Synthesis and design of a polygeneration scheme for the tourist sector: comparison of the Spanish and Italian conditions

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ABSTRACT – This paper presents first the synthesis and design of a polygeneration scheme providing power, heat, cold and desalted water to a tourist resort in Spain. A MINLP optimization process was used to first select the appropriate technology to provide the four commodities to a hotel, and then to propose the adequate size to each technology. The proposed scheme was constituted by an internal combustion engine, a desalination system (RO unit), a LiBr-water absorption chiller, and the complementary heat exchangers, as well as some auxiliary equipment required for the system. Liability of PV systems was also analyzed as additional power suppliers to the hotel. GAMS software was used to solve the MINLP problem based on the maximization of the External Rate of Return (ERR) of the investment, which is complemented with a series of equality and inequality constraints related to heat and mass balances, minimum part load conditions and combined efficiencies, and so on.

The results show that the optimum design strongly depends on the regulatory framework and primary energy prices. Thus, second part of the paper dealt with the effect of those externalities on the same polygeneration scheme, if the hotel were translated to similar Spanish and Italian locations. Better results were slightly found for the Spanish conditions (both options were also tested with PV support in hotel roof), reaching a maximum value of 12.7% in the ERR.

In general, in those schemes economic optimum (as the performed here) do not coincide an thermodynamic based one. Therefore, a multi-objective optimization was also performed: a Pareto front relating all the optimal designs is obtained, which allows one to select schemes characterized by high efficiencies with competitive costs.

1. INTRODUCTION

Polygeneration and multi-generation are equivalent and reproduce the advantages of cogeneration and trigeneration [1,2]: a reduction of greenhouse gases, a reliable energy supply, economic saving and reduction of the network losses [3-5]. In water scarce coastal areas, fresh water coming from a desalting unit could be the fourth product which, integrated in the polygeneration plant, also reduces the strong dependency of that critical resource in those regions.

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Anyway, and related to this new concept, there exist many challenges to assess the feasibility of these multi-product systems. They range from the criteria definition to assess their profitability to the selection of technologies (synthesis), the design and (among others), the cost allocation. In this sense, the challenge of assessing and establishing a quite general procedure to select and integrate a multiproduct system is a wide, open line of research where this work is framed, especially in the tourist sector, in where each resort presents a stochastic behaviour regarding its energy and water demands.

Sizing procedures for cogeneration and tri-generation plants could be found in [1,6,7]. Simplest methods are based on the thermal duration curves, which both provide the prime mover and the thermally activated cooler capacities. Then, operating strategies could be analyzed and a first estimation of the system feasibility is then easily calculated. However, economic aspects and GHG assessment are not dealt with [7,8]. A polygeneration system could also be integrated through specific software packages, which could estimate capacities, but a reduced combination of technologies could be tested and therefore they rarely provide the appropriate results for a case study [9-11].

Mathematical optimization seems to be the best formula to synthesize, design and operate a multigeneration unit. It allows including the required constraints regarding profitability, energy saving and environmental impact. In general, three different “objective functions” can be distinguished: annual cost minimization, economic profit maximization, and any combination of the previous ones (so including a multi-objective optimization). Solutions to each approach can be achieved through diverse optimization techniques, such as evolutive and genetic algorithms, linear and non-linear programming [1].

In thermal systems, a two-steps optimization sequence is usually applied: a preliminary sizing and equipment selection are faced within a first level, while the definite capacities and the plant operation are studied in a second level to obtain the best operating strategy [6,12]. One year is the lowest time period commonly considered to carry out the optimization. In such time periods, the system operation is assumed as a succession of stationary states, so avoiding some dynamic effects of the equipments operation [13]. Anyway, a monthly averaged analysis is required for the first step, whereas an hourly one is required to estimate the highest benefit when the plant operation is being optimized.

In this paper, the application of the first-level procedure (to choose a first size and technology per demand) is presented. The results are obtained for an existing 450 room tourist resort (including two four-stars hotels), upon the Spanish and Italian scenario, in order to analyze if present economic and legal framework is adequate to spread this type of installation in southern Europe.

2. SYNTHESIS AND DESING OF THE POLYGENERATION PLANT

Apart from sizing, selection of the best technology to include in a polygeneration plant is not trivial since multiple options appear in a multipurpose scheme. As an example, internal combustion engines, microturbines or fuel cells, among others, could be the candidates as prime mover (PM) devices; there are more than a few thermal activated technologies (TAT) for cooling (based on absorption or adsorption effect), and to produce fresh water there are also a number of available desalination (DES) technologies. In addition to that, renewable energies (RES), such as solar-thermal, photovoltaic and biomass gasification can be considered to enhance the environmental benefits of the whole system, but usually they present higher investment costs, so reducing the economic profitability of the plant.

