DESIGN OPTIMIZATION AND EVALUATION OF THE PERFORMANCE OF A POLYGENERATION SCHEME FOR THE TOURIST SECTOR

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ABSTRACT

This paper presents a reliable and economic manner to provide for the tourist sector energy, heat, cold and desalted water starting from a polygeneration scheme. The proposed scheme is constituted by a power plant (internal combustion engine), a desalination system (RO unit), absorption chiller, and the complementary heat exchangers, as well as some auxiliary equipment required for the system. Water and power surpluses could be sold to their respective networks, so increasing the plant profitability.

The design optimization of the scheme shows that nowadays thermodynamic (energy) and economic optimums are yet quite far, since process integration is always profitable from the point of view of energy efficiency but not always from Economics, especially under Spanish regulatory framework. The optimum was then used to select the set of equipment required for a further detailed analysis, and better results are obtained if demands are dealt with considering hourly periods. Anyway, the economic results obtained are quite encouraging for the future of those schemes that solve the water and energy scarcity in Mediterranean and other highly-populated and/or tourist areas, since trend of water and energy prices, as well as CO_2 penalties will improve its benefits.

INTRODUCTION

Tourism is one of the fast growing sectors in the Mediterranean Area, and continuing growth may jeopardise the achievement of sustainable development and, unless properly managed, may affect social conditions, cultures and local environment of tourism areas; it may also reduce the benefits of tourism to the local and wider economy. The European Mediterranean countries have scarce energy resources, producing a 26% of the energy demand; on the other hand, energy demand and water scarcity increase considerably with population in summer time, where 147 million people arrive to these countries mostly for leisure recreation and holidays (69%) [1]. Moreover, these arrivals are increasing every year, making the sustainable growth of the tourism sector nonviable. Therefore, the development of innovative and efficient energetic systems providing the complete set of services demanded by tourism (electricity, heat, cold and fresh water) is a key issue in order to decrease pollution levels and external energy and water dependency in the coastal (European) areas. This paper shows one of those efficient systems throughout the application of process integration techniques.

Some other polygeneration arrangements for different sectors can be found in [2-3], and a thermoeconomic analysis and a preliminary optimization were presented by the authors in [4-5] for a real tourist resort located in Tarragona (Spain). Here, the design optimization of the scheme is made, starting from an energy optimum, and then the “fine tuning” of the scheme is made by means of an hourly analysis of water and energy (including heat and cold) demands.

HOTEL DEMANDS

A typical Mediterranean hotel [6] (latitude 41.04º N, longitude 1.11º E) was taken for the analysis, with a total surface of 20,000 m^2 and 2 hotels and an apartment building (with 452 double rooms, 16 of them are suites). Reception, three restaurants, offices and shops are located, as wells as diverse convention rooms.

Common areas and rooms are completely acclimatised (total surface is 12,000 m^2) by means individually-controlled fan-coils.

Installed capacity and annual consumptions are shown in Table 1 for energy issues. Water supply comes from public network, with a maximum consumption of about 300 m^3/d (swimming pool is opened from June to September). Hot sanitary water (HSW) demand is on average the 62.3% of total water consumption.

Table 1. Installed capacity of the tourist complex

Total installed capacity			
Heat	HSW	1521,82	kWt
	Heating	467,53	kWt
		1989,35	kWt
Cold	Chiller	454,34	kWe
	Averaged COP	2,82	
		1281,23	kWc
Electricity	Hotel uses	708,16	kWe
	Total (including chiller)	1162,5	kWe

Detailed information about demand profiles is not available, since only water, electricity and fuel bills are given by the hotel owners. Anyway, a preliminary estimation of water, energy, cold and heat demands could be done: although many factors could affect energy and water consumption in the hotel sector, occupancy rate and climatology are sure the most important ones [7-10]. So, water and energy demands will be analyzed every month as a function of those external parameters for the design optimization. Figure 1 shows minimum and maximum temperatures and occupancy rate for the case study.

