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Feasibility analysis of a combined cooling-heating-power and desalted water plant for a non-residential building

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ABSTRACT

A preliminary design of a polygeneration system (combined cooling-heating-power plant with a desalination unit), is proposed for a tourist resort located on the Spanish coast. The well-known trigeneration concept is enhanced to the included production of desalted water, considering for the purpose three different options: Reverse Osmosis (RODP), Multi-effect (MEDP) and a combination of RODP and MEDP units. The preliminary design is obtained with a model established as an optimization problem. The influence of the operation mode is also considered in the analysis. The results show that the integration of an internal combustion engine, a LiBr-H_2O single effect absorption chiller and a MEDP desalination unit is the most suitable configuration. From an economical point of view, the optimal operation mode is achieved when the prime mover works at full load, but in this case, the lowest greenhouse gas (GHG) emission reduction and primary energy savings (PES) are obtained. The second profitable operation mode is the one following the thermal demand which achieves the highest GHG emission reduction and PES.

Keywords

Polygeneration, energy saving, GHG emission reduction, desalination, optimization.

1.Introduction

Tourism is one of the fast growing sectors in the Mediterranean area, and continuing with this growth rate it 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 26% of its primary energy demand; furthermore, 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 [1].

Nowadays trigeneration plants (CCHP) and dual-purpose power-desalination plants are being used to cover energy and water requirements due to better thermodynamic efficiency and economical profit, than the single purpose power generation or water production plants. This fact encouraged the proposal of integrate CCHP with a desalination plant under the premise that it could improve even more the global efficiency and other related parameters, as the authors demonstrated in preliminary studies [2-3].

These innovative and energy-efficient systems are a kind of polygeneration systems, where more

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than one primary energy sources and end-use are feasible. Their main advantage is a higher overall efficiency compared to conventional systems and improved reliability of energy and water supply [4].

In this work, the feasibility analysis of a polygeneration system composed by an internal combustion engine (ICE), a LiBr-H_2O absorption chiller and RODP/MEDP desalination plant, is performed in a non-residential building in order to determine the viability and profitability of the system proposed upon the Spanish regulatory and pricing framework.

2. Estimation of demands

A typical Mediterranean tourist complex (latitude 41.04° N, longitude 1.11° E) was taken for the analysis, with a total surface of 20,000 m^2, including two hotels and an apartment building with up to 452 double rooms (16 suites). Reception, three restaurants, offices and shops are also included, as well as diverse convention rooms. Common areas and rooms are completely acclimatised (its total surface is 12,000 m^2).

Detailed information about demand profiles is not available, since only water, electricity and fuel bills were previously gathered. Since the scope of the study is not focused on high accuracy energy demand calculations, only monthly demands are obtained. Electricity and water demands are estimated from the bills and the occupancy rate along the year. Heating (including hot sanitary water, HSW), and cooling demands are estimated by means of the method described in [5] using monthly heating and cooling degree-days, design temperatures and empirical factors which represents the influence of solar gains, wind and some other thermal insulating effects. The energy and water demands estimations are shown in Figure 1. The annual energy and water requirements are presented in Table 1.

The annual cost 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) is about 335180 € per year, this amount is in good agreement with the one obtained with current bills.

On the other hand, with the purpose of determining the evolution of heating and cooling loads along the year, their corresponding load duration curves were constructed as shown in Figure 2. The load duration curves show the level of the energy demanded and the duration at that level, in this manner a preliminary size of the prime mover and the absorption chiller can be proposed to select a starting point in the optimization model [6].

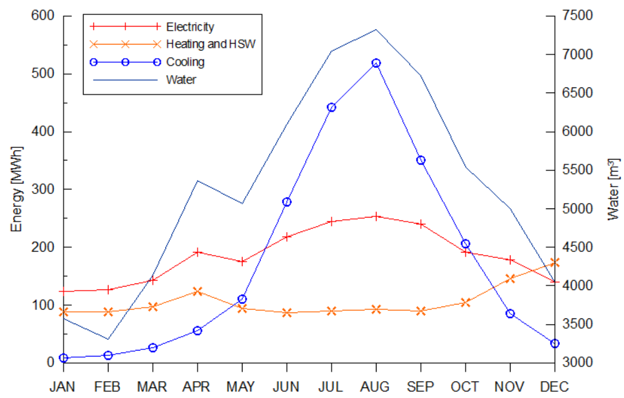

Fig.1: Energy (electricity, heating and cooling) and water (on the right) demands along the year.

