Desalination and Water Treatment
www.deswater.com

7 (2009) 132–141

1944-3994 / 1944-3986

Polygeneration plants to supply energy and desalted water in hotels located at the Spanish coast

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Received 30 September 2008; accepted in revised form 27 May 2009

ABSTRACT

The Mediterranean area is a very suitable location for tourism, and every year the arrivals to the Mediterranean are continuously augmenting. This fact represents an economic growth but it is associated with the consumption of natural resources to provide energy and water demands, especially in summer due to the high occupancy rate in tourism destinations. Power consumption derived from the massive use of air conditioning systems is sometimes causing problems in grids. Moreover, fresh water supply is more and more difficult to assure in the Mediterranean area, and desalination is becoming the alternative to surface and ground waters. Therefore, there is a clear need to confront the above-mentioned problems. Polygeneration systems can be a means to provide the energy and water with more advantages than individual conventional systems. Their main benefit is the primary energy saving (PES) obtained because of their higher overall efficiencies, which could be even increased with integrated renewable systems and their associated reduction of greenhouse gases (GHG) emissions. Furthermore, dependency and losses of power and water grids are considerably reduced, contributing to the "*distributed generation concept*" usually only pursued to electricity issues but followed by the UE. In this paper an in-depth optimization sequence of the design of a polygeneration plant has been carried out. It provides simultaneously power, heat, cold and desalted water to a hotel located in the Spanish Mediterranean coast. The main aspects investigated here are: hotel location, desalination process, operation mode (following heat/power demand, or full load operation), and legal issues as the possibility of selling water and power surpluses. According to polygeneration scheme constraints, only two types of desalination plants were considered: LT-MED and RO units. The results show that the first two above mentioned points mainly affect the plant design and definite configuration (that is, which the technologies and capacities which are more convenient for the selected hotel); and the last two points (operation mode and legislation) only have strong influence on the plant feasibility once polygeneration plant was designed. Recent optimization techniques have been used to conclude those results, which could be exported to similar multiple-demand installations.

Keywords: MINLP optimization; Polygeneration; Integration; Energy saving; Tourism

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Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

1. Introduction

Tourism is very important for the economy in the Mediterranean area. Spain is maybe the most representative country, since in 2006 it received more than 58 million tourists (2nd in the world, after France) supposing the 10.8% of its Gross Domestic Product (GDP) and the 12.7% of its working population [1]. However, its continuing growth may jeopardise the achievement of sustainable development and, unless properly managed, may affect social conditions, cultures and local environment of those areas; it may also reduce the benefits of tourism to the local and wider economy. The European Mediterranean countries have scarce energy resources, producing only the 26% of their primary energy demand; furthermore, water scarcity is increasing every summer season with tourist pressure and pessimistic estimations derived from the climate change predictions.

Trigeneration plants (CCHP) and dual-purpose power and desalination plants (DPPW) are being used to provide energy (power, heat and cold) and water respectively with better thermodynamic and economic efficiencies than single purpose power/heat generation and/or water production plants. Derived from this, integration of a CCHP with a desalination plant (CCHPW) could improve even more those efficiencies and other related parameters. These innovative and energy-efficient systems are really a kind of polygeneration systems, where more than one of primary energy sources and end energy uses are feasible in the same scheme. Their main benefit is a higher overall efficiency compared to the baseline systems and improved reliability of supply and distribution networks [2]. Use of desalted water as an energy storage is an additional advantage that CCHPW systems have with respect to CCHP or DPPW schemes.

In earlier papers the potential to implement a polygeneration scheme in the hotel sector has been proved [3–5]. Following this research line, the synthesis and design of a polygeneration system is analyzed here: the effect of some aspects, such as hotel location, type of desalination plant, operation mode and legal framework, was studied. It is the first part of a systemic procedure that also includes the optimization of the operation of the CCHPW system selected with this approach.

The general procedure to carry out the study is based on these main steps:

- Estimation of energy and water demands for the selected locations. This information will be considered as input data to the optimization model.
- A polygeneration system is proposed. In this paper, an ICE is selected as prime mover device, a single effect LiBr-H_2O absorption chiller provides chilled water, plate exchangers to produce heat and finally an small desalting unit.
- Construction of an optimization model including binary variables to select the desalination unit (LT-MED or RO) and the operation mode of the scheme.
- Solution of the optimization model and results analysis.

Specific software has been used to deal with this complex problem that incorporates an economic objective function to maximize the net present value (NPV) of the proposed CCHPW scheme.

