THE EFFECTS OF EXOGENOUS VARIABLES ON THE OPTIMAL DESIGN OF STEAM PLANTS FOR COGENERATION

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ABSTRACT

The paper deals with the simulation and the optimal design of steam power plants for power generation and cogeneration. The simulation is carried out making use of a thermodynamic model of a general steam power plant with regeneration, reheating and cogeneration. Furthermore, the model analyzes the economic feasibility of the power-plant, estimating the investment and operation costs.

The paper shows the results of optimization analyses performed on a case study by varying the exogenous variables (i.e. fuel price, electrical and thermal loads) evidencing the achievement of the optimal trade-off between performance and investment.

The computer code is built in Matlab® and performs optimization analyses with a short computational demand.

1. INTRODUCTION

The liberalization of energy markets and the aims of climate protection promote an increasing use of Combined Heat and Power (CHP) generation, intended as simultaneous production of two energy forms (electrical or mechanical, and heat in the form of steam and/or hot water) from one energy source. With CHP, the waste energy from electricity production is cascaded and used in the production of District Heating (DH) or to satisfy the industrial heat and/or steam demand. As it is known, with conventional production methods, where the waste thermal energy is dumped directly into the local ecosystem, the fuel efficiency is approximately from 40 to 45%, while in a CHP plant a global efficiency of 85–90% can be achieved (Cogen, 1997), with obvious benefits on the reduction of pollutant emissions and greenhouse effect.

Steam plants are largely used for CHP applications, mainly for medium and large scale applications, while reciprocating engines are usually preferred for small scale applications (Micro-Cogeneration) and Gas Turbines are adopted in the cases where heat at higher temperature is needed (El Wakil M.M., 1984; Horlock J.H., 1987). The use of steam plants makes it possible to use different and inhomogeneous fuels such as biomass, wood waste and fuels derived from refuse, less dangerous than fossil fuels regard to climate effects. On the other hand, steam plants are characterized by larger initial investments and by higher thermal inertia and lower operational flexibility with respect to the other solutions. Therefore, the economic benefits of the application of a steam plant for CHP must be carefully assessed, both in order to compare it with conventional or alternative solutions and to determine optimal plant structure and management strategies.

Several mathematical models and studies on steam power plants and cogeneration are available in literature (Benelmir and Michel, 1998; Habib *et al.*, 1999; Lucas, 2000; Mastrullo, 1992). A simulation model for commercial cogeneration plants, written in ASPEN, has been developed (Zheng and Furimsky, 2003). A general model (COGEN) for assessing the economic potential of cogeneration venture in Brasil has been applied (Szklo, 2000), using simulation and sensitivity analysis.

Optimization techniques have also been applied to the design and the management of cogeneration plants. Evolutionary programming approach has been adopted to determine the optimal plant operation under variable electrical and thermal loads (Tsay *et al.*, 2001). A multi-objective programming approach for the pre-feasibility analysis has been proposed (Balestieri and De Barros Correia, 1998) while mixed integer linear programming techniques have been used by Arivalagan (Arivalagan, 1995). Optimal operation of CHP plants with thermal storage for District Heating (DH) via non-linear programming has been investigated by Zhao et al. (1998).

A computer code (VAPOTT) for the study of steam power plants has been developed by the authors (Rizzo, 1995). The code, formerly written in Quick Basic®, has been used in some Italian universities and at the University of Halifax, mainly for educational purposes. The model allows to perform simulation, parametric analysis and optimization of steam power plants for power generation, with powerful graphical capabilities. The computed code has been re-written and converted in Matlab®, due to large diffusion of this tool in the engineering framework and to the availability of powerful scientific libraries. The model has been substantially extended and improved to include cogeneration and to describe economic aspects (Marano, 2003; Arsie *et al.*, 2004). The main features of the model are described in the next chapter, and some significant applications are presented.

2. NOMENCLATURE

Symbol	*Description*	*Unit*
CB	Base Plant Cost	K€
CI	Total Plant Cost	K€
Ee	Net Electrical Energy	kJ
Ep	Primary Energy	kJ
Et	Thermal Energy to the User	kJ
FC	Global Perturbation Factor for the Plant	/
f_i	Perturbation Function expressing the effect of technology on the component cost	/
h	Enthalpy	kJ/kg
IEN	National Energy Index (for Italian Legislation)	/
IRR	Internal Rate of Return	%
NPV	Net Present Value	K€
p	Pressure	bar
P_i	Weight of the i-th component on plant cost	/
s	Entropy	kJ/kg·K
T	Temperature	K

Pedices	*Description*
CR	Critical Point
F	Saturated Liquid
G	Saturated Steam
s	Saturation
TP	Triple Point

