A cogeneration system for the city of Perugia: energetic analysis and technical solutions

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In the last decades technological development showed cogeneration as one of the technical solutions able to combine the different and often contrasting requirements of energetic consumptions and environmental effects for energetic conversion processes. Nevertheless, the optimised dimensioning of combined electricity and heat generation plants needs an accurate evaluation of thermal and electrical loads, as well as their interactions.
The present paper reports the characterization of heating, cooling and electric consumption of a cogeneration plant feeding the minimetro electrical loads in Perugia (a city transport system moved by a funicular traction) and a district heating/cooling net, by means of absorption machines.
The energetic analysis shows that, because of the strong loads variability, the electrical generation system could be employed if the generated power could be modulated. The proposed plant is therefore made by a modular system, with different groups size; the power chocking is obtained simply by excluding part of the modules. It's showed that the rising of the initial costs could be balanced by the global efficiency of the system, positioning the installation in the area of a medium term investment, with a reasonable payback period.

Keywords: cogeneration, thermal loads, greenhouse gases.

1. INTRODUCTION

Following the technical developments of the recent past, cogeneration proved as an efficient solution in matching different (and often contrasting) requirements linked to the increasing energetic consumptions and the environmental matters due to the energetic conversion processes [1].

In the city of Perugia, in middle Italy, a urban transport system called "minimetro" is on the stocks; it is characterized by cages moving on funicular railways and it will need a big supply of electric energy.

The town-planning scheme foresees a deep change of the urban asset in the zone of the minimetro starting station, designed to host an internal source of electrical feeding and equipped with the necessary connections for the distribution of the power delivered to the whole line [2]. Therefore, a design of a cogeneration plant is presented, serving the minimetro and feeding a heating/cooling net for the considered zone. The feasibility study could be divided into three phases: an analysis of electrical and thermal loads, where the characteristics of the users are analyzed, an economical investigation and a final definition of the environmental advantages arising from the realisation of the plant.

2. ELECTRIC AND THERMAL LOADS ANALYSIS

The choice of the place for the cogeneration plant installation was due to different motivations [3, 4]:

- logistic: availability of spaces adequately served by infrastructures;
- urbanistic: a deep change of the urban asset will take place;
- users: the zone is rich of public buildings which represent an almost ideal connection to the heating/cooling net;
- variability of loads: the different destinations of the buildings in the area provide enough variability of the energy demand; it gives the possibility of adapting the thermal production to the electrical load;
- minimetro: the main user of the electrical energy produced by the plant could be constituted by the minimetro, that represents a privileged customer for energy selling.

2.1 Electrical loads

Beyond the minimetro, the electrical loads connectable to the cogeneration plant are a group of buildings in the area: the existing ones and the ones that will be realized in the next few years.

The minimetro should be considered as formed by two subsystems (fig. 1):

- electromechanic transport system, where the powering machines are installed, interacting with the cages and guaranteeing their movement;
- infrastructures serving the transport system, constituted essentially by the stations where devices for the conduction are located.

Figure 1: part of the minimetro virtual track in Perugia.

The electrical power required varies with the number of passengers; in fig. 2 the daily load in three different conditions is sketched: maximum, medium and minimum affluence.

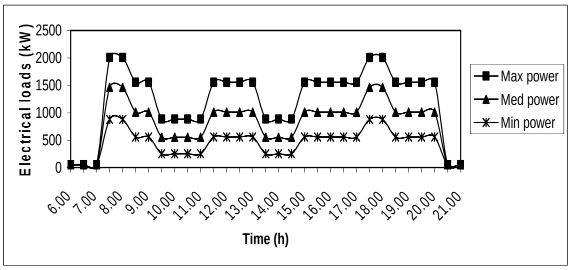

Figure 2: daily electrical load with maximum, medium ad minimum affluence of passengers.

In order to evaluate the amount of electrical loads required by the buildings, a daily power demand curve was determined for each kind of construction (residential/hotel, tertiary/office districts, industrial/utilities, commercial and sport plants). As an example, curves for residential/hotel buildings are reported in fig. 3.