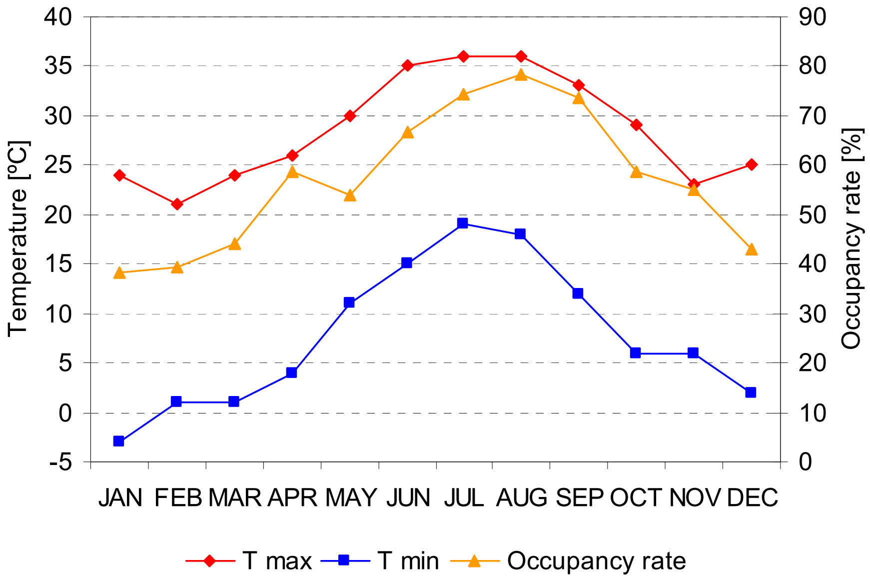


Figure 1. Maximum and minimum temperatures and occupancy rate of the hotel along the year.

Occupancy rate (OR) is calculated by means of the quotient between the people which is on average in the hotel every month and the maximum lodging capacity (np_T) of the hotel:

$$OR(i) = \frac{np(i)}{np_T} \qquad (1)$$

Electricity consumption (We) is only a function of the OR and maximum consumption (registered in August, We_{max}):

$$We(i) = We_{\max} \cdot OR(i) \qquad (2)$$

Hot sanitary water (HSW) consumption each month WV_{HSW} is also calculated as a function of the OR and typical conditions for this end use (see table 2). Heat required for that use (Q_{HSW}) is then immediately calculated:

$$WV_{HSW}(i) = WC_{HSW} \cdot n_{PT} \cdot \Delta t \cdot OR(i) \qquad (3)$$

$$Q_{HSW}(i) = WV_{HSW}(i) \cdot (\rho \cdot Cp)_{water}(T_u - T_i) \qquad (4)$$

Table 2. HSW conditions for the case study.

HSW conditions		
Consumption (per capita, WC)	145	Litres/person & day
Persons	800	Maximum
Inlet temperature (T_i)	10	ºC
Prepared temperature (T_p)	60	ºC
Use temperature (T_u)	50	ºC

On the contrary, heating and cooling requirements depend on the OR and outdoor temperature. As a first assumption, and neglecting transient and storage effects in the hotel, an overall heat transfer coefficient (UA) has been calculated in the worst conditions for winter and summer periods [11], taking into account local weather climatology and heating and cooling installed capacity (in that case, a COP=3 was taken):

$$UA_{heat} = \frac{HP_{installed}}{(Ti_{h,d} - To_{h,d})} \qquad (5)$$

$$UA_{cool} = \frac{CWe_{installed} \cdot COP_{chiller}}{(Ti_{c,d} - To_{c,d})} \qquad (6)$$

Then, heating and cooling requirements are only a function of those UA and the occupancy rate and indoor-outdoor temperature drop (Ti-To)

$$Q(i) = UA \cdot (Ti - To) \cdot \Delta t \cdot OR(i) \qquad (7)$$

The term (Ti-To)·Δt is very similar to the degree-day (DD) concept used to estimate heating and cooling demands [12]. Heat gains due to solar irradiation, lighting and human activity could be included by changing indoor temperature Ti by a lower value called balance temperature Tb [13] (see table 3 for design data).

Table 3. Design conditions for the heating and cooling requirements.

Design conditions (ºC)		
	Winter	Summer
Ti	22	25
Tb	15	21
To	0	36

Monthly demands (of electricity, water, heat and cold) calculated by means of eqs. (1-7) are shown in figure 2, and table 4 includes the annual demands. Note that natural gas consumed in kitchen services is not included in the analysis.