3. THERMODYNAMIC MODEL

The model describes a general steam power plant for power generation and cogeneration. Steam properties are computed by the relationships proposed by Irvin and Liley (Irvin and Liley, 1984), whose error in properties evaluation is less than 1%, except in the region near the critical point. For further details on steam properties model, the reader is addressed to the original textbook of Irvin and Liley. The following hypotheses are adopted:

- Constant pressure heat addition and heat subtraction.
- Constant values for turbine adiabatic efficiency along expansion lines.
- Liquid properties computed by the saturated liquid ones.
- Pump work computed considering non-ideal process.
- Real boiler operation considering heat and combustion losses.
- In case of reheating, the exit temperature is equal to the maximum cycle temperature.
- In case of regeneration, closed or open feedwater heaters can be adopted, with assigned efficiency.
- Variable electrical and thermal load assigned by the user.
- Input/design variables: minimum and maximum pressure, maximum temperature, steam mass flow rate, number and pressure of steam extraction, number and pressure of reheats, minimum temperature of thermal user in case of cogeneration, efficiency of the power plant components.

The model can be used for simulation, parametric analysis and optimization with respect to maximum efficiency.

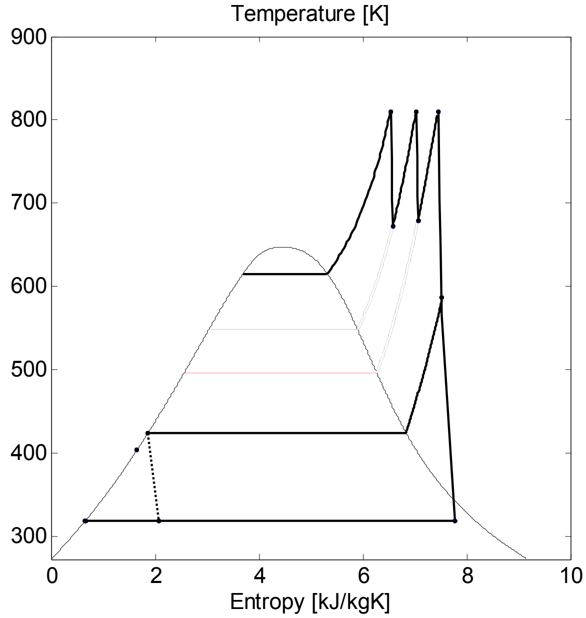

Fig. 1- Thermodynamic cycle on (T,s) plane

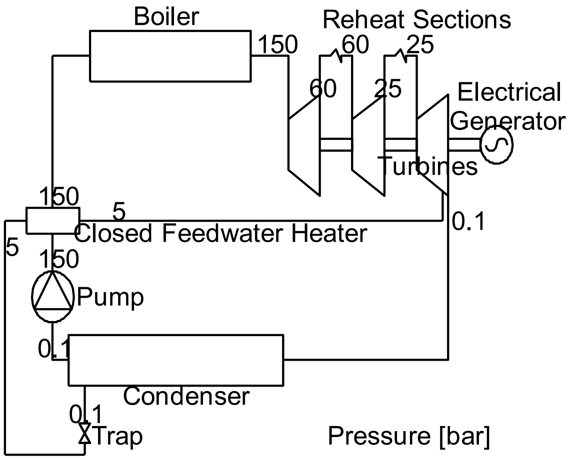

Fig. 2- Plant scheme with pressure values (bar)

Thermodynamic cycles can be represented both on (T,s) and (h,s) planes as shown in Fig. 1. Simplified plant schemes can be also drawn, with values of pressure, temperature and enthalpy. Fig. 2 shows an example, referred to a plant with two reheats and one stage of regeneration .

In order to reduce the complexity of the functional scheme, only the main components which directly affect the thermodynamic cycle are represented in Fig. 2; hence the scheme is simplified with respect to the actual plant (e.g. the pump symbol includes both condensate pump and main pump; deaerator and other auxiliaries are not indicated).

4. ECONOMIC MODEL

The economic model can be used to evaluate the operation costs for both power generation and cogeneration. In this latter case, according with the italian electric energy provider, the variability of electrical and thermal loads are considered by purchasing a series of five different time histories, each representative of a reference day: winter working day, winter holiday, summer working day, summer holiday, august day.

For the estimation of the operation costs, the eventual integration of thermal and/or electrical energy and the revenues due to electrical energy surplus are considered. Electrical costs and prices are computed starting from time slots and energy index, according to the Italian legislation; hence the model can evaluate the most convenient arrangement with the provider for the energy buy/sale.

The total cost of the plant is computed including operational, maintenance and investment costs. The investment costs are estimated by means of the following relationship:

$$CI = CB \cdot FC \tag{1)}$$

where CB is the reference cost for a “base” plant and is assigned as function of net electrical power (Fig. 3), starting from literature data (Mastrullo *et al.*, 1992). The base plant is intended as composed by standard components (i.e. standard efficiency) with a standard lay-out (nr. of reheatings and extractions). FC is a perturbation factor which accounts for the difference of the actual plant/components from the standards.

