Multiobjective optimization of trigeneration systems considering economic and environmental aspects

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Abstract

The increasing need for economically attractive and environmentally sounder energy supply systems requests the development of new criteria and determines new design rules. Designing such systems involves conflicting objectives as environmentally friendly technologies are usually more expensive. This paper deals with the simultaneous consideration of economic and environmental criteria in the synthesis of a trigeneration system to be installed in a 500-bed hospital in Zaragoza, Spain. Optimization includes optimal configuration (commercially available equipment) and optimal operation throughout the year. The multiobjective optimization accounts for minimization of total annual cost and annual environmental loads in the design and operational stages. The environmental loads considered were the CO_2 emissions released in the atmosphere and the Eco-indicator 99 (EI-99) score (to broaden environmental considerations in the impact assessment). A set of Pareto solutions is obtained from the solution of a Mixed Integer Linear Programming (MILP) model, representing optimal trade-offs between the economic and environmental objectives. Two bi-criteria problems were solved: 1) annual cost (€/year) versus CO_2 emissions (kg CO_2/year), and 2) annual cost (€/year) versus EI-99 Single Score (points/year). The Pareto solutions consist of optimal configurations that adapt their operational strategy during a specific range in the Pareto frontier. Solutions are compared and it is observed that some configurations are more stable along the Pareto frontier, and that solutions close to the environmental minimum are associated with a steep increase in the economic objective. After the judgment of the solutions obtained and the trade-offs involved, one configuration is selected, which performs better and presents a flexible range of adaptability in the economic/CO_2 and economic/EI-99 optimizations.

Keywords

Multiobjective, trigeneration, optimization, CO_2 emissions, Eco-indicator 99, Life Cycle Assessment.

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1. Introduction

Energy supply systems are a hot issue nowadays and most likely to remain so for the next years, as *current* energy supply systems (from primary energy sources to final energy services) are becoming unsustainable. A transition to *alternative* energy supply systems is presently in the spotlight, propelled by concerns on global warming caused by greenhouse gas emissions and dependence on depleting fossil fuel reserves. This transition will certainly involve meeting the future energy demand with greater efficiency. Polygeneration systems have important socioeconomical benefits related to its efficient use of energy resources and the enhanced economic competitiveness of the products obtained [1].

Polygeneration is defined as the concurrent production of two or more energy services and/or manufactured products that, benefiting from the energy integration of the processes in its equipment, extracts the maximum thermodynamic potential of the resources consumed. In buildings in Mediterranean countries, the need for heating is restricted to a few winter months, limiting the application of cogeneration systems thus far. However, there is a significant need for cooling during the summer period. By combining cogeneration and heat-driven absorption chillers, the energy demand covered by cogeneration could be extended into the summer months to match cooling loads via trigeneration [2-3].

In recent years, the analysis and design tools for energy systems have undergone important developments. Particularly, the synthesis and design of trigeneration systems in the residential-commercial sector has become increasingly elaborate, with numerous possibilities for energy sources and technological options. The optimal configuration for a polygeneration system remains a complex problem throughout the years in the residential-commercial sector, because of the wide variety of technology options for the provision of energy services, great diurnal and annual fluctuations in energy consumption, and volatile energy prices.

The synthesis of trigeneration systems implies searching for a design that minimizes or maximizes an objective function, such as economic cost, environmental load, or thermodynamic efficiency. The search process is bound by the system’s model, which is expressed by equality and inequality mathematical restrictions. The design methodology must provide systems that produce energy services efficiently, are capable of adapting to different economic markets and demand conditions, and operate optimally [4].

Focusing on the criteria adopted to the design of trigeneration systems in the residential-commercial sector, a purely economic standpoint has been taken by the majority of optimization studies [5-10]. Environmental concerns have been a growing issue when planning energy supply systems. The need to consider the environment as an additional design factor arises due to an ever-increasing environmental conscience worldwide and stricter requirements to reduce the environmental impact of modern society. A purely environmental viewpoint has also been the focus of optimization studies specifically targeting polygeneration in buildings [11-16].