2. Energy and water requirements

As a base case, a typical Mediterranean tourist complex was taken for the analysis, with a total constructed surface of 20,000 m^2, but only 12,000 m^2 of it are completely acclimatised. Detailed information about demand profiles is not available, since only water, electricity and fuel bills were previously obtained for a hotel located in Tarragona. This hotel represents typical behaviour in power and water consumption of the Spanish coast. For heating (including hot sanitary water, HSW) and cooling demands, the method described in [6] that uses the concept of heating and cooling degree-days has been applied, which also considers design temperatures and empirical factors that include the influence of solar gains, wind and some other thermal insulating effects. Since the scope of the study is not focused on energy demand calculations, only monthly demands were obtained (approach valid only in the early stage of the study, when sizing the capacity of the diverse devices that performs the CCHPW system).

2.1. The hotel location

The same building can present different benefits for different locations, mainly due to weather conditions. To assess the effects of this change (the location), electrical, DHW, and water demands are kept constant (Fig. 1). Regarding heating and cooling demands (Figs. 2 and 3, respectively), six Spanish cities were selected to assess the location effect and occupancy rate: three cities repre-

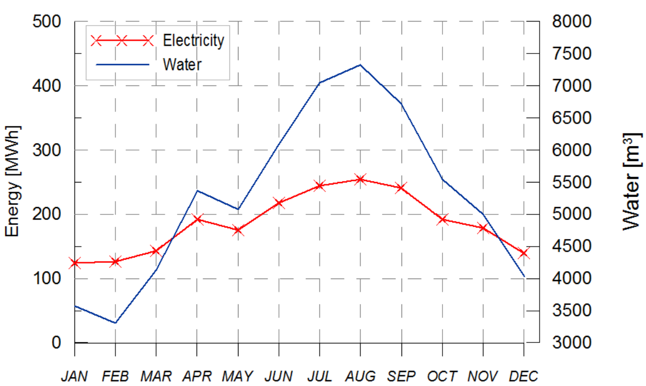

Fig. 1. Evolution of electricity and water demands during the year.

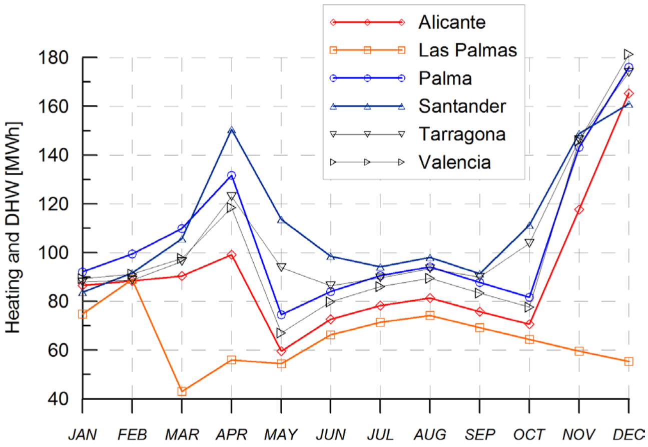

Fig. 2. Heat requirements for the cities under study.

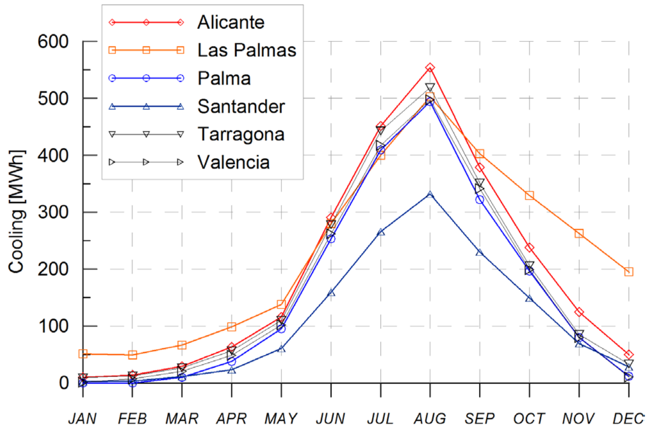

Fig. 3. Cold requirements for the six Spanish coastal cities studied here.

Table 1
Annual costs (€/year) of individual CCHPW scheme

Alicante	334,307
Las Palmas	330,912
Palma	335,735
Santander	335,534
Tarragona	335,182
Valencia	335,412

senting the Mediterranean coast (Alicante, Valencia and Tarragona), one representing the North coast (Santander) and two cities located in the Balearic Islands (Palma de Mallorca) and Canary Islands (Las Palmas).

Annual costs (in €/y) to cover these requirements throughout the use of conventional systems (i.e. electricity from the grid, natural gas from the local supplier and water from local network) are presented in Table 1. Now, the integrated CCHPW system is proposed.