The following seven components have been considered for the cost analysis: pump, turbine, boiler, condenser, electrical generator, reheats, number of feedwater heaters (i.e. stages of regeneration). For each component, a suitable reference variable, representative of cost, is considered: efficiency is adopted for turbine, boiler, electric generator and pump; the cost due to reheats and regeneration is expressed as a function of the number of reheats and steam extractions, respectively; in this application the variability of the cost of condenser has not been considered.

The perturbation factor FC is computed by the following equation:

$$\mathrm{FC} = \sum_{i=1}^{7} P_i \cdot f_i \qquad \mathbf{2)}$$

in which the relationships between efficiencies and cost for each component are expressed by means of suitable perturbation functions f_i. A typical trend is reported in Fig. 4, for the turbine. The perturbation function is 1 (dashed line) when the reference variable (turbine efficiency) is equal to the standard value, and reaches very high values when the turbine efficiency approaches 1.

The term P_i is a weight factor describing the influence of each sub-system on the plant cost. The detail of the economic analysis can be improved making use of a more extended set of data concerning cost and efficiency of the components provided by the producers.

The proposed approach allows analyzing the influence of components performance and efficiency vs. costs, in order to detect the optimal trade-off between costs and performance by means of an optimization analysis, as it is shown in the following chapters.

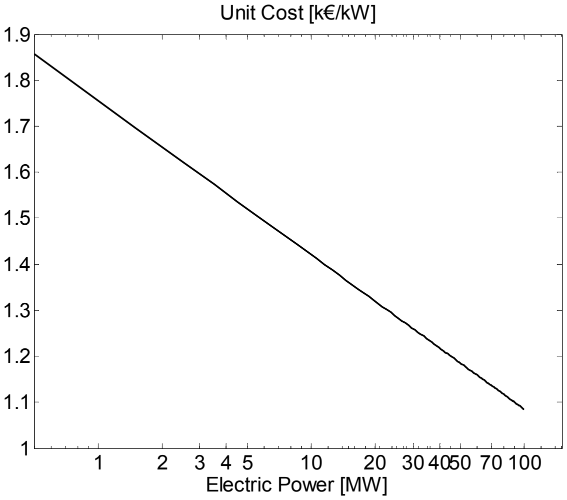

Fig. 3 – Base Plant Cost vs. Electrical Power

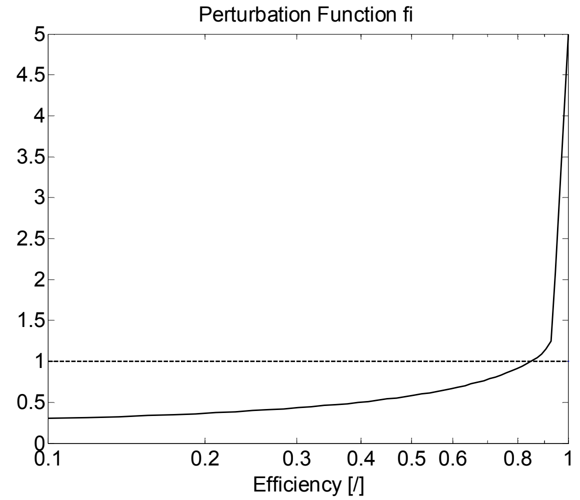

Fig. 4 - Relationship between efficiency and cost

Finally, the economic feasibility of a cogeneration plant is evaluated by comparing the total costs of the plant with those related to the conventional solution, where electrical energy is bought by the provider and thermal energy is obtained by a conventional boiler. NPV, Pay-Back and IRR (Internal Rate of Return) can be computed for each solution. The optimal contract with the energy provider (according to the Italian legislation) and the optimal plant operation are also computed by the model. Sensitivity analysis of the optimal solutions can be performed, in order to check the technical feasibility of the proposed solutions.

5. SIMULATION AND PARAMETRIC ANALYSIS

In a previous paper (Arsie *et al.*, 2004), some typical results obtained by simulation and parametric analysis have been presented and discussed. In particular, it has been shown that, in presence of multiple re-heatings and feedwater heating, discontinuities in efficiency and in costs may occur when the extraction pressure changes around the extraction pressures.