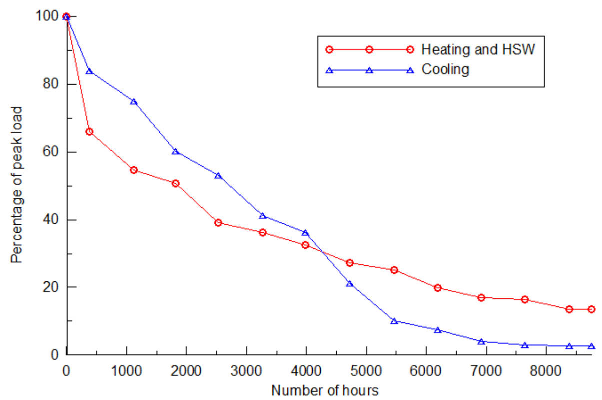

Fig.2: Load duration curve for heating (including HSW) and cooling demands.

Table 1. Annual energy and water requirements for the hotel.

Demand	Value	Unit
Electricity	2228	MWh
Heating and HSW	1273	MWh
Cooling	2130	MWh
Water	63200	m^3

3. Description of the system proposed (problem statement)

The main goal of the feasibility analysis is to determine the best polygeneration configuration that satisfy the energy and water requirements (see Figure 1), is profitable compared to the conventional system and also achieves a PES and GHG emission reduction. Considering the energy and water demands three possible configurations are proposed:

Plant A. CCHP and RODP desalination unit (CCHP+RODP)
Plant B. CCHP and MEDP desalination unit (CCHP+MEDP)
Plant C. CCHP and hybrid desalination unit (CCHP+RODP/MEDP)

Figure 3 shows the superstructure of the proposed configurations, it is composed of an internal combustion engine (ICE) fed by natural gas as a prime mover device, a lithium bromide-water absorption chiller (LBSE) as a base load cooling device and a desalination plant (RODP/MEDP) to supply water requirements. Heat recovered from the ICE will feed both the heating and HSW demands and the absorption chiller, and when MED plant is selected, part of this heat is also employed to activate the plant; if heat deficit is detected it will be covered by an auxiliary boiler. Cooling deficit will be covered by means of a compression chiller (CMPC).

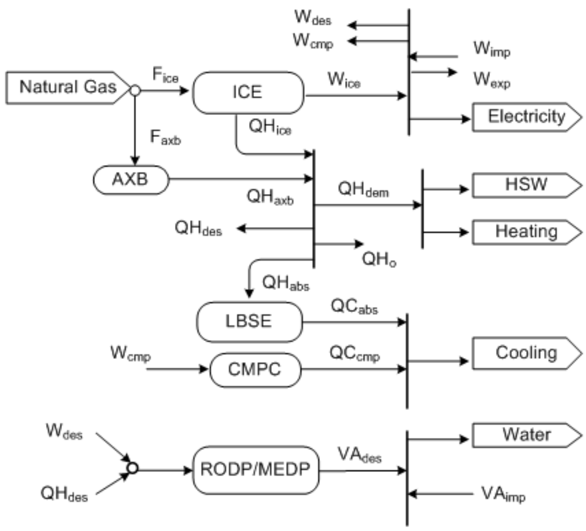

Fig.3: Polygeneration scheme proposed for the feasibility analysis.

Electricity produced by the ICE will supply the internal electricity requirements, both of the compression chiller and the RODP unit (if selected).

Electricity and water deficits will be provided from the grid and water supply network respectively. Hypothetical electricity surpluses could be delivered to the grid

The following set of assumptions is considered in the feasibility analysis:

- Temperature levels of the prime mover match the thermal requirements of each technology (absorption chiller, MEDP unit, heating and hot sanitary water demands, further details can be found in [7-8]),
- Electricity surplus or deficit can be sold or bought from the electricity grid,
- The boiler and the electric chiller from the current installation of the building will be used as auxiliary equipment, so, they will not be included in the investment costs,
- Performance parameters at part load are evaluated on average figures,
- No water surpluses are generated, and water deficit could be covered with water coming from the local network,
- The possible operation modes considered in the analysis are: heat tracking mode, electricity tracking mode and full load mode, although some others can be found as in [6].