3. Problem statement and system proposed

The main goal of the work is to determine the best CCHPW configuration that would satisfy the energy and water requirements (Figs. 1–3) for the selected locations. The obtained configuration must be profitable compared to the conventional systems and also must achieve primary energy savings (PES) and greenhouse gases (GHG) emission reduction.

Fig. 4 shows the general structure of the proposed configuration. It consists of an internal combustion engine (ICE) fed by natural gas as a prime mover device, a single-effect lithium bromide water absorption chiller (LBSE) as a base load cooling device and a desalination plant (RO or LT-MED) to supply water. Heat recovered from the ICE feeds both the heating and HSW demands and the LBSE, and when LT-MED plant is selected, part

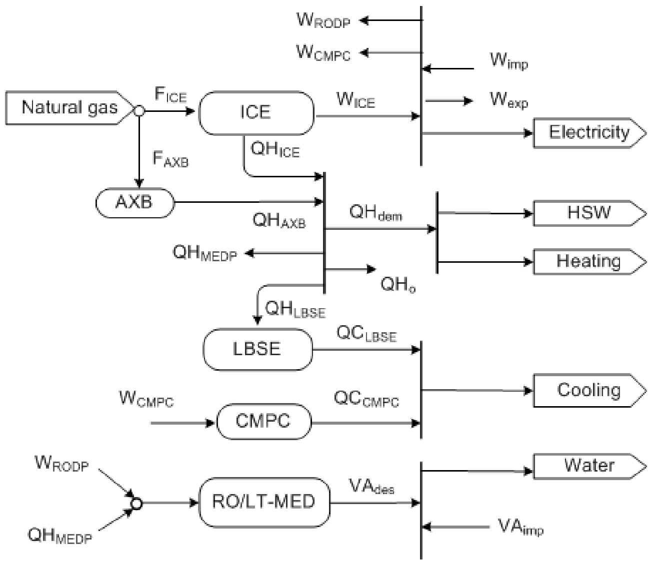

Fig. 4. Scheme of the system proposed considering both alternatives to desalt water.

of this heat is also consumed to activate the plant; if heat deficit is detected it is covered by an auxiliary boiler. Cooling deficit is covered by means of a compression chiller (CMPC). Electricity produced by the ICE supplies the internal power and both CMPC and RO plant (if it was selected). Power and water deficits will be provided from the grid and water supply network respectively. Hypothetical electricity surpluses are delivered to the grid.

3.1. Type of desalination plant

Only two types of desalination plants were considered due to specific characteristics of available heat to activate them: the LT-MED and RO units. Literature shows generally that RO has advantages over other desalination technologies [7]; but when properly integrated with power producer, the options that are not so clear. The optimization model will investigate this fact.

3.2. Operation mode of the scheme

In a polygeneration system, operation strategy usually follows one of the diverse demands: Heat tracking mode (HTM) follows heat demand, and electricity tracking mode (ETM) — the electricity demand. Other option is a full-load operating mode (FUL) of the ICE. These three options are the most implemented ones [8]. The operation mode has a direct effect on the economy, energy savings and GHG emissions of the polygeneration system leading to different conclusions.

3.3. Legal framework

Legal framework is another aspect affecting the viability of a polygeneration system. In the case of Spain, apart from Special Regime for power cogeneration [9] and the European CHP Directive [10] that impose the fulfilment of technical aspects and environmental issues, if surplus of desalted water could be sold to the local water company, the viability of the polygeneration plant increases considerably.

The feasibility analysis will be carried out under the following assumptions:

- Temperature levels of the prime mover fit thermal requirements of each technology (absorption chiller, LT-MED plant, heating and hot sanitary water demands); further details can be found in [11,12]).
- Electricity surplus or deficit can be sold or bought from the electricity grid.
- The boiler and the electric chiller from the existing installation will be used as auxiliary equipment and therefore they will not be included in the investment costs.
- Each piece of equipment can operate either at partial load or full load assuming a constant value. (Typical values and performance at partial load can be found in [13])
- Water surpluses could be generated or not (depending on the legal framework), and water deficit could be covered with water from the local network.