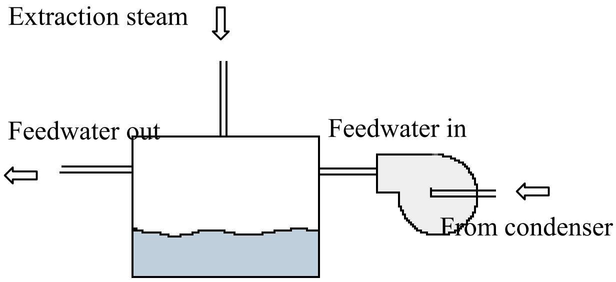

Fig. 5 – Scheme of an open feedwater heater

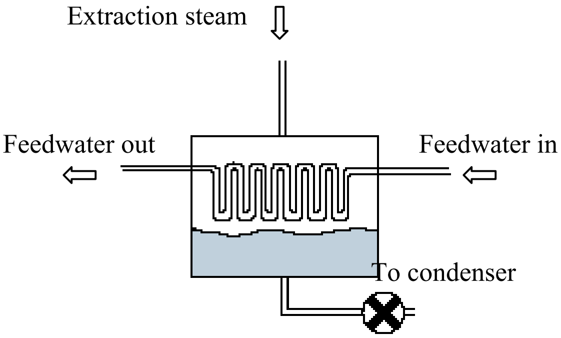

Fig. 6 - Scheme of a closed feedwater heater

In this paper, a comparison between the results obtained with open and closed feedwater heaters are presented.

The schemes of open and closed feedwater heaters are shown in Figs. 5 and 6. As it is known, while in the first case the extraction pressure has the same value of the outlet pressure of the pump, in the closed feedwater the extraction pressure and the liquid pressure are independent; the condensed steam exiting the heat exchanger passes through a lamination valve and goes to the condenser (as it is known, different layouts can be considered in the case of closed feedwater, according to the path of condensed steam).

The following results have been obtained by a Rankine cycle, without reheating and with a single extraction. The extraction pressure has been varied between 0.5 and 80 bar.