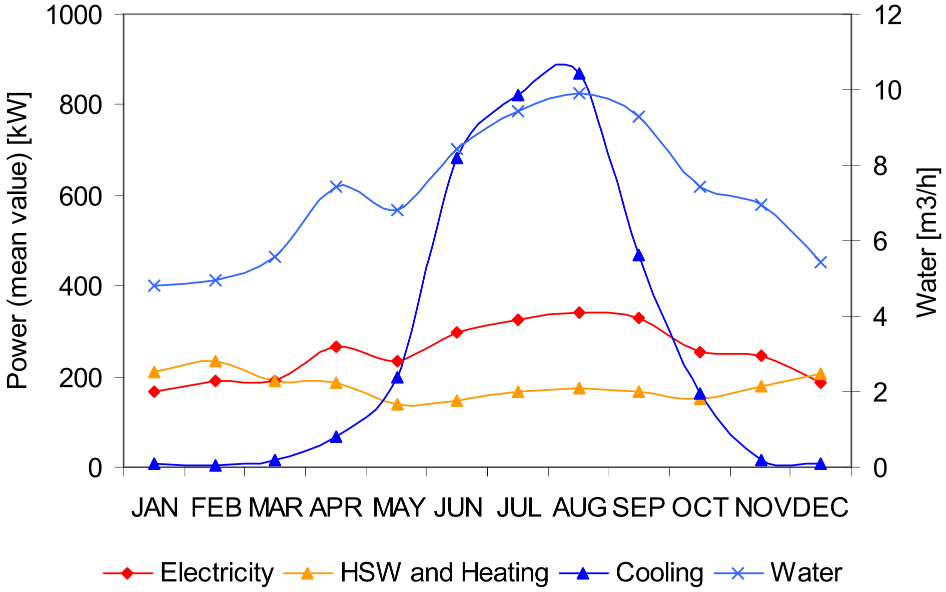


Figure 2. Power, HSW and heating, cooling and water (on the right) demands.

Table 4. Annual demands of water and energy in the studied hotels.

D1-Electricity kWh/year	D2-Heating kWh/year	D3-HSW kWh/year	D4-Cooling kWh/year	D5-Water m^3/year
2171944,8	182254,7	1463621,2	1169012,2	67384,3

SELECTED SCHEME AND FIRST DESIGN

Once demands were calculated, it is time to select the equipment for producing electricity, heat, cold and desalted water. The prime mover will be an internal combustion engine (ICE), heat will be recovered by means of plate exchangers, and cold will be obtained by a Li-Br absorption chiller. A detailed energy analysis was previously made [14] to select a small Reverse Osmosis (RO) plant as the desalination technology to provide water. Figure 3 shows the energy flows for the selected scheme studied here, including extra equipment needed when demands are not fully covered by the integrated scheme (note that power and water could be sold to their respective networks).

