District heating and cooling for business buildings in Madrid

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Abstract

Energy needs for heating and cooling in Spain are of paramount interest in the context of the European roadmap to a decarbonized environment; because of that, it is highly desirable that more examples of district heating and cooling networks are developed. The present work evaluates the implementation of one of them into the climatic environment of Madrid. It consists on a complex of business office buildings with a total useful surface of 50,000 m^2, linked with heating and cooling rings of 1 km of loop length. Basic energy needs of buildings leads to the following design values: 1.7 MW of electricity, 1.3 MW of heating and 2 MW of cooling. This will be supplied by the tri-generation plant here proposed, which relies on an internal combustion engine.

The high demand of cooling for air conditioning makes the dimensioning of the engine critical because of the large differences between the heat demand for summer and the one for winter. If the total amount of the cooling demand is covered with an absorption chiller, the heat demand during the summer reaches about 5 MW. In consequence, a critical decision has to be taken relative to the way the cooling demand is attended: with an absorption chiller (one or two effects) or with a conventional chiller powered by electricity. Applying the criteria developed in the present work, which are focused on maximum primary energy reduction, the fraction of the cooling demand to be attended with each technology is determined as a function of the engine nominal power, on the grounds of the instantaneous demand.

The high cooling demand during the summer season suggests the inclusion of a thermal solar collector field, to be used for complementing the waste heat rejection from the engine to drive the absorption chiller. During the winter, the solar heat could be applied in attending a fraction of the heating demand. Thus a hybrid Trigeneration Plant is introduced. This way, the over sizing of the engine can be avoided, as the electric demand is small.

The analysis is based on the solution of energy and mass balance equations for a tri-generation plant. Monthly demands and environmental conditions (ambient temperature and solar irradiance) are introduced as input data into the model. Monthly and annual primary energy consumption and CO_2 emission reductions are obtained as outputs. Economical data, such as fuel and operating costs, electricity prices, tariffs and subsidies are considered in order to optimize the size of the plant in terms of its payback period.

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Keywords

Trigeneration, solar thermal energy, absorption cooling, district heating and cooling.

Introduction

The sizing of Trigeneration Plants (TP) is a complex task. The principal reasons come from the time variability of the energy demands, from the economical environment, which is affected not only by a short payback period requirement, but also from the nowadays regulations and of course, from the decisions needed to adopt for the suitable operation of the power plant [1]. Energy and economy simulations, as they are here presented, aim to help in this task by predicting the time evolution of the TP performances and their economy consequences [2].

Trigeneration turns out to be attractive in business office buildings because of their significant amount of cooling and heating requirements [4]. The time period of these demands is predictable and stable throughout the day and throughout the year. Moreover, many business activity sectors involve buildings with both similar constructive characteristics and final usage, resulting in a predictable demand for complexes and business parks, allowing a local energy network being efficient and of reasonable cost.

The Spanish regulation [5] allows the TP operators to sell not only all the generated electric power, but also the heating and cooling services using private networks in response to the European Council directive [6].

Alternatively, the TP operator may sell the whole electric power generated to a national grid. In this case, special care must be taken on the TP efficiency in order to maximize the economic income; because, as the higher the efficiency is, the higher is the regulated electric feed-in tariff to be perceived.

Nothing about the heating and cooling prices appears in the present Spanish regulation. This way, the TP operator may decide the selling price in order to be economically competitive to the potential clients.

The present work shows an energy and economic model that can be applied for office building complexes in the climatic environment of the outskirts of Madrid City.

Once the electric, heating and cooling demands are determined, the TP layout, based on reciprocating internal combustion engines fed with Natural Gas (NG) and on an absorption chiller, as main components, is proposed. This study considers as backup a boiler and an electrically driven chiller.

Firstly, a theoretical description of the TP is presented. The system of balance equations is completed by the operation conditions. This way the selected energy efficiency criterion allows taking decisions about how the heating and cooling demands can be attended.

The sizing of the TP main components is then considered. Finally, the time evolution of the TP performance is predicted on a monthly basis.

A thermal solar collector field is proposed to produce hot water. Thus the absorption chiller of the TP could attend a higher fraction of the cooling demand. During winter, the solar heat could be applied for attending a fraction of the heating demand. This hybrid proposal is supported by the high solar irradiance availability in the region [7].

Finally, with the purpose of determining the annual profit and the payback period, an economic analysis is performed. Particularities of the Spanish Regulations, such as efficiency based additional subsidiary bonus and schedule discriminations are considered. Specific operating costs and income from generated electric power feed-in tariff, purchase prices and NG tariffs depending on the TP size are also incorporated in the analysis.

Decisions about the hot and cold water selling prices need to be taken, so several proposals are included in the analysis.