4. Optimization model

4.1. Objective function

The objective function to evaluate the feasibility and the best configuration is the net present value (NPV), and it is expressed as follows:

$$\mathrm{NPV} = \left\{\mathrm{CF}_{\mathrm{con}} - \left(\mathrm{O}_{\mathrm{cost}} + \mathrm{OM}_{\mathrm{cost}}\right)_{\mathrm{pol}}\right\} \cdot f_{\mathrm{act}} - \left(1 + f_{\mathrm{cost}}\right) \cdot I_{\mathrm{tot}} \quad (1)$$

Annual cash flow (CF) is the difference of the cash flow obtained by using conventional systems and the polygeneration scheme. The cash flow of the polygeneration plant is composed by the operational costs (cost for natural gas, imported electricity, and water and profits derived from selling power and water surpluses) and operation and maintenance costs (O&M), as follows:

$$\begin{aligned} \mathrm{O}_{\mathrm{cost}} &= c_{\mathrm{ng}} \cdot \sum_p \left(F_{\mathrm{ICE}} + F_{\mathrm{AXB}}\right) \cdot t_p + c_{ep} \cdot \sum_p W_{imp,p} \cdot t_p \\ &\quad + c_{\mathrm{agp}} \cdot \sum_p VA_{net,p} \cdot t_p - c_{es} \cdot \sum_p W_{\exp,p} \cdot t_p \end{aligned} \quad (2)$$

O&M costs are composed by the costs originated from ICE, LBSE and by either the RO or MED desalination plant operation:

$$\begin{aligned} \mathrm{OM}_{\mathrm{cost}} &= \mathrm{OM}_{\mathrm{ICE}} \cdot \sum_p W_{\mathrm{ICE,p}} \cdot t_p + \mathrm{OM}_{\mathrm{LBSE}} \cdot \sum_p QC_{\mathrm{LBSE,p}} \cdot t_p \\ &\quad + \sum_{\mathrm{des}} \left(\mathrm{OM}_{\mathrm{des}} \cdot Y_{\mathrm{des}}\right) \cdot \sum_p VA_{\mathrm{des,p}} \cdot t_p \end{aligned} \quad (3)$$

Investment in equipment is calculated as a linear function of their main design parameters, (i.e. power output for the ICE, cooling capacity for the LBSE and daily water production for desalination plants), in Eq. (4) an index cost ($I_{\mathrm{ms,u}}$) is used to update the investment costs.

$$\begin{aligned} I_{\mathrm{tot}} &= \left(a_{\mathrm{ICE}} \cdot P_{\mathrm{max,ICE}} + b_{\mathrm{ICE}}\right) \cdot I_{\mathrm{ms,ICE}} \\ &\quad + \left(a_{\mathrm{LBSE}} \cdot P_{\mathrm{max,LBSE}} + b_{\mathrm{LBSE}}\right) \cdot I_{\mathrm{ms,LBSE}} + \\ &\quad + \sum_{\mathrm{des}} \left(a_{\mathrm{des}} \cdot P_{\mathrm{max,des}} + b_{\mathrm{des}}\right) \cdot I_{\mathrm{ms,des}} \cdot Y_{\mathrm{des}} \end{aligned} \quad (4)$$

In the above equations the following sets are defined:

$\forall p \in \mathrm{PERIODS}$,

$\mathrm{PERIODS}=\{\mathrm{JAN,FEB,...,DEC}\}$

$\forall u \in \mathrm{UNITS}$

$\mathrm{UNITS}=\{\mathrm{ICE,LBSE,RODP,MEDP}\}$

$\forall \mathrm{des} \in \mathrm{DESALTERS}$

$\mathrm{DESALTERS}=\{\mathrm{RODP,MEDP}\}$

Prices considered for the analysis were 21.34 €/MWh for natural gas; 79.77 and 98.8 €/MWh for power purchased and sold respectively, and 1.3 €/m^3 for potable water from the local network [14]. The O&M costs considered are tabulated in Table 2. Data for coefficients a_u and b_u obtained by means of linear regression are valid only for a small scale range, i.e. 100 kW–1 MW for power generation. They are expressed in €/kWh, except those marked with (*) expressed in €/m^3. For the ICE the electric performance is the main parameter (MP) and thermal performance is the secondary parameter (SP). For the LBSE and desalination plants the coefficient of performance (COP) and the inverse value of the specific consumption (SC) are used as the main parameters, respectively.

In order to calculate the actualization factor (f_{act}), it

Table 2
Parameters and other information used in the model

Equipment	a_u (€/P_{max})	b_u (€)	$I_{ms,u}$	O&M	Main parameter	Secondary parameter	PL_{min}
ICE	268.8	155306	1.19	0.01	0.36	0.46	0.4
LBSE	122.9	58785	1.07	0.0057	0.7	—	0.2
RODP	7970.4	35196	1.01	0.13*	1/4	—	0.7
MEDP	25440	0	1.01	0.1*	1/50	—	0.6

is assumed an interest rate of 5% and a life time for the equipment of 15 years. An installation factor (f_{cost}) of 38% additional to the investment cost, takes into account installation costs, piping, and storage vessels.

