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Multi-objective optimization and sensitivity analysis of a cogeneration system for a hospital facility

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Abstract

Combined heat and power plants are recognized as very effective solutions to achieve the increasingly stringent requirements in primary energy saving. The paper addresses the use of a specifically developed methodology to conduct several analyses on the basis of the loads of a specific hospital facility and through the study of the cogeneration system-user interaction. Predictive analyses are carried out using a multi-objective approach to find optimized plant configurations that approaches the best energetic results while ensuring a reasonable profit.
Optimized plant configurations and management strategies indicate primary energy savings exceeding 17%. Finally, a sensitivity analysis is carried out to evaluate the robustness of the results

Keywords: Combined Heat and Power (CHP); Multi-Objective Optimization; Hospital Facility; Internal Combustion Engine (ICE)

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1. Introduction

Energy supply and energy demand are certainly critical problems in developed countries, as deeply discussed in [1]. For this reason, the development of an energetic system that is stable and environmentally sustainable cannot be separated from a more efficient use of energy and an increasing use of renewable energy sources. Moreover, studies conducted as part of the Global Climate Energy Project at Stanford University clearly showed the enormous exergetic potential available and currently unexploited [2].

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Nomenclature

ASL	Local Healthcare Company (According to Italian law: Azienda Sanitaria Locale)
CHP	Combined Heat and Power
DII	Department of industrial engineering of the University of Naples Federico II
MOGA	Multi-Objective Genetic Algorithm
MPESM	Maximum Primary Energy Savings Management logic
MPM	Maximum Profitability Management logic
PEC	Primary Energy Consumption
PES	Primary Energy Saving
SPB	Simple Payback period
TPES	Total (or Technical) Primary Energy Supply
Pt	Average hourly thermal load in the hour "t"
PTnom	CHP plant nominal thermal power

In that scenario, the widespread application of cogeneration technology could play a key role [3]. The development of a distributed power generation system, which is the logical culmination of a mature and large-scale application of cogeneration processes, could increase the potential reduction of global energy demand.

The recognition of the strategic role of combined heat and power (CHP) [4] led many research center to focus its efforts on the study and prototyping of micro-CHP based on internal combustion reciprocating engines [5]. In fact, combined heat and power plants are recognized as very effective solutions to achieve the increasingly stringent requirements in primary energy consumption reduction and greenhouse emissions reduction. The potential of cogeneration led even to the adoption of specific European directives promoting this technique.

Equally important is the study of the possibility of an effective utilization of the recovered heat through a CHP system-user interaction analysis, because the energy saving is not always assured without an adequate exploitation of the recovered thermal power.

To estimate the potential advantages of cogeneration technology in real-world applications, a specifically developed methodology has been used [1] to conduct several analyses on the basis of the loads of a specific hospital facility and through the study of the cogeneration system-user interaction. A predictive analysis of this interaction was conducted using a simulative thermo-economic approach. In particular, to find optimum solutions (engine size, plant configuration, management logic, engine number, etc.) that approaches the best energetic results while ensuring a reasonable profit, a multi-objective approach was used.

Finally, a sensitivity analysis is carried out to evaluate the robustness and reliability of the calculated results.

2. Method of calculation

The study of the CHP system-user interaction, whose results will be presented below, particularly investigated CHP applications using reciprocating internal combustion engines fueled by natural gas, given the dominance of this technology in the field of small and medium electrical power generation (up to 3-5 MW), especially where there are thermal energy demands at low temperature.

One of the choices underlying the calculation procedure was the representation of the variables of interest through their respective hourly average values, which will allow a sufficient level of accuracy in the estimation of the expected results. Although this approach offers the possibility to simulate, within a year, the hourly operation of the entire plant, it lowers the level of detail in the estimation of the profile loads of the end user. This objective, as already shown in previous work [1, 6], is not always easy to achieve, thus introducing uncertainty that has repercussions on the reliability of the results. ON/OFF operating conditions have been imposed to the CHP engines, with the engine on or off depending on the profitability or energetic advantage of their exercise.

To estimate plant operating costs, it was necessary to characterize the electrical load profile according to the time band of purchase from the mains. All analyses are based on the average hourly cogenerated heat, as calculated from thermodynamic considerations. This calculation is essential in defining the operation field of the CHP plant, whether one seeks to maximize the energetic or the economic results. In the first case, any hour of the year when the contribution to total primary energy savings is negative with respect to the separate production of the same amount of energy is excluded from the operation field of the cogeneration system. In the second case, the plant is switched off whenever the cost of the cogenerated electric kWh is higher than the reference cost as they are defined in [1].