Evaluation of electric, heating and cooling demands

The business complex considered is composed of 18 buildings, located in the outskirts of Madrid City, and placed inside a square of 500 m side. The total amount of built useful surface is of 55,000 m^2.

Heating demand, once determined as a function of the ambient temperature and the building envelope characteristics, has been affected by a security coefficient of 1.2. Applying a similar calculation for the cooling demand, a security coefficient of 3 is applied. The reason for the use of those coefficients is the consideration of the year to year variability of environmental conditions in the climatic area, especially during the summer season.

The electric demand has been calculated considering the variability of space lighting throughout the year as a function of the solar time during the working period. Electric demand includes the consumption for the cooling demand to be attended by electrically driven vapour compression chillers of the conventional type.

Figure 1 shows the evolution of the monthly demands throughout the year. The so-called "Heat+Abs" concept, considers the heating demand plus the thermal energy involved in attending the cooling demand by a single effect water-LiBr absorption chiller.

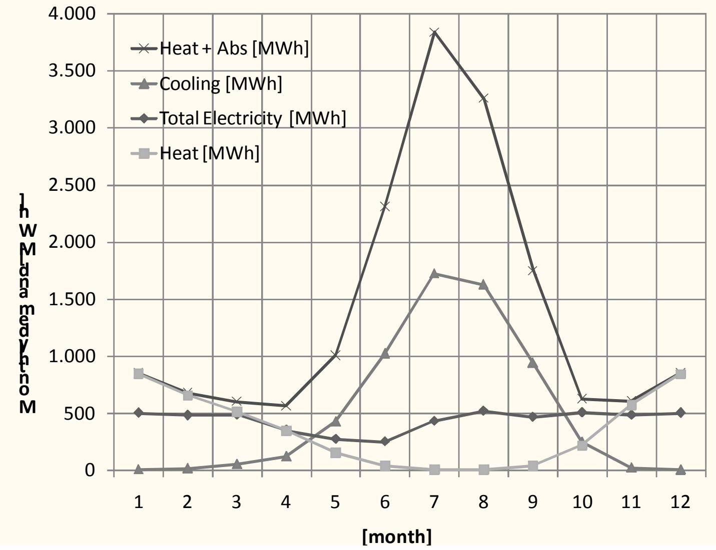

Figure 1: Monthly electric, heating and cooling demands.

In Table 1, the maximum and averaged values of the calculated demands are shown. Those values are applied to the sizing of the TP.

Maximum values:	
Total Electric power [MW]	**1.98**
Heating [MW]	**3.20**
Cooling [MW]	**6.53**
Heating + Abs [MW]	**14.54**

Averaged values:	
Total Electric power [MW]	**1.66**
Heating [MW]	**1.34**
Cooling [MW]	**1.96**
Heating + Abs [MW]	**5.35**

Table 1: Maximum and averaged values of the business park demands

As can be seen in Figure 1, the electric demand is quite uniform throughout the year. The heating/electricity ratio is near 3.2, showing a strong variation throughout the year, with a ratio max/min heating demand of 6 for the case Heat+Abs. This is so because of the high demand of thermal energy needed for absorption cooling. This determines a large nominal power of the engines, which would work at low load or with some of them stopped from November to May.

Conceptual model of TP

The main components of the TP are shown in Figure 2. The hot water distribution network for heating is also included in order to consider the thermal losses of this component, which consists in a simple ring. There is another ring for cold water distribution for cooling, not included in the diagram for clarity, but considered in the calculations in a similar way than the heating ring.

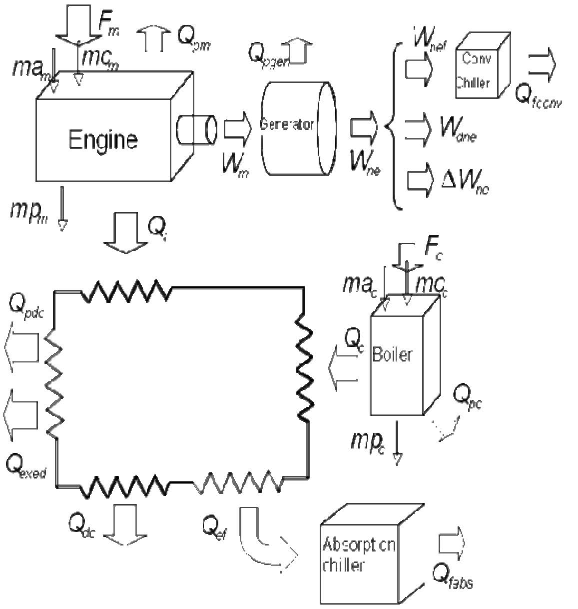

Figure 2: Main components for the conceptual model of the TP.

