

**Optimal synthesis of trigeneration systems
subject to environmental constraints.**

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ABSTRACT

Environmental information obtained through Life Cycle Analysis techniques has been incorporated into a Mixed Integer Linear Programming (MILP). The solution of the model provides the optimal configuration and operation of an energy supply system to be installed, minimizing the environmental burden associated with production of equipment and consumption of resources. Starting from a superstructure of cogeneration system with additional components highly interconnected, the energy supply system was optimized considering specific demands of a hospital located in Zaragoza, Spain. The objective functions took into account the kilograms of CO₂ released and Eco-indicator 99 Single Score. Also considered were price of energy resources, price and amortization possibilities of the equipment and options for selling surplus electricity to the electric grid. The effect of electricity generation conditions on the optimal configuration was examined by varying the source of electricity production in Spain and considering natural gas/electricity mixes from alternate countries. The ratio between local electricity emissions and natural gas emissions (α factor) was found to have the highest impact on the configuration of the system. Therefore the α factor could be considered the strongest influencing factor when deciding the optimal configuration of a system that minimizes environmental loads.

Keywords: Trigeneration; Mixed Integer Linear Programming (MILP); Optimization; Eco-indicator 99; CO₂ emissions; Life Cycle Assessment (LCA).

1. INTRODUCTION

The need to consider environmental loads/impacts as an additional design factor in energy supply systems is ever increasing due to rising environmental conscience worldwide and stricter requirements to reduce the environmental impact of modern society. The Life Cycle Assessment is a tool that provides a global perspective of environmental loads and has the potential to fulfill this need for an adequate design tool [1].

Life Cycle Assessment (LCA) is an objective process that evaluates the environmental loads associated with a product, process, or activity, identifying and quantifying the use of mass and energy as well as the emissions to the environment. LCA also determines the impact of using such resources and emissions by evaluating and carrying out strategies of environmental improvement. Interestingly, LCA has been given other uses, such as identifying steps of industrial processes that need improvement and comparing systems, processes, services and alternative products [2]. LCA can therefore be considered an adequate environmental design tool for energy supply systems, as it is a suitable methodology to evaluate alternative technical proposals for the same issue and identify the most favorable alternative for the environment.

According to IPCC [3], increasing emissions of greenhouse gases (GHG) related to human activities since preindustrial times have led to marked increases in atmospheric concentrations of the long-lived GHG carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF₆), hydrochlorofluorocarbons (HCFCs), and other ozone-depleting substances at varying rates. Human activities that contribute to climate change include major burning of fossil fuels,

occurring when coal, oil, or natural gas are burned to produce energy for transportation, manufacturing, heating, cooling, and electricity generation.

Since 1993, the Council Directive 93/76/EEC [4] (regarding the limitation of CO₂ emissions through the improvement of energy efficiency in buildings) explicitly recognizes the important role of buildings for total CO₂ emissions. However, gradual changes towards a service economy and new installations for thermal comfort have considerably increased energy consumption and emissions of buildings. According to Directive COM 2002/91/EC [5] on the energy performance of buildings, residential and tertiary sectors are responsible for more than 40% of final energy consumption in the European Community. This directive imposes that new buildings with a total usable space area over 1000 m² take into account the technical, environmental, and economic feasibility of alternative energy systems, such as cogeneration, before construction starts. Following this, Directive COM 2004/8/EC [6] favored microcogeneration systems (<50 kWe) and small-scale cogeneration (<1000 kWe), promoting such cogeneration technologies in residential and tertiary sectors. In Spain, RD 616/2007 [7] (transposing of COM 2004/8/EC in Spanish legislation) created a stable framework for extensive promotion and public support of cogeneration.

Polygeneration systems have an important potential for reducing the consumption of energy and natural resources, but are undoubtedly underutilized [8]. Incorporating sustainable development into the design and planning process should consider, among others, the following concepts: i) increased efficiency of energy and materials; ii) reduction of unit cost of final products; and iii) reduction of environmental burden.

The synthesis of energy systems implies searching for a design that minimizes or maximizes an objective function, such as cost, environmental load, and thermodynamic efficiency. The search process is bound by the system's model, which is expressed by equality and inequality mathematical restrictions. The design methodology must provide systems that produce energy services efficiently, are capable of adapting to different markets and demand conditions, and operate with minimal cost. The review by Chicco and Mancarella [9] summarizes the characteristics of optimization methods for polygeneration systems presented in recent publications, including time scale, objective function, and solution method. Integer programming methods satisfy the stated requirements and capture the complexity of polygeneration systems by i) considering a superstructure that contains all alternatives, ii) representing all possible options of configuration/operation through binary variables (0-1), and iii) expressing flows and funds (physic and economic) by continuous variables [10-14].

In this paper the synthesis of a trigeneration system to be installed in a hospital located in Zaragoza (Spain) has been accomplished from an environmental viewpoint, considering the kilograms of CO₂ released in the atmosphere and the Eco-indicator 99 (EI-99) Single Score. The latter was included to broaden environmental considerations in the impact assessment. The objective function was then changed to optimize the annual total cost (€/y) and verify the changes implied. Innovations of this study include a unique analysis of the impact of environmental criteria on the optimal synthesis of trigeneration systems and the proposal of a design parameter that provides information on the optimal structure.

2. TRIGENERATION SYSTEM AND ECONOMIC EVALUATION

This study analyzed the energy demands of a medium-sized hospital with 500 beds, located in Zaragoza (Spain). The energy demands considered were heat (domestic hot water and heating), cooling, and electricity.

The synthesis of a trigeneration system's configuration begins with the creation of a superstructure which must include all feasible process options and connections, based on appropriate process integration [15]. Heat integration methodologies are particularly powerful tools that should be included in the synthesis of trigeneration systems. In this respect, a broader perspective on the consideration of heat integration in the configuration of the superstructure of a polygeneration system is presented in [8]. Furthermore, Ryan [16] presents considerations on heat recovery, selection of the best absorption chiller type and configurations for optimal integration. Simulation of the main components of a trigeneration system and a fast and interactive way to design optimal heat integrated schemes using commercial equipment data is presented in [17].

The superstructure must include all features that are potentially part of an optimal solution, even if presented in a redundant manner. After the optimization process, the superstructure is reduced to an optimal configuration. In this study, selection of equipment took into account input/output utility flows based on appropriate energy process integration. The superstructure shown in Figure 1 is proposed considering heat and power sources (gas turbine, gas engine, steam boiler, hot water boiler, to name a few). Also considered were the requirements - temperature, heat, power, and cooling - of i) the energy services demanded by the consumer

center; ii) different pieces of equipment. Technical production coefficients of equipment were evaluated prior to the inclusion in the superstructure.