In general, the configuration and operating conditions of a system yielding the best economy are pushed into a range where environmental loads are higher than the least otherwise possible. Multiobjective optimizations tackle the issue of conflicting objective functions (such as environment and economy), finding a ‘balanced’ optimal solution. Although the situation of trigeneration systems providing energy services to the residential-commercial sector has already been proposed and analyzed, the complexity and number of feasible options is high and there is a lack of multicriteria studies regarding trigeneration systems.

This paper will propose an integrated energy-planning framework based on Mixed Integer Linear Programming (MILP) to determine the optimal configuration and operation of a trigeneration system to be installed in a hospital located in Zaragoza, Spain. Hospitals are good candidates for trigeneration systems because of their high energy requirements (heat for domestic hot water and space heating, cooling and electricity) compared to other commercial buildings as well as their need for high power quality and reliability. A multiobjective optimization procedure will be presented, considering simultaneously the total annual cost and total annual environmental loads (CO_2 emissions or Eco-indicator 99 points) involved in the design and operation of trigeneration systems. Note that all equipment considered herein is commercially available, which further enriches the applicability of results.

2. Trigeneration system

This paper considers a medium size hospital with 500 beds, located in Zaragoza (Spain). The energy demands considered were heat, cooling, and electricity. The heat load included heat for sanitary hot water (SHW) and for heating. Steam demand could also have been considered, to attend laundry and sterilization necessities. However, the current trend is to eliminate such a service, subcontracting an external company, and for this reason steam demand was not considered in this investigation.

In order to establish the energy demands for the hospital, a study period of one year was considered, distributed in 24 representative days (one working day and one holiday/weekend day for each month), each day being divided into 24 hourly periods. Energy demand patterns for each representative day were calculated according to the procedure described by Sánchez [17], which estimated demand profiles of the representative days based on the size of the hospital and its geographical location in Spain. The annual electricity consumption of the hospital was E_d = 3250 MWh, the cooling demand was R_d = 1265 MWh, and the heat requirements (SHW + heating) were Q_d = 8059 MWh.