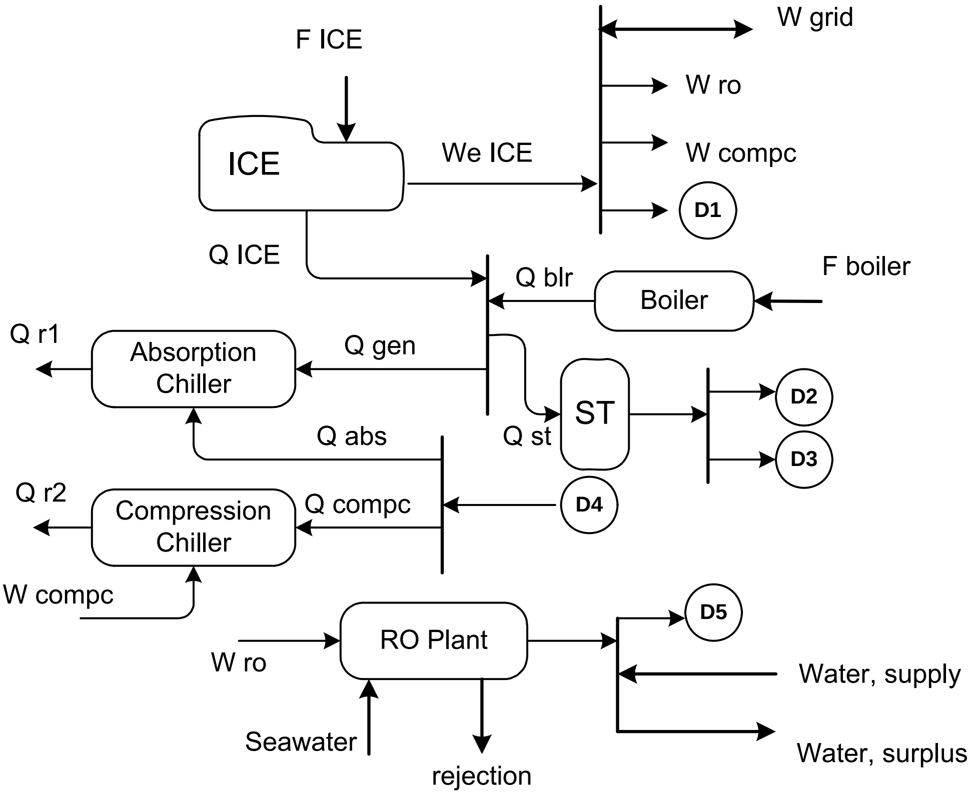


Figure 3. Complete polygeneration scheme proposed for the hotel.

In order to choose the first sizing of that equipment, methodology adopted in [15] was taken, in which the curves of the annual covered demand are constructed multiplying the number of hours per year of each demand by the capacity required as a function of the capacity of the equipment. Peaks of those curves will be the initial size of the plant (see figure 4 for the annual heat demand covered by the ICE). The selected values will be given in table 7 (called case base).

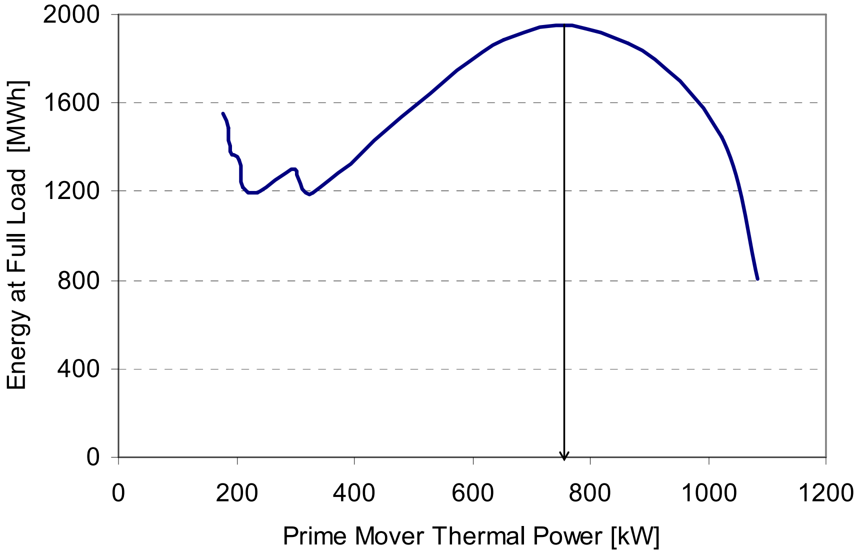


Figure 4. Annual heat demand curve covered at full load by the ICE.

OPTIMIZATION PROCESS

A simple model (see [14] for details) was applied, containing the heat recovered and fuel consumed by the ICE depending of its size, energy parameters, and diverse inequalities analyzing if power, heat, cold and water demands are covered (or not) by the polygeneration scheme. Power and water surpluses are also analyzed; in that case benefits will be calculated.

As the objective function is an economic-type one, actualized purchase and O&M costs are required for the equipment required. Table 5 shows that parameters:

$$C_{eq}(i) = a \cdot P(i)^{b} \cdot CI \qquad (8)$$

$$CI = \frac{25{,}003 \cdot y_p - 48889}{25{,}003 \cdot y_b - 48889} \qquad (9)$$

Table 5. Cost coefficients and O&M cost for main equipment.