Figure 1

The superstructure of a trigeneration system that satisfies energetic demands of heat (domestic hot water and heating), cooling, and electricity should account for the possibility of installing energy production technologies such as TGVA (gas turbine + recuperation boiler, producing steam and hot water), CGVA (steam boiler), MGWH (gas engine + hot water heat recovery system), ICVA (steam-hot water heat exchanger), CGWH (hot water boiler), ICWH (hot water-cooling water heat exchanger), FAVA (double effect absorption chiller, driven by steam), FAWH (single effect absorption chiller, driven by hot water), FMWR (mechanical chiller, driven by electricity and cooled by water), and ICWR (cooling tower, to evacuate the heat from the cooling water). The functional unit (reference to all inputs and outputs of the system) was the production of energy services during one year (y) of operation (8760 hours) of the trigeneration plant.

The available utilities were CG (natural gas), VA (high temperature steam, 180°C), WH (hot water, 90°C), WR (cooling water, $t_0 + 5^\circ\text{C}$), AA (ambient air, t_0), WC (cold water, 5°C), and EE (electricity).

2.1 Energy demand

The study extended over a period of one year, distributed in 24 representative days (one working day and one holiday/weekend day for each month), each day being divided into 24

hourly periods. Representative energy demand patterns for each representative day were calculated according to the procedure described by Sanchez [18], which estimated monthly, daily, and hourly profiles of the different energy demands based on the size of the hospital and its geographical location in Spain. Annual electricity consumption of the hospital was 3250 MWh/y, cooling demand was 1265 MWh/y, and heat requirements (domestic hot water and heating) were 8059 MWh/y.

2.2 Equipment

Table 1 depicts the selected equipment and technical production coefficients for the superstructure. The rows contain potential technologies for installation and the columns contain the utilities. The production coefficient with a highlighted **1** shows the flow that defines the equipment's capacity. Positive coefficients indicate that the utility is produced, while negative coefficients indicate the consumption of such utility.

Table 1

Taking MGWH technology in Table 1 as an example, electricity is the main product as its coefficient is 1. To produce 1 MW of electricity (EE), 2.45 MW of natural gas (CG) will be consumed, recuperating 0.96 MW of hot water (WH), and evacuating 0.20 MW of heat to cooling water (WR). Consequently, the electrical efficiency of MGWH is $1/2.45$ (~41%). All technology and equipment considered in the optimization were commercially available; therefore the size/configuration of the system was determined in terms of pieces of equipment. The data shown in Table 1 was obtained from equipment catalogs and consultations with manufacturers. CI_i was the investment cost of the equipment of technology

i, obtained from catalog prices and multiplied by a simple module factor that took into account aspects such as transportation and installation. According to current conditions in Spain, an amortization and maintenance factor $f_{am} = 0.23 \text{ y}^{-1}$ was considered.

2.3 Gas and electricity rates

In the case of natural gas in Spain, the consumer chooses the most adequate rate for the consumption volume and supply pressure. This investigation considered a constant purchase cost of $C_g = 0.025 \text{ €/kWh}$ for natural gas [19], which includes taxes and the distribution of fixed costs throughout the estimated annual consumption.

Electricity rates are composed of two terms, a power term (dependent on the contracted capacity) and an energy term (dependent on energy consumption). Considering other costs such as taxes, and approximating the distribution of fixed costs, an electricity purchase price of 0.095 €/kWh [20] was utilized throughout the studied year. However, there is a supplement that discriminates the price of electricity by hour of use. The day was divided into two periods: 4 on-peak hours with a 37% increase in price, and the 20 remaining hours with no increase or discount in price [20]. Final electricity price, C_{ep} , was 0.095 €/kWh for off-peak hours, and 0.130 €/kWh for on-peak hours.

For the sale of surplus autogenerated electricity, the tariff and premium depend on the power output and fuel utilized by the plant. Considering the energy demand of the hospital and the nominal power of the cogeneration modules (cogeneration installations using natural gas, 1000-10,000 kW capacity), $C_{es} = 0.077 \text{ €/kWh}$ was obtained as the price for sold electricity [21]. Spanish legislation establishes the Equivalent Electrical Efficiency (EEE, calculated on

an annual basis), which compares the efficiencies of cogeneration systems with electricity-only generation systems:

$$EEE = 100 W_c / (F_c - Q_{cc}/0.9) \quad (1)$$

where W_c is the cogenerated work, F_c the consumption of natural gas by the cogeneration module, and Q_{cc} is the cogenerated useful heat. Spanish legislation demands that cogeneration systems must have an EEE equal or higher than the electrical efficiency of the reference central power plant using the same type of energy source in order to be licensed. For natural gas, minimum EEE is 59% for turbines and 55% for engines [21]. Although EEE can be considered a pillar of high efficiency cogeneration assessment, it was not included among the methodologies for determining the efficiency of the cogeneration process in Directive COM 2004/8/EC [6]. The EEE eligibility criterion was considered because it takes into account Spanish legislation - although this same reason is a source of controversy for authors around the conclusions the use of EEE leads to [22].

3. ENVIRONMENTAL EVALUATION

Environmental optimization was carried out based on two criteria: i) CO₂ emissions and ii) Eco-indicator 99 (EI-99). Global warming and its associated climate change are one of the main medium- and long- term identified threats of GHG with great consequences on the global scale. CO₂ emissions were chosen for optimization in this study because they accounted for 77% of total global anthropogenic GHG emissions in 2004 [23]. EI-99 is a global environmental indicator that encompasses several impact categories and was included to broaden the environmental perspective.

Both criteria, CO₂ emissions and EI-99, were evaluated by applying the LCA technique. An LCA study consists normally of four stages [1]: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. Databases were utilized in the LCI to obtain CO₂ emission values. The EI-99 method was utilized for the LCIA, where the values of eleven impact categories were added into three damage categories, weighted and aggregated into an index. This index is the Single Score, which represents the overall environmental load and where one point can be interpreted as one thousandth of the annual environmental load of one average European inhabitant.

Changes in lifestyle and behavior can contribute to climate change mitigation across all sectors. Similarly, management practices can also have a positive role through the use of technologies that result in considerable reduction of environmental impacts related to energy use in buildings, for example. Substantial reductions in CO₂ emissions from energy use in buildings can be achieved using energy-efficient technologies that already exist, with significant savings in primary energy being possible. Design strategies for energy-efficient buildings should include a selection of systems that make the best use of energy sources and also operate optimally. Additionally, CO₂ emissions from electricity use in buildings can also be altered on the supply side since electricity can be derived from fuels with lower carbon content than currently available fuels. Because climate change mitigation in the buildings' sector includes numerous measures aimed at electricity saving, it is useful to associate mitigation potentials to carbon dioxide emissions.

The extent of the impact of climate change strategies is connected to the choices of primary energy for consumption and the efficiency of technologies used for heating and cooling needs.

The Mitigation of Climate Change report by IPCC [24] refers to co- and tri- generation systems as effective GHG mitigation options in buildings.

In EI-99, adverse effects on the environment are divided into three broad damage categories: Human Health, Ecosystem Quality (flora and fauna), and Resources of the Earth.