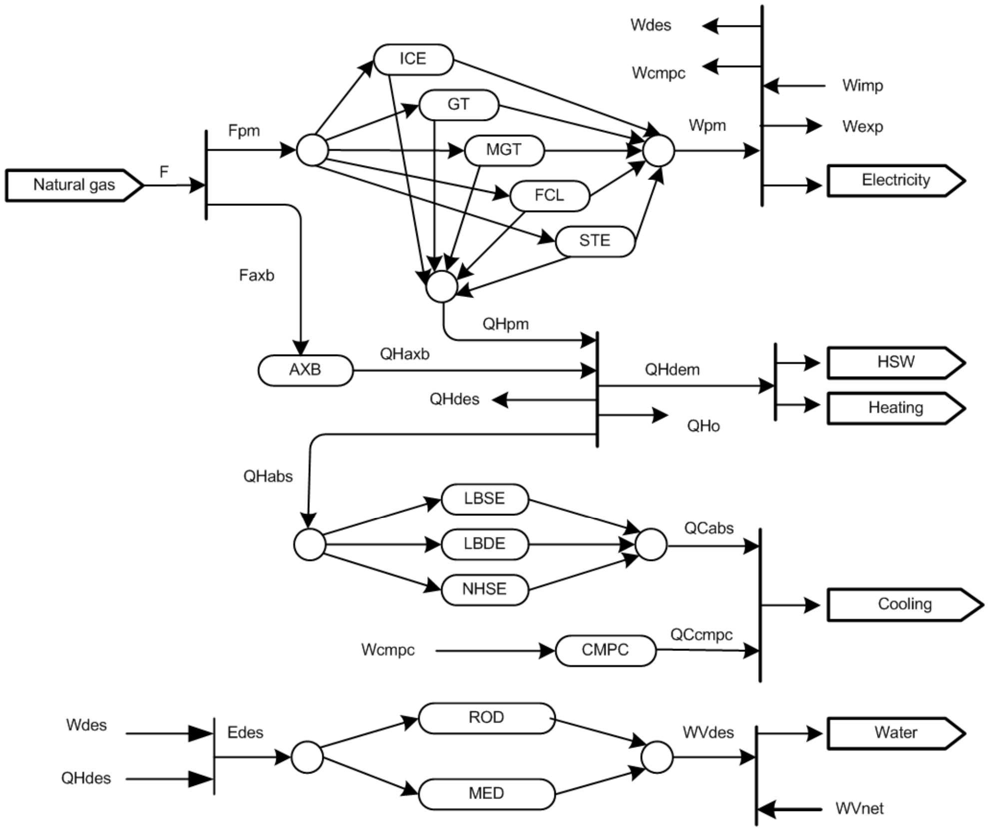
Of course, the technologies finally adopted will be highly dependent on the formulation of the optimization model [1,9,14], technical compatibility among them, as well as their part load operation range and local legal framework. Consequently, a compendium of energetic, environmental and economic optimums is really found [15]. Therefore, selection and sizing of the appropriate technology in a polygeneration scheme including a desalination unit is a complex problem to solve. Successive approaches were made by the authors in order to find out the definite solution [16-18].

For that purpose, the superstructure concept, which contains the technically feasible configurations to integrate the polygeneration plant, is a key tool. An optimization process based on a MINLP (Mixed Integer Non-linear Programming) problem was designed to select the technologies. It included an economic objective function complemented with environmental, energetic constraints and other technical limits (such as minimum part load operation). Here, environmental benefits were evaluated throughout the GHG emission reduction. Energy efficiency was studied by diverse ratios (depending on the location). Monthly-averaged data were enough at this level to deal with power, heating, cooling and water demands. Main free-design variables were: prime mover rated power output (PM), thermally activated technology (TAT) capacity (cooling capacity), desalination capacity (DES) and capacity supported by photovoltaics (PV), although diverse renewable sources (RES) could also be included without any problem.