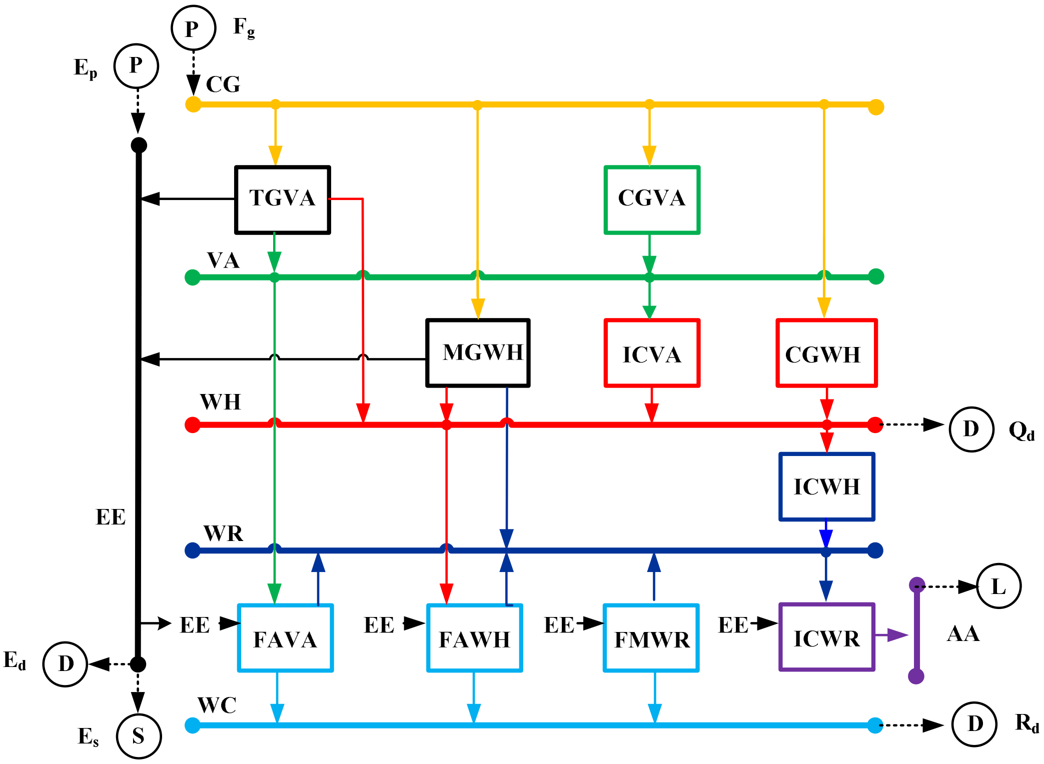

Figure 1: Superstructure of the energy supply system

Table 1: Selected equipment and matrix of production coefficients

Technology *i*	Selected equipment		Utility *j*						
	Cost CI (10^3 €)	Nominal Power P_{nom} (MW)	CG	VA	WH	WR	AA	WC	EE
TGVA	1 530	1.21	-4.06	+1.83	+0.53				**+1**
MGWH	435	0.58	-2.45		+0.96	+0.20			**+1**
CGVA	182	0.78	-1.20	**+1**					
CGWH	30	0.57	-1.08		**+1**				
ICVA	2.5	0.40		-1.00	**+1**				
ICWH	6.5	0.40			-1.00	**+1**			
FAVA	370	1.26		-0.83		+1.83		**+1**	-0.01
FAWH	200	0.49			-1.50	+2.50		**+1**	-0.01
FMWR	175	0.49				+1.23		**+1**	-0.23
ICWR	25	1.00				-1.00	**+1**		-0.02

Selection of equipment took into account input/output utility flows based on appropriate energy process integration. The superstructure of a trigeneration system (Figure 1) that satisfies energetic demands of heat, cooling, and electricity should account for the possibility of installing energy production technologies such as TGVA (gas turbine + heat recovery boiler, producing steam and hot water), MGWH (gas engine + hot water heat recovery system), CGVA (steam boiler), CGWH (hot water boiler), ICVA (steam-hot water heat exchanger), ICWH (hot water-cooling water heat exchanger), FAVA (double effect absorption chiller, driven by steam), FAWH (single effect absorption chiller, driven by hot water), FMWR (mechanical chiller, driven by electricity and cooled by water), and ICWR (cooling tower, to evacuate the heat from the cooling water to the ambient air). The available utilities are: CG (natural gas), VA (saturated steam, 180ºC), WH (hot water, 90ºC), WR (cooling water, t_0 + 5ºC), AA (ambient air, t_0), WC (chilled water, 5ºC), and EE (electricity). D, S, P and L refer to, respectively, demand, sale, purchase and waste/loss of a utility.

Table 1 depicts the selected equipment and technical production coefficients for the superstructure. The rows contain potential technologies for installation and the columns contain the utilities. The production coefficient with a values in bold shows the flow that defines the equipment's capacity. Taking MGWH technology in Table 1 as an example, electricity is the main product as its coefficient is 1. To produce 1 MW of electricity (EE), 2.45 MW of natural gas (CG) will be consumed, recuperating 0.96 MW of hot water (WH), and evacuating 0.20 MW of heat to cooling water (WR). Consequently, the electrical efficiency of MGWH is 1/2.45 (≈ 41%). All technology and equipment considered in the optimization were commercially available; therefore the size/configuration of the system was determined in terms of pieces of equipment. The data shown in Table 1 was obtained from equipment catalogs and consultations with manufacturers. $P_{nom}(i)$ is the nominal power of the equipment selected of technology i, CI(i) was its investment cost obtained from catalog prices and multiplied by a simple module factor that took into account aspects such as transportation and installation.