4. Optimization model

Objective Function

The objective function to evaluate the feasibility of the proposed polygeneration plant is the net present value, NPV, which can be stated as:

$$\max NPV = \left(CF_{con} - (O_{\mathrm{cost}} + OM_{\mathrm{cost}})_{pol}\right) f_{act} - (1 + f_{\mathrm{cost}}) \sum_{u} (a_u P_{\max,u} + b_u) I_{ms,u} \quad (1)$$

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

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

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

$$O_{cost}=c_{ng}\sum_p F_{ng,p}\cdot t_p+c_{ebuy}\sum_p W_{imp,p}\cdot t_p+c_{wbuy}\sum_p VA_{imp,p}\cdot t_p-c_{esold}\sum_p W_{exp,p}\cdot t_p \quad (2)$$
$$\forall p\in \text{PERIODS},$$
$$\text{PERIODS}=\{JAN,FEB,...,DEC\}$$

The O&M costs are composed by the costs originated from the operation of the ICE, the LBSE chiller and by either the RODP or MEDP desalination unit:

$$OM_{cost}=OM_{ice}\sum_p W_{ice,p}\cdot t_p+OM_{lbse}\sum_p QC_{lbse,p}\cdot t_p+OM_{des}\sum_p VA_{des,p}\cdot t_p \quad (3)$$

The prices considered in the analysis are: natural gas 21.34 €/MWh; electricity (purchased), 79.77 €/MWh; electricity (sold), 98.8 €/MWh and 1.3 €/m^3 for the water from the local network. The O&M costs considered are: 0.9 c€/kWh for the ICE, 0.1 c€/kWh for the LBSE chiller, 13 c€/m^3 of desalted water for the MEDP unit and 10 c€/m^3 for the RODP unit.

In the equation (1) a linear model is used for the investment costs due to its low capacity. Table 2 shows the parameters for each kind of equipment; they are valid only in this small-scale range.

Table 2. Parameters employed in the investment costs of each kind of equipment.

Equipment	**a_u [€/Pmax]**	**b_u [€]**	**$I_{ms,u}$**
ICE	268.8	155306	1.19
LBSE	122.9	58785	1.07
RODP	7970.4	35196	1.02
MEDP	25440	0	1.01

For the actualization factor (f_{act}), it is assumed an interest rate of 5% a life time of 15 years. An installation factor (f_{cost}) of 38% of the total investment cost is added to take into account installation costs, piping, and storage vessels. The Marshall & Swift index cost ($I_{ms,u}$) is used for update the investment costs when necessary.

4.2 Equality Constraints

Equality constraints are derived from the energy and mass balances and the performance parameter of each device. For importing electricity the power balance can be stated as (see Figure 1):

$$W_{imp,p}-\left(D_{e,p}+W_{cmpc,p}+W_{des,p}-W_{ice,p}\right)=0 \quad (4)$$

If power is exported to the grid, the power balance is:

$$W_{ice,p}-(D_{e,p}+W_{cmpc,p}+W_{des,p})-W_{exp,p}=0 \quad (5)$$

For the energy balance (heat flow) the equation is expressed as:

$$QH_{ice,p}+QH_{axb,p}-D_{h,p}-QH_{des,p}-QH_{abs,p}=0 \quad (6)$$

Cooling deficit is obtained by means of:

$$QC_{lbse,p}+QC_{cmpc,p}-D_{c,p}=0 \quad (7)$$

Mass balance for water is expressed as:

$$VA_{des,p}+VA_{imp,p}-D_{w,p}=0 \quad (8)$$

The energy balance for the total fuel required by the plant is:

$$F_{ng,p}-F_{ice,p}-F_{axb,p}=0 \quad (9)$$

Characteristic performance parameters have been used to relate input/outputs in each device. For the ICE thermal output can be expressed as a function of nominal power using the thermal and electrical performance, equation (10), while power and thermal output at part load are defined as in equation (11) and (12), respectively:

$$QH_{\max,ice}\eta_{e,ice}-W_{\max,ice}\eta_{t,ice}=0 \quad (10)$$
$$PL_{ice,p}\cdot W_{\max,ice}-W_{ice,p}=0 \quad (11)$$
$$QH_{ice,p}\eta_{e,ice}-W_{ice,p}\eta_{t,ice}=0 \quad (12)$$