The hourly verification of the profitability of the cogenerated kWh of electricity allows the engine operating field to be determined. Therefore, it is possible to determine the coverage of the electrical, heating and cooling loads and the number of hours/year in which the CHP plant is on/off, along with an estimation of the overall energetic and economic quantities (TPES, SPB, etc.) and an estimation of the value of legal index to verify the ability to take advantage of legal benefits. This index is the Primary Energy Saving (PES), defined as follows (for more details see [7]):

$$PES = \left(1 - \frac{1}{\dfrac{\eta_e}{\eta_{eref}} + \dfrac{\eta_t}{\eta_{tref}}} \right) \cdot 100 > 0$$

Positive values of the PES helps to qualify the plant as cogeneration plant. The threshold value of zero for the PES specifically refers to plants with an electrical power output not exceeding 1 MW and increases to 0.1 for larger plants. With an increase of installed power, in fact, it is reasonable to expect an increase in electrical efficiency.

The knowledge of the carbon dioxide specific emission coefficients for the integrated electricity (kg CO_2/kWh), for boilers and natural gas engines (kg CO_2/kWh of primary energy of the fuel) allow the benefits in terms of greenhouse emissions to be estimated.

3. User monitoring: profile load definition

Once the methodology was developed, there was the need to apply it to a reference user. The existence of a partnership with the local healthcare company ASL Napoli 1, aimed at upgrading the energy efficiency of the S. Paolo Hospital in Naples, suggested the monitoring of the above facility.

To estimate the electrical load profile for the entire hospital and to extend the analysis to thermal and cooling loads, data from the literature were also used [8]. The estimated weekly load diagram for the whole hospital has been obtained along with the thermal and cooling weekly loads [1]. Finally, the electrical load has been characterized on the basis of the time band of levy from the mains.

4. Analyses and results

The results achievable through the installation of a CHP plant depend on a large number of variables, including CHP engine energetic performance, user’s load profile and magnitude, plant layout, plant operating logic, and energy costs. Furthermore, in the reference energetic scenario, the regulatory and tariff contexts are constantly evolving, and it is not always easy to predict their dynamics. In this context, it is quite difficult to estimate the potential benefits of combined energy production.

Starting from the load profiles of S. Paolo of Naples hospital, analyses were conducted to identify the potential energetic and economic benefits achievable for the small hospital sector.

5. Multi-objective optimization approach

The authors have already demonstrated the importance of a predictive investigation conducted on a wide number of possible plant configurations [1] to achieve optimized energetic and economical results. In fact, the number of variables involved in the problem could also completely change energetic and cost savings with changes in regulation, tariffs or reference energetic scenarios. For this reason, the problem needs complex numerical methods. Sometimes this aim is pursued through a multi-objective approach [9, 10]. Vector optimization [11 - 14] is useful to conduct a predictive and exhaustive analyses on a significant sample of plant configurations, thus allowing to deduce general conclusions, especially with regard to a possible trade-off between energetic and the economic objectives (TPES and SPB, or other significant quantities). It is thus possible to identify a set of optimal plant configurations providing a compromise between the various targets as a result of a constrained optimization.

The methodology adopted in this paper required the coding of the calculation algorithms using a common programming language, as this coding allows the procedure to be easily automated by interfacing the code with a commercial optimization solver. The calculation was particularly performed both for the algorithm related to optimal energy management of the plant, named MPESM, and the optimal economic management, named MPM [1]. Moreover , it was necessary to properly define the variation in the rated electrical and thermal efficiency with the plant size. They were obtained on the basis of the rated values of some CHP reciprocating gas engines currently on the market, as already shown in [1], and in the electric power range between 150 and 1000 kW[1].

Similarly, it was defined the specific investment cost of the single CHP unit with the plant size. Thus, the results achievable by means of over 2600 plant configurations were analyzed; these were obtained by properly constraining the decision variable space constituted by the size of the single CHP unit, which varies from 150-1000 kW, and by their number, which can vary from 1-9. With reference to the two objective functions TPES (to be maximized) and SPB (to be minimized), the procedure allowed the Pareto optimal solutions to be identified, as shown in Fig. 1.

The analysis was conducted using the algorithm MOGA II, belonging to the class of genetic methods [9, 10] and implemented in the optimization software modeFRONTIER®. Statistical multi-objective optimization algorithms can be effectively used when a large and discrete decision variable space is considered in order to find solutions that are probably close to the global optimum.