Human Health includes the idea that all human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities and premature deaths. *Ecosystem Quality* includes the idea that non-human species should not suffer from disruptive changes to their populations and geographical distribution. Lastly, *Resources* includes the idea that the nature's supply of non-living goods, which are essential to human society, should also be available for future generations [25].

Under the damage category of *Human Health*, EI-99 accounts for the number of people as well as the length of illnesses and life years lost due to premature death from environmental effects. This method is used by the World Health Organization and the World Bank [26]. Impacts on human health are well expressed by the Disability Adjusted Life Years (DALY). DALY is a health-gap measure that extends the concept of potential years of life lost due to premature death to include equivalent years of 'healthy' life lost by virtue of being in state of poor health or disability [27]. One DALY, therefore, is equal to one year of healthy life lost. Human Health accounts for effects caused by ozone layer depletion, effects caused by ionizing radiation, damage caused by climate change, respiratory effects caused by organic and inorganic substances, and carcinogenic effects on humans.

Ecosystem Quality quantifies environmental impacts on species' diversity, including vascular plants and lower organisms, considering reversible or irreversible disappearance or stress on a species in a certain region during a certain time-frame. This damage category accounts for the consequences of land use, damage caused by combined effects of acidification and eutrophication, and damage caused by ecotoxic effects. There is no uniform parameter for this purpose, such as the DALY [25]. Toxicity is measured by the Potentially Affected Fraction of species (PAF, in $\text{PAF}\cdot\text{m}^2\cdot\text{y}$), which quantifies the toxic effect on organisms (mostly lower forms) that live in water and soil (toxic stress). Damages resulting from acidification, eutrophication and land-use are measured as the percentage of species that have disappeared in a certain area due to the environmental load (Potentially Disappeared Fraction, PDF, in $\text{PDF}\cdot\text{m}^2\cdot\text{y}$). As PAF and PDF are very different measures, the damage cannot be simply added. Considering the level at which species (assuming all species have equal importance) become affected and at which level they disappear, a conversion factor has been developed in which the PAF results are divided by 10 before they can be added to the PDF [25].

With respect to the damage category of *Resources*, the models in EI-99 only consider the effects caused by extraction of minerals and fossil fuels. These effects are evaluated as the additional energy needed in the future to extract lower grade mineral and fossil resources. The additional energy is called *surplus energy* and is measured in MJ surplus. For minerals, lower grade ores are considered to require more effort to process and larger amounts of electrical or fossil fuel energy per unit of metal produced [26]. For fossil fuels, surplus energy is based on future use of nonconventional resources, especially oil shale and tar sands. The point in the future has been chosen as the time at which five times the cumulative extraction of the resource before 1990 has been extracted [25].

EI-99 presents three different approaches to obtain the EI-99 Single Score (combining the contribution of each damage category): Egalitarian, Hierarchist, and Individualist. The Hierarchist version (H/H) was selected for the damage model herein because of its balanced time perspective, as a consensus among scientists determined inclusion of environmental effects [25] and strong-held belief in preventing environmental problems through regulation [28]. In the Hierarchist version (H/H), Human Health and Resources each contribute 30% , while Ecosystem Quality contributes 40% to the final value of EI-99 Single Score [25].

Figure 2 shows the relative contribution of the eleven impact subcategories considered in the three damage categories to the overall result of the Single Score (Hierarchist approach, H/H) within Europe. Respiratory Effects, Climate Change and Carcinogenic Effects dominate Human Health damages. Land-use dominates Ecosystem Quality, and Resources is dominated by fossil fuels.

Figure 2

SimaPro [29] was the specialized LCA tool used to calculate the CO₂ emissions and EI-99 Single Score associated with each piece of equipment included in the superstructure and with the natural gas and electricity consumed in the energy production system. SimaPro includes several inventory databases containing thousands of processes, in addition to the most important impact assessment methods.

3.1 CO₂ emissions calculation

Natural gas was characterized utilizing the related emissions of combustion of natural gas (*Energy gas I*) from the IDEMAT database [30] and the total aggregated system inventory for a natural gas user in Spain (*Natural Gas, high pressure, at consumer/ES E*) from the Ecoinvent database [31]. *Natural Gas, high pressure, at consumer/ES E* considers gas field exploration, natural gas distribution, natural gas production, long distance transport, regional distribution, and local supply. The CO₂ emissions associated with the consumption of natural gas in Spain were obtained by utilizing SimaPro, calculated as $EM_g = 0.272$ kg CO₂ per kWh of consumed natural gas.

The CO₂ emissions associated with the local electricity (Spanish electricity mix) were also calculated by SimaPro, utilizing the Ecoinvent database and considering the following proportions: 25.8% Coal, 24.4% Natural Gas –combined cycle-, 19.7% Nuclear, 10.4% Others (biomass, Natural Gas –cogeneration-, minihydraulic), 9.4% Eolic, 9.4% Hydraulic and 0.9% Fuel-gas [32]. The average CO₂ emissions associated with electricity in Spain in 2007 was $EM_e = 0.385$ kg CO₂ per kWh consumed.

3.2 EI-99 Single Score calculation

In order to calculate the EI-99 score, the following steps are necessary:

1. *Evaluation of the inventory of resource extraction, land-use and all relevant emissions in all processes that form the life cycle of the equipment or utility.* The combustion of 1 kWh of natural gas (*Energy gas I*, from the IDEMAT database) was chosen to illustrate the calculation of the EI-99 Single Score. The inventory is shown in Table 2.

Table 2

2. *Consultation of the characterization factors (Table 3) to evaluate the contribution of each substance of the inventory towards the different impact categories (Table 4).*

Table 3

Values in Table 4 were obtained by multiplying each substance of the inventory (Table 2) by its corresponding characterization factor (Table 3). Substances can contribute to more than one impact category. For example, nitrogen oxides contribute to respiratory effects and acidification/eutrophication impact categories. The different impact categories are combined into the three damage categories (Human Health, Ecosystem Quality, and Resources).

Table 4

3. *Multiplication of the damage category values (A in Table 4) by their corresponding normalization factors (B in Table 5) in order to build the damage model. This multiplication yields the dimensionless value C, which represents the normalized environmental load corresponding to each damage category.*

Table 5

4. *Application of a set of weighting factors (D values in Table 6) to the C values of the damage categories in order to obtain the EI-99 Single Score,.*

Table 6

Further EI-99 calculations are not presented herein due to space limitations. The same procedure was applied to the total aggregated system inventory for both natural gas and electricity mix users in Spain. The Single Score obtained was $SS_g = 0.0378$ points per kWh consumed for natural gas and $SS_e = 0.0226$ points per kWh consumed for the Spanish electricity mix.

Table 7 shows the EI-99 Single Score (total and contribution of each damage category) and CO₂ emissions for 1 kWh of consumed natural gas.