In the case of natural gas in Spain, the consumer chooses the most adequate rate for the consumption volume and supply pressure. This investigation considered a constant purchase cost of 0.025 €/kWh for natural gas [18], which includes taxes and the distribution of fixed costs throughout the estimated annual consumption. Considering other costs such as taxes, and approximating the distribution of fixed costs, an electricity purchase price of 0.095 €/kWh for off-peak hours, and 0.130 €/kWh for on-peak hours was considered [19]. For the sale of surplus cogenerated electricity, the tariff and premium depend on the power output and fuel utilized by the plant. Considering the energy demand of the hospital and the nominal power of the cogeneration modules (cogeneration installations using natural gas, 1000-10,000 kW capacity), the price for sold electricity was 0.077 €/kWh [20].

3. Environmental data

Life Cycle Assessment (LCA) provides a comprehensive view of the environmental aspects of a product or process and a more accurate picture of the true environmental trade-offs in product and process selection [21]. LCA analyzes the environmental impacts associated with a process or product from *the cradle to the grave*, which begins with the gathering of raw materials from the earth to create the product/service and ends at the point when all materials are returned to the earth [22]. SimaPro [23] is a specialized LCA tool and was utilized to calculate the impact associated with the configuration (equipment) and operation of the system.

A framework for LCA has been standardized by the International Organization for Standardization (ISO) in the ISO 14040 series [24-25]. This LCA framework consists of the following elements: (1) Goal and Scope definition, which specifies the goal and intended use of the LCA and delineates the assessment (system boundaries, function and flow, required data quality, technology and assessment parameters); (2) Life Cycle Inventory analysis (LCI), which includes the collection of data on inputs and outputs for all processes in the product system; (3) Life Cycle Impact Assessment (LCIA), which translates inventory data on inputs and outputs into indicators about the product system's potential impacts on the environment, human health, and availability of natural resources; and (4) Interpretation, the phase where the results of the LCI and LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis are performed to qualify the results and conclusions.

CO_2 emissions were selected to quantify the environmental loads because global heating and the associated climate change are one of the main medium- and long- term identified threats, with great consequences on a global scale [26].

The Eco-indicator 99 (EI-99) method was included to broaden environmental considerations in the impact assessment, being selected because it is widely used in LCA, incorporating relevant environmental burdens into different impact categories that allow the evaluation of damages to human health, ecosystem quality, and resources. The EI-99 method considers the values of eleven impact categories, which are added into three damage categories, weighted, and then aggregated into an index (the Single Score) that represents the overall environmental load in points [27]. The higher the EI-99 Single Score, the higher the environmental impact of this component/process along its operational life. The Hierarchist perspective (H/H) of the EI-99 was selected.

Table 2 summarizes the technologies and their associated main material composition, CO_2 emissions (CO_2I), and the Single Score (SSI) obtained by applying EI-99. Carvalho [28] present more details on environmental data.

Table 2: Technologies main material composition, CO2 emissions and EI-99 Single Score

Technology	Main material composition (kg)	CO_2I (kg CO_2)	SSI (points)
TGVA	9080 kg steel, 500 kg aluminum	80,500	8700
MGWH	5700 kg steel	37,350	4030
CGVA	1000 kg cast iron, 1850 kg steel, 50 kg aluminum	15,810	1420
CGWH	850 kg steel, 25 kg aluminum	3050	205
ICVA	360 kg stainless steel	2350	251
ICWH	760 kg stainless steel	5010	532
FAVA	3700 kg iron alloy, 10,044 kg steel	98,600	11,100
FAWH	9000 kg steel	58,900	5890
FMWR	20 kg aluminum, 2000 kg steel, 500 kg copper, 1000 kg H-I PVC	85,420	3130
ICWR	3500 kg steel, 1605 kg H-I PVC	23,530	2990

The CO_2 emissions associated with the consumption of natural gas in Spain were calculated as 0.272 kg CO_2 per kWh of consumed natural gas (related emissions of the combustion of natural gas and total aggregated system inventory for a user in Spain).