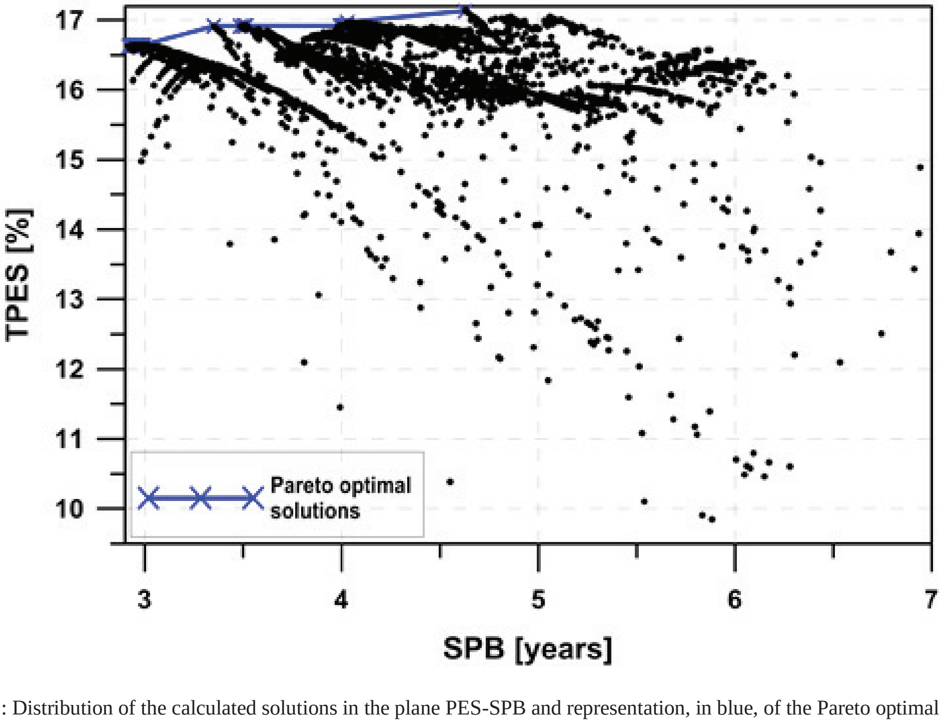

Fig. 1: Distribution of the calculated solutions in the plane PES-SPB and representation, in blue, of the Pareto optimal front.

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[1] Assuming an ON/OFF operation of the CHP gas engine in nominal conditions, the electrical power output of the plant depends on the engine size.

Solutions from the Pareto optimal front show that configurations aimed at the maximization of the overall energy savings lead to the worsening of the payback period, in agreement with results reported in the literature [16 - 18]. The slight trade-off between TPES and SPB, according to the results shown in [1], is probably mitigated by the computation of the Italian legislative incentives now introduced in the calculation procedure.

Fig. 2 shows the values of the legislative PES for the same calculated solutions. You may notice that the solutions with the highest values of the PES are not characterized by the highest TPES values because the TPES is a global quantity obtained from the energetic balance on the whole plant (CHP units plus user) while the legislative PES only qualifies the fraction of the energy delivered by the CHP system and generated concurrently with an effective exploitation of the thermal energy.