The set of technologies to supply each demand composed a complex tree-form scheme, the named “superstructure”, in which natural gas was the unique fossil fuel (renewable energy was later on included, once the natural gas scheme-based or base case was solved). The five supported demands (electricity, heating, cooling, fresh and hot sanitary water, HSW) were also included. The available technologies are briefly described in the following list:

- Power generation (PMS set): Internal combustion engine (ICE), gas turbine (GT), micro-gas turbine (MGT), fuel cell (FCL) and Stirling engine (STE).
- Heating: heat plate exchangers and an auxiliary boiler (AXB) for peak demands.
- Cooling (TAT set): Lithium-bromide single (LBSE) and double effect (LBDE), water-ammonia single effect (NHSE), and conventional compression cooling (CMPC) to supply cooling peaks.
- Water (DES set): A pre-selection was made to choose reverse osmosis (RO) as a membrane-based technology, and Multi-effect Distillation (MED) as the most efficient distillation unit.

Figure 1 shows the superstructure used in this paper (PV is not included)



ICE–Internal Combustion Engine, **GT**–Gas Turbine; **MTG**–Microturbine; **FCL**–Fuel Cell; **STE**–Stirling Engine; **AXB**–Auxiliary Boiler; **LBSE**–Single Effect LiBr-H2O Absorption Chiller; **LBDE**–Double Effect LiBr-H2O Absorption Chiller; **NHSE**-Ammonia Water Absorption Chiller; **CMPC**-Auxiliary Compression Chiller; **ROD**-Reverse Osmosis Unit; **MED**-MultiEffect Desalination Unit; **W**-Electric Power; **QC**-Cooling Power; **QH**-Heating Power; **F**-Fuel; **WV**-Flow rate.

Figure 1. Sketch of the superstructure to select technologies of a polygeneration system for a tourist resort.

Even without considering the renewable sources (RES set), the number of configurations for the base case could reach to 30 (5 options for PM set x 3 options for TAT set x 2 options for DES set, see Figure 2). Additionally, some predefined operating modes will be also selected by the optimization model. Fortunately, the number of feasible solutions will be reduced into a few ones when the complete set of constraints is finally included in the optimization model

3. OPTIMIZATION MODEL

The selection and sizing procedure for the superstructure was based on the definition of an optimization problem, including an objective function and several constraints. Binary variables (Y_x) were inserted in order select only one technology per u set. Operating mode was also modelled with a binary variable. This methodology is an extension of a procedure based on the synthesis of chemical processes [21].

On the other hand, the state of the art in the optimization of polygeneration schemes suggest to include an economic objective function, being the Net Present Value (NPV) of the new installation the most experienced one [22]. However, and although the authors have been widely used the NPV, it is an absolute value and trends to increase the size of the plant if is the unique parameter in the objective function (higher size means higher benefits). Therefore, in this paper a relative parameter like the ERR (external rate of return) has been used, which is defined as follows:

$$ERR = \sqrt[n]{\frac{FW_{inc}}{CFIX}} - 1 \qquad (1)$$

where FW_{inc} and CFIX are respectively the future worth at the year n and the total investment cost of the installation (referred to year 0). Relationship between FW and PW are given by the expression:

$$FW = PW \cdot (1+k)^{n} \qquad (2)$$

where PW is the present worth (net present value), k is the interest rate and n is the life time of the installation (15 years). Calculation of the PW is obtained if yearly cash-flow of the plant Q is given, as follows (eq. 3)

$$PW = -CFIX + \sum_{j=1}^{n} \frac{Q}{(1+k)^{j}} \qquad (3)$$

Investment cost is f the installation is a function of the size of each device. Constant parameters (AU and BU) where used to estimate the end cost, see table 1 for details, in which O&M costs and efficiencies, as well as minimum part load operation (PL_{min}) allowed are shown. Marshall and Swift index was introduced to update the corresponding costs.

$$CFIX = \sum_{i=mps,ref,dis} \{[AU(i) \cdot PMAX(i) + BU(i)] \cdot I_{M\&S}(i) \cdot Y(i)\} \qquad (4)$$

Device	***AU***	***BU***	$I_{M\&S}$	***O&M***	η_{el}	η_{th}	PL_{min}
	€/kW	€	--	--	--	--	--
ICE	268,8	155.306,0	1,19	10	0,36	0,46	0,40
GT	781,0	0,0	1,19	50	0,30	0,60	0,40
MTG	2.185,0	0,0	1,01	20	0,23	0,57	0,40
FCL	4.000,0	0,0	1,19	26	0,40	0,44	0,35
STE	3.500,0	0,0	1,07	10	0,22	0,70	0,50
LBSE	122,9	58.785,0	1,01	5,7	0,7	-	0,20
LBDE	400,0	50.000,0	1,01	5,7	1,2	-	0,20
ROD	7.970,4	35.196,0	1,01	0,13	1/4	-	0,70
MED	25.440,0	0,0	1,01	0,10	1/50	-	0,60