Equipment	a	b	y	O&M cost
ICE	3036	-0,272	2001	0,009 [€/kWhe]
Absorption chiller	10637	-0,6123	2005	0,001 [€/kWhc]
RO unit	4447,6	-0,2654	2005	0,1 [€/m^3]

Total investment includes an additional percentage of 28% for piping, control, civil works, indirect costs, other services, and so on:

$$C_{Teq} = \sum_{i=1}^{neq} C_{eq}(i) \qquad I_T = 1{,}28 \cdot C_{Teq} \tag{10}$$

Operating costs of the new polygeneration scheme are calculated month by month:

$$C_{CHCPW} = \sum_{i=1}^{12} C_{Tmonth}(i) \tag{11}$$

$$C_{Tmonth}(i) = C_{ng\_ICE}(i) + C_{ng\_boi}(i) + C_{e,imp}(i) + C_{O\&M}(i) - \left[C_{e,\exp}(i) + C_{dw}(i)\right] \tag{12}$$

where power and desalted water are considered as incomes if water and power surpluses are available. Table 6 includes applied energy and water prices.

Table 6. Operating unitary costs.

Resource	Unitary cost (p)
Natural gas	0,021586 €/kWh
Electricity, imported	0,079771 €/kWh
Electricity, exported	0,0988 €/kWh
Water, imported	1,3 €/m^3
Water, exported	1,17 €/m^3

Benefit obtained with the polygeneration scheme is calculated by comparing the costs of the alternative conventional scheme (see eq. 13):

$$YB = C_{TC} - C_{CHCPW} \quad C_{TC} = C_{e,n} + C_{ng} + C_{e,c} + C_{w,n}$$

(13)

Now, the net present value (NPV) of the installation is taken as the objective function [16], once time that the total investment (I_T) and yearly benefit (YB) were calculated. Interest rate (r) taken was the 5%, and life time expected for the analysis (n) was 15 years. The objective function has three degrees of freedom: ICE power, absorption chiller and RO capacity.

$$\min NPV = -\left(-I_T + YB \cdot \left[\frac{(1+r)^{n-1}}{r(1+r)^n} \right] \right) \qquad (14)$$

Optimization method required here has to manage non-linear objective functions, and equality and non-equality constraints. So, and after an in-depth analysis, the SQP (Sequential Quadratic Programming) method, available in Matlab Optimization Library package [17], was used for the process. Table 7 shows the main results obtained.

Table 7. Main results of the optimization process by using the SQP method.

	Base case	Optimum	Unit
W_{ICE}	576,57	783,03	kWe
Q_{abs}	490	571,41	kWf
DC_{RO}	15	15	m^3/h
SRT	9,14	8,50	years
NPV	130730	241550	€
IRR	6,93	8,11	%

DETAILED ANALYSIS OF THE PLANT PERFORMANCE

Once the design optimization of the polygeneration scheme is performed, a more detailed analysis, including daily profiles (hour by hour) is required, in order to find out the operation strategy of the plant, taking into account the existing regulation.

As a first step, real equipment is selected for the scheme (the closest existing devices to the optimum previously obtained), then:

- The ICE is the *package NUTEC-800* with *Perkins engine 4016-TESI*, with a power rate of 810 kWe and a heat rate of 1141 kWt.
- The absorption chiller is the model *Ibersolar LWM-K019*, with a rate capacity of 630 kWc, water is chilled from 12ºC to 7ºC with hot water at 95ºC.
- *Filmtec Dowtex* membranes are taken for the RO unit.

A new optimization process in order to find out the best operating point for the 8760 hours of the year is not possible (due to time computing constraints), so the main parameters of the plant performance have been evaluated for energy and water hourly demands per month (see figure 5 for heating and cooling demands, as an example).