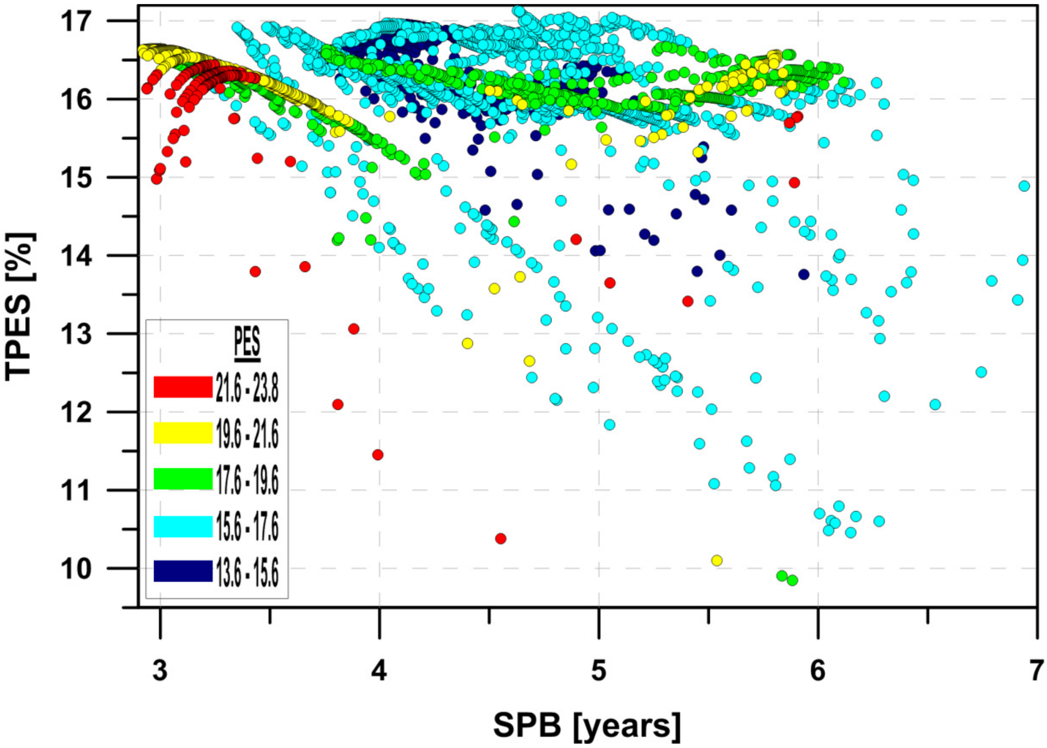

Fig. 2: Values of legislative PES for calculated solutions.

It should be noted that the choice made by the optimization algorithm for the number of CHP systems is guided by the calculation code that is properly thermal efficiency oriented through the definition of a filter quantity It_{thr} that will be discussed in the following. This occurrence ensures that clearly inefficient plant configurations should not be analyzed even among the initialization set of points belonging to the DOE. Despite of the introduction of this decision variable, analyses demonstrates how different could be the economic and energetic expected results, which respectively vary in the range 2.9-8 years for the SPB and 6.5-17.2 for the TPES. The results confirm the inability to conduct comprehensive predictive analysis without the use of advanced mathematical techniques.

Fig. 3 shows, in bubble chart, the distribution of the calculated solutions with reference to the two fitness functions and the two decision variable: number of engines (N°CHP) and nominal power output (i.e. CHP plat size). Multiple gas engine solutions characterized by 2 or 3 engines provide a good compromise between energetic and economic results. In particular, the Pareto dominant solutions for the MPESM logic are concentrated around values of energy saving greater than 16%, SPB period ranging from 2.9-4.6 years, number of engines ranging from 1-3 and electrical power ranging from 260-570 kW. Moreover, among the Pareto optimal front, the minimum SPB solution consists of a single CHP gas engine of electric 554 kW.

This kind of representation is also a valuable tool for the delimitation of the optimal solution set in the decision variable space following the definition of economic or energetic constraints.