The CO_2 emissions associated with the Spanish electricity mix considered the proportions (25.8% Coal, 24.4% Natural gas in combined cycle, 19.7% Nuclear, 10.4% Others (biomass, cogeneration, minihydraulic), 9.4% Eolic, 9.4% Hydraulic, and 0.9% Fuel-gas to produce the electricity [29]. The average CO_2 emissions associated with electricity in Spain in 2007 were calculated as 0.385 kg CO_2 per kWh consumed.

The EI-99 Single Score obtained was 0.0378 points per kWh consumed for natural gas and 0.0226 points per kWh consumed for the Spanish electricity mix.

4. Multiobjective optimization

In the case of multiple objectives, a solution that is best with respect to all objectives usually does not exist because most often a solution is best in one objective but worst in another. Therefore, there usually exists a set of solutions for the multiple-objective case, which cannot simply be compared with each other. For such solutions, called Pareto optimal solutions or non-dominated solutions, no improvement is possible in any objective function without sacrificing at least one of the other objective functions.

Many methods are available for solving multiobjective optimization problems [30-33], and some methods involve converting the multiobjective problem into a series of single objective optimization problems. Generating methods with a posteriori analysis of Pareto fronts are preferred and among them, the $\in$-constraint has been applied by various authors to similar problems [34-35].

The design task is posed as a bi-objective (economic and environmental) programming problem, which can be expressed as

$$\text{Min } f(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x})\}$$

The solution to this problem is given by a set of efficient or Pareto optimal points representing alternative process designs, each achieving a unique combination of environmental and economic performances. The $\in$-constraint method is based on formulating an auxiliary model for the calculation of the Pareto points, which is obtained by transferring one of the objectives of the original problem to an additional constraint. This constraint imposes an upper limit on the value of the secondary objective. The problem is repeatedly solved for different values of $\in$ to generate the entire Pareto set; it is a relatively simple technique, yet it is computationally intensive [36]. The $\in$-constraint version of the bi-objective problem can be mathematically expressed as

$$\text{Min } f_2(\mathbf{x}), \text{ subject to } f_1(\mathbf{x}) \leq \in_j \text{ with } \in_j = \in_1, \in_2, \ldots \text{ and } \mathrm{Lim}_{inf} \leq \in_j \leq \mathrm{Lim}_{sup}$$

where $f_2(\mathbf{x})$ is the economic objective function and $f_1(\mathbf{x})$ is the environmental objective function. The extreme points of the interval [lim_{inf}, lim_{sup}] within which $\in$ should fall, can be determined by solving each single objective problem separately.

The economic objective function considered the economic aspect of the energy supply system installed in terms of the total annual cost (in €/year), which minimized equipment and fuel costs as well as purchase/sale of energy services. The environmental objective functions minimized the total annual environmental load, which included the annual fixed load of the equipment and the annual operation load associated with operation of the system. The detailed optimization model can be found in Lozano *et al.* [9] and Carvalho [28].

4.1 Economic and CO_2 emissions bi-objective optimization

The solution of each single optimization problem provided the optimals: lim_{inf} = 3,785,617 kg CO_2/year (environmental optimal) and lim_{sup} = 5,831,105 kg CO_2/year (economic optimal). The interval [lim_{inf}, lim_{sup}] was partitioned into sub-intervals, and the model was solved for each of the limits of these sub-intervals. It is interesting to point out the fact that the optimization carried out encompasses not only the operational strategy of a system, but also the configuration.

Figure 2 shows the Pareto frontier and the corresponding configurations, where E = gas engine, B = hot water boiler, A = single effect absorption chiller, and M = mechanical chiller. The set of optimal solutions was composed of configurations that were able to adapt their strategy only within a specific range of the Pareto frontier.