The equations of the conceptual TP model, which have to be solved in order to calculate the output of the different kinds of energy (Q_{fconv}, ,ΔW_{ne}, Q_{fabs}, Q_{exced}) of the TP for each demand (Q_{df}, Q_{dc}, W_{dne}), are the following:

Energy balance of the engine: $F_m = W_m + Q_r + Q_{pm} + mp_m \cdot cp_a \cdot (T_{em} - T_0)$ (1)

Engine efficiency: $$\eta_m = \frac{W_m}{F_m} \tag{2}$$

Engine primary energy and flows:

$$F_m = mc_m \cdot L_i \tag{3}$$

$$RAC_m = \frac{ma_m}{mc_m} \tag{4}$$

$$mp_m = ma_m + mc_m \tag{5}$$

Energy balance of the generator: $$W_m = W_{ne} + Q_{pgen} \tag{6}$$

Generator efficiency: $$\eta_{gen} = \frac{W_{ne}}{W_m} \tag{7}$$

Energy balance of the boiler: $F_c = Q_c + Q_{pc} + mp_c \cdot cp_a \cdot (T_{ec} - T_0)$ (8)

Boiler efficiency: $$\eta_c = \frac{Q_c}{F_c} \tag{9}$$

Boiler primary energy and flows:

$$F_c = mc_c \cdot L_i \tag{10}$$

$$RAC_c = \frac{ma_c}{mc_c} \tag{11}$$

$$mp_c = ma_c + mc_c \tag{12}$$

Energy balance of the heating ring: $Q_r + Q_c = Q_{ef} + Q_{dc} + Q_{pdc} + Q_{exed}$ (13)

Electric energy balance: $W_{ne} = W_{nef} + W_{dne} + \Delta W_{ne}$ (14)

Absorption chiller COP: $Q_{fabs} = Q_{ef} \cdot COP_{abs}$ (15)

Conventional chiller COP: $Q_{fconv} = W_{nef} \cdot COP_{conv}$ (16)

Energy balance of the cooling ring: $Q_{df} + Q_{pdf} = Q_{fabs} + Q_{fconv}$ (17)

For closing the system, additional equations must be included. Those are relatives to the operating conditions. For example, in a TP adapted to the heating demand, the value of Q_c would be:

$$Q_c = 0 \tag{18}$$

However, under operating conditions far from the design conditions when there is not enough waste heat available from the engine, it could be impossible to satisfy this condition. Consequently, it is necessary to decide about which demand should be mainly attended: the heating or the absorption cooling. To conduct this decision, a coefficient of merit is introduced. This coefficient is based on the primary energy consumption required for attending the cooling demand with both techniques: the conventional chiller or the absorption chiller:

$$C_f = \frac{F_{f,conv}}{F_{f,abs}} = \frac{COP_{abs}}{COP_{abs}} \cdot \frac{\eta_c}{\eta_m \cdot \eta_{gen}} \tag{19}$$

This coefficient is applied as follows:

- If $C_f > 1$, the residual waste heat from the engine is applied first for cooling, being the rest of the heating demand attended with the backup boiler. As can be seen in Figure 1, there simultaneously exist heating and cooling demand during spring and autumn.
- If $C_f < 1$, the residual waste heat from the engine is applied first for heating, being the rest of the cooling demand attended with the backup conventional chiller.

Additionally, this coefficient must be used to take the decision on how the non-satisfied cooling demand has to be attended:

- If $C_f > 1$, the absorption chiller, being powered by the backup boiler, has to attend it.
- If $C_f < 1$, a conventional chiller, being electrically powered, has to attend it.

As the COP of each cooling machine type is dependent of the external ambient temperature, and the engine efficiency is dependent of the operating point of the TP, a decision has to be taken on-line.

Inputs to the model

Besides the electric, heating and cooling demands, the following parameters, which are variables along the year, must be collected to serve as inputs to the model:

- External ambient temperature: variations from 6.2ºC to 24.4ºC for monthly averaged values are reported by meteorological stations in the zone of interest.
- Generator efficiency: a constant representative value of 0.97 has been considered.
- Engine efficiency: engine nominal power, external ambient temperature and working load are the most important parameters affecting the efficiency of the engine. All three are implemented into the model.
- Air/fuel ratio of the engine and of the boiler.
- Lower heating value of NG.
- Direct thermal losses and exhaust-gases non recovered heat of the engine and of the boiler: considered as a percentage of its primary energy consumption.
- Minimum exhaust-gases temperature for avoiding the condensation of corrosive liquids in the exhaust track: 120ºC.
- COP of both conventional and absorption chillers: their variation with external ambient temperature is considered in the model. COP for conventional chiller ranges from 5.76 to 2.12 throughout the year. Single and double effect absorption chillers were considered, in order to perform a comparison of both options. The COP of the single effect absorption chiller ranges from 0.351 to 0.602. The COP interval for the double effect absorption chiller ranges from 0.7 to 1.2. The highest values of COPs correspond to January, being the lowest ones corresponding to July.