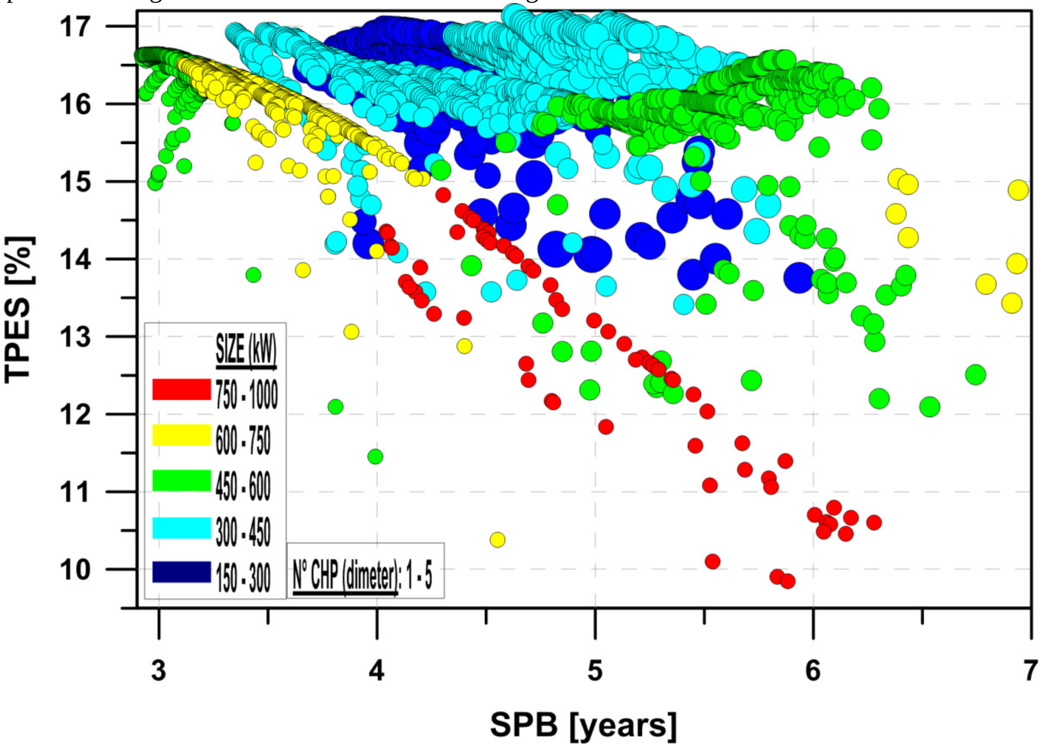

Fig. 3: Bubble chart representing gas engine size and number for the calculated solutions in the objective functions space.

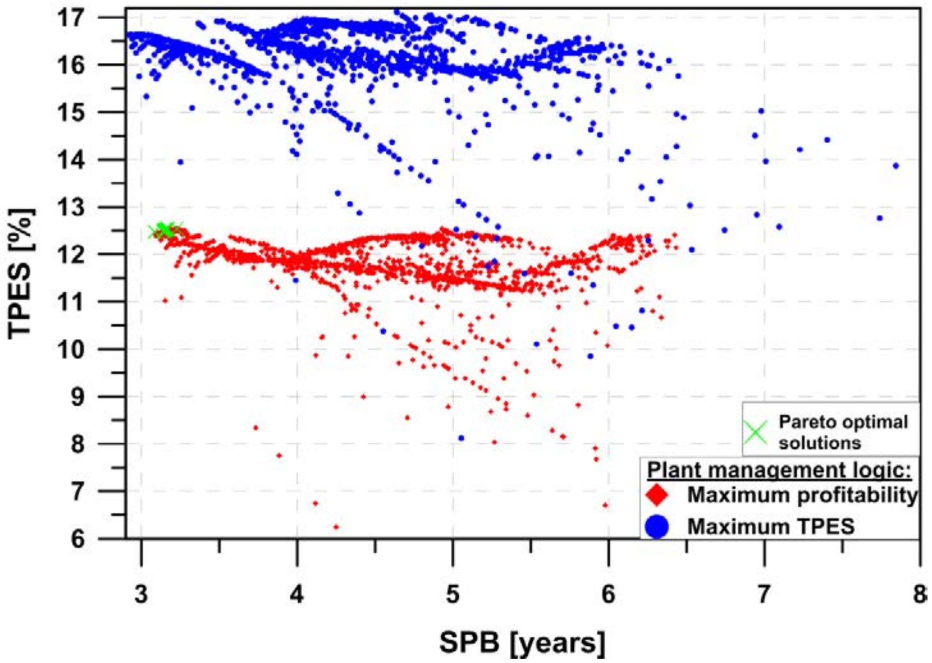

Fig. 4: Parallel multi-objective optimization solutions for the two defined management logic: MPESM and MPM.

To evaluate the effects of the plant management logic on the results a further analysis has been conducted performing a parallel multi-objective optimization making use of the two management logic previously described. The parallel calculation ensures that the value of the objective functions refers to the same set of values of decision variables for the DOE solutions. Fig. 4 shows that the adopted strategy highly influences the global results, with values of the TPES that drop about 5% if the MPM is used.

The MPM logic make use of approximated tariff for natural gas and electricity to evaluate the number of hours a year that the plant is turned on while their actual values are only subsequently evaluated. This approximation can explain the reason of the paradoxical SPB results (the minimum values of the SPB for the MPM logic seems slightly greater than the MPESM) and therefore it is expected that the real distribution for the MPM solutions could be shifted more left. However, this approximation, which can be overcome by iteratively calculating the tariffs, does not affect the generality of the conclusions.