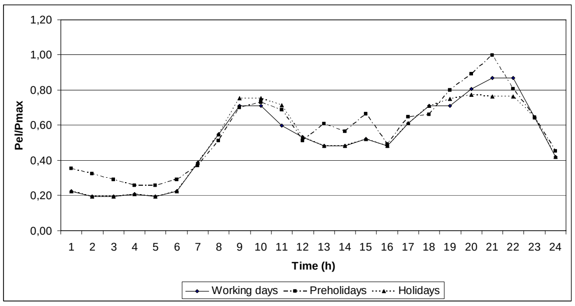

Figure 3: daily electric power demand curves for residential/hotel buildings.

The unitary maximum electrical power required (kW/m^3) on monthly base was then defined; hence, multiplying the above mentioned curves by these values and by the global volume of the buildings, the total electrical load was determined; for a typical working day it is sketched in fig. 4; the maximum value of the electrical power required results approximately equal to 3.7 MW.

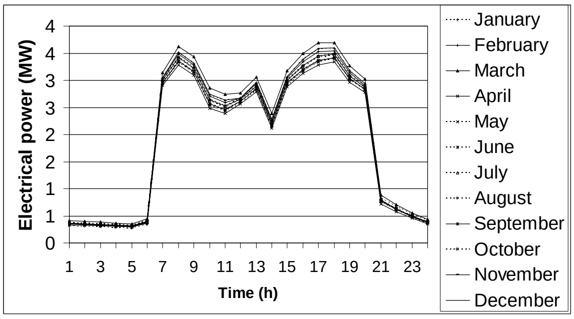

Figure 4: total electrical charge curves for a typical working day.

2.2 Thermal loads

The evaluation of thermal loads was carried out with a methodology similar to the one adopted for electrical needs [5]: for each type of building, the daily trend of the maximum power required was calculated, both for heating and cooling (fig. 5 and 6 for residential/hotel constructions).

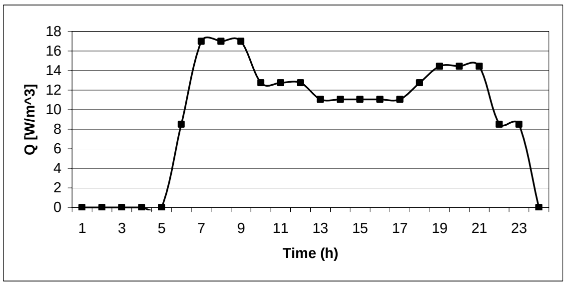

Figure 5: unitary daily heating power demand for residential/hotel buildings.

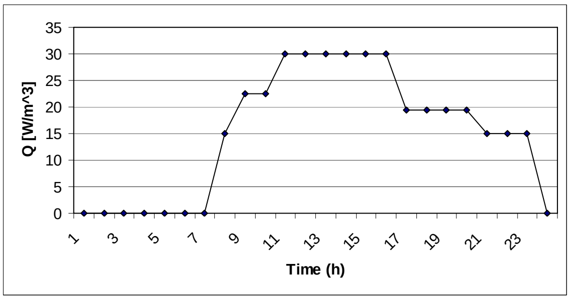

Figure 6: unitary daily cooling power demand for residential/hotel buildings.

Once the daily curves were defined, an accurate monthly analysis was conducted, taking into account the meteorological data. Starting from the heating season, it is reasonable to assume that the users' need is proportional to the temperature difference between indoors and outdoors, neglecting the free contributions. The maximum power required corresponds to the nominal outdoors temperature (-2°C for Perugia, that means a $\Delta T_{n,h}$ of 22°C); therefore, for each month, it is possible to define a typical curve by decreasing the nominal one by an amount proportional to the monthly temperature difference $\Delta T_{i,h}$. In tab. I the $\Delta T_{i,h}$ are reported, coupled with the correspondent attenuation factors $f_{a,h}$ of the load curves, obtained as a ratio between $\Delta T_{i,h}$ and $\Delta T_{n,h}$.

Table I: heating attenuation factors.