Simulation results: Sizing of the TP

As a first application of the developed model, the sizing of the TP from the yearly averaged values of the demands has been performed. As global results, the typical cogeneration parameters have been derived from the simulation results as follows:

Artificial Thermal Efficiency:
$$REE = \frac{W_{ne} + Wm_{deficit}}{Fm_{cogen-\frac{Qm_{util}+Q_c}{\eta_c}}} \tag{20}$$

According to the Spanish regulation [5], a minimum value for this parameter must be demonstrated throughout the year. When using internal combustion engines fed with NG, this minimum value is of 0.55.

Overall Efficiency:
$$FUE = \frac{W_{ne} + Wm_{deficit} + Qm_{util} + Q_c}{Fm_{cogen}} \tag{21}$$

Primary Energy Saving:
$$IAE = \frac{\Delta F}{Fm_{conv}} \quad ; \quad \Delta F = Fm_{conv} - Fm_{cogen} \tag{22}$$

where:

$$Fm_{conv} = \frac{Q_{dc}}{\eta_c} + \frac{W_{dne} + \Delta W_{ne}}{\eta_m \cdot \eta_{gen}} \tag{23}$$

$$Fm_{cogen} = F_m + F_c + \frac{Wm_{deficit}}{\eta_m \cdot \eta_{gen}} \tag{24}$$

Results are presented in Figure 3, for double (left) and single effect (right) absorption chillers. The minimum value of *REE* required is also plotted in both figures as a reference.

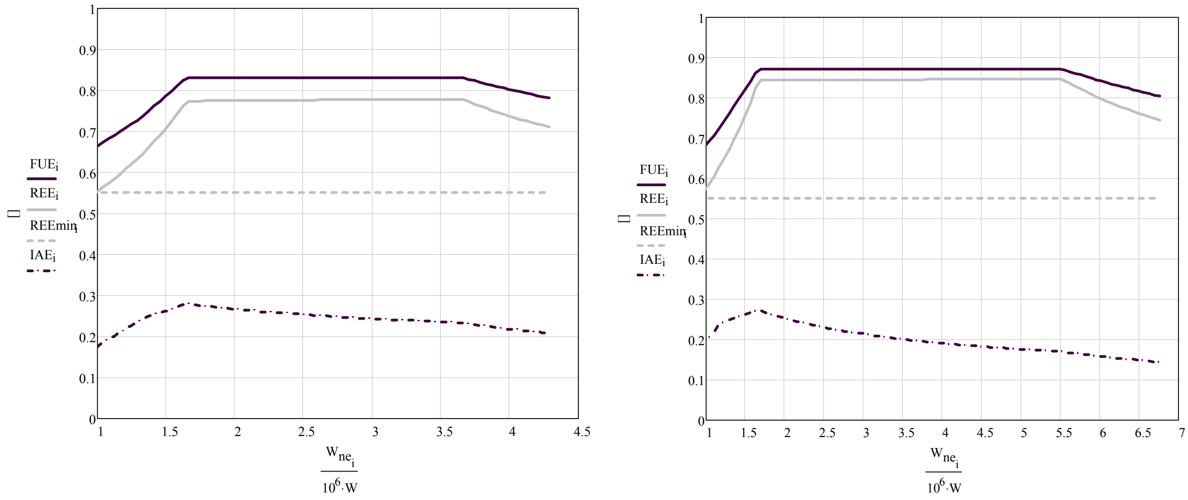

Figure 3: Performance parameters of the TP vs. engine nominal power, for a double effect (left) and for a single effect (right) absorption chiller.

Comparing both figures, a lower value can be observed in the *FUE* and *REE* for the double effect absorption chiller; this is because the exhaust gases temperature at the exit of the heat exchanger with the chiller is near 200ºC. The engine nominal power range for optimal values of these parameters is wider for single effect. The higher value of the engine nominal power is limited for the one corresponding to a TP adapted to the heating demand.

The *IAE* exhibits the same maximum value in both cases. This maximum corresponds to a TP adapted to the electric demand. From this point, the *IAE* values are higher for the double effect absorption chiller when the engine nominal power increases.

Simulation results: Economy considerations

Keeping in mind the Spanish regulations [5], there are three different operation modes for the TP management:

- Self consumption mode: Clients are part of the TP business. This way, the TP provides the electricity, heating and cooling that they need. The surplus of electric power generated may be sold to the national grid, but the waste rejection heat from the engine must be completely consumed.
- Electricity, heating and cooling selling mode: Clients must pay to the TP manager for the three kinds of energy. Different prices for each one of them have to be established by the TP manager.
- Heating and cooling selling mode: Clients buy electricity to the national grid, and the heating and cooling to the TP. Prices for heating and cooling must be established by the TP manager.