Table 1. Main parameters to calculate CFIX of diverse technologies depending on their capacity

Regarding the calculation of the cash flow Q, different equations have to be applied in order to estimate the income related to power delivered to the grid (EN). For instance, in Italy is calculated on the form:

$$EN = (c_{elv} \cdot E_{e}) + \frac{E_{th}}{F_{MJTep}} \cdot TEE + \frac{E_{e}}{F_{MJTep}} \cdot TEE \qquad (5)$$

where c_{elv} is the electricity price obtained (€/MWh), E_e is the energy delivered, E_{th} is the thermal energy produced and TEE is the Energy Efficiency Title (see below). Alternatively, for Spain the formula is the next one:

$$EN = (c_{elv} \cdot E_e) + E_e \cdot RD_e + E_e \cdot RD_r \tag{6}$$

and RD_e and RD_r constitute respectively the bonus obtained by energy efficiency and reactive balance of the power delivered to the grid. Apart from investment costs, operating costs of the installation are constituted by the cost of commodities (CVAR) and O&M costs of the installation (OM), which takes into account the prime mover (pms), cooling (ref) and desalination unit (dis), here Italian and Spanish case are similar:

$$CVAR = c_{GN} \cdot F + c_{elc} \cdot E_{ac} + c_{H2O} \cdot A_{ac} \tag{7}$$

$$OM = O\,\&\,M(mps) \cdot E_e \cdot Y_{mps} + O\,\&\,M(ref) \cdot E_{rf} \cdot Y_{ref} + O\,\&\,M(dis) \cdot A \cdot Y_{dis} \tag{8}$$

where c_{GN}, c_{elc} and c_{H2O} are the respective costs of natural gas consumed every year (F), electricity taken from the grid (E_{ac}) and water acquired (A_{ac}) to municipality. Cold and water produced every year (E_{rf}) are also noted in eq. (8).

Selection of the equipment to each demand is controlled by the use of equations 9 to 11 (only one device is allowed per demand), for the prime mover (pms), cooling (ref) and desalting (dis) units:

$$\sum_{mps} Y_{mps} = 1 \tag{9}$$

$$\sum_{ref} Y_{ref} = 1 \tag{10}$$

$$\sum_{dis} Y_{dis} = 1 \tag{11}$$

Equality constrains are in general all those related to fulfil the energy and mass balances of the installation included in Figure 1. Obviously, in those balances the tourist resort demands should be given. Table 2 includes the monthly demands of power (DE), heating (DH), cold (DC) and water (DW) in a typical year.

	DE [MWh]	**DH** [MWh]	**DC** [MWh]	**DW** m^3/h
January	166,02	204,57	10,50	4,83
February	188,52	188,04	21,06	4,95
March	191,56	178,65	43,55	5,57
April	263,93	200,20	161,19	7,43
May	234,13	148,61	265,51	6,81
June	299,12	152,70	411,73	8,42
July	323,53	165,44	570,82	9,41
August	340,55	174,40	546,79	9,90
September	329,91	167,72	406,23	9,28
October	255,41	160,08	205,70	7,43
November	246,33	215,99	34,21	6,93
December	187,30	218,78	11,78	5,45

Table 2. Monthly demands of the case study analyzed here.

Regarding the **inequality constraints**, again Spanish and Italian pictures give diverse parameters to control the energy efficiency of the scheme, for instance a thermal limit (LT) and a index of thermal saving (IRE) is pursued in Italy:

$$LT = \frac{E_{th}}{E_e + E_{th}} \geq LT_{\min} \tag{12}$$

$$IRE = 1 - \frac{NC}{\dfrac{E_e}{\eta_{e,rif} \cdot c} + \dfrac{E_{th}}{\eta_{th,rif}}} \geq IRE_{\min} \tag{13}$$

$$c = \frac{p_{im} \cdot E_e + p_{auto} \cdot DE}{E_e + DE} \tag{14}$$

The cogeneration coefficient c measures the energy required and produced in the scheme. On the contrary, in Spain minimum energy efficiency equivalence (REA) determines if the system saves primary energy, as those:

$$REA = \frac{E}{F - {H}/{0.9}} \geq REA_{\min} \tag{15}$$

H is the heat provided to the system (at present, power self-consumption is not required at all in the Spanish installations). Finally, economic constraints are controlled by means of simple equations:

$$ERR > k \tag{16}$$

$$PW > 0 \tag{17}$$

The only RES studied here was the introduction of PV in the remaining space available at the tourist complex. A total amount of 900 m^2 was predicted here, technical characteristics of selected PV panels are shown in the next table.