Month	**$\Delta T_{i,e}$ °C**	**Attenuation factor $f_{a,h} = \Delta T_{i,h}/22$**
October	5.9	0.268
November	10.6	0.482
December	14.5	0.704
January	16.0	0.727
February	15.0	0.682
March	11.9	0.540
April	8.5	0.386

The attenuation factors reduce the nominal thermal load curve, as showed in fig. 7, where the daily trend of heating power required for residential/hotel buildings is sketched, month by month.

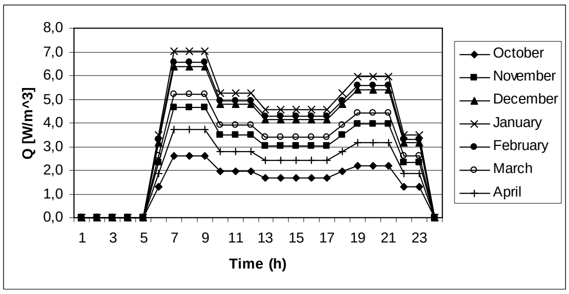

Figure 7: daily and monthly variation of the heating load for residential/hotel buildings.

The calculation methodology for cooling loads is the same employed for the heating season [6]. The only difference is linked to the evidence that, at the aim of taking into account of the strong variability of outdoors conditions, it is necessary to use the maximum temperatures instead of the average ones (tab. II).

Table II: maximum monthly temperatures on cooling season (city of Perugia).

May	June	July	August	September
28.3°C	32.0°C	35.5°C	34.7°C	31.8°C

The maximum power required corresponds to the nominal outdoors temperature of 40°C (considering 25°C indoors, it means a $\Delta T_{n,c}$ of 15°C).
In tab. III the $\Delta T_{i,c}$ are showed, coupled with the correspondent attenuation factors $f_{a,c}$ of the load curves, obtained as a ratio between $\Delta T_{i,c}$ and $\Delta T_{n,c}$.

Table III: cooling attenuation factors.

Month	**$\Delta T_{i,c}$ °C**	**Attenuation factor $f_{a,c} = \Delta T_{i,c}/15$**
May	3.3	0.220
June	7.0	0.467
July	10.5	0.704
August	9.7	0.647
September	6.8	0.453

The unitary thermal load of each kind of buildings was multiplied by their volumes; hence, the entire amount of the heating and cooling needs (differentiated in working days, preholidays and holidays) was obtained, considering also the demand contemporaneity.
In fig. 8 and 9 the total heating and cooling load are respectively displayed; the maximum power request amounts to 20 MW in heating configuration and 12 MW in cooling configuration.

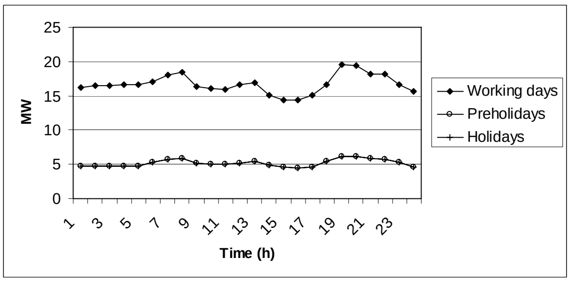

Figure 8: maximum heating curves.

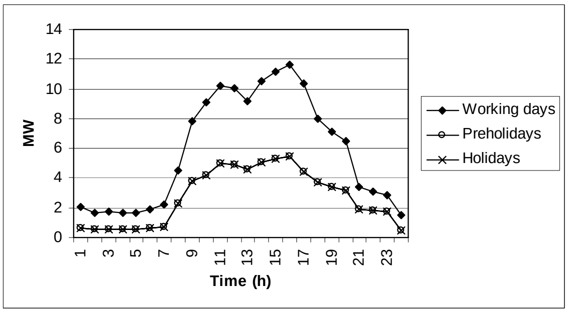

Figure 9: maximum cooling curves.

3. TECHNICAL SOLUTIONS

Electrical and thermal loads were used to evaluate the primary engines most suitable to satisfy them; they are constituted by gas fed reciprocating engines and gas turbines [7].