The two first modes require a private local grid for electricity. Nevertheless, connexion to the national grid is needed to grant the supply when there is not enough electric power produced by the TP, or during maintenance periods.

TP electricity price for selling may be assumed to be the same as the price of the national grid. A higher one would dissuade the client to buy the electricity to the TP manager, whilst a lower one would lead to a worthless business for the TP.

In relation to heating and cooling, the selling prices must be estimated as a function of the real cost for the conventional way of production, as follows:

$$Qc_{price} = \frac{NG_{price}}{\eta_G} \quad ; \quad Qf_{price} = \frac{Elec_{price}}{COP_{conv}} \qquad (25)$$

A discount of 15% over those prices is also considered in the study. This is for inducing the potential client to buy the heating and the cooling from the TP.

The electricity feed-in tariffs to the national grid are prescribed by the Spanish Regulations [5], depending on the TP size, the technology, the fuel used (NG in this case study) and the TP efficiency. For this study, it ranges from 1.25 to 1.3 times the purchase price from the national grid. In this regulation, the efficiency is specially favoured, by adding an efficiency additional subsidiary bonus calculated as follows:

$$Effic_{compl} = 1.1 \cdot \left(\frac{\frac{1}{REE_{min -1}}}{REE} \right) \cdot NG_{price} \tag{26}$$

The NG purchase price is also dependent of the annual NG consumption and of the supply pressure. When sizing the TP those different prices were taken into account. The prices and tariffs corresponding to 2007 were applied in the present study, as a reference.

As a global economic result, the annual benefits are calculated as a function of the engine nominal power. It should be mentioned that the cooling capacity of the absorption chiller, and the other main components of the TP, are depending of the engine nominal power. In the investment, the installation of a district heating and cooling ring is included, from a basic engineering design, in order to evaluate its thermal and mechanical losses.

Finally, the payback period was calculated also as a function of the engine nominal power. The results are shown in Figure 4 for a double effect and for a single effect absorption chiller.

The subscripts in the figures indicate the mode which the TP is operated:

- "auto": Self consumption mode
- "vecf": Electricity, heating and cooling selling mode
- "vcf": Heating and cooling selling mode
- "vcfr": Heating and cooling selling mode with a 15% discount in prices.

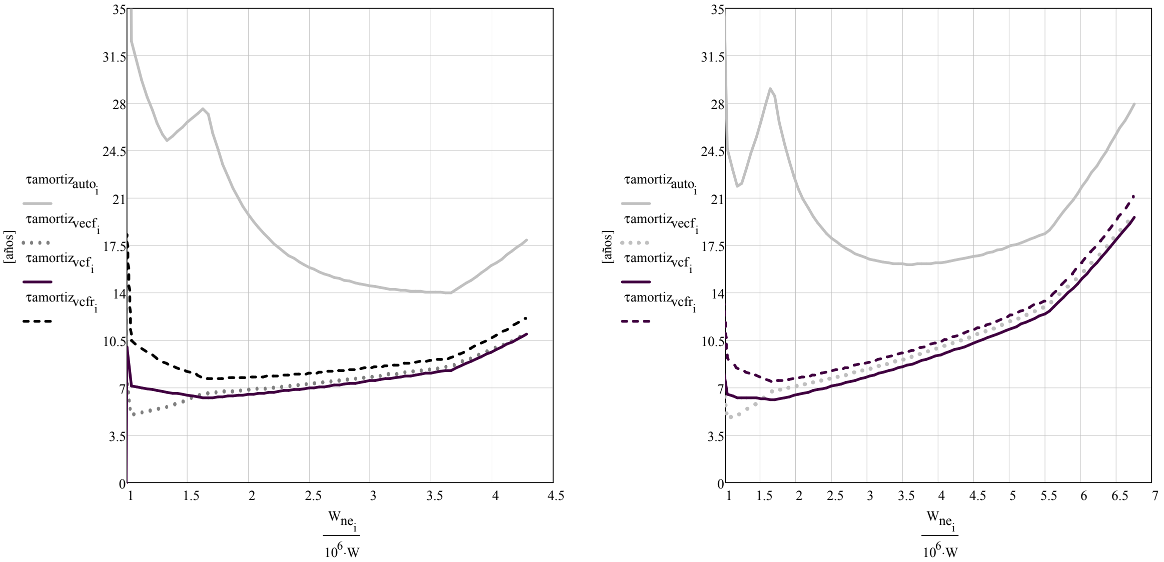

Figure 4: Payback period (τamortiz) of the TP vs. the engine nominal power, for a double effect (left) and for a single effect (right) absorption chillers.