Parameter	**unit**	**Value**
Total Power	kW	147,00
Panel power	W	210,00
Total Area	m^2	900,00
Panel Area	m^2	1,24
Number of panels	#	700,00
Equivalent hours	h	1300,00
Energy produced per year	kWh	191100,00
Panel cost	€	672,00
Cost of PV array	€	470400,00
Total cost (inverter, installation)	€	493920,00

Table 3. Technical requirements of the PV panels.

Price of electricity produced in PV panels in Italy and Spain was paid respectively at 42.2 and 31.16 c€/kWh. PV investment obviously increments so much the CFIX value, so PV is not always a competitive solution in multipurpose schemes.

RESULTS

Four different results were obtained (Italy, Spain, with and without PV support). Only **Italian case** will be described in detail, but similar results of both options are available. First, main technologies and optimum capacities (i.e. those ones that obtain the higher ERR) are shown in table 4.

Parameter	**Value**	**unit**
ERR	0,108	%
Prime mover selected	**ICE**	-
Cooler selected	**LBSE**	-
Desalination unit selected	**RO**	-
Electric power	1000,00	kW
Cooling power	205,70	kW
Desalination capacity	6,90	m^3/h

Table 4. Results for the Italian case.

Then, it is interesting to analyze the part load behaviour around the year. Figure 2 shows the results for the Italian case (without PV)

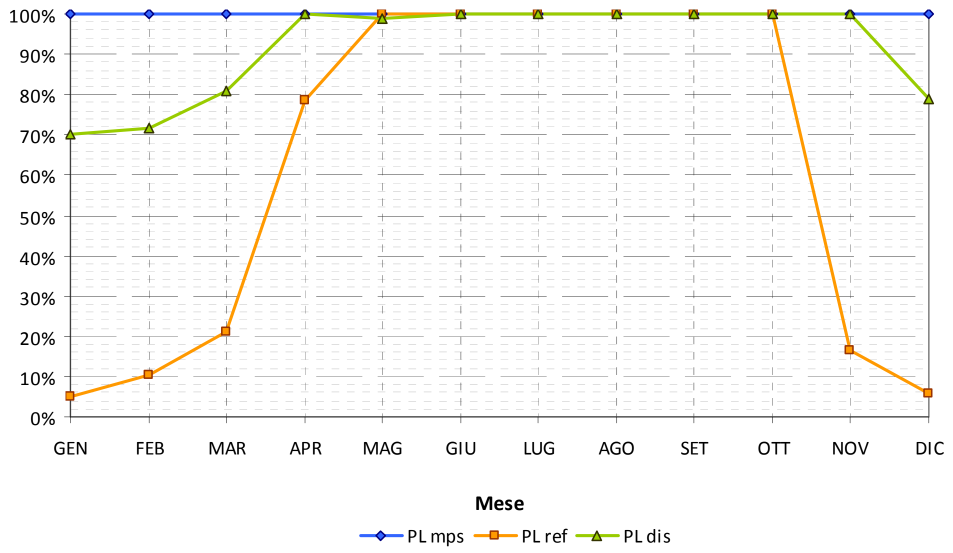


Figure 2. Part load behaviour of the polygeneration scheme selected for the Italian case.

Power delivered to the grid is also included in figure 3, showing that higher production can be sold in winter period. This is mainly due to the power consumed in the auxiliary chiller which covers the summer peaks, as shown in figure 4. Finally, it is interesting to note that potable water from municipality is also required in summer time, as it is shown in figure 5.