The installation could present three different configurations:

1) plant with reciprocating engines;
2) plant with gas turbines;
3) plant with gas turbines for base load and reciprocating engines to follow the electric demand peaks.

Nevertheless, the last hypothesis seems difficult to realize because of the complexity of the thermal and electric coupling management both in the constructing and maintenance phases; for this reason, a comparison was implemented only between the two first possibilities. The chosen solution was the installation of 6 reciprocating engines (750 kW each), for the following considerations:

- lower initial costs;
- high modularity and consequent better adherence to the electric load;
- higher electrical efficiency (lower fuel consumption);
- maintenance costs of the reciprocating engines comparable to the gas turbine ones.

The cooling demand is thought to be satisfied with a group of absorption machines.

4. ECONOMICAL EVALUATIONS

Methods used for the plant economical assessment consist on the payback period, the net present value and the return on investment calculations.

The initial investment is necessary to purchase the machinery, the heat recovery system, the installation, the emission monitoring system, the pre-engineering and planning, the piping, the digging, the heat exchangers, the electro pumps and the absorption machines; it amounts to about 6.5 M€.

During the exercise of the plant, the benefits consist on the selling of electrical energy, the selling of thermal energy and the green certificate subsidies (a form of incentives existing in Italy for energy produced by renewables and cogeneration plants). On the other hand, the exercise costs derive from the fuel, the maintenance and the taxes for producing and delivering energy.

The payback period results of 8 years, with a net present value of 6.8 M€ and a return on investment equal to 29%; therefore, the economical aspect is absolutely satisfying.

5. ENVIRONMENTAL ANALYSIS

The main advantage of the cogeneration systems is based on the possibility of producing energy (heat and electricity) more efficiently than producing heat and electricity separately. Consequently, the fuel consumption of these systems results low, implying less environmental pollution.

It was assessed how much pollution could be avoided, estimating the pollutant quantity produced by a common heater to achieve the same heat quantity produced by the cogeneration plant and it was done exactly the same with electrical energy.

The average CO_2 emission value produced by an Italian thermoelectric plant is estimated as 700 gCO_{2eq}/kWh [8]; the CO_2 emission level created by producing electricity with a cogeneration plant is about 520 gCO_2/kWh, saving 180 gCO_{2eq}/kWh.

Moreover, if 1 electrical kWh is created in this specific plant, 1.3 thermal kWh is also produced. So, considering that producing 1 thermal kWh with the most modern technologies creates 186 gCO_{2eq}, with this cogeneration plant further emissions of 241.8 gCO_{2eq}/kWhe could be avoided. The global CO_2 saving is 421,8 gCO_{2eq}/kWhe and, multiplying for the annual electric production of the plant (about 17,500,000 kWhe), the total amount of the annual emission saving is obtained: 7,380 ton CO_{2eq}.

6. CONCLUSION

A feasibility study for a cogeneration plant feeding a city transport system moved by a funicular traction (minimetro) together with a district heating and cooling net is proposed.

The first step consisted on outlining the thermal and electrical loads of the users covered by the plant; the minimetro technical data and the forecasts on passengers' fluxes permitted the evaluation of the maximum, medium and minimum electric load profiles. Adding the electric demand of the building surrounding the plant, the maximum electric power was evaluated, together with the daily curves of the load required.

The thermal loads analysis started from the study of the unitary demand curves, evaluating the nominal total power trend with the worst external temperature conditions. These curves, attenuated by factors depending on average monthly temperatures of the city of Perugia, permitted a setting of the monthly profile both in the heating and cooling period.

A plant of 4.5 MWe was chosen, composed by 6 reciprocating engines of 750 kWe power each; once the primary engines was defined, the district heating net was designed considering that all the heat produced has to find a user.

The economical analysis revealed that the investment presents good performances, in term of payback period and return on investment.

Finally, the plant shows its sustainability considering that the main electrical user is constituted by an alternative mobility system and the emissions abatement linked to the combined generation of electricity and heat brings to a saving of 7,380 ton CO_{2eq}/year.

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