The most economically interesting mode is the "Heating and cooling selling mode" for an engine nominal power higher than 1.5 MW_e. Spanish Regulation reduces the subsidies for a TP older than 10 years. Introducing as a limiting criterion a payback period of 10 years, the possible nominal power for the engine ranges from 1 to 4 MW_e, using either double or single effect absorption chillers.

Simulation results: Monthly evolution of the TP

As it can be observed, the previous calculations, which were based on annually averaged values, are excessively optimistic. The main reason is the high variation of the energy demands throughout the year. At least a monthly description of the TP performance must be carried out in order to give a more accurate payback period. Three engines of 730 kW_e of nominal electric power each one and two double effect absorption chillers of 1,100 kW_c of nominal cooling capacity each, were selected for this purpose. Only the "Heating and cooling selling mode" (vcf) will be considered for the following calculations. The modularity applied to the power plant allows a higher efficiency compared to the use of a single engine of 2.2 MW_e, because only one of them operates at partial load. Some engine may be turned off during periods of low heat demand.

Figure 5 (left) shows the monthly evolution of the cogeneration parameters. As can be seen, during summer a significant reduction in efficiency occurs. The reason is that the system is not able to attend the whole cooling demand with the absorption chiller, as Figure 5 (right) shows. Five conventional backup chillers of 1,000 kW_c of cooling capacity each and a backup boiler of 670 kW are needed for this configuration. The last one is needed for attending the heating demand in January and December, when waste heat from the engine, being operated at full load, is not enough to attend the total heating demand. Increasing the engines nominal power is not recommended because the payback period increases.

The economical benefit becomes negative during the summer period, giving a payback period of 10.6 years for the TP and the district heating and cooling rings, with an annual benefit of 0.27 M€/year. The capital cost arrives to 2.8 M€. The reduction in CO_2 emissions reaches 1,527 Tm/year.

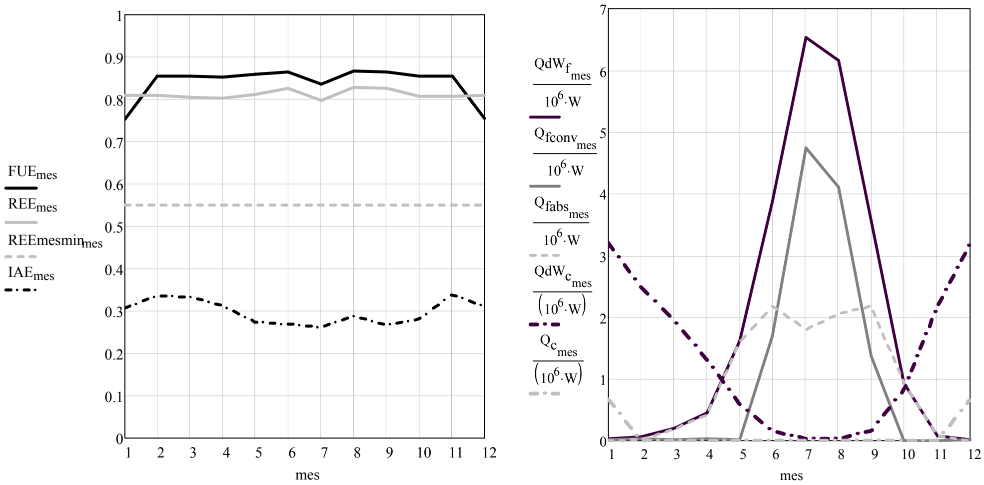

Figure 5: Performance parameters of the TP for each month (left). TP: Cooling demand is attended partially by the absorption chiller (Q_{fabs}) and by the conventional chillers (Q_{fconv}). Qdw_f is the total amount of cooling demand, and Q_c is the heat produced by the boiler in order to attend a fraction of the heating demand (QdW_c) (right).

Thermal solar plant implementation

Figure 5 suggests applying a diversification in energy sources during the summer season, here as a Thermal Solar Plant (TSP). A thermal solar cooling could be a good proposal, but the performance of TP+TSP should be evaluated throughout the whole year, to study what happens during the winter season, when the heating demand is partially attended by the solar heat.

For this purpose, the performance of a TSP based on flat plate vacuum collectors (model 400V from Thermosolar), placed on a horizontal surface, is studied throughout the year. The result is a monthly variable thermal energy supply, which can be managed jointly with the demands shown in Figure 1. The simulation of the TSP was performed on the grounds of real data taken from the experimental solar plant of the UC3M in Leganés (Madrid) [3]. Figure 6 shows results for the monthly thermal energy obtained from the collector field.