Fuel consumption for the ICE is determined with:

$$F_{ice,p}\eta_e-W_{ice,p}=0 \quad (13)$$

In the case of the LBSE chiller the heat required to drive it, is related through the coefficient of performance (14), and its actual cooling capacity at part load by the equation (15):

$$QH_{lbse,p}COP_{lbse}-QC_{lbse,p}=0 \quad (14)$$
$$PL_{lbse,p}\cdot QC_{\max,lbse}-QC_{lbse,p}=0 \quad (15)$$

The cooling capacity and power required to drive the auxiliary chiller is related through the coefficient of performance (COP):

$$W_{cmpc,p} COP_{cmpc} - QC_{cmpc,p} = 0 \qquad (16)$$

The natural gas required by the auxiliary boiler is obtained using the thermal efficiency definition:

$$F_{axb,p} \eta_{axb} - QH_{axb,p} = 0 \qquad (17)$$

For both the RODP and MEDP desalination plant, the input and the output are related through the definition of specific consumption (SC) according to:

$$E_{des,p} - VA_{des,p} SC_{des} = 0 \qquad (18)$$

In eq. (18), $E_{des,p}$ represents the power required to produce desalted water. It must be considered that the MEDP plant is activated with thermal energy and the RODP plant consumes electricity. In this case part load definition for the desalination unit is:

$$PL_{des,p} \cdot VA_{\max,des} - VA_{des,p} = 0 \qquad (19)$$

In the above equations (10) to (19), the values considered for the performance parameters are: η_e= 36% and η_t= 46% for the ICE; COP_{lbse}= 0.7 for the LBSE chiller; COP_{cmpc}= 4 for the CMPC chiller; SC_{des}= 4 kWh/m^3 for the RODP unit; and SC_{des}= 15 kWh/m^3 for the MEDP unit.

Additionally, to link the optimization model with the energy and water requirements for the three operation modes, we have defined four parameters that will be used as load level indicators; cooling load, water requirement, heat load and electricity load indicators, equations (20) – (23), respectively:

$$LL_{cold,p} = \frac{D_{c,p}}{QC_{\max,lbse}} \qquad (20)$$

$$LL_{water,p} = \frac{D_{w,p}}{VA_{\max,des}} \qquad (21)$$

$$LL_{heat,p} = \frac{D_{h,p} + QH_{des,p} + QH_{lbse,p}}{QH_{\max,ice}} \qquad (22)$$

$$LL_{power,p} = \frac{D_{e,p} + W_{des,p} + W_{cmpc,p}}{W_{\max,ice}} \qquad (23)$$

For illustration, in the case of the cooling load indicator, if $LL_{cold,p}$ is greater than 1, it means that the absorption chiller works at full load and auxiliary cooling is required, otherwise, no auxiliary cooling is required and $LL_{cold,p}$ give the part load level required to meet the cooling load.

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 guarantee reduction of environmental impact. In the case of the part load limits of the equipments, the following restriction is applied:

$$PL_{\min,u} \le PL_u \le PL_{\max,u} \qquad (24)$$

For the ICE the minimum part load value considered is 40%, 20% for the LBSE chiller, 70% for the RODP unit and 60% for the MED unit, an upper limit of 100% is considered in each component.

Two legislations are taken into account: The Spanish Order in Council for Special Regime [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 fuel burned, for facilities under or equal to 1 MW the minimum required is less stringent (49.5%). Therefore, the constraint for the minimum EEP and the limit imposed to the electrical power of the engine are:

$$EEP_{\min} - EEP_{pol} \le 0 \qquad (25)$$

$$0kW \le W_{\max,ice} \le 1000kW \qquad (26)$$

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

$$PES_{\min} - PES_{pol} \le 0 \qquad (27)$$

To verify that the configuration achieve a GHG emission reduction, the resourchers have imposed the following constraint:

$$\Delta GHG_{\min} - \Delta GHG_{pol} \leq 0 \quad (28)$$

In the evaluation of GHG emission reduction the emission factors considered are 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 RODP and MEDP plants, respectively [11].

4.4 Decision variables

The decision variables in the model are the size of the ICE, the cooling capacity of LiBr-H_2O chiller and the capacity of RODP or MEDP desalination plant that satisfy all the equality and inequality constraints stated above.