4.2. Equality constraints

Equality constraints are derived from the energy and mass balances and the performance parameter of each device, in this work equality constraints are grouped according to the main device of the polygeneration plant.

4.2.1. Desalination plant (RODP or MEDP)

Mass balance for desalted water production, water demand DW and water deficit or surplus is expressed as:

$$\mathrm{DW_p} = \mathrm{VA_{des,p}} + \mathrm{VA_{imp,p}} \tag{5}$$

Desalted water production at part load is modelled as:

$$\mathrm{VA_{des,p}} = \sum_{\mathrm{des}} \mathrm{PL_{des,p}} \cdot P_{\mathrm{max,des}} \cdot Y_{\mathrm{des}} \tag{6}$$

For the case of an RO unit the following equation is applied to determine the amount of electrical energy required:

$$W_{\mathrm{des,p}} = Y_{\mathrm{RODP}} \cdot \sum_{\mathrm{des}} \mathrm{PL_{des,p}} \cdot \frac{P_{\mathrm{max,des}}}{MP_{\mathrm{des}}} \cdot Y_{\mathrm{des}} \tag{7}$$

When LT-MED is selected then Eq. (8) is used to determine the amount of the thermal energy to activate the plant:

$$QH_{\mathrm{des,p}} = Y_{\mathrm{MEDP}} \cdot \sum_{\mathrm{des}} \mathrm{PL_{des,p}} \cdot \frac{P_{\mathrm{max,des}}}{\mathrm{MP_{des}}} \cdot Y_{\mathrm{des}} \tag{8}$$

In the above equations $\mathrm{MP_{des}}$ is the main parameter characterizing the energy performance of the desalination technology, i.e. the specific energy consumption. It can be seen also that in Eqs. (6)–(8) a binary variable, Y_{des}, was introduced to select the appropriate desalination technology.

4.2.2. Absorption cooling (LBSE) and auxiliary cooling (CMPC)

For the absorption chiller, the energy balance, the part load equation and the link with the performance parameter (COP) are included in the next equations:

$$\mathrm{DC}_p = \mathrm{COP_{CMPC}} \cdot W_{\mathrm{CMPC,p}} + QC_{\mathrm{LBSE,p}} \tag{9}$$

$$QC_{\mathrm{LBSE,p}} = \mathrm{PL_{LBSE,p}} \cdot P_{\mathrm{max,LBSE}} \tag{10}$$

$$\mathrm{COP_{LBSE}} \cdot QH_{\mathrm{LBSE,p}} = PL_{\mathrm{LBSE,p}} \cdot P_{\mathrm{max,LBSE}} \tag{11}$$

In Eq. (9) the power required by the auxiliary compression chiller to cover a possible deficit is included, situation that can appear mainly in the hottest months with almost the 100% of occupancy rate (August).

4.2.3. Energy balances and prime mover (ICE)

According to Fig. 4, thermal and electrical energy balances are written as:

$$\begin{aligned} QH_{\mathrm{ICE,p}} + F_{\mathrm{AXB,p}} \cdot \eta_{\mathrm{AXB}} &= DH_p + QH_{\mathrm{MEDP},p} \\ &+ QH_{\mathrm{LBSE},p} + QH_{o,p} \end{aligned} \tag{12}$$

$$W_{\mathrm{imp,p}} - W_{\mathrm{exp},p} = DE_p + W_{\mathrm{RODP},p} + W_{\mathrm{CMPC},p} - W_{\mathrm{ICE},p} \tag{13}$$

ICE equations are expressed as a function of the rated power output (P_{max}):

$$MP_{\mathrm{ICE}} \cdot F_{\mathrm{ICE,p}} = PL_{\mathrm{ICE,p}} \cdot P_{\mathrm{max,ICE}} \tag{14}$$

$$\frac{MP_{\mathrm{ICE}}}{SP_{\mathrm{ICE}}} \cdot QH_{\mathrm{ICE}} = PL_{\mathrm{ICE},p} \cdot P_{\mathrm{max,ICE}} \tag{15}$$

$$W_{\mathrm{ICE,p}} = PL_{\mathrm{ICE,p}} \cdot P_{\mathrm{max,ICE}} \tag{16}$$

The use of the binary variable Y_{des} supposes an additional constraint.

$$\sum_{\mathrm{des}} Y_{\mathrm{des}} = 1 \tag{17}$$

Finally, the equations to model the operation modes for HTM, ETM and FUL are respectively:

$$QH_{o,p} \cdot Y_{\mathrm{HTM}} = 0 \tag{18}$$

$$\left(W_{\mathrm{imp,p}} - W_{\mathrm{exp},p}\right) \cdot Y_{\mathrm{ETM}} = 0 \tag{19}$$

$$PL_{\mathrm{ICE,p}} \cdot Y_{\mathrm{FUL}} = 1 \tag{20}$$

For all the above equations a new binary variable have been introduced to activate or deactivate the equation; however as only one operation mode must to be selected, an expression similar to Eq. (17) must be applied.