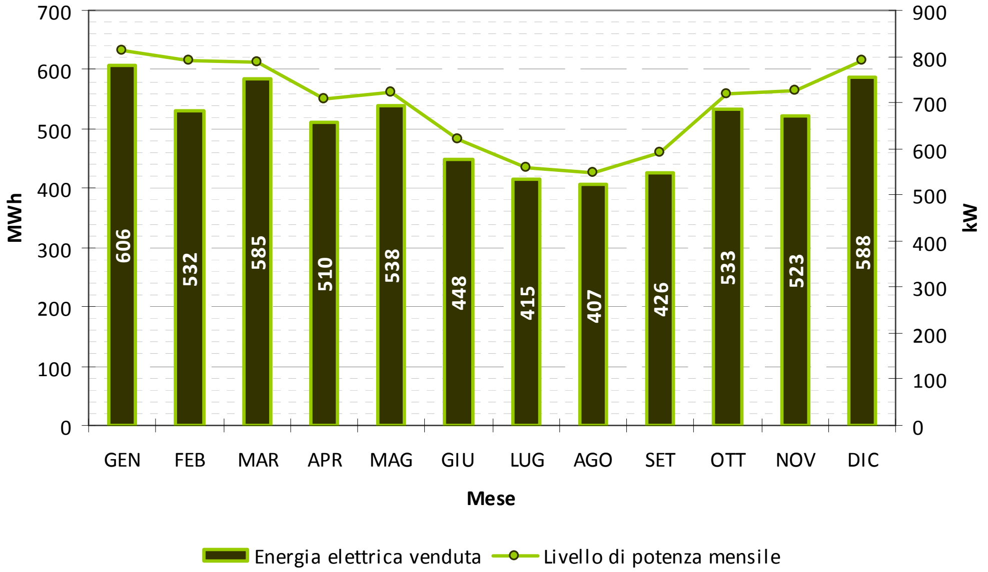


Figure 3. Electricity (power) delivered to the grid.

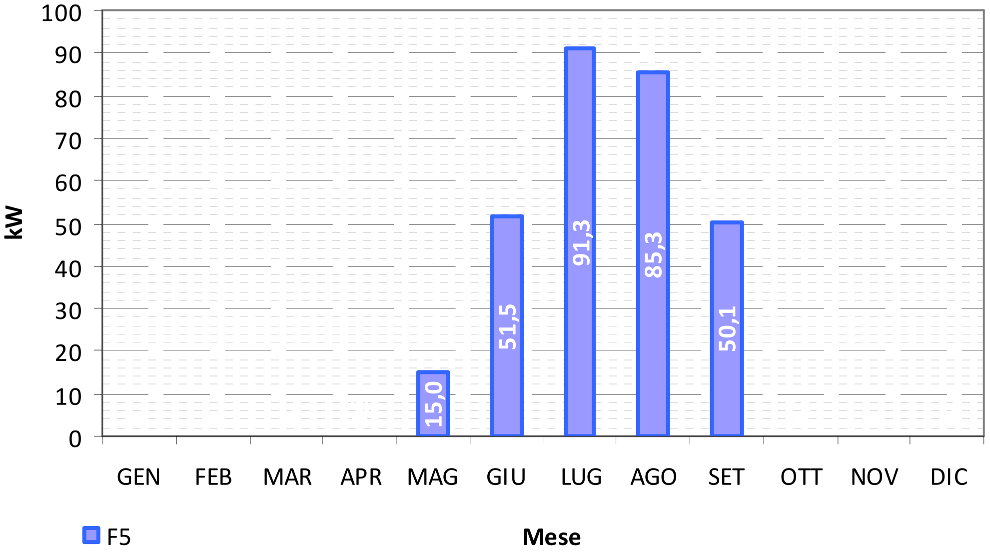


Figure 4. Power consumed by the summer-peak cooling compressor.