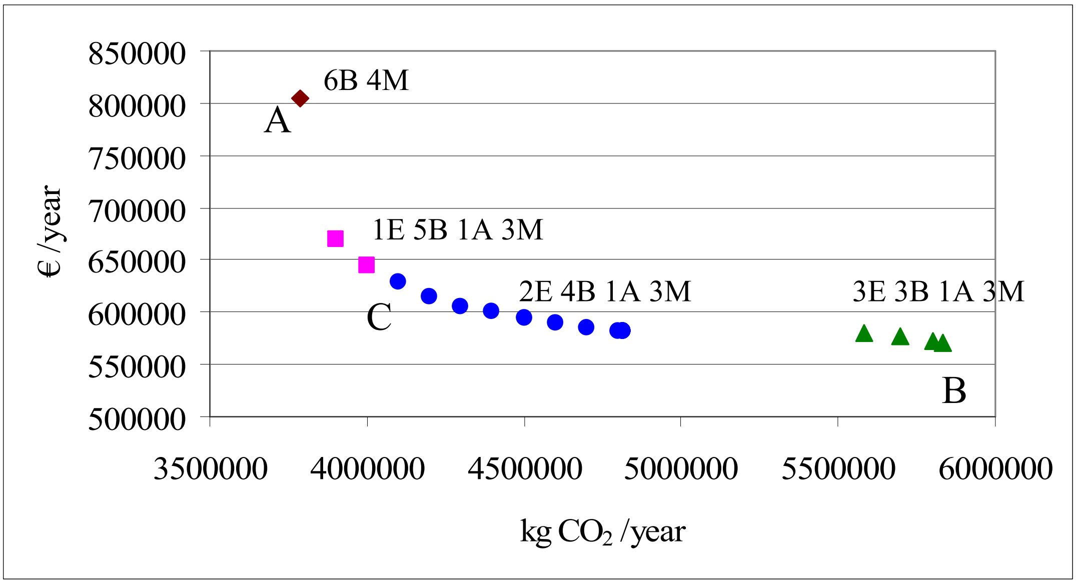

Figure 2: Pareto frontier considering the annual cost and annual CO_2 emissions

Point C (configuration 2E 4B 1A 3M, i.e., 2 gas engines, 4 hot water boilers, 1 single effect absorption chiller and 3 mechanical chillers) represented the preferred intermediate Pareto optimal solution in the interval [lim_{inf}, lim_{sup}]. Point C was chosen because it was considered to be a good trade-off between CO_2 emissions and cost, after systematic calculations of decrease in emissions versus increase in cost for each point of the interval [lim_{inf}, lim_{sup}]. Point C presented a pronounced decrease in cost (- 22%) compared to point A and a small sacrifice in CO_2 emissions (+ 9%) compared to point B. Configuration 2E 4B 1A 3M presented a wide range of possible operation modes and was an adequate option, adaptable to different market and operational circumstances.

Significant reductions in costs could be attained if the decision-maker was willing to compromise the environmental performance of the system. The considerable drop in annual cost between point A and point C was due to installation of cogeneration modules and consequent sale of electricity to realize profit. From point A on, the consumption of natural gas and sale of cogenerated electricity increased, and the purchase of electricity from the grid decreased.

4.2 Economic and EI-99 Single Score bi-objective optimization

The two extreme points of the Pareto frontier were obtained by optimizing each objective function separately: lim_{inf} = 411,986 points/year (environmental optimal) and lim_{sup} = 1,158,005 points/year (economic optimal).

Figure 3 shows the Pareto frontier obtained. Each point in the Pareto frontier represented a different optimal system (optimal configuration and operation, as both configuration and operational conditions may vary) which operated under a set of specific conditions. Furthermore, each trade-off solution involved a different compromise between both criteria.