4.3. Inequality constraints

The optimization model considers inequality constraints imposed by the minimum part load operation of each technology, the current legislation for this kind of plants and the reduction of the environmental impact. In the case of the part load limits for devices, the following restriction is applied:

$$PL_{\min,u} \le PL_u \le PL_{\max,u} \tag{21}$$

Minimum part loads considered here were 40% for the ICE 20% for the LBSE chiller, the 70% for the RO plant and 60% for the LT-MED plant. The upper limit of 100% was considered for both devices.

As early mentioned, two legislations were taken into account: The Spanish Order in Council for Special Regime to cogenerate power [9] and the European CHP Directive [10]. In the case of the Spanish legislation it is necessary to satisfy a minimum Equivalent Electric Performance (EEP) of the 55% when thermal engines are used and natural gas is the burned fuel, for facilities under or equal to 1 MW the minimum required is less restrictive (49.5%). Therefore, the constraint for the minimum EEP and the limit imposed to the electrical power of the engine are:

$$0\,\text{MW} \le P_{\max,\text{ICE}} \le 1\,\text{MW} \tag{22}$$

$$\text{EEP}_{\min} - \text{EEP}_{\text{pol}} \le 0 \tag{23}$$

On the other hand, the CHP European Directive requires at least a 10% of primary energy saving (PES) compared to the appropriate reference case. If facilities have a capacity of less than 1 MW, the requirement is only a positive PES. Thus it can be written as an inequality constraint as:

$$\text{PES}_{\min} - \text{PES}_{\text{pol}} \le 0 \tag{24}$$

To verify that the configuration achieve a GHG emission reduction, the following constraint has been imposed:

$$\Delta\text{GHG}_{\min} - \Delta\text{GHG}_{\text{pol}} \le 0 \tag{25}$$

In the evaluation of GHG emission reduction the emission factors considered were 0.455 $kgCO_2$/kWh for electricity, 0.202 $kgCO_2$/kWh for natural gas, 1.78 and 1.11 $kgCO_2/m^3$ of desalted water for RO and MED plants (the last one considering supplied by residual heat), respectively [14].

4.4. Free-design variables

The main independent free-design variables which will be optimized in the model are the required binary variables and design ones for the devices, ICE power rate, cooling capacity of LBSE and capacity of RO or LT-MED desalination plant that satisfy all the equality and inequality constraints stated above.

4.5. Optimization algorithm

The optimization model is composed by a single objective function, equality and inequality constraints and binary variables to select the appropriate desalination technology and operation mode, resulting in a formulation classified as a mixed integer non-linear programming (MINLP) with the following general form [16]:

$$\begin{aligned} &\min_{x,y} f(x,y) \quad \text{s.t.} \\ &h(x,y) = 0 \\ &g(x,y) \le 0 \\ &x \in X \subseteq R^n \quad y \in Y = \{0,1\}^q \end{aligned}$$

A number of algorithms have been developed to address the MINLP problem and some of them have been implemented in the general purpose algebraic modelling system (GAMS) [17]. DICOP algorithm (based on the outer-approximation algorithm) with CONOPT module as the NLP Solver were selected to address the problem of this work. However, it is worth noting that when there is no availability of MINLP solvers other approach could be employed to deal with the problem through the proper linearization of equations, having in this way a MILP problem [18].

5. Results

Table 3 shows the results obtained solving the optimization model, it can be seen in all cases that LT-MED is the most suitable desalination technology and FUL is the most profitable mode of operation.

With regard to the location, Las Palmas presents the highest NPV and Valencia the lowest one, and the other locations have almost the same value. The values of the power output of the ICE and the capacity of absorption chiller present a similar behaviour. The capacity of the LT-MED desalination plant has the same value for all locations excepting Las Palmas. The EEP and PES satisfy the minimum value imposed in the inequality restrictions but again Las Palmas presents a slightly better performance. The reduction in GHG is on average of 200 tonnes per year. Is worth noting that in the FUL case there is a great amount of heat discharging into the atmosphere and this fact could be reduced by imposed limits to the PES restriction for small installations.