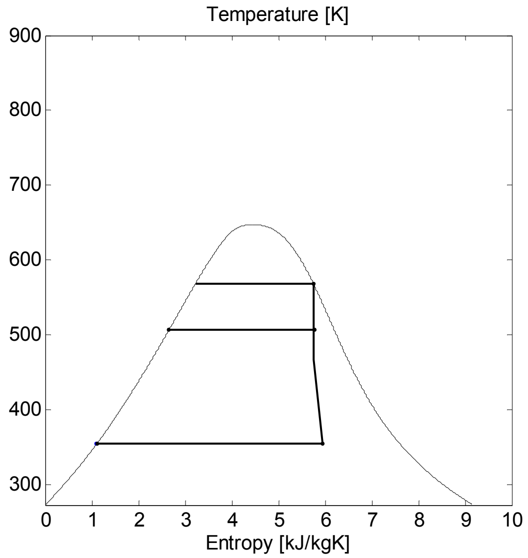

Fig. 7 - Thermodynamic cycle of the analyzed cycle

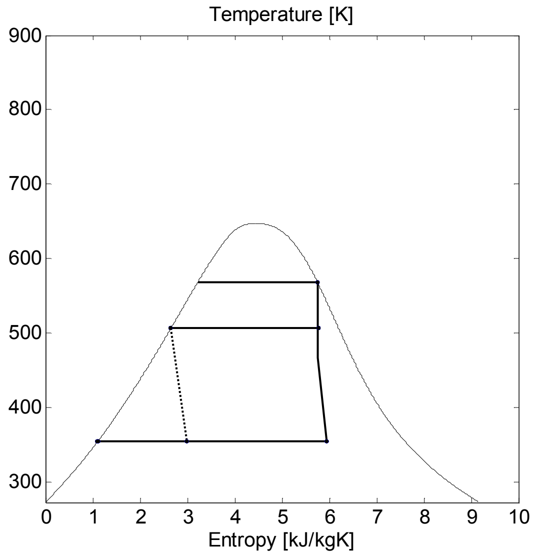

Fig. 8 - Thermodynamic cycle of the analyzed

with open feedwater heater *cycle with closed feedwater heater*

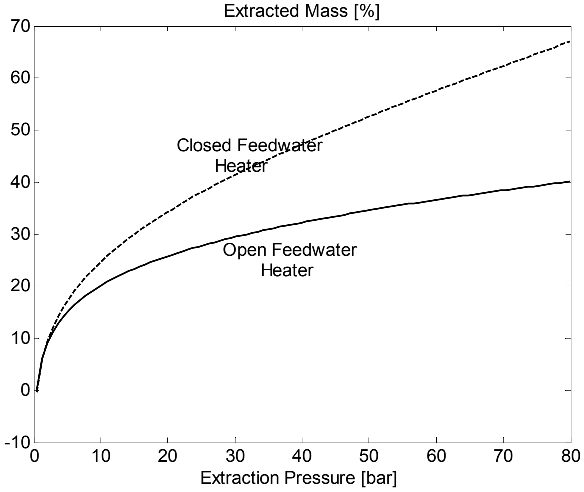

Fig. 9 – Extracted Mass vs. Extraction Pressure

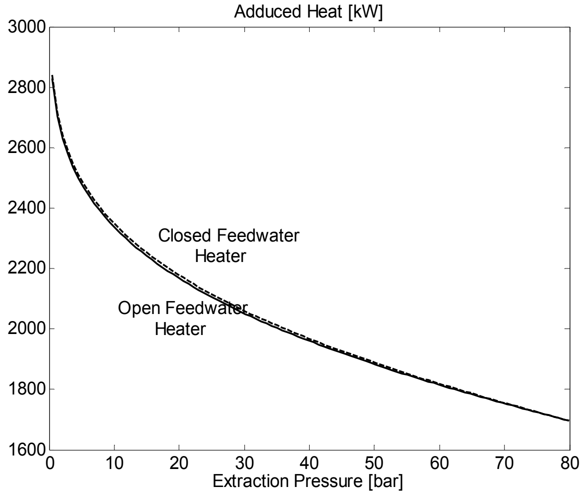

Fig. 10 – Adduced Heat vs. Extraction Pressure

When the extraction pressure rises, the closed feedwater requires higher extracted mass with respect to open case (Fig. 9), with a reduction in net mechanical power, while the adduced heat is the same in the two cases (Fig. 10). Consequently, lower efficiency is reached with the closed feedwater heater with respect to the open one (Fig. 12). This difference can be explained considering that, while in the open case there in only an irreversibility related to the finite temperature difference between extracted steam and feedwater in input, in the closed case there is also a further irreversibility source due to lamination (Fig. 8). It can be also observed that, for open feedwater, the curve of the efficiency vs. pressure (Fig. 12) agrees with the theoretical results (Acton and Caputo, 1992), predicting that no benefits are obtained for extraction pressure equal to maximum or minimum values. In the closed feedwater, instead, the efficiency can even reach lower values with respect to the no regenerative cycle, for high values of extraction pressure, due to the incidence of the lamination process.

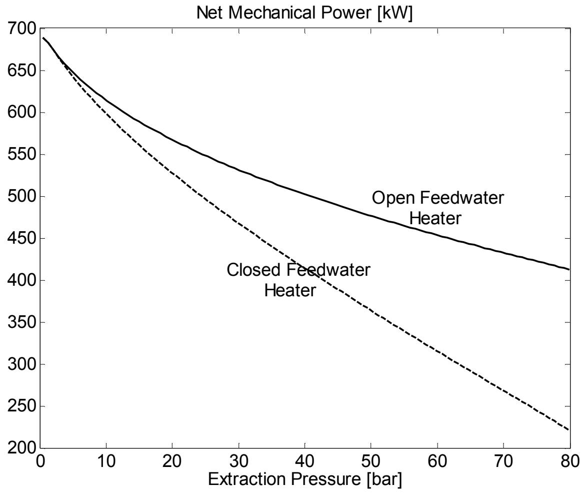

Fig. 11 – Net Mechanical Power vs. Extraction Pressure

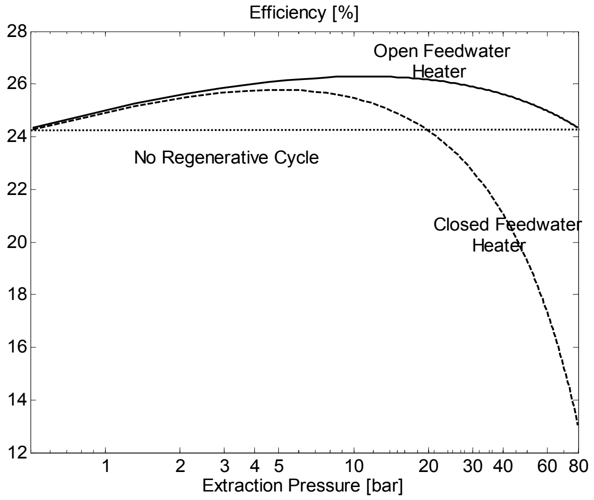

Fig. 12 – Efficiency vs. Extraction Pressure

6. OPTIMIZATION ANALYSIS

Although simulation and parametric analysis are powerful tools for studying the effects of design variables on plant performance and costs, the optimal plant design and/or the determination of optimal management strategy could not be effectively accomplished by an exclusive recourse to these approaches. In fact, the presence of complex non-linear interactions between input and output variables would require a prohibitive number of model evaluations to completely characterize the system. This is particularly true for a real power plant, where a significant number of design variables, moving in a wide range, has to be considered (Gill *et al.*, 1981). For such applications, optimization techniques represent the best choice.