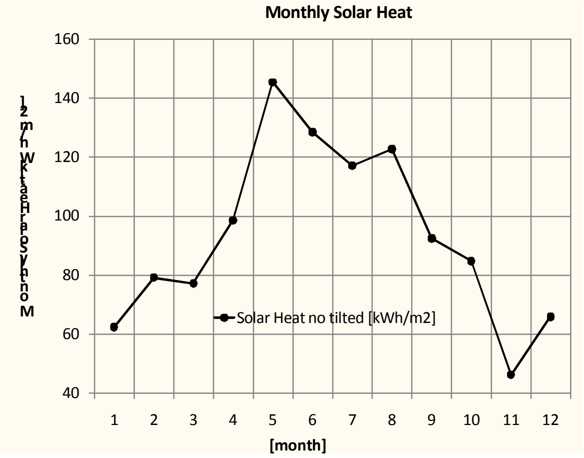

Figure 6: TSP monthly thermal energy obtained from a collector field per unit of surface.

Repeating the previously monthly calculation, now integrating a TSP for the "Heat and cooling selling mode" (vcf) the results shown in Figure 7 are obtained.

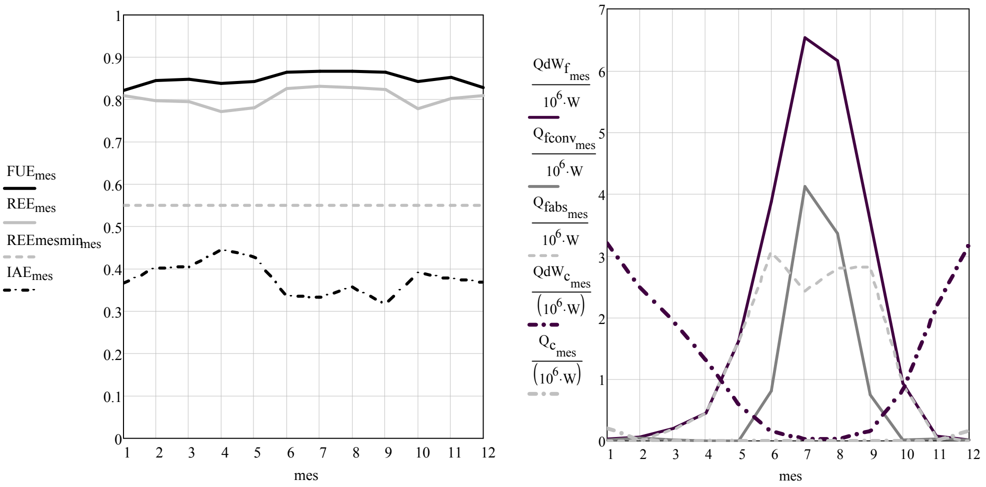

Figure 7: Performance parameters of TP+TSP for each month (left). TP+TSP: Cooling demand is attended partially by the absorption chiller (Q_{fabs}) and by conventional chillers (Q_{fconv}). Qdw_f is the total amount of cooling demand, and Q_c is the heat produced by the boiler in order to attend a fraction of the heating demand (QdW_c) (right).

The final configuration selected for this application includes three engines with 730 kW_e of nominal electric power each. The double effect absorption chiller has a cooling nominal capacity of 3 MW_c. The TSP is a collector field of 2,000 m^2. A conventional chiller of 4 MW_c and a 200 kW_h boiler are needed for backup.

The payback period has increased to 11.6 years, due to the additional investment on the TSP. The capital cost now arrives to 3.32 M€. A grant of 60% of the purchase price for the TSP has been applied. The annual benefit reaches 0.29 M€/year; this is due to the reduction in fuel consumption and the increase in the artificial thermal efficiency (*REE*). As can be observed by comparing Figures 5 and 7, the bad performance on the overall efficiency (*FUE*) during January, July and December, is ameliorated with the TP+TSP configuration. Low values of January and December are attributable to the need of using the boiler in order to attend a fraction of the heating demand. Its incidence is lower in the TP+TSP configuration thanks to the solar heat, raising the *FUE* from 0.78 for the TP to 0.82 for the TP+TSP. The reduction in

CO_2 emissions reaches 1,760 Tm/year. An increase in the Primary Energy Saving (*IAE*) is obtained with this hybrid solution (TP+TSP), giving an annually averaged value of 0.38.

Conclusions

In this work, a methodology for Trigeneration Plants (TP) sizing for business buildings applications has been proposed. Due to the high variability of the thermal demands, a monthly evolution has been revealed of paramount importance for an accurate dimensioning and for a suitable prediction of the TP performance.

As closing equation for the proposed model system of equations, a coefficient of merit based on primary energy saving, is proposed as a tool for deciding how the TP must be operated. This coefficient allows deciding the preference for heating or for cooling and the better way to drive this last one: heat or electricity.