Table 3
Results obtained from the optimization model

Variable	Alicante	Las Palmas	Palma	Santander	Tarragona	Valencia
W^*_{ICE}, kW_e	910.2	1000	869.5	876.2	909.1	868.5
QC^*_{LBSE}, kW_f	272.4	559.1	200	200	239.8	207
VA^*_{RO}, m^3/h	0.0	0.0	0.0	0.0	0.0	0.0
VA^*_{MED}, m^3/h	8.0	7.5	8.0	8.0	8.0	8.0
NPV, M€	2.36	2.65	2.30	2.46	2.38	2.29
EEP, %	49.6	50.8	49.6	49.6	49.6	49.6
PES, %	0.0	1.6	0.0	0.0	0.0	0.0
ΔCO_2, ton/y	224.91	204.52	254.74	262.35	245.92	248.60
Y_{RODP}	0	0	0	0	0	0
Y_{MEDP}	1	1	1	1	1	1
Y_{HTM}	0	0	0	0	0	0
Y_{ETM}	0	0	0	0	0	0
Y_{FUL}	1	1	1	1	1	1

Table 4
Second optimal solution that correspond to the heat tracking mode (HTM)

	Alicante	Las Palmas	Palma	Santander	Tarragona	Valencia
W^*_{ICE}, kWe	700.0	859.5	631.9	639.7	678.8	635.0
QC^*_{LBSE}, kWf	272.4	442.7	200	200	239.8	207
VA^*_{RO}, m^3/h	0.0	0.0	0.0	0.0	0.0	0.0
VA^*_{MED}, m^3/h	8.0	7.45	8.0	8.0	8.0	8.0
NPV, M€	1.47	1.73	1.43	1.57	1.47	1.42
EEP, %	66.7	63.9	68.3	68.5	67.5	68.1
PES, %	15.6	13.9	15.5	16.7	16.1	16.4
ΔCO_2 ton/y	567.02	507.01	594.41	606.42	594.48	586.00
Y_{RODP}	0	0	0	0	0	0
Y_{MEDP}	1	1	1	1	1	1

Table 4 shows the results for the optimization process if only HTM was followed; again it can be seen that for all locations the best desalination technology is LT-MED. In this case the ICE power is reduced with respect to FUL analysis, but absorption chiller and desalination plant remain the same outputs except of Las Palmas with a reduced capacity of 442 kW_f instead of 559 kW_f within the FUL mode. In this case the CCHPW plant reduces its benefits but obtains a maximum in its energy efficiency parameters as PES and GHG emission reduction. Here, the ETM mode has obtained the worst figures and therefore no comments will be made.

In all cases again the LT-MED presents a better opportunity of integration than RO unit, besides of its lower specific consumption. This is due to the fact that thermal demand is increased and consequently the power design capacity of the ICE and consequently the power surpluses sold to the grid at interesting prices, since power demand is maintained. However, in the case of RO desalination plant, delivered power reduces the chance to sell electricity and therefore penalizes the viability of the overall system.

Regarding the possibility of selling water surpluses, Tables 5 and 6 show the results when water surplus is allowed: the optimal results are again obtained for the FLM and the second better alternative is also the HTM. It can be seen that RO technology seems more profitable, except in the case of Las Palmas, where LT-MED shows better results.

6. Conclusions

It can be stated that location and type of desalination plant affects mainly on the CCHPW plant design and configuration, that is, the selection of appropriated technologies and the optimum capacities to cover the required demands; and the operation mode and legislation have a strong influence on the plant feasibility.

Table 5
Results from the optimization model (FLM) considering water surpluses

Variable	Alicante	Las Palmas	Palma	Santander	Tarragona	Valencia
W^*_{ICE}, kW_e	415.1	1000	374.51	381.142	414.12	373.47
QC^*_{LBSE}, kW_f	272.4	13.89	200.0	200.0	239.8	207.0
VA^*_{RO}, m^3/h	UB	0.0	UB	UB	UB	UB
VA^*_{MED}, m^3/h	0.0	23.696	0.0	0.0	0.0	0.0
NPV, M€	2.526	3.502	2.466	2.621	2.540	2.455
EEP, %	49.6	73.1	49.6	49.6	49.6	49.6
PES, %	0.0	18.89	0.0	0.0	0.0	0.0
ΔCO_2, ton/y	17.86	1559.8	47.72	55.3	38.882	41.57
Y_{RODP}	1	0	1	1	1	1
Y_{MEDP}	0	1	0	0	0	0
Y_{HTM}	0	0	0	0	0	0
Y_{ETM}	0	0	0	0	0	0
Y_{FUL}	1	1	1	1	1	1