Table 7

According to Table 7, the *Resources* category was most frequently the category with highest contribution to the total EI-99 Single Scores. For example, combustion of natural gas contributed 47% (0.0178 points per kWh of consumed natural gas) to the EI-99 Single Score of natural gas. In general, the aspects considered in the aggregated inventory for a natural gas user in Spain have a considerable contribution to the EI-99 Single Score. An important share of the environmental burden is related to the production and processing of natural gas [33]. With respect to CO₂ emissions, the highest contribution (almost 89%) corresponded to natural gas combustion.

Table 8 shows the EI-99 Single Scores and CO₂ emissions for the different contributors to the electricity mix in Spain. The final value for the electricity mix in Spain is obtained by multiplying each contributor by its corresponding proportion. Values in Table 8 were

obtained from the Ecoinvent database, which provides environmental loads associated with the production of electricity at each specific power plant.

Table 8

When analyzing the electricity mix breakdown in Spain, it becomes apparent that the utilization of natural gas is penalized in combined cycle and in cogeneration (i.e. high EI-99 points for Resources). Natural gas is a more environmentally sound fuel than coal when considering only CO₂ emissions. However, when applying the EI-99 method, the difference in characterization factors between natural gas and coal (4.55 MJ surplus/kg for natural gas and 0.252 MJ surplus/kg for coal [29]) balances out the impact category of fossil fuels, resulting in similar final Single Scores for both. Coal contributes towards 25.8% of the electricity mix and is responsible for 46% of the final value of the EI-99 Single Score. In a similar fashion, natural gas in a combined cycle contributes towards 24.4% of the electricity mix and is responsible for 41% of the final environmental load (EI-99 Single Score).

3.3 Equipment

The CO₂ emissions and EI-99 Single Score associated with the production of each type of technology were calculated utilizing SimaPro following the same procedure explained in the previous sections.

Data on the material composition and manufacturing of the equipment were obtained from consultation with the manufacturers and incorporated into SimaPro through IDEMAT,

Ecoinvent, and ETH-ESU [34] databases. The databases accounted for natural resources, emissions, and impact of every material entered, beginning at the extraction from the ore/mine/well and including the transformations necessary to produce the material and assemble the equipment. Average product manufacturing was considered for each material (Ecoinvent) and transportation of the equipment (average of 300 km) fulfilled European directive EURO V [35]. The following assumptions were also made: i) 100% of materials was landfilled (worst case scenario, with no recycling), ii) any oil or fluid was considered as an emission into the soil, and iii) gases (R134a, for example) were considered to be discharged into the atmosphere.

Table 9 presents the technologies and their associated main material composition, CO₂ emissions, CO₂I, and the Single Score obtained by applying EI-99, SSI.

Table 9

4. OPTIMIZATION MODEL

The issue to be solved consists of selecting the optimal combination of technologies, specifically the type of technology and installed power that meets the energy demands set by the consumer center and establishes the operational mode for the installed technologies for each defined time period of the year.

An optimization model was built based on mixed integer linear programming and its solution provides the means for selecting the most convenient configuration and operation modes. The model represented the superstructure, considering all possible configuration and operation options as well as particular circumstances (such as demand and tariffs).

The first environmental objective function considered was to minimize the total annual carbon dioxide emissions (CO_{2tot}), which included the annual fixed emissions of the equipment (CO_{2fix}) and the annual operation emissions (CO_{2ope}) associated with operation of the system.

$$\text{Min } CO_{2tot} = CO_{2fix} + CO_{2ope} \quad (2)$$

The annual fixed impact of the equipment (CO_{2fix}) was expressed by

$$CO_{2fix} = fam_e \cdot \sum_i NIN(i) \cdot CO_2I(i) \quad (3)$$

where $NIN(i)$ and $CO_2I(i)$ were, respectively, the number of pieces of equipment installed and the environmental impact required to produce each piece of equipment for technology i . The environmental amortization factor (fam_e) represents the share of global environmental impact throughout the system's lifetime and was considered equal to 0.10 y^{-1} .

Considering that the year was divided into d representative days, which were in turn subdivided into h hours, (d,h) represented the h th hour of the d th representative day. The annual operation impact (CO_{2ope}) associated with the operation of the system was expressed by

$$CO_{2ope} = \sum_d \sum_h [EM_g \cdot F_g(d,h) + EM_e \cdot E_p(d,h) - EM_e \cdot E_s(d,h)] \quad (4)$$

F_g was the consumption of natural gas, and E_p and E_s were the amount of electricity purchased and sold, respectively. $EM_e \cdot E_s(d,h)$ was considered as the impact avoided elsewhere with the sale of electricity produced by the cogeneration module.

The second environmental objective function was to minimize the EI-99 Single Score, which evaluated global environmental impact (considering human health, ecosystem quality, and consumption of resources). This score considered the total annual impact (SS_{tot}), including the annual fixed impact of the equipment (SS_{fix}) and the annual operation impact (SS_{ope}) associated with the operation of the system. Equations (2) – (4) were changed to

$$\text{Min } SS_{tot} = SS_{fix} + SS_{ope} \quad (5)$$

$$SS_{fix} = fam_e \cdot \sum_i NIN(i) \cdot SSI(i) \quad (6)$$

$$SS_{ope} = \sum_d \sum_h [SS_g \cdot F_g(d,h) + SS_e \cdot E_p(d,h) - SS_e \cdot E_s(d,h)] \quad (7)$$

A third objective function was introduced into the model to consider the economic aspect of the energy supply system installed in terms of the total annual cost C_{tot} (in €/y), which minimized equipment and fuel costs as well as purchase/sale of energy services. Equations (2) – (4) were changed to:

$$\text{Min } C_{\text{tot}} = C_{\text{fix}} + C_{\text{ope}} \quad (8)$$

$$C_{\text{fix}} = \text{fam} \cdot \sum_i \text{NIN}(i) \cdot \text{CI}(i) \quad (9)$$

$$C_{\text{ope}} = \sum_d \sum_h [C_g \cdot F_g(d,h) + C_{ep}(d,h) \cdot E_p(d,h) - C_{es} \cdot E_s(d,h)] \quad (10)$$

Operation was subject to capacity limits, production restrictions, and balance equations, which were presented in Lozano et al. [13]. The investigation led to a complete economic study considering legal constraints imposed to feed the surplus autogenerated electricity into the grid at a regulated feed-in tariff. The effects of the financial market conditions and energy prices in the optimal structure of the system were also considered.

5. RESULTS AND DISCUSSION

Once the scenario was completely defined by the optimization model and conditions previously specified (energy demands, economic and environmental evaluations), the following results were obtained. The model was solved by LINGO [36] by freely selecting the technologies to be installed and minimizing the different objective functions considered. Table 10 shows the results for the optimization of annual CO₂ emissions, EI-99 Single Score, and the total annual cost.

Table 10

The configuration obtained for the optimal CO₂ and EI-99 Single Score is the same and both suggest the installation of “conventional” equipment, including hot water boilers, mechanical chillers, and cooling towers.