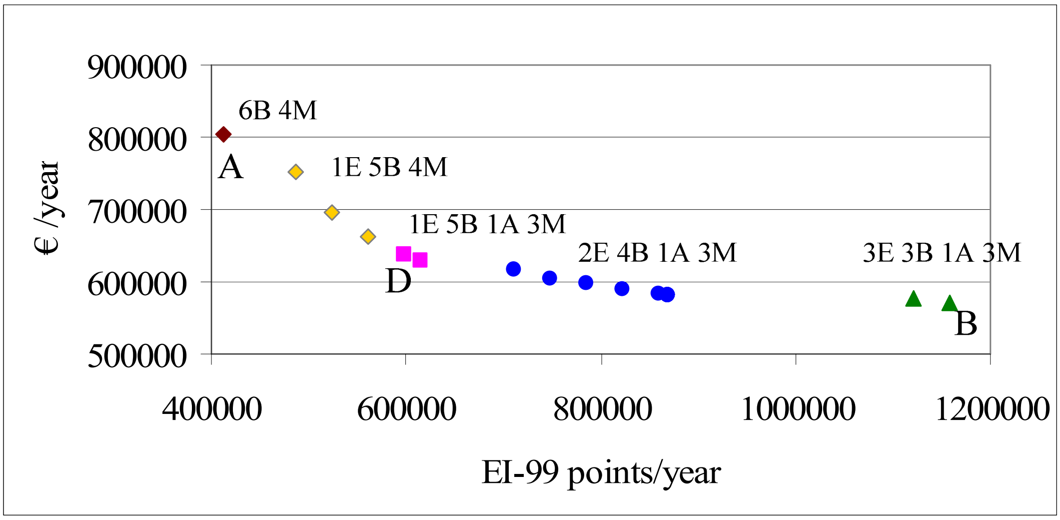

Figure 3: Pareto frontier considering the annual cost and annual EI-99 points

Point D (configuration 1E 5B 1A 3M) represented the preferred intermediate Pareto optimal solution in the interval [lim_{inf}, lim_{sup}], being a good trade-off between EI-99 and cost, after systematic calculations of decrease in points versus increase in cost for each point of the interval [lim_{inf}, lim_{sup}]. Point D presented a pronounced decrease in cost (- 21%) compared to point A, but also a considerable increase in EI-99 points (+ 45%). Note that limit x-coordinate values of this graph were much more separated than those of Figure 2, implying an expected greater increase in EI-99 points when traveling along the Pareto frontier towards minimum cost.

Similarly to the trend in the economic and CO_2 bi-objective solutions, the consumption of natural gas and sale of cogenerated electricity increased with the increase of EI-99 Single Scores, while purchase of electricity from the grid decreased. The system slowly installed cogeneration modules and removed hot water boilers, while the production of cooling remained almost fixed by one absorption chiller and three mechanical chillers.

4.3 Multiobjective optimization

Table 3 shows the main features of solutions A, B, C and D.
Configuration 1E 5B 1A 3M in the EI-99 multiobjective optimization presented a smaller range of *adaptability* when compared to configuration 2E 4B 1A 3M in the CO_2 multiobjective optimization.
The ultimate choice of one configuration considering economic and environmental viewpoints led to the choice of configuration 2E 4B 1A 3M, which presented a wider range of adaptability in the economic/CO_2 bi-objective optimization. Note that configuration 2E 4B 1A 3M did not perform significantly worse in the economic/EI-99 bi-objective optimization, as the designer may accept small increases in costs over the economic minimum and still guarantee optimal conditions under small increases in the annual EI-99 Single Score.