UB — upper bound (30 m^3/h for the results of this table)

Table 6
Results for HTM and when water surpluses exist

Variable	Alicante	Las Palmas	Palma	Santander	Tarragona	Valencia
W^*_{ICE}, kW_e	265.749	363.32	270.129	247.81	264.715	263.77
QC^*_{LBSE}, kW_f	171.246	267.031	164.776	133.15	152.77	162.86
VA^*_{RO}, m^3/h	UB	UB	UB	UB	UB	UB
VA^*_{MED}, m^3/h	0.0	0.0	0.0	0.0	0.0	0.0
NPV, M€	2.008	2.168	2.067	2.165	2.041	2.047
EEP, %	62.6	59.4	64	65.2	63.8	63.7
PES, %	13.1	10.7	14.01	14.82	13.94	13.86
ΔCO_2, ton/y	148.74	101.46	174.82	187.42	175.85	166.60
Y_{RODP}	1	1	1	1	1	1
Y_{MEDP}	0	0	0	0	0	0

UB — upper bound (30 m^3/h for the results of this table)

Particularly, the following conclusions arose:

- For all the locations studied here, characterized by mild winters, it can be stated that it is possible to implement a CHCPW plant with economic and environmental benefits with respect to conventional individual installations. Simple paybacks periods (SP) obtained are around 6–7 years with the optimum scheme. Water costs of the CHCPW need a cost analysis approximation since four products are supplied to the hotel [4], therefore they are not included in the results.
- Regarding the operation mode, full load mode (FUL) offers the best economic performance and the heat tracking mode (HTM) the best environmental performance. ETM is always the worst solution since thermal storage and dissipative systems necessary in this mode increase the CCHPW investment costs up to non-affordable schemes.
- Contrary to the present inertia for selecting RO as the unique solution for desalting water despite of its lower energy consumption with respect to MED, the imposed restrictions, the higher thermal energy required and the integrated evaluation of the CCHPW system as a whole, provokes that small MED units could offer better benefits from the economic and environmental point of view in those specific CCHPW systems (if water surpluses are not sold to municipality).
- If desalted water surpluses are possible, RO unit is the best alternative for the CCHPW if municipal potable water supply is around 1 €/m^3, in that case RO unit capacity should exceed by far the water demands for the hotel.

Finally, note that since those microgeneration systems are immersed in the list of "active" measures to obtain energy efficient buildings, new subsidies are being proposed in the UE and Spanish legislation that could improve even more the feasibility of the CCHPW systems.

Acknowledgements

The authors wish to acknowledge the financial support for this research project received from the Spanish Ministry of Science and Education (Energy Program) under the POLIMED project (ENE2005-08283).

Symbols

c	—	Price or cost
CF	—	Cash flow, €
COP	—	Coefficient of performance
DC	—	Cooling demand, kW
DE	—	Electricity demand, kW
DH	—	Heating and DHW demand, kW
DW	—	Water demand, m^3/h
EEP	—	Equivalent electric performance, %
ETM	—	Electricity tracking mode
F	—	Fuel, kW
f	—	Actualization or installation factor
FLM	—	Full load mode
GHG	—	Greenhouse gases, ton/y
HTM	—	Heat tracking mode
I	—	Index cost or Investment
MP	—	Main parameter of performance
NPV	—	Net present value, M€
O	—	Operational costs, €
OM	—	Operation and maintenance costs
P	—	Capacity or size
PES	—	Primary energy savings, %
PL	—	Part load
QC	—	Heat flow, cooling, kW
QH	—	Heat flow, heating, kW
SP	—	Simple payback, y
t	—	Time period, h
VA	—	Flow rate, m^3/h
W	—	Electric power, kW
Y	—	Binary variable

Greek

η	—	Efficiency

Subscripts

act	—	Actualization
AXB	—	Auxiliary boiler
c	—	Cooling
con	—	Ref. case (conventional systems)
des	—	Desalination or desalters
ep	—	Electricity purchased
es	—	Electricity sold
exp	—	Exported
h	—	Heat
imp	—	Imported
ICE	—	Internal combustion engine
LBSE	—	Lithium bromide single effect
MEDP	—	LT-MED desalination unit
max	—	Maximum or nominal capacity
min	—	Minimum
ms	—	Marshall and Swift Index
ng	—	Natural gas
o	—	Heat discharged to atmosphere
p	—	Periods
pol	—	Polygeneration
RODP	—	Reverse osmosis unit
u	—	Units

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