Economic optimization suggested the installation of cogeneration modules, hot water-cooling water heat exchangers, and one absorption chiller. The system took advantage of the lower purchase cost of natural gas and achieved profit by selling the cogenerated electricity to the electric grid.

The study by Carvalho et al. [37] obtained and analyzed the thermal loads of a tertiary sector building while considering different geographic locations to represent the climatic variation in Spain. Thermal loads experienced important variation with climatic conditions, resulting in different power to heat ratios for buildings. Influences of local economic/environmental conditions on the optimal configuration of the energy supply system were also studied in [37]. However, even with such different heat/cooling demands, the installation of cogeneration modules only reduced emissions in the Canary Islands, which have a different electricity mix mostly based on fuel-gas. The optimal environmental results suggested the installation of conventional equipment and purchase of electricity from the Spanish electric grid for peninsular locations. The economic optimal results suggested the installation of trigeneration for all locations except those with no cooling demand.

Cogeneration and trigeneration systems present higher efficiency than conventional energy supply systems. However, this does not necessarily represent reduction in emissions, which depends on the local energy supply [38-47].

Given the energy demands, production coefficient for technologies, system lifetime and environmental loads associated with construction of equipment, the parameters that could significantly influence the optimal system structure and operation are the environmental loads

associated with the consumption of natural gas and of electricity. Therefore, the following subsections represent two sensitivity analyses to study the influence of different energy supply combinations on the optimal configuration of an energy supply system. For this purpose, the α factor was developed and defined as the ratio between local electricity emissions and natural gas emissions. In this ratio, *Local electricity emissions* was defined as the total CO₂ emissions resulting from generation of electricity in the power plants that supply the grid (which could be single or mixed fuel sources); while *Natural gas emissions* was defined as the CO₂ emissions related to combustion of natural gas plus the total aggregated system inventory for a natural gas user (details in subsection 3.1).

5.1 Effect of the variation of the source of electricity in Spain

For this analysis, 100% of electricity was considered to originate from a single-fuel representative power plant (data from Table 8). Table 11 shows the α factors, the configuration of the system, and main flow values as a function of the origin of electricity.

Table 11

It was previously noted (Table 10) that cogeneration was not installed when Spanish natural gas and electricity mix ($\alpha=1.42$) were considered. However, Table 11 shows that for natural gas combined cycle systems, cogeneration was installed ($\alpha=1.46$). Trigeneration (cogeneration with absorption chillers) was installed for fuel-gas ($\alpha=2.38$) as well as for coal systems ($\alpha=3.75$). The results obtained confirm that the emission savings by cogeneration and trigeneration depend highly on the source of electricity substituted.

The primary factors that alter CO₂ emissions from electricity generation are the growth in demand for electricity, the type of fuels or energy sources used for generation, and the thermal efficiencies of the power plants. A number of contributing factors influencing these primary factors can also be identified: economic growth, price of electricity, amount of imported electricity, weather, fuel prices, and amount of available generation from hydroelectric, renewable, and nuclear plants. The contribution of weather can be seen, for example, in the contribution of hydraulic electricity to the total available electricity, where the amount of available hydroelectric power is strongly affected by precipitation patterns.

From 1996 to 2007, the values of the CO₂ emissions associated with the production of electricity in Spain have oscillated between 0.350 and 0.450 kg CO₂/kWh [49]. The CO₂ emissions associated with the Spanish electricity mix considered in this paper ($EM_e=0.385$ kg CO₂/kWh) have the particular feature of being the limit value at which cogeneration modules are not installed. When changing the value of α to 1.43 ($EM_e=0.390$ kg CO₂/kWh), the solution of the model yields an optimal configuration that presents cogeneration modules.

Options to limit the emission of CO₂ from electricity generation are to encourage reduction of the overall consumption of electricity through energy efficiency and conservation initiatives, and/or to replace fossil-fueled generation with nonfossil-fueled alternatives, such as nuclear, hydroelectric, and other renewable energy sources.

From the beginning of 2003 until the end of 2008, the electrical power installed in peninsular Spain increased by 31,058 MW (from 59,820 MW to 90,878 MW). Natural gas combined-cycle systems contributed with an increase of 18,359 MW (from 3136 MW to 21,675 MW), which represents 60% of the total increase. Between 2002 and 2008, the net electricity

generation of the Spanish peninsular electricity system increased by 65,157 GWh/y (from 213,144 GWh/y to 278,301 GWh/y). The increment in the production of natural gas combined-cycle systems between 2002 and 2008 was 85,978 GWh/y (from 5308 GWh/y to 91,286 GWh/y), which not only allowed coverage of the increase in net electricity generation but also displaced part of the electricity production from coal and/or fuel-gas. If such a displacement is maintained (which is the current trend in Spain [49]), it can be deduced that combined cycle is a good reference for an environmental analysis of cogeneration and other alternative electricity sources.

5.2 Effect of the variation of the electricity and natural gas supply

This subsection analyzes the effects of using different values for the emissions of CO₂ associated with electricity and natural gas on the configuration and operation of systems. For this, it was assumed that the hospital located in Zaragoza could be supplied with electricity and natural gas originating from alternate countries. Table 12 shows the countries, emission values, and associated α factors indicating the ratio between local electricity CO₂ emissions and natural gas CO₂ emissions. Table 13 shows the optimal configurations of the systems and main flows.

Table 12

Table 13

It was observed that there was a starting point between the range of 1.42 – 1.53 (Spain and Japan) at which cogeneration was installed, and between the range of 1.53 – 2.61 (Japan and

United Kingdom), where installation of trigeneration started. Therefore, cogeneration was installed when the α factor was higher than 1.43 and from 2.00 onwards, absorption chillers were also installed.

6. CONCLUSIONS AND FINAL REMARKS

The optimal configuration of trigeneration systems was obtained by considering the following environmental criteria: kilograms of carbon dioxide (CO₂) released and Eco-indicator 99 method (EI-99). The latter was included in order to consider more environmental aspects in the impact assessment.

Optimal configurations based on conventional equipment (such as hot water boilers, steam compression chillers and cooling towers) were obtained by separately minimizing CO₂ emissions and then EI-99 Single Score for current conditions in Spain. Surprisingly, both optimal solutions maintained similar configurations in which the energy demands of the consumer center were satisfied utilizing conventional equipment. This demonstrates that emissions savings by cogeneration are highly dependent on the ratio between local electricity emissions and natural gas emissions.

Interestingly, switching to an economic objective required the installation of cogeneration modules and an absorption chiller, which are non-conventional equipment. The optimal solution revealed the possibility for sale of electricity to the electric grid as a means to profit, therefore achieving minimal annual final cost.