Table 3: Solutions A, B, C and D

	A	D	C	B
System composition				
MGWH Gas engines	0	1	2	3
CGWH Hot water boilers	6	5	4	3
ICWH Heat exchangers WH→ WR	0	1	1	4
FAWH Single effect absorption chillers	0	1	1	1
FMWR Mechanical chillers	4	3	3	3
ICWR Cooling towers	3	3	3	3
Natural gas (total) MWh/y	8703	16,538	20,370	37,324
Purchased electricity MWh/y	3572	226	203	29
Sold electricity MWh/y		1537	4070	11,389
Cost of equipment €/y	219,650	320,045	413,195	510,830
Cost of natural gas €/y	217,582	413,452	509,252	933,092
Cost of electricity €/y	366,951	23,003	20,278	3207
Profit with the sale of electricity €/y	0	- 118,353	- 313,396	- 876,960
Total annual cost €/y	*804,184*	*638,148*	*629,329*	*570,169*
Emissions of equipment kg CO_2/y	43,057	44,336	47,775	52,699
Emissions of natural gas kg CO_2/y	2,367,296	4,498,336	5,540,660	10,152,037
Emissions purchased electricity kg CO_2/y	1,375,264	87,010	78,297	11,168
Avoided emissions kg CO_2/y	-	- 591,745	- 1,566,980	4,384,799
Total annual emissions kg CO_2/y	*3,785,617*	*4,037,937*	*4,099,743*	*5,831,105*
Single Score of equipment points/y	2272	2984	3366	3908
Single Score of natural gas points/y	328,984	625,140	769,986	1,410,835
Single Score of electricity points/y	80,730	5102	4588	656
Avoided Single Score points/y	-	- 34,737	- 91,982	257,393
Total annual Single Score points/y	*411,986*	*598,488*	*685,958*	*1,158,005*

5. Conclusions

The issue of multiobjective optimization was addressed in this paper, where two bi-criteria optimizations (minimization of annual cost versus CO_2 emissions, and minimization of annual cost versus EI-99 points) were carried out. The solution of the MILP model provided sets of Pareto optimal design alternatives, which were analyzed and evaluated based on trade-offs. This detailed analysis highlighted the important role of the decision maker in solving and using their specialized judgment in the multiobjective problem.
Comparison of economic and environmental optimals showed clearly different structures. Optimal configurations based on conventional equipment (such as hot water boilers, mechanical chillers and cooling towers) were obtained by separately minimizing CO_2 emissions and then EI-99 Single Score for current conditions in Spain. Surprisingly, both

optimal solutions maintained similar configurations in which the energy demands of the consumer center were satisfied utilizing conventional equipment.

Multiobjective optimization techniques allow the enlargement of the perspective of single-objective energy system analyses and the determination of the complete spectrum of solutions that optimize the design according to more than one objective at a time. As in most practical problems, multiple objectives compete with one another and a unique optimal solution with respect to all of them cannot be identified. The issue of multiobjective optimization was tackled, in the form of a bi-criteria programming problem. The same mathematical model of single-objective optimization was adapted for application of the ϵ-constraint method, and the solution of the model provided a set of Pareto optimal design alternatives.

Two bi-objective optimizations were carried out, considering economic (annual cost) and environmental viewpoints (represented separately by annual CO_2 emissions and EI-99 points). Solutions close to the environmental minimum were associated with a steep increase in the economic objective. Problems were compared and it was observed that some configurations were more stable along the Pareto frontier. The judgment of the solutions and the trade-offs involved led to the choice of configuration 2E 4B 1A 3M. Significant reductions in the environmental impact could be attained if the economic performance was compromised.

Nomenclature

AA:	Ambient air
CG:	Natural gas
CGVA:	Steam boiler
CGWH:	Hot water boiler
D:	Demand of a utility
E_d:	Electricity demand of the hospital
EE:	Electricity
EI-99:	Eco-indicator 99
FAVA:	Double effect absorption chiller
FAWH:	Single effect absorption chiller
FMWR:	Mechanical chiller
ICVA:	Steam-hot water heat exchanger
ICWH:	Hot water-cooling water heat exchanger
ICWR:	Cooling tower
L:	Loss of a utility
MGWH:	Gas engine
MILP:	Mixed Integer Linear Programming
P:	Purchase of an utility
Q_d:	Heat demand (SHW + heating) of the hospital
R_d:	Cooling demand of the hospital
S:	Sale of a utility
SHW:	Sanitary hot water
TGVA:	Gas turbine
VA:	Saturated steam
WC:	Chilled water
WH:	Hot water
WR:	Cooling water

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