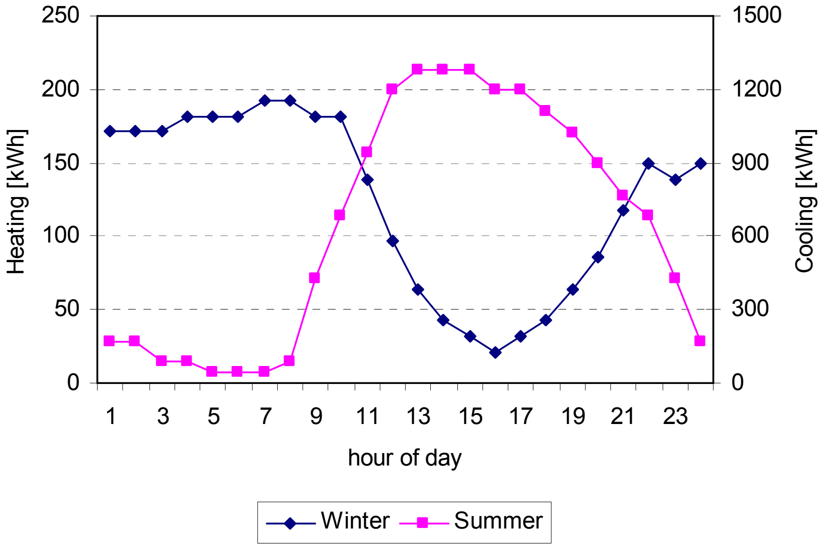
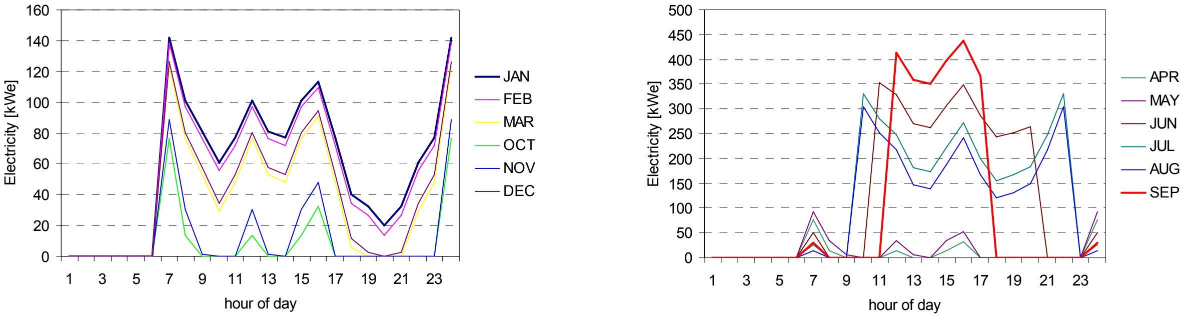


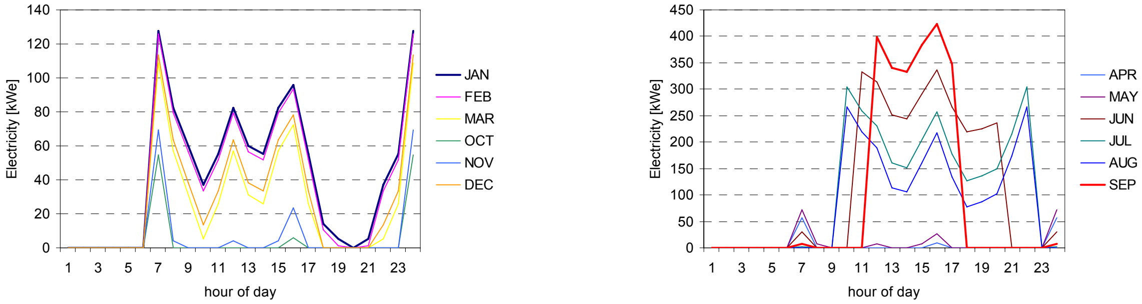
Figure 5. Typical heating and cooling demands for a winter day (january) and summer day (august).

The results shows that ICE operates only 18 hours per day, since from 1 to 6 in the morning heat demand is so low. Figure 6 shows, as an example, power exported to grid following the same operating rules adopted for the optimization scheme.