4.5 Description of the optimization algorithm

For the solution of the optimization problem a commercial optimization package was used. The optimization algorithm employed in the package is based on sequential quadratic programming that leads to solve a quadratic programming sub-problem. It must be mentioned that different starting points were tried in order to prevent local optimums instead of the global one but there is no guarantee that global optimum is attained.

5. Results

The results obtained once the optimization model is solved are shown in Table 3, for space reasons only the results for plant B (best configuration) are tabulated. The results show that the worst configuration is the hybrid plant (CCHP+RODP/MEDP) and the second better alternative is the plant A (CCHP+RODP).

In the case of the plant B, the HTM and FLM cases, show the highest value of NPV, and the ETM case shows the lowest value. Since market equipment does not cover all the capacities, the obtained results could be established as a guide to select the appropriate device.

Regarding the operation mode, the final choice will depend on the restrictions imposed by regulations or local legislation. For the three configurations analysed the most profitable mode of operation is the FLM case (see Figure 4), however in this case a great amount of useful heat is wasted (QH_o), even though the lowest PES and GHG emission reductions are achieved. The high profitability of this case is due to the fact that a high amount of electricity (W_{exp}) is put into the grid. It can be seen also that the cooling covered with the LBSE is around 25 to 57% of the total cooling demand.

Figures 5 to 6 show the evolution of cooling and heating delivered by the best configuration (plant B) compared to the cooling and heating demands (hatched area) for the three operation modes.

6. Conclusions

A feasibility analysis of a CCHP and desalination plant was carried out. The results show that the proposed scheme is viable and a detailed analysis considering hourly demands, variable part load and other effects, can be applied. It is worth noting that the results are very site specific but the procedure employed here can be extrapolated to other locations.

From the above data, we can state that although the RODP consumes less energy than MEDP, due to the imposed restrictions, the very high variability of the demands and the evaluation of the systems as a whole, MEDP unit offers better benefits. From the economical point of view the plant seems to be not quite profitable, but it is necessary to consider the other benefits that it brings: energy saving and GHG emission reduction, in order to state the potential advantages.

The optimization procedure was solved only under economic parameters leading to acceptable results by the imposition of several constraints. However, it is necessary to establish a trade-off between profitability, PES and GHG emission reduction to assure the best configuration and operational mode.

Table 3. Main results for plant B
(CCHP and MED desalination plant).

Optimum values	HTM	ETM	FLM
W_{ICE}* (kW_e)	405	278	529
QC_{LBSE}* (kW_f)	197	60.4	239
VA_{MED}* (m^3/h)	7.4	7.8	8
Other parameters			
NPV (M€)	1.016	0.803	1.521
SP (years)	3,81	4,10	3,18
IRR (%)	25.31	23.3	30.87
EEP (%)	61.66	58.73	49.50
PES (%)	14.66	12.80	1.69
ΔCO_2 (ton/year)	293.35	229.31	131.81

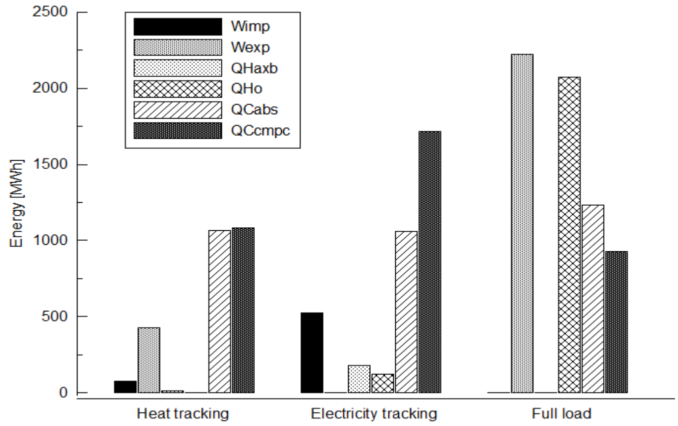

Fig.4: Main parameters for the optimum case showing the three modes of operation.