A sensitivity analysis was performed in order to examine the most influential factors on the structure and the operation of the system. This analysis kept all other values constant and maintained the objective function as the minimization of CO₂ emissions. Thus, the ratio between local electricity emissions and natural gas emissions was initially modified by varying the origin of electricity in Spain. The results verified that cogeneration modules were

installed when the energy supply was highly dependent on fossil fuels. A second analysis considered that the system could be supplied by energy supply mixes from different countries (varying only natural gas and electricity mix values). Based on this, the α factor (ratio between local electricity emissions and natural gas emissions) was found to have the highest impact on the configuration of a system that minimizes environmental loads.

The substantial impact of the α factor demonstrates that more energy-efficient technologies are not always the most appropriate from an environmental viewpoint. Reductions in environmental loads also depend on factors other than just the obvious energy consumption. This highlights the need for a more global perspective when considering the optimal configuration and operation of an energy supply system, which was demonstrated herein through the integration of environmental information into a MILP model.

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NOMENCLATURE

AA	Ambient air
C_{es}	Market price of the electricity sold to the grid [€/kWh]
C_{ep}	Market price of the electricity purchased from the grid [€/kWh]
C_g	Market price of natural gas [€/kWh]
C_{fix}	Annual cost of the equipment [€/y]
C_{ope}	Annual operation costs [€/y]
C_{tot}	Total annual cost [€/y]
CG	Natural gas
CGVA	Steam boiler
CGWH	Hot water boiler
CH ₄	Methane
CI(i)	Investment cost of the equipment of technology i [€]
CO ₂	Carbon dioxide
CO ₂ I(i)	CO ₂ emissions of the production of each piece of technology i [kg CO ₂]
CO ₂ tot	Total annual CO ₂ emissions [kg CO ₂ /y]
CO ₂ fix	Annual fixed CO ₂ emissions of the equipment [kg CO ₂ /y]
CO ₂ ope	Annual operation CO ₂ emissions [kg CO ₂ /y]
D	Demand
DALY	Disability-Adjusted Life Year
E_d	Electricity demand [MWh/y]
E_p	Purchased electricity [kW]
E_s	Sold electricity [kW]
EE	Electricity
EEE	Equivalent electrical efficiency [%]
EI-99	Eco-indicator 99
EM _e	CO ₂ emissions associated with electricity [kg CO ₂ /kWh]
EM _g	CO ₂ emissions associated with natural gas [kg CO ₂ /kWh]
F_c	Consumption of natural gas by cogeneration modules [MWh/y]
F_g	Consumption of natural gas [kW]
fam	Amortization and maintenance factor [y ⁻¹]
fame	Environmental amortization factor [y ⁻¹]
FAVA	Double effect absorption chiller

FAWH	Single effect absorption chiller
GHG	Greenhouse gas
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
FMWR	Mechanical chiller
ICVA	Vapor-hot water heat exchanger
ICWH	Hot water-cooling water heat exchanger
ICWR	Cooling tower
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
MGWH	Gas engine + hot water recovery system
MJ surplus	additional energy that will be needed in the future to extract resources
MILP	Mixed linear integer programming
N ₂ O	Nitrous oxide
NIN(i)	Number of pieces of equipment installed for technology i
P	Purchase
PAF	Potentially Affected Fraction of species
PDF	Potentially Disappeared Fraction
P _{nom} (i)	Nominal power of the equipment for technology i [MW]
PES	Primary Energy Savings
PFCs	Perfluorocarbons
Q _{cc}	Cogenerated useful heat [MWh/y]
Q _d	Heat demand [MWh/y]
R _d	Cooling demand [MWh/y]
S	Sale
SF ₆	Sulphur hexafluoride
SS _{fix}	Fixed impact of the equipment, in terms of EI-99 Single Score [points/y]
SS _{ope}	Operation impact, in terms of EI-99 Single Score [points/y]
SS _{tot}	Total annual impact, in terms of EI-99 Single Score [points/y]
SS _e	EI-99 Single Score for electricity [points/kWh]
SS _g	EI-99 Single Score for natural gas [points/kWh]
SSI(i)	EI-99 Single Score for the production of each piece of equipment i [points]

t_0	Ambient temperature [$^{\circ}\text{C}$]
TGVA	Gas turbine + heat recovery boiler
VA	High temperature steam
W_c	Cogenerated work by cogeneration modules [MWh/y]
W	Waste
WC	Cold water
WH	Hot water
WR	Cooling water
α	Ratio between local electricity CO_2 emissions and natural gas CO_2 emissions

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FIGURE CAPTIONS

Figure 1: Superstructure of the energy supply system.

Figure 2: Relative contribution of the impact categories to the European damage according to the hierarchist perspective, using the hierarchist weighting set.

TABLES

Table 1 Selected equipment and matrix of production coefficients.

Technology <i>i</i>	Selected equipment		Utility <i>j</i>						
	Cost CI (10 ³ €)	Nominal Power P _{nom} (MW)	CG	VA	WH	WR	AA	WC	EE
TGVA	1530	1.21	-4.06	+1.83	+0.53				+1
MGWH	435	0.58	-2.45		+0.96	+0.20			+1
CGVA	182	0.78	-1.20	+1					
CGWH	30	0.57	-1.08		+1				
ICVA	2.5	0.40		-1.00	+1				
ICWH	6.5	0.40			-1.00	+1			
FAVA	370	1.26		-0.83		+1.83		+1	-0.01
FAWH	200	0.49			-1.50	+2.50		+1	-0.01
FMWR	175	0.49				+1.23		+1	-0.23
ICWR	25	1.00				-1.00	+1		-0.02

Table 2 Inventory for the combustion of natural gas (1 kWh)

Substance	Compartment	Unit	Quantity
Nitrogen oxides	Air	kg	$6.54 \cdot 10^{-4}$
Sulphur oxides	Air	kg	$8.53 \cdot 10^{-6}$
Carbon monoxide	Air	kg	$4.74 \cdot 10^{-6}$
Carbon dioxide	Air	kg	0.2410
Gas, natural, 30.3 MJ per kg, in the ground	Raw	kg	0.0947

Table 3 Characterization factors for EI-99 (Hierarchist perspective)

	Human Health		Ecosystem Quality	Resources
	Respiratory Inorganics DALY/kg	Climate Change DALY/kg	Acidification and Eutrophication PDF·m ² ·y/kg	Fossil Fuels MJ surplus/kg
Nitrogen oxides	$8.87 \cdot 10^{-5}$	-	5.713	-
Sulphur oxides	$5.46 \cdot 10^{-5}$	-	1.041	-
Carbon monoxide	-	$3.22 \cdot 10^{-7}$	-	-
Carbon dioxide	-	$2.10 \cdot 10^{-7}$	-	-
Gas, natural, in the ground	-	-	-	4.55

Table 4 Characterization of inventory for the combustion of natural gas (1 kWh)

