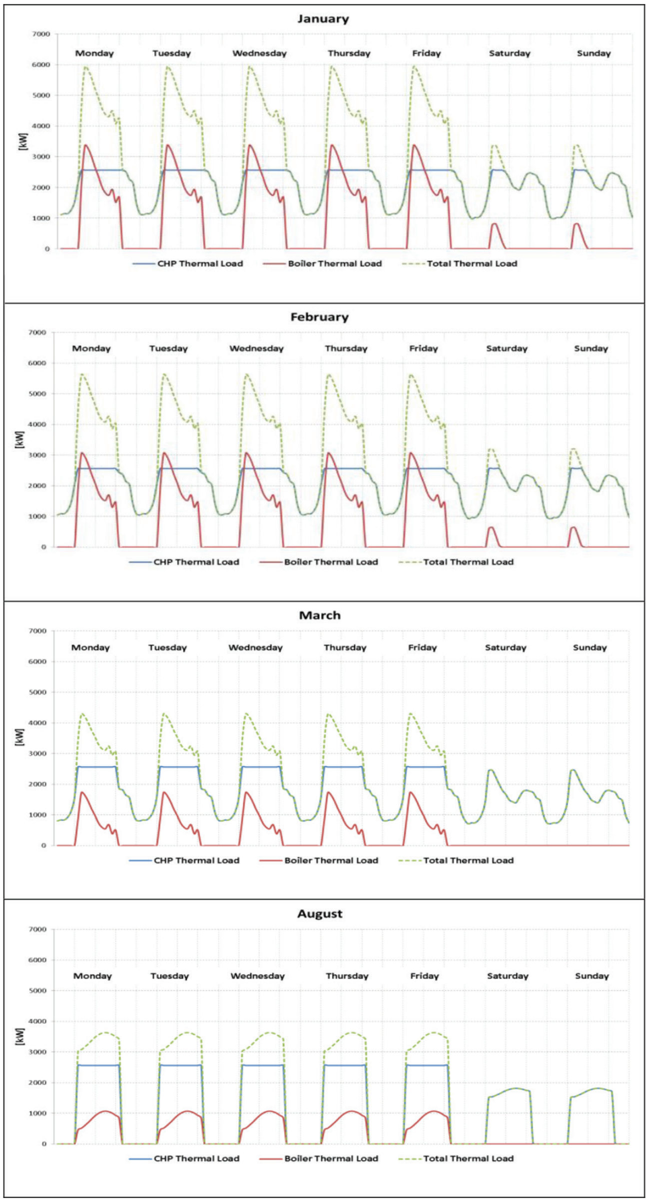

Figure 6: Weekly thermal loads for scenario 1 in three winter and one summer months.

Engines shall work up to 4178 hours thus achieving a very high capacity factor. Having split the power system into three distinct motors allows, under all conditions, to work with a load always near the rated load. The balance between electricity taken and received is positive in the months of January, February, March, November and December only.

In the second half of April and in the months of May and June, the cogeneration unit shall be off and the auxiliary boiler will satisfy the very low demand of heat, associated to the demand for hot water only.

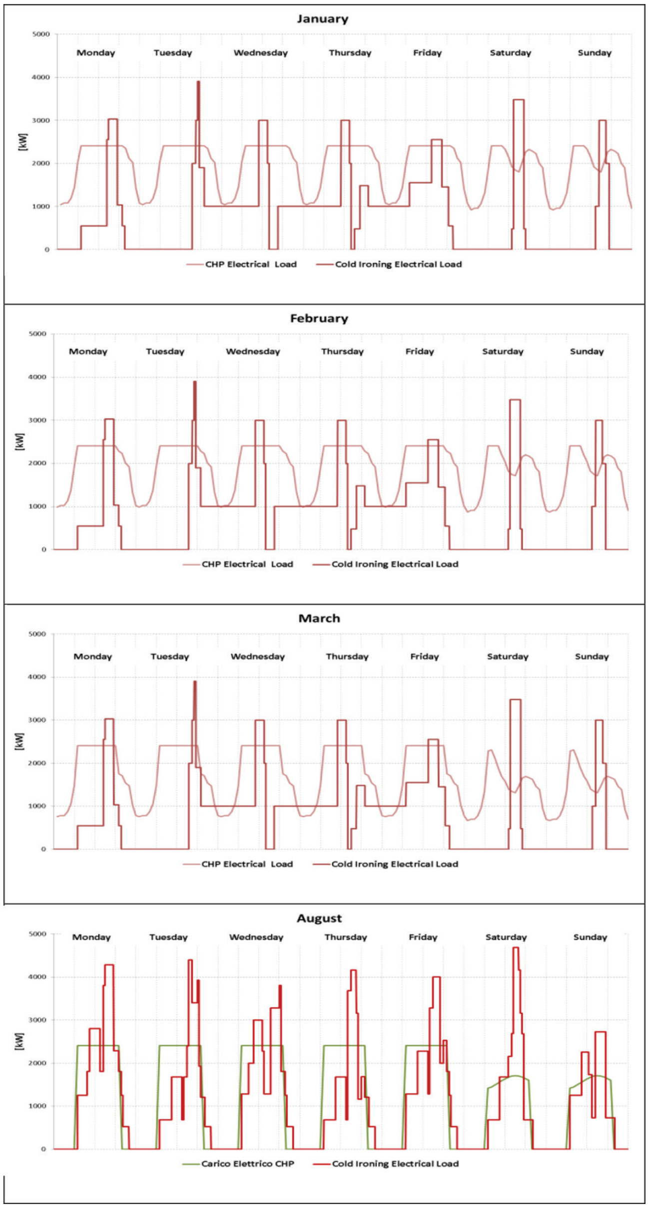

Figure 7: Weekly electrical loads for scenario 1 in three winter and one summer months.

5 CONCLUSIONS

Cold ironing and its market are now consolidated and the environmental benefits that such systems can produce are proven by numerous studies and applications. However, the diffusion of electricity feeding from the docks cannot take off, especially in those countries (among them Italy) where the high price of electricity is the key impediment. Our research investigated the current situation of the Ancona port and tried to bypass this problem through the development of an energy self-supply system based on a high-efficiency cogeneration plant combined with an efficient district heating network. After having fully determined the electric loads to be supplied to the moored vessels and the thermal loads for the district heating service, three plant hypotheses with different power levels of the CHP were analysed: the first CHP is capable to produce 2400 kW of electricity, the second one 3600 kW and the third one 4800 kW.

After a full set of simulations, the CHP of the first scenario (i.e. the one with the least installed power) resulted to be the best plant, since it can guarantee the highest primary energy saving and the highest capacity factor of the cogeneration unit. From the economic analysis, the CHP of the second scenario resulted to be the most viable. In fact, it would realize the shortest payback period (namely 5 years and 5 months) and the highest Internal Rate of Return (14.6%). However, we found all three scenarios economically viable, being their Amortization Time less than six years and achieving an Internal Rate of Return of more than 13% and a Net Present Value largely positive.

The environmental analysis led to very positive results. In fact, in all scenarios environmental improvement was evident since emissions of about 110 tonnes of nitrogen oxides, more than 2 tonnes of PM10 and more than 4 tonnes of sulphur oxides per year could be avoided. Again, the best performance was obtained by the system hypothesized in the first scenario. It would achieve the highest percentage reduction for all pollutants considered: nitrogen oxide emissions would be reduced by 98.58% and PM10 by 79.06%, while sulphur oxides emissions would be entirely prevented.

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