Different modes of managing the TP are compared in economic terms under the Spanish regulations scenario. Conclusive results are shown. They indicate that the “Heating and cooling selling mode” is the most competitive, leading to the minimum payback period. In the other side, the “Self consumption mode” leads to the higher payback period, never lower than 14 years.

A Thermal Solar Plant (TSP) is incorporated to the TP. This hybrid solution (TP+TSP) leads to a slight increase in the payback period due to the TSP capital cost. Nevertheless this solution allows a higher reduction in the CO_2 emissions and a slight increase in the annual benefits. Primary energy saving (*IAE*) is higher for this hybrid proposal.

Nomenclature

C_f:	Cooling coefficient of merit []
COP_{abs}:	Coefficient of performance of the absorption chiller []
COP_{conv}:	Coefficient of performance of the conventional vapor compression chiller []
cp_a:	Specific heat of air [J/(kg·K)]
$Effic_{compl}$:	Efficiency additional subsidiary bonus [€/kWh$_e$]
$Elec_{price}$:	Purchase price for electricity [€/kWh$_e$]
F_c:	Primary energy consumption of the backup boiler per unit of time [MW$_c$]
$F_{f,abs}$:	Primary energy consumption of absorption chiller per unit of time [MW$_c$]
$F_{f,conv}$:	Primary energy consumption of conventional chiller per unit of time [MW$_c$]
F_m:	Primary energy consumption of the engine per unit of time [MW$_c$]
Fm_{cogen}:	Primary energy consumption of the TP [MW$_c$]
Fm_{conv}:	Primary energy consumption of a conventional plant per unit of time [MW$_c$]
FUE:	Overall efficiency []
IAE:	Primary energy saving []
L_i:	Lower heating value of fuel [MJ/kg]
MW$_e$:	Electric power [MW]
MW$_h$:	Heating power [MW]
MW$_c$:	Cooling power [MW]
ma_c:	Air flow rate of the backup boiler []
ma_m:	Air flow rate of the engine [kg/s]
mc_c:	Backup boiler fuel flow rate [kg/s]
mc_m:	Engine fuel flow rate [kg/s]
mp_c:	Backup boiler exhaust flow rate [kg/s]
mp_m:	Engine exhaust flow rate [kg/s]
NG:	Natural Gas
NG_{price}:	Purchase price for Natural Gas [€/kWh$_c$]
Q_c:	Heat provided by the backup boiler per unit of time [MW$_h$]
Qc_{price}:	Selling price for heating [€/kWh$_h$]
Q_{dc}:	Heat demand per unit of time [MW$_h$]

Q_{df}: Cooling demand per unit of time [MW_c]
Q_{ef}: Heat applied to the absorption chiller per unit of time [MW_h]
Q_{exed}: Surplus heat provided by the engine per unit of time [MW_h]
Q_{fabs}: Cooling energy provided by the absorption chiller per unit of time [MW_c]
Q_{fconv}: Cooling energy provided by the conventional chiller per unit of time [MW_c]
Qf_{price}: Selling price for Cooling [€/kWh_c]
Qm_{util}: Thermal energy provided by the engine that is applied to the demand [MW_h]
Q_{pc}: Thermal losses of the backup boiler per unit of time [MW_h]
Q_{pdc}: Thermal losses in the district heating ring per unit of time [MW_h]
Q_{pdf}: Thermal losses in the district cooling ring per unit of time [MW_c]
Q_{pgen}: Electricity generator thermal losses per unit of time [MW_h]
Q_{pm}: Engine thermal losses per unit of time [MW_h]
Q_r: Residual heat provided by the engine per unit of time [MW_h]
RAC_c: Air to fuel ratio of the backup boiler []
RAC_m: Air to fuel ratio of the engine []
REE: Artificial Thermal Efficiency []
REE_{min}: Minimum value of artificial thermal efficiency allowed by Spanish regulations []
T_0: Ambient temperature [K]
T_{ec}: Exhaust temperature of the backup boiler [K]
T_{em}: Exhaust gas temperature of the engine [K]
TP: Trigeneration Plant
TSP: Thermal Solar Plant
W_{dne}: Electric energy demand per unit of time [MW_e]
W_m: Mechanical Energy provided by the engine per unit of time [MW]
$Wm_{deficit}$: Electric demand not provided by the TP [MW_e]
W_{ne}: Electricity provided by the engine per unit of time [MW_e]
W_{nef}: Electricity supplied to the conventional vapor compression chiller per unit of time [MW_e]
ΔF: Primary Energy difference between conventional and TP per unit of time [MW_c]
ΔW_{ne}: Electricity sold to the national grid per unit of time [MW_e]
η_c: Backup boiler energy efficiency []
η_{gen}: Electricity generator efficiency []
η_m: Engine mechanical efficiency []

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