Fig. 5 shows the TPES as a function of the decision variable It_{thr}. It was defined to quickly guide the hour by hour definition of the number of CHP gas engines evaluated by the optimization process toward more efficient plant configurations. This quantity, here called threshold thermal index, is defined, hour by hour, as the ratio between the user's thermal load and the nominal thermal power delivered by one CHP engine, and has values from 1 to 2. It is used within the code as follows: if a threshold value of 1.3 is fixed by the algorithm, a second engine is considered useful at the *i-th* hour of the year only if the thermal load required by the user exceeds the maximum thermal power allowable by the first one of over 30% (i.e. $Pt/Ptnom>1.3$); similar considerations can be done for every further CHP engine and for every hour of the year. The results of the optimization process clearly show that solutions characterized by higher values of the TPES (and so the Pareto optimal solutions) require values of It_{thr} in the range 1.4 – 1.6 for both the management logics. Anyway this range is expected to vary as the user changes because the TPES is affected by the simultaneous demand for thermal and electrical power (in particular their ratio) once the energetic characteristics of the CHP plant are fixed.

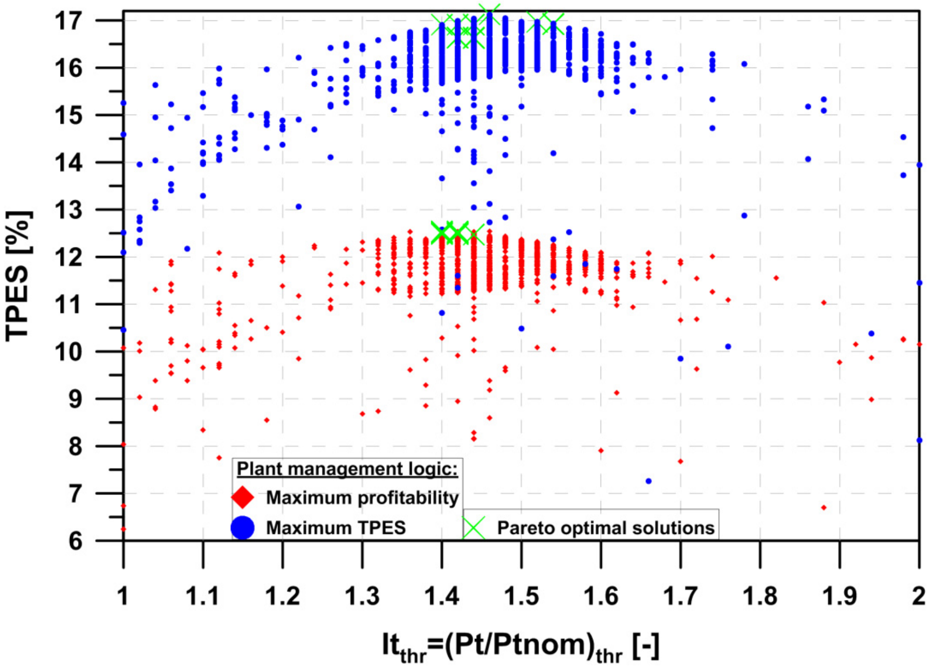

Fig. 5: Parallel multi-objective optimization results for the TPES as a function of the It_{thr}.

Fig. 4 has already shown that the Pareto optimal front is less fragmented but much less extended for the MPM logic. Furthermore Fig. 6 highlights how a change in the management logic could even greatly reduce the degrees of freedom available to define an optimized plant configuration. For example, if you limit the investigation to the MPM logic, all the Pareto optimal solutions are characterized by use of 1 CHP engine along with values of TPES of approximately 12.5%, SPB period under 3.2 years and engine size of about 550kW. The Pareto optimal front ultimately collapses and the trade-off between the objective functions becomes negligible.