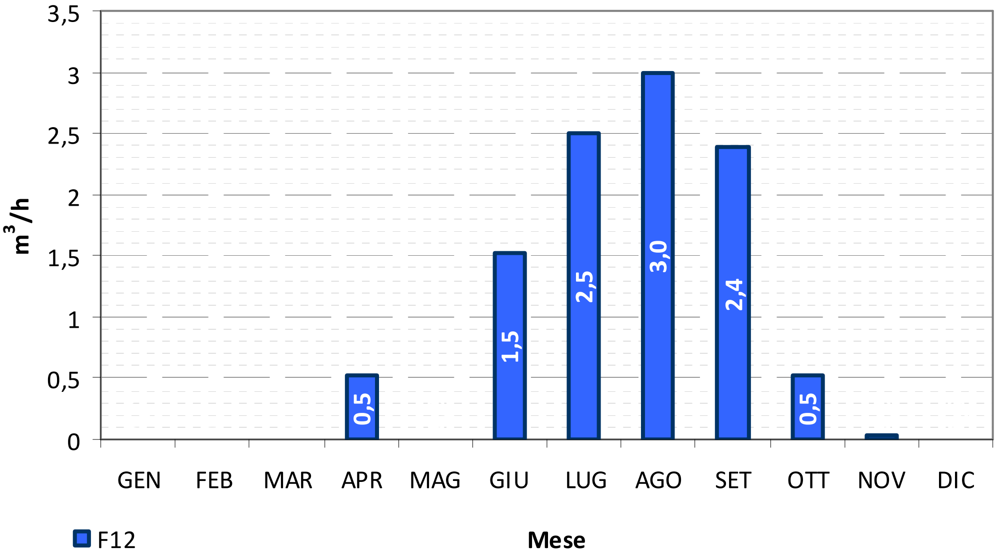


Figure 5. Water coming from water network.

With respect to economic figures and energy efficiency parameters, table 5 shows the main results.

Parameter	Symbol	Value	Unit
Future worth	FW	3,19E+06	€
Cash flow (income)	EN	8,24E+05	€/y
Present worth (net present value)	PW	1,53E+06	€
Investment cost	CFIX	6,83E+05	€
Operating and maintenance cost	OM	1,01E+05	€/y
Variable cost (energy)	CVAR	5,09E+05	€/y
Thermal limit	LT	0,561	%
Thermal saving index	IRE	0,327	%
Cogeneration coefficient	c	0,972	-
Primary energy consumption	N_c	2,43E+07	MWh
Electricity generation (annual)	E_e	8,76E+06	MWh
Thermal energy generation (annual)	E_{th}	1,12E+07	MWh

Table 5. Results for the Italian case (not including PV).

With respect to the **addition of PV** to the tourist resort in Italy, worst figures were obtained for ERR but better for FW. Cooling capacity is increased a lot due to higher power generation.

Parameter	Value	Unit
ERR	0,084	%
Prime mover selected	**ICE**	-
Cooler selected	**LBSE**	-
Desalination unit selected	**RO**	-
Electric power	1000,00	kW
Cooling power	350,00	kW
Desalination capacity	6,90	m^3/h
Future worth	3,95E+06	€

Table 6. Results for the Italian case (not including PV).

In the **Spanish case**, first it is noteworthy that a MED unit is now the selected technology to provide water. Thus, and although it should be suggested that higher prime mover size should be required for the plant in order to produce the extra heat required to the MED unit, lower values were found for the ICE power capacity. As heat produced is better, and externalities were in favour of Spanish case than in Italian one, higher ERR and FW values were found for the optimal solution. Table 6 shows the results and figure 6 compares the heat use of the optimum (Italy vs. Spain) that reinforces the abovementioned idea.

Parameter	**Value**	**Unit**
ERR	0,127	%
Prime mover selected	**ICE**	-
Cooler selected	**LBSE**	-
Desalination unit selected	**MED**	-
Electric power	791,07	kW
Cooling power	325,43	kW
Desalination capacity	7,40	m^3/h
Future worth	6,56E+06	€

Table 6. Results for the Spanish case.

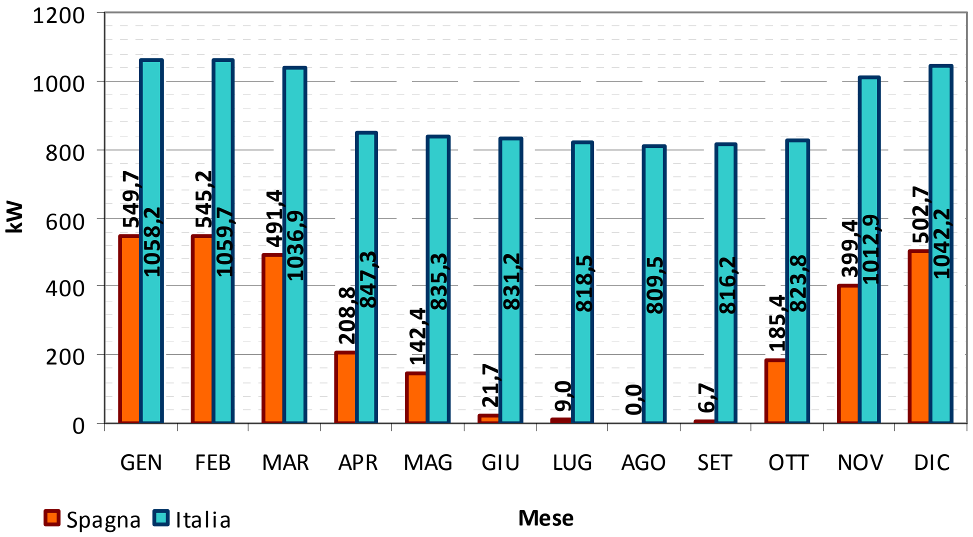


Figure 6. Heat use (waste heat) of the polygeneration scheme. Comparison between the Spanish and Italian scenarios.