The proposed model allows performing optimal design analysis considering both technical and economic aspects in the objective function. Three different cases can be considered:

- Maximum thermodynamic efficiency (3);
- Maximum value of the energy index IEN (4), considering electrical and thermal output of cogeneration plant (Mastrullo *et al.*, 1992);
- Maximum Net Present Value (NPV) (Horlock, 1987).

$$\eta = \frac{W}{Ep} \qquad 3)$$

$$IEN = \frac{Ee}{Ep} + \frac{Et}{0.9 \cdot Ep} - \left[\left(\frac{1}{0.51} - 1 \right) \left(0.51 - \frac{Ee}{Ep} \right) \right] \qquad 4)$$

where W is net mechanical work, Ep is primary energy, Ee is electrical energy and Et is thermal energy to the user.

Furthermore, several constraints can be considered, taking into account of:

- Minimum pressure at the condenser.
- Maximum temperature at turbine inlet.
- Maximum allowable moisture content of the steam at turbine outlet (usually 0.85).
- Maximum capital investment.
- Maximum allowable pay-back.
- Minimum allowable energetic index (in order to access to financial benefits provided by the Italian government for energy saving).

The constrained optimization has been performed making use of classical mathematical programming techniques, implemented in the routine FMINCON of Matlab® (Branch and Grace, 1999).

Sensitivity analysis of the optimal solutions can be also performed, in order to check the feasibility of the proposed solutions.

This classical approach leads to a very efficient optimum search, but it assumes that the design variables and the output function should be continuous. Therefore, the simultaneous study of the effects of continuous (e.g. pressure and temperatures) and discrete (e.g. number of reheats and of regeneration stages) variables (Mixed Optimization) cannot be accomplished. Furthermore, this approach could be unsuccessful in the determination of the global optimum, due to the possible presence of discontinuities in the optimized function.

7. OPTIMIZATION RESULTS

The optimal design analysis has been carried out on the data provided by the company De Matteis Alimentare Spa, referred to the farm located in Flumeri (AV). The energetic load for a typical working day is plotted in Fig. 13. The figure evidence a constant thermal load over the 24 hours while the electric load exhibits a variation lower than 100 kW.

The reference thermodynamic cycle of the power plant is summarized in Tab. 1. The optmization analyses have been performed imposing, in turn, a variation of the exogeneous variables, such as gas price and thermal load. In all cases the Net Present Value has been assumed as objective function, constraining the moisture fraction at the Low Pressure (LP) Turbine Outlet greater than 0.85, the IEN greater than 0.6 and the investment cost lower than k€ 1300. Tab. 2 shows the optmization results achieved for variable gas price and evidences that, as this latter increases, a more efficient Boiler is requested in order to maximize the achievable thermal power. On the other hand, the turbine efficiency is reduced to find out the best trade off between energetic efficiency and investment costs. The distribution of the operational costs for the considered gas prices are plotted in Fig. 14, while Fig. 15 shows the trends of investment cost, saving and NPV vs. the fuel price. As expected, from Fig. 14 emerges that as the gas price increases the relative costs of gas and gas taxes increase with respect to the cost of the electrical energy to be supplied by the provider. Fig. 15 exhibits an increase of the savings while the investment cost is constant with an overall improvement of the NPV. The optmization results refeered to the variation of the thermal load are reported in Tab. 3 and Fig. 16-Fig. 17. Tab. 3 summarizes the optmized steam flow rate, the extracted mass for cogeneration and the reheating pressure for various thermal load from 1573 to 5112 kW. Fig. 16 shows the thermal and electrical power requested by the user and provided by the plant for the four considered cases. Fig. 17 shows the behavior of the energetic and economic indexes, normalized with respect to the actual case (first case), as the thermal load is increased. The figure evidences, as expected, that the steam power plants achieve the maximum benefits as the ratio between thermal and electrical load increases.