	Human Health		Ecosystem Quality	Resources		
	Respiratory Inorganics (DALY)	Climate Change (DALY)	Acidification and Eutrophication (PDF·m ² ·y)	Fossil Fuels (MJ surplus)		
Nitrogen oxides	$5.80 \cdot 10^{-8}$		$3.74 \cdot 10^{-3}$	-		
Sulphur oxides	$4.66 \cdot 10^{-10}$		$8.88 \cdot 10^{-6}$	-		
Carbon monoxide		$1.53 \cdot 10^{-12}$	-	-		
Carbon dioxide		$5.06 \cdot 10^{-8}$	-	-		
Gas, natural, in the ground		-	-	0.431		
Total (A)	$1.09 \cdot 10^{-7}$	DALY	$3.75 \cdot 10^{-3}$	PDF·m²·y	0.431	MJ surplus

Table 5 Damage model (Hierarchist perspective) for the combustion of natural gas (1 kWh)

	Human Health	Ecosystem Quality	Resources
Normalization factors (B)	65.1 (1/DALY)	$1.95 \cdot 10^{-4}$ (1/PDF·m ² ·y)	$1.19 \cdot 10^{-4}$ (1/MJ surplus)
Total (C = A · B)	$7.09 \cdot 10^{-6}$	$7.30 \cdot 10^{-7}$	$5.13 \cdot 10^{-5}$

Table 6 Weighting factors (H/H) and EI-99 points for the combustion of natural gas (1 kWh)

	Human Health	Ecosystem Quality	Resources
Weighting factors (D)	$0.3 \cdot 10^{-3}$	$0.4 \cdot 10^{-3}$	$0.3 \cdot 10^{-3}$
C · D	$2.13 \cdot 10^{-3}$	$2.92 \cdot 10^{-4}$	$1.54 \cdot 10^{-2}$
EI-99 Single Score	$2.13 \cdot 10^{-3} + 2.92 \cdot 10^{-4} + 1.54 \cdot 10^{-2} = \mathbf{1.78 \cdot 10^{-2}}$ points		

Table 7 EI-99 Single Score (points/kWh) and CO₂ emissions (kg CO₂/kWh) per damage category, for 1 kWh of consumed natural gas.

	Eco-Indicator 99 Single Score (points/kWh)			CO ₂ emissions	
	Human Health	Ecosystem Quality	Resources	TOTAL EI-99 SS	kg CO ₂ /kWh
Natural gas combustion (complete)	$2.13 \cdot 10^{-3}$	$2.92 \cdot 10^{-4}$	$1.54 \cdot 10^{-2}$	$1.78 \cdot 10^{-2}$	$2.41 \cdot 10^{-1}$
Natural gas, at user	$3.64 \cdot 10^{-4}$	$1.00 \cdot 10^{-4}$	$1.95 \cdot 10^{-2}$	$2.00 \cdot 10^{-2}$	$3.10 \cdot 10^{-2}$
Natural gas consumed in Spain (1 kWh)	$2.49 \cdot 10^{-3}$	$3.92 \cdot 10^{-4}$	$3.49 \cdot 10^{-2}$	$3.78 \cdot 10^{-2}$	$2.72 \cdot 10^{-1}$

Table 8 EI-99 Single Score (points/kWh) and CO₂ emissions (kg CO₂/kWh) per damage category, for 1 kWh of electricity produced by different power plants and Spanish mix.

	Eco-Indicator 99 Single Score (points/kWh)			CO ₂ emissions	
	Human Health	Ecosystem Quality	Resources	TOTAL EI-99 SS	kg CO ₂ /kWh
Coal ¹	$2.97 \cdot 10^{-2}$	$3.66 \cdot 10^{-3}$	$7.50 \cdot 10^{-3}$	$4.09 \cdot 10^{-2}$	1.02
Natural gas in combined cycle ²	$2.58 \cdot 10^{-3}$	$2.80 \cdot 10^{-4}$	$3.55 \cdot 10^{-2}$	$3.84 \cdot 10^{-2}$	$3.98 \cdot 10^{-1}$
Nuclear ³	$7.64 \cdot 10^{-4}$	$9.45 \cdot 10^{-5}$	$3.85 \cdot 10^{-4}$	$1.24 \cdot 10^{-3}$	$7.10 \cdot 10^{-3}$
Hydraulic ⁴	$1.76 \cdot 10^{-4}$	$5.61 \cdot 10^{-5}$	$1.38 \cdot 10^{-4}$	$3.70 \cdot 10^{-4}$	$3.60 \cdot 10^{-3}$
Eolic ⁵	$6.42 \cdot 10^{-4}$	$6.43 \cdot 10^{-4}$	$1.42 \cdot 10^{-3}$	$2.71 \cdot 10^{-3}$	$1.70 \cdot 10^{-2}$
Fuel-gas ⁶	$1.62 \cdot 10^{-2}$	$4.31 \cdot 10^{-3}$	$6.49 \cdot 10^{-2}$	$8.55 \cdot 10^{-2}$	$6.46 \cdot 10^{-1}$
Others ⁷	$1.37 \cdot 10^{-3}$	$2.62 \cdot 10^{-4}$	$1.15 \cdot 10^{-2}$	$1.31 \cdot 10^{-2}$	$1.32 \cdot 10^{-1}$
Spanish electricity mix (1 kWh)	$8.83 \cdot 10^{-3}$	$1.17 \cdot 10^{-3}$	$1.26 \cdot 10^{-2}$	$2.26 \cdot 10^{-2}$	$3.85 \cdot 10^{-1}$

Spanish electricity mix: 25.8% Coal, 24.4% Natural gas –combined cycle-, 19.7% Nuclear, 9.4% Hydraulic, 9.4% Eolic, 0.9% Fuel-gas, and 10.4% Others (Biomass, Natural gas –cogeneration-, Minihydraulic) [32].

¹ Coal: average net efficiency of Spanish hard coal power plants (35.8%).

² Natural gas in combined cycle: refers to the best technology, based on operation data of a German plant built in 2001, with net efficiency of 57.5%.

³ Nuclear: Swiss nuclear mix (electricity delivered in the period 1995 - 1999) of 55% Pressure Water Reactor and 45% Boiling Water Reactor (U enriched 3.8%).

⁴ Hydraulic: Includes shares of electricity produced by of run-of-river and reservoir hydropower plants in Spain. Electricity production shares are determined on annual average and on the level of net production, average efficiency 78%.

⁵ Eolic: Technology of a specific 600 kW wind power plant in Mt. Crosin, Switzerland; the capacity factor is 14 % (efficiency 93%).

⁶ Fuel-gas: estimation for the Spanish specific efficiency of transformation, data were given aggregated for oil and gas use (fuel-gas for peninsular Spain), with an average overall efficiency of 34%.

⁷ Others: Equal shares of Biomass (efficiency 32%), Natural gas –cogeneration- (efficiency 44%), Minihydraulic (efficiency 78%)

Table 9 Technologies, main material composition, CO₂ emissions, and EI-99 Single Score.