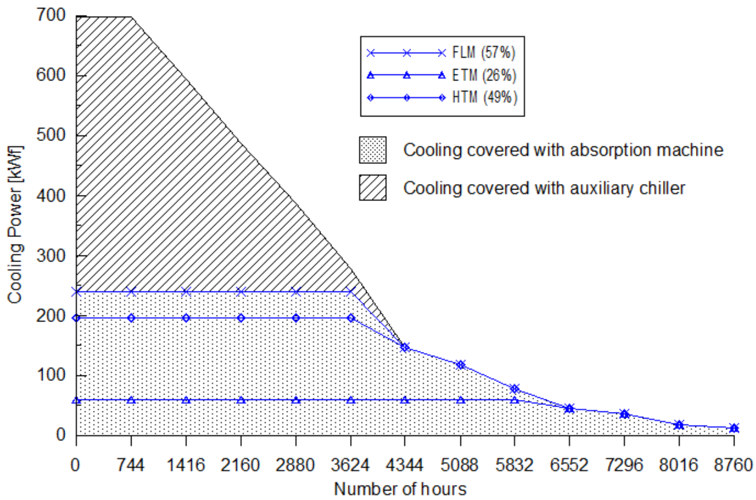

Fig.5: Cooling demand and cooling covered with the absorption machine.

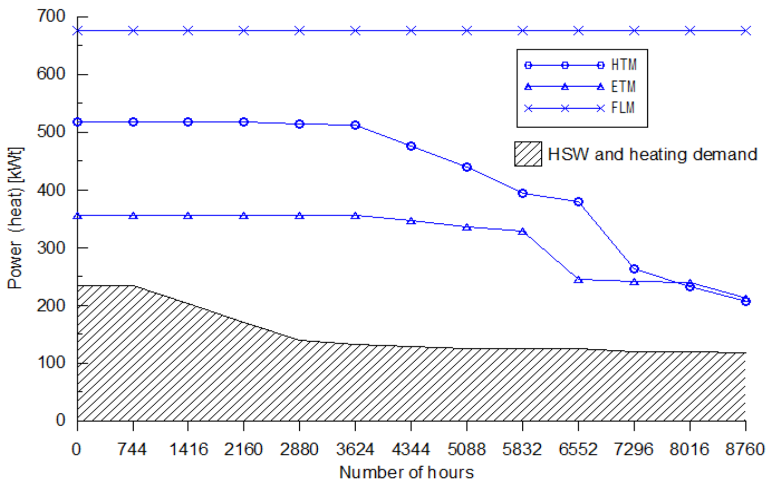

Fig.6: Heating demand and HSW and heat surplus to activate the absorption chiller and MED plant

As polygeneration schemes are one-step-more to CHP and CCHP, it is necessary to define a set of parameters to evaluate the real potential of energy savings and greenhouse gas emission reduction because the legislation does not consider this kind of installation explicitly. Finally, it is important to note that in those configurations, renewable energy can be considered, enhancing in this way the energy saving and GHG reduction.

7. Acknowledgements

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8. Nomenclature

a,b	investment cost factor
c	price or cost [€/unit]
CHP	cogeneration
CCHP	trigeneration
CF	cash flow [€]
CMPC	compression chiller
COP	coefficient of performance
D	demand (energy or water)
E	energy [kW]
EEP	Equivalent Electric Performance
ETM	electricity tracking mode
F	cost factor
F	fuel [kW]
FLM	full load mode
GHG	greenhouse gases
HSW	hot sanitary water
HTM	heat tracking mode
ICE	internal combustion engine
IRR	internal rate of return
LBSE	single effect absorption chiller
LL	load level indicator
MEDP	multi-effect desalination unit
NPV	net present value [€]
O	operational costs [€]
OM	operation and maintenance cost [€]
P	capacity or size
PES	primary energy saving
PL	part load
RODP	reverse osmosis desalination unit
QC	heat flow, cooling [kW]
QH	heat flow, heating [kW]
SC	specific consumption [kWh/m^3]
SP	simple payback [years]
T	time period [hours]
VA	flow rate (m^3/h)
W	electric power (kW)

Greek letters

H	efficiency

Subscripts

Act	actualization
Axb	auxiliary boiler
C	cooling
Cmpc	compression chiller
Con	actual plant-conventional case
Des	desalination
E	electricity
Ep	electricity purchased
Es	electricity sold
Exp	exported
H	heat
Ice	internal combustion engine
Imp	imported
Lbse	single effect absortion chiller
Max	maximum
Min	minimum
Ms	marshal & swift
Ng	natural gas
P	period
Pol	polygeneration
T	thermal
U	unit
W	water
Wp	water purchased

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