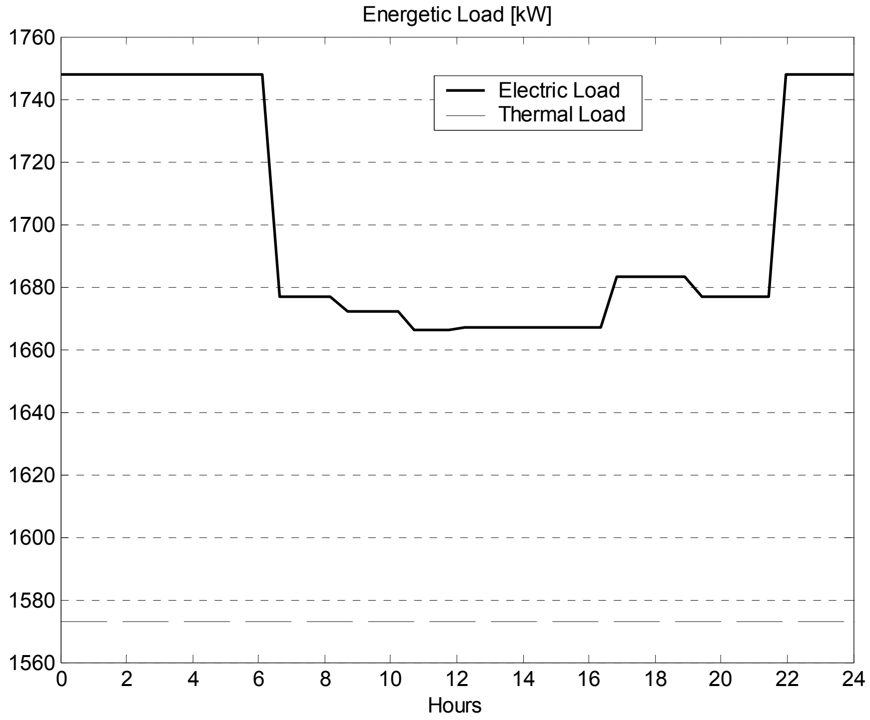

Fig. 13 – Electric and thermal load for a typical working day of the reference farm

Tab. 1 – Thermodynamic cycle of the power plant

Minimum pressure	*bar*	*0.5*
Maximum Pressure	*bar*	*80*
Maximum Temperature	*K*	*810*
Number of Reheating	*-*	*1*
Reheating Pressure	*bar*	*60*
Number of feedwater heaters	*-*	*2*
Extraction Pressure	*bar*	*30 ÷ 5*
Steam Mass Flow Rate	*Kg/s*	*1*
Turbine Efficiency	*/*	*0.91*
Boiler Efficiency	*/*	*0.85*
Pump Efficiency	*/*	*0.85*
Heat Exchanger Efficiency	*/*	*0.80*
Electrical Gen. Eff.	*/*	*0.93*

Tab. 2 – Optmization results for the imposed gas price

Cost/Actual Cost	*0.5*	*0.625*	*0.75*	*0.875*	*1*	*1.125*	*1.250*	*1.375*	*1.5*
Case	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Mass Flow Rate [kg/s]	0.6563	0.6563	0.6563	0.6563	0.6563	0.6562	0.6562	0.6562	0.6562
Turbine Eff. [%]	92.789	92.778	92.759	92.738	92.720	92.707	92.687	92.669	92.634
Steam Gen. Eff. [%]	96.596	96.810	96.864	96.928	96.960	96.983	97.000	97.000	97.000