Finally, when the PV field is added to the Spanish scenario, the optimum solution maintains technologies but they vary a bit their optimum sizes. Similar values were obtained than in Italian case (lower ERR and FW than the studio without the PV support). Table 7 resumes the main results of this scheme.

Parameter	**Value**	**Unit**
ERR	0,085	%
Prime mover selected	**ICE**	-
Cooler selected	**LBSE**	-
Desalination unit selected	**MED**	-
Electric power	799,11	kW
Cooling power	317,43	kW
Desalination capacity	8,05	m^3/h
Future worth	5,81E+06	€

Table 7. Results for the Spanish case (including PV).

THE ALTERNATIVE MULTI-OBJECTIVE APPROACH: A PARETO FRONT

As shown in figures 3 and 6, the application to the Italian case is convenient with excess production of electricity and significant waste heat. The reason is related to the incentives for cogeneration and the small efficiency of the thermoelectric production. This means that the installation of smaller engines may result in smaller NPV but larger primary energy savings.

For this reason, a multi-objective optimization is worth to be performed. Two competing objective functions may be considered: net present value and primary energy savings.

The analysis is conducted considering a single objective function, the NPV, but a penalty function is introduced for primary energy savings lower than a specified value. This value is progressively increased in order to obtain a Pareto front relating the optimal configurations.

The Pareto front for the Italian case is shown in Figure 7. The quantity on the abscissa is the primary energy savings with respect to the optimal economic design presented above. It is shown that significant increases in the primary energy savings can be achieved with some reductions in the NPS. This is important as the proposed system should be compared with an evolving electrical system, characterized by a progressively increasing efficiency.

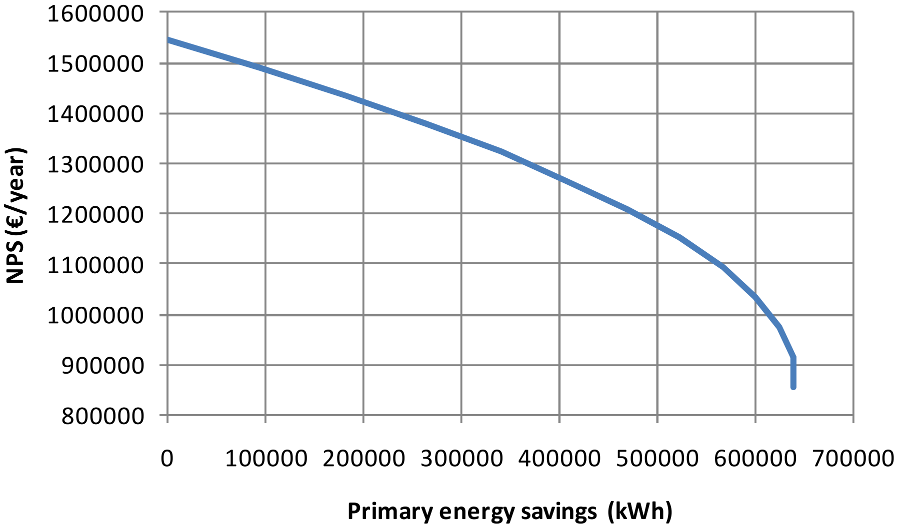


Figure 7. Multi-objective optimization in the Italian case.

CONCLUSIONS

It has been demonstrated in this paper the powerful of an appropriate synthesis procedure to select a multipurpose scheme providing power, heat, cold and water to a tourist resort. If the same problem is studied upon diverse scenarios, diverse technologies could be the best to provide some demands. Of course, great differences are obtained in energy and economic indexes for the same case study.

Anyway, the preliminary sizing that the procedure also provides, has to be definitely fixed when a second-step optimization procedure, including an in-depth hourly analysis of the scheme. Here, different power prices (depending on the daily period according to legislation) and energy storage techniques will have sense. Here, it is not needed to use a MINLP procedure, with a non-linear programming technique (NLP) the optimization could be performed.

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