Technology	Material composition (kg)	CO ₂ I (kg CO ₂)	SSI (points)
TGVA	9080 kg steel, 500 kg aluminum	80,500	8700
MGWH	5700 kg steel	37,350	4030
CGVA	1000 kg cast iron, 1850 kg steel, 50 kg aluminum	15,810	1420
CGWH	850 kg steel, 25 kg aluminum	3050	205
ICVA	360 kg stainless steel	2350	251
ICWH	760 kg stainless steel	5010	532
FAVA	3700 kg iron alloy, 10,044 kg steel	98,600	11,100
FAWH	9000 kg steel	58,900	5890
FMWR	20 kg aluminum, 2000 kg steel, 500 kg copper, 1000 kg high-impact PVC	85,420	3130
ICWR	3500 kg steel, 1605 kg high-impact PVC	23,530	2990

Table 10 Results for the Eco-indicator 99 optimal, CO₂ optimal, and economic optimal.

Composition	CO ₂		Eco-indicator 99		Economic	
	Number	Installed Power	Number	Installed Power	Number	Installed Power
TGVA, CGVA	-	0	-	0	0	0
MGWH	-	0	-	0	3	1739 kW
CGWH	6	3420 kW	6	3420 kW	3	1710 kW
ICWH	0	0	0	0	4	1600 kW
ICVA, FAVA	0	0	0	0	0	0
FAWH	0	0	0	0	1	490 kW
FMWR	4	1960 kW	4	1960 kW	3	1470 kW
ICWR	3	3000 kW	3	3000 kW	3	3000 kW
F_g	8703 MWh/y		8703 MWh/y		37,324 MWh/y	
E_p	3572 MWh/y		3572 MWh/y		29 MWh/y	
E_s	-		-		11,389 MWh/y	
Cost of equipment	219,650 €/y		219,650 €/y		510,830 €/y	
Cost of F_g	217,582 €/y		217,582 €/y		933,092 €/y	
Cost of E_p	366,951 €/y		366,951 €/y		3207 €/y	
Profit with E_s	-		-		- 876,960 €/y	
<i>Total cost</i>	804,184 €/y		804,184 €/y		570,169 €/y	
Environmental load of equipment	43,057 kg CO ₂ /y		2272 points/y		52,699 kg CO ₂ /y	
$EM_g \cdot F_g$	2,367,296 kg CO ₂ /y		328,984 points/y		10,152,037 kg CO ₂ /y	
$EM_e \cdot E_p$	1,375,264 kg CO ₂ /y		80,730 points/y		11,168 kg CO ₂ /y	
$EM_e \cdot E_s$	-		-		4,384,799 kg CO ₂ /y	
<i>Total environmental load</i>	3,785,617 kg CO ₂ /y		411,986 points/y		5,831,105 kg CO ₂ /y	

Table 11 Configuration and main flows of the system, in function of the origin of electricity (CO₂ optimal).

	Coal	Fuel-gas	Natural gas (Combined cycle)
α factor	3.75	2.38	1.46
Composition	Number	Number	Number
TGVA, CGVA	-	-	-
MGWH	5	5	3
CGWH	1	1	3
ICWH	3	2	1
ICVA, FAVA	-	-	-
FAWH	4	3	-
FMWH	-	1	4
ICWR	6	5	3
F_g	42,882 MWh/y	29,300 MWh/y	17,148 MWh/y
E_p	0	0	1573 MWh/y
E_s	13,969 MWh/y	8522 MWh/y	3951 MWh/y
PES ¹	9.77 %	18.15 %	22.21 %
CO ₂ I	58,161 kg CO ₂ /y	57,959 kg CO ₂ /y	53,848 kg CO ₂ /y
$EM_g \cdot F_g$	11,663 871 kg CO ₂ /y	7,969,723 kg CO ₂ /y	4,664,244 kg CO ₂ /y
$EM_e \cdot E_p$	0	0	626,166 kg CO ₂ /y
$EM_e \cdot E_s$	- 14,247,966 kg CO ₂ /y	-5,505,467 kg CO ₂ /y	- 1,572,353 kg CO ₂ /y
<i>Total emissions</i>	- 2,525,935 kg CO ₂ /y	2,522,215 kg CO ₂ /y	3,771,904 kg CO ₂ /y

¹ Primary Energy Savings (PES) in comparison with the separate production of heat and power, calculated in accordance with COM 2004/8/EC [6] and COM 2007/74/EC [48].

Table 12 Emissions associated with electricity and natural gas, per country.

Country	CO ₂ emissions associated with consumption		α factor
	Electricity (Mix)	Natural gas	
United States of America (U.S.A.) ¹	0.603 kg CO ₂ /kWh	0.191 kg CO ₂ /kWh	3.15
United Kingdom (U.K.) ²	0.537 kg CO ₂ /kWh	0.206 kg CO ₂ /kWh	2.61
Japan ³	0.380 kg CO ₂ /kWh	0.248 kg CO ₂ /kWh	1.53
Spain	0.385 kg CO ₂ /kWh	0.272 kg CO ₂ /kWh	1.42
Canada ⁴	0.222 kg CO ₂ /kWh	0.179 kg CO ₂ /kWh	1.24

(1) U.S. [50, 51]; (2) U.K. [52]; (3) JAPAN [53]; (4) CANADA [54].

Table 13 Configurations of the systems and main flows, per country (CO₂ optimal).

	U.S.A.	U.K.	Japan	Canada
Composition	Number	Number	Number	Number
TGVA, CGVA	-	-	-	-
MGWH	5	5	4	-
CGWH	1	1	2	6
ICWH	3	3	1	-
ICVA, FAVA	-	-	-	-
FAWH	4	4	-	-
FMWH	-	-	4	4
ICWR	6	6	3	3
F_g	42,886 MWh/y	42,886 MWh/y	17,861 MWh/y	8703 MWh/y
E_p	0	0	1544 MWh/y	3572 MWh/y
E_s	13,970 MWh/y	13,970 MWh/y	4412 MWh/y	0
PES ¹	9.76 %	9.76%	22.15 %	0
CO ₂ I	58,161 kg CO ₂ /y	58,161 kg CO ₂ /y	57,278 kg CO ₂ /y	43,057 kg CO ₂ /y
$EM_g \cdot F_g$	8,191,253 kg CO ₂ /y	8,834,545 kg CO ₂ /y	4,429,424 kg CO ₂ /y	1,557,889 kg CO ₂ /y
$EM_e \cdot E_p$	0	0	586,889 kg CO ₂ /y	793,010 kg CO ₂ /y
$EM_e \cdot E_s$	- 8,424,087 kg CO ₂ /y	- 7,502,048 kg CO ₂ /y	- 1,676,537 kg CO ₂ /y	0
<i>Total emissions</i>	- 174,674kg CO ₂ /y	1,390,658 kg CO ₂ /y	3,397,053 kg CO ₂ /y	2,393,956 kg CO ₂ /y

¹ Calculated as in Table 11.

FIGURES

Figure 1