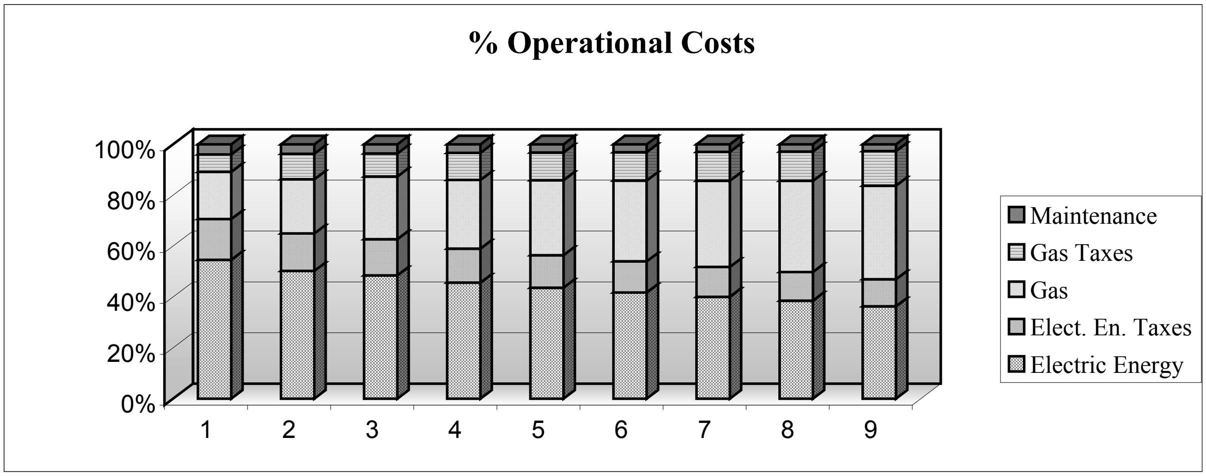

Fig. 14 – Distribution of the operational costs vs. imposed gas price

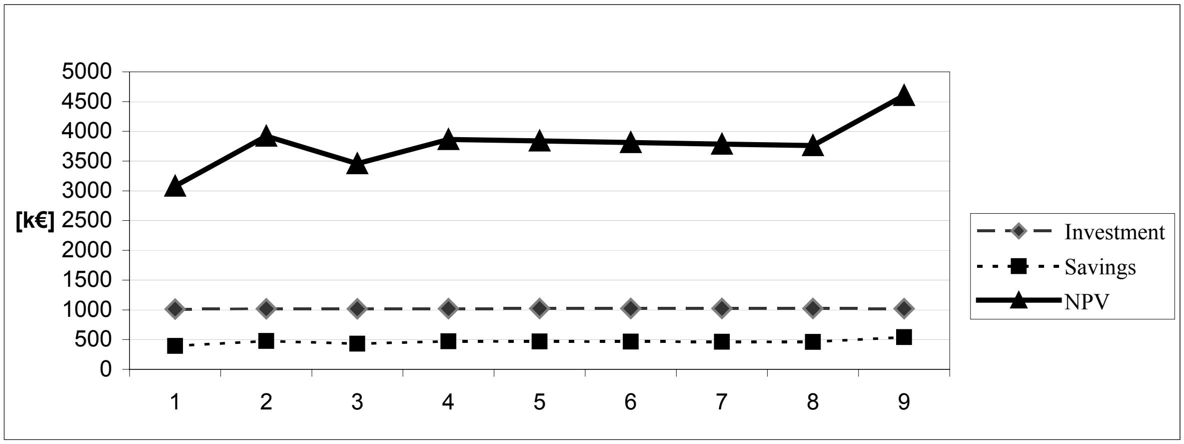

Fig. 15 – Investment Cost, Savings and NPV vs. imposed gas price

Tab. 3 - Optimization results for the imposed thermal loads

T [kW]	*1573*	*2752.75*	*3932.5*	*5112.25*
Steam Mass Flow Rate [kg/s]	0.463	0.717	1.034	1.471
Extracted Mass for Cogeneration [%] (P= 5 [bar])	74.675	72.576	74.673	70.718
Reheating Pressure [bar]	70	40.336	37.874	74.997

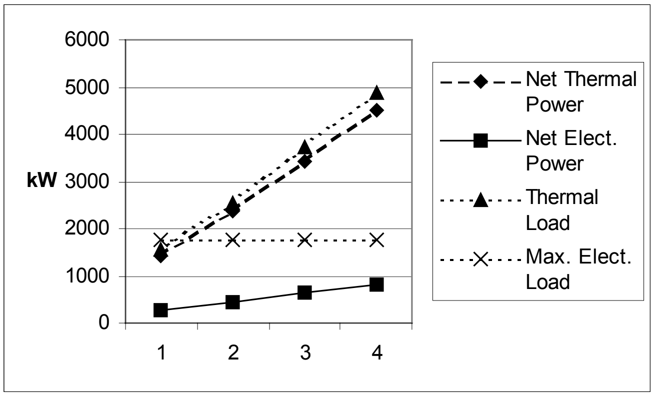

Fig. 16 – Thermal and max. electrical load and thermal and electrical power provided by the plant for the considered four cases.

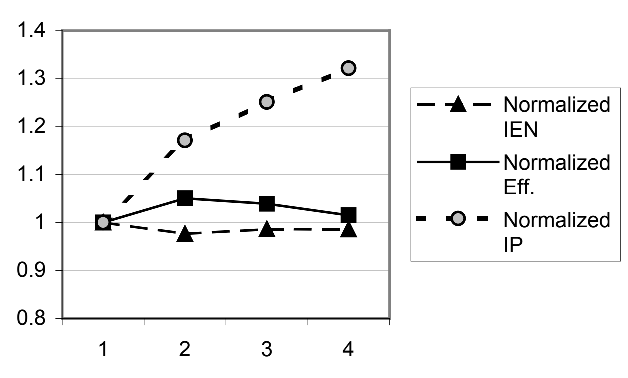

Fig. 17 – Trend of the main energetic and economic indexes

The model has been implemented on PC. The optimization analyses shown in this paper have required a computational time ranging from 2 and 10 minutes, depending on number of variables, model structure, initial values and assigned tolerance. This result is compatible with the computational exigencies in the industrial and professional framework, considering that further improvements could be achieved with a proper optimization of numerical and computational aspects.

8. CONCLUSIONS AND FUTURE WORKS

A simulation tool has been presented for the thermodynamic and economic analysis of a steam power plant for power generation and cogeneration.

The tool allows analyzing the influence of each component on the overall plant cost, also considering the effects of the technological level of the single component over energetic and economic outcomes. Some results, obtained by optimization analysis, have demonstrated the capability of the model to adapt the optimal plant size and its lay-out to variable external loads, fuel price and components cost. The results also evidence that the proposed solutions are in many cases non trivial and hardly predictable without recourse to complex optimization methodologies.

Further work is needed to improve the accuracy of the economic model, making use of an extended dataset provided by the industry; further improvements can be obtained by including the thermal storage modeling and by a more detailed description of variable operation and off-design conditions. Specific attention will be paid toward the integration of steam power plant with renewable sources (Hybrid Power Plants). Genetic algorithms will be integrated into the actual classical optmization techniques, in order to improve the features of the tool, in considering both continuous and discrete variables, representative of real operation.

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