a) during the week day type, winter period

b) during the week day type, summer period

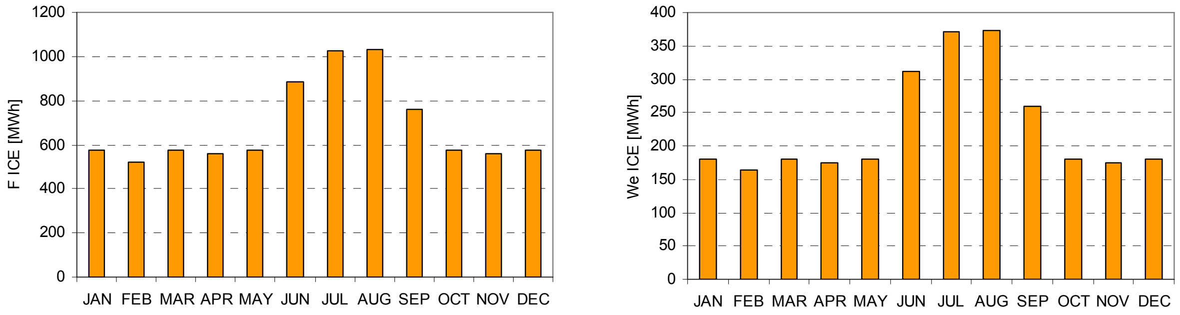


c) weekend day type, winter period

d) weekend day type, summer period

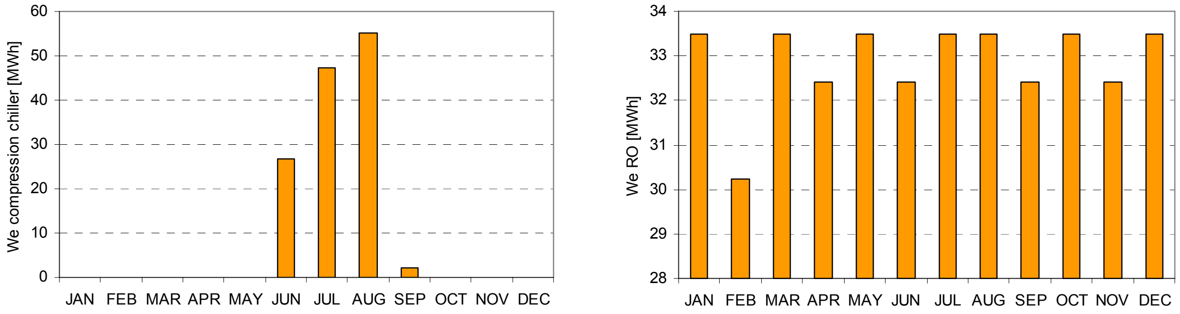
Figure 6. Exported power profiles in the poligeneration scheme.

Total monthly results are resumed in figure 7. It is important to note that the system is only working at full load from June to September, since as aforementioned heat demand falls in winter season significantly.



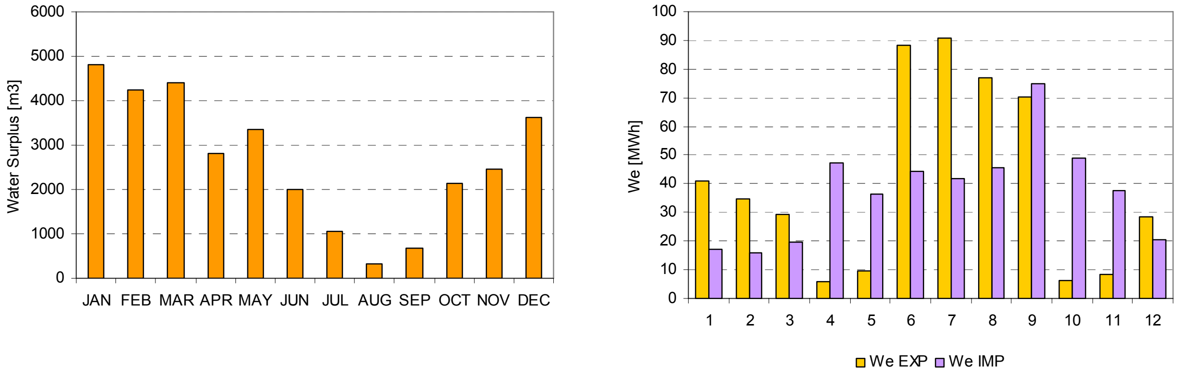
a) Natural gas consumed by ICE

b) Power produced by ICE



c) Power consumed by auxiliary chiller

d) Power consumed by RO unit



e) Desalted water sold to network

f) Exported and imported power

Figure 7. Main consumptions and surpluses, grouped by month.

Table 8 shows the main efficiency and operating parameters of the polygeneration scheme, taking into account that winter period is November-April, and summer period is considered from May to October. The obtained values remark that efficiency parameters (like PESR or EEE) when absorption chiller is not used do not reach the expected values.

Table 8. Efficiency and operating parameters of the plant

Parameter	Winter	Summer	Annual	Unit
$CHPH_\eta$	**26,18**	39,40	33,96	%
$CHPE_\eta$	31,38	34,56	33,25	%
OE	**57,21**	66,62	62,74	%
EEE	**44,01**	53,69	49,46	%
PESR	**-6,94**	12,84	5,65	%

Finally, economic results are summarized in table 9. Note that NPV and IRR values are improved with respect to the design optimization, which considered a constant hourly demand profiles per month.