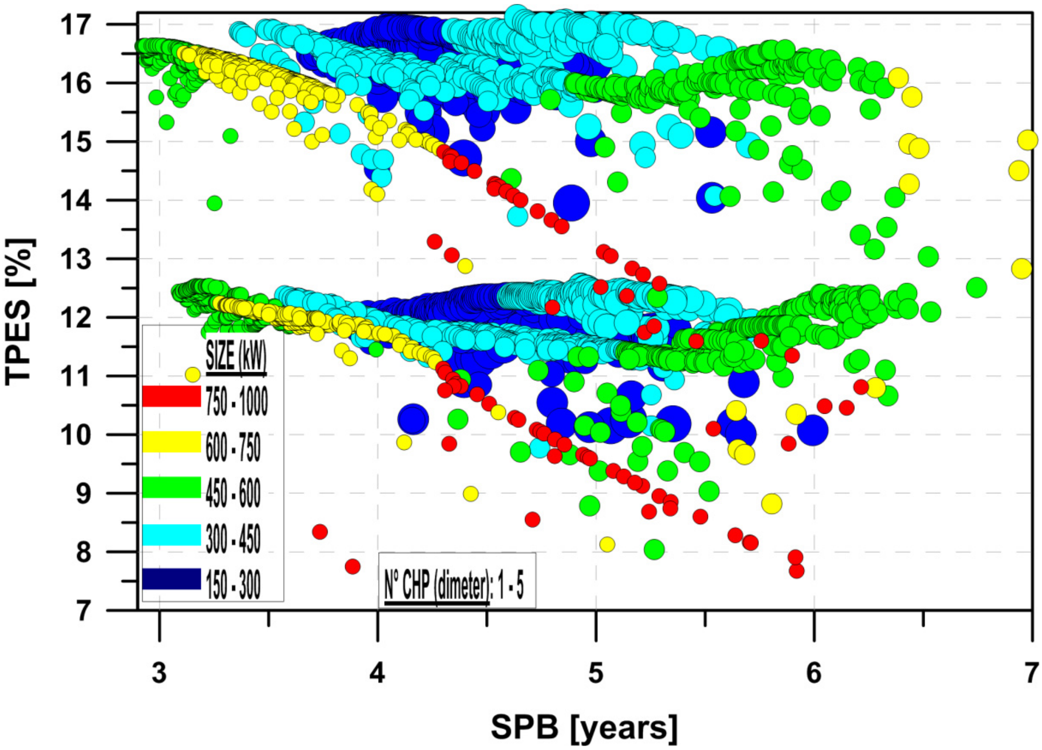

Fig. 6: Bubble chart representing gas engine size and number for the parallel multi-objective optimization in the objective functions space.

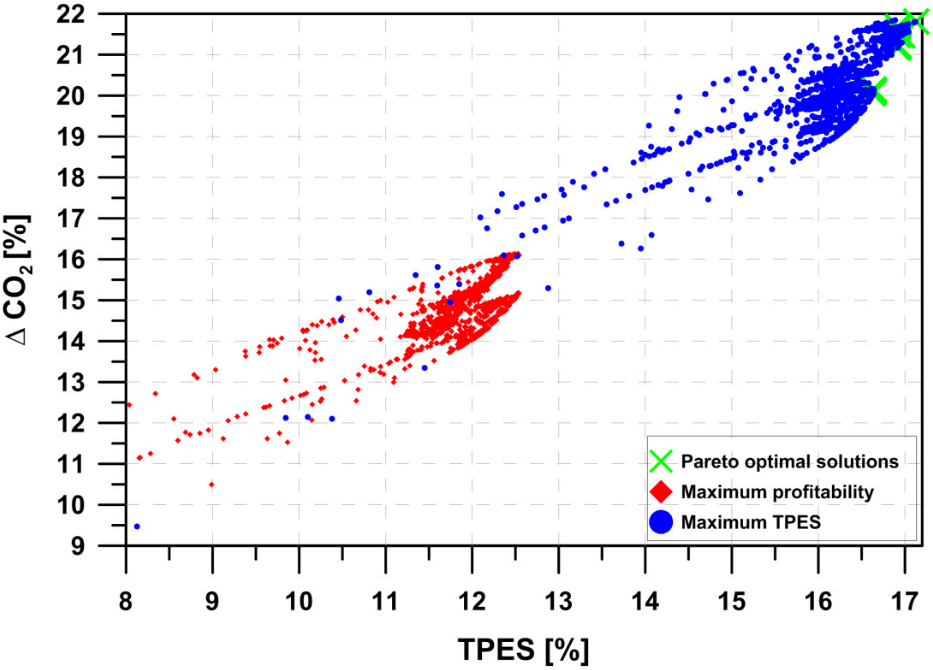

Fig. 7: Parallel multi-objective optimization solutions for the CO2 reduction as a function of the TPES.

However, it should be emphasized that the introduction of tight constraints can result in a significant decrease in the available system configurations even if the MPESM logic is considered. For example, if the search for optimal solutions is limited to SPB values less than 3 years, all feasible solutions involve the use of a single engine with electrical power ranging from 550-575 kW and characterized by energy savings of 16.5-16.7%. Therefore, the Pareto optimal set loses a dimension, and the degrees of freedom in plant design are reduced.

Finally, Fig. 7 shows how the maximization of the TPES should even ensure the best performance in term of CO_2 emission reduction. This is not an obvious result if you consider that the analyzed CHP engines are fueled by natural gas while the power generation in Italy is obtained through a mixture of fossil fuels whose carbon dioxide specific emissions coefficient could lead the best TPES solutions to a worsening of the CO_2 results.