Table 9. Main economic results of the hourly analysis.

Concept	Value	Unit
Total investment	1.216.800	€
Conventional expenditure	373386	€/year
Polygeneration expenditure	208491	€/year
Benefit	164895	€/year
Simple return time	7,37	years
Net Present Value	494790	€
Internal rate of Return	10,54	%

CONCLUSIONS AND REMARKS

After analyzing the results obtained in the sequence of processes followed in this paper, we could argue that:

- RO is lightly favourable than other desalination techniques (see [14]) to perform polygeneration schemes for the tourist sector, in the sense that from the point of view of energy efficiency, all power produced should be destined to produce desalted water.
- The use of the HDD and CDD (heating and cooling degrees-day) is useful to first estimate acclimatization demands without any significant error (less than 5% of difference with respect to fuel, water and electricity bills).
- First design based on the maximum heat demand annually covered gives lower capacities than the economic optimum based on NPV maximization, since electricity and water bonus for surpluses, as well as better efficiencies for the equipment are found for higher equipment capacities. PESR found is not very high (9.16%), but integration provides energy savings with respect to the conventional supply of the four demands.
- Optimization method applied (SQL method) is valid to deal with non-linear objective functions and equality/inequality constraints, with a quite reduced computing expenditure and simplicity.
- The detailed analysis of the selected polygeneration scheme shows that the ICE should stop by night. Anyway, main energy and economic parameters are improved with respect the averaged monthly analysis if it is performed hour by hour.

It is also noteworthy to say that some guidelines are yet opened in this work, as for instance:

- To study the low-heat demand periods (winter), with the analysis of an hybrid scheme for producing desalted water (by means of an additional MED unit consuming heat recovered by the ICE in this period).
- Starting from the design optimization presented here, try to really optimize the operation strategy of the scheme, including the 8760 hours of the year.
- To know the real energy costs of water, electricity, heat and cold since only one fuel is consumed in the plant. Exergy analysis is the most appropriate technique to do that.
- To study the advantage of storing water in low-demand periods, from the point of view of energy and economics.

NOMENCLATURE

a	Base coefficient (equipment costs)
b	Exponential coefficient (equip. costs)
C	Cost [€]
CDD	Cooling Degree-Day
CI	Cost Index
CHPHη	Polygeneration heat efficiency
CHPEη	Polygeneration electricity efficiency
CHCPW	Combined Heat, Cold, Power, Water.
COP	Coefficient of OPeration
Cp	Heat specific Capacity [kJ/kg·K]
CWe	Electricity for Cooling [kWh]
D	Demand [kWh or m^3]
DC	Desalination Capacity [m^3/h]
EEE	Electrical Equivalent Efficiency
F	Fuel consumption [kWh]
HSW	Hot Sanitary Water
HDD	Heating Degree-Day
ICE	Internal Combustion Engine
IRR	Internal Rate of Return [years]
kWc	Cold power
kWe	Electricity power
kWt	Heat power
MED	Multiple-Effect Distillation
MSF	Multi-Stage Flash distillation
n	Number of years
np	Number of persons
neq	Number of devices
NPV	Net Present Value [€]
OE	Overall Efficiency polyg. scheme [%]
OR	Occupancy Rate [%]
PESR	Primary Energy Saving Ratio [%]
Q	Thermal load [kWh]
r	Interest rate [%]
RO	Reverse Osmosis
SQP	Sequential Quadratic Programming
SRT	Simple Return Time [years]

T	Temperature [ºC]
Tb	Balanced temperature [ºC]
Ti	Indoor temperature [ºC]
To	Outdoor temperature [ºC]
UA	Overall heat transfer coeff. [kW/K]
W	Power [kW]
WC	Water Consumption
We	Electricity [kWh]
WV	Water Volume [m^3]
YB	Annual Benefit [€/year]
	SUBSCPITS
abs	absorption
b	bought (year)
boi	boiler
c	cooling
d	design
dw	desalted water
e	electricity
eq	equipment
exp	exported
h	heating
i	Inlet
imp	imported
n	network
ng	natural gas
O&M	Operation and Maintenance
p	present/preparation
T	Total
TC	Total Conventional
w	water
	GREEKS
Δt	Time [hour/month]
ρ	Density (kg/m^3)

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