6. Sensitivity analysis: multi-objective robust design optimization

As in many engineering design problems, many input quantities may only be known to some tolerance or may change during the plant life. For this reason, designing a CHP plant for a specific environmental or economic scenario could not guarantee good performance when the scenario changes. Therefore a dominant solution may not be the best stable solution.

The authors took into account the robustness of the results, which is defined as the characteristic of the system to be insensitive to small changes in the input parameters.

In robust design optimization the problems make use of probabilistic or stochastic models instead of the deterministic model. In this paper some input variable parameters have been added to the previous. In particular, the selling price of the electricity in the different time bands and the selling price of the energy efficiency certificates recognized by the Italian legislation has been thus described by a normal probability distribution and the multi-objective robust design optimization has been performed. Therefore the objective functions will also become stochastic. Since we are looking for a stable economic solution, we aim at minimizing the mean value of the SPB while getting a low standard deviation value. The MPESM strategy has been adopted at first in the current analysis while the effects of the management logic on the reliability of the results will be the object of subsequent further studies.

The first analyses show that the best stable solutions under the adopted assumptions are also the lower SPB solutions, thus characterized by the use of only one CHP engine with power output ranged 430-560 kW, even if most of the calculated solutions do not exceed values of 0.8 as standard deviation. Anyway, Pareto optimal solutions seem to be intrinsically not very sensitive with regard to the variation of the defined economical input variables (Fig. 8).

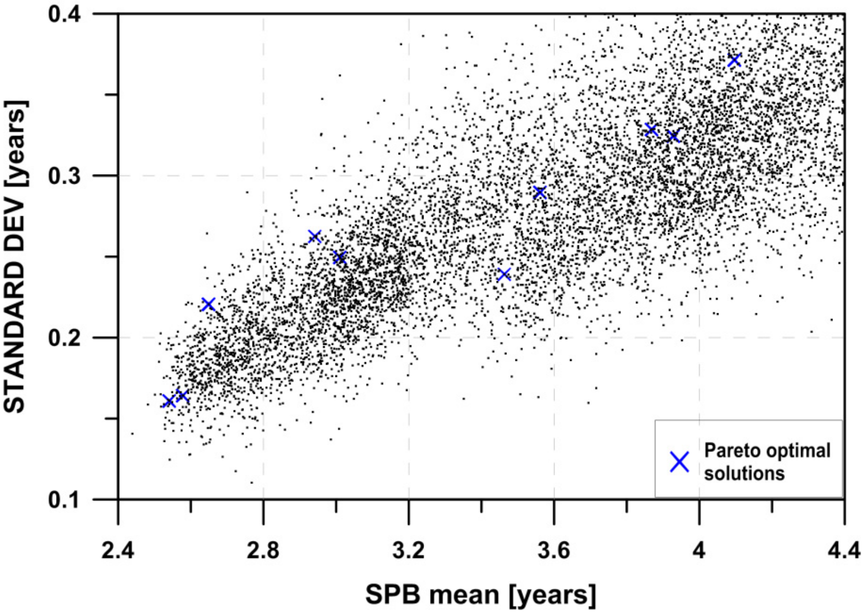

Fig. 8: Standard deviation as a function of the SPB mean value.

7. Conclusions

The achievement of optimal energetic and economic results through combined heat and power plants is a complex problem. In fact, the number of variables involved in the problem could also completely change energetic and cost savings with changes in regulation, tariffs or reference energetic scenarios. Equally significant is the dependence on the plant configuration and its management strategy. The study, for example, has revealed that the overall energy savings can vary in the range of 4.2-17.2% and SPB from 2.9 to 8.5 years.

Therefore, a predictive analysis such as the one proposed in this study is important in determining a plant solution (engine size, plant configuration, management logic, engines number, etc.) that approaches the best energetic solution while ensuring a reasonable profit. The results of the multi-objective approach show how the search for configurations aimed at maximizing the global energy saving leads to a worsening of the simple payback period.

Moreover the potential energy savings of combined heat and power justifies the attention given to the cogeneration technology. The plant configurations and management strategies analyzed in this work, liable to further improvements, indicate primary energy savings over 17% for hospital facilities along with SPB of approximately 3.5 years for multi-gas engine solutions. The result is even more interesting when you consider that the load variability in the civil sector often affects, at least partially, the potential benefits of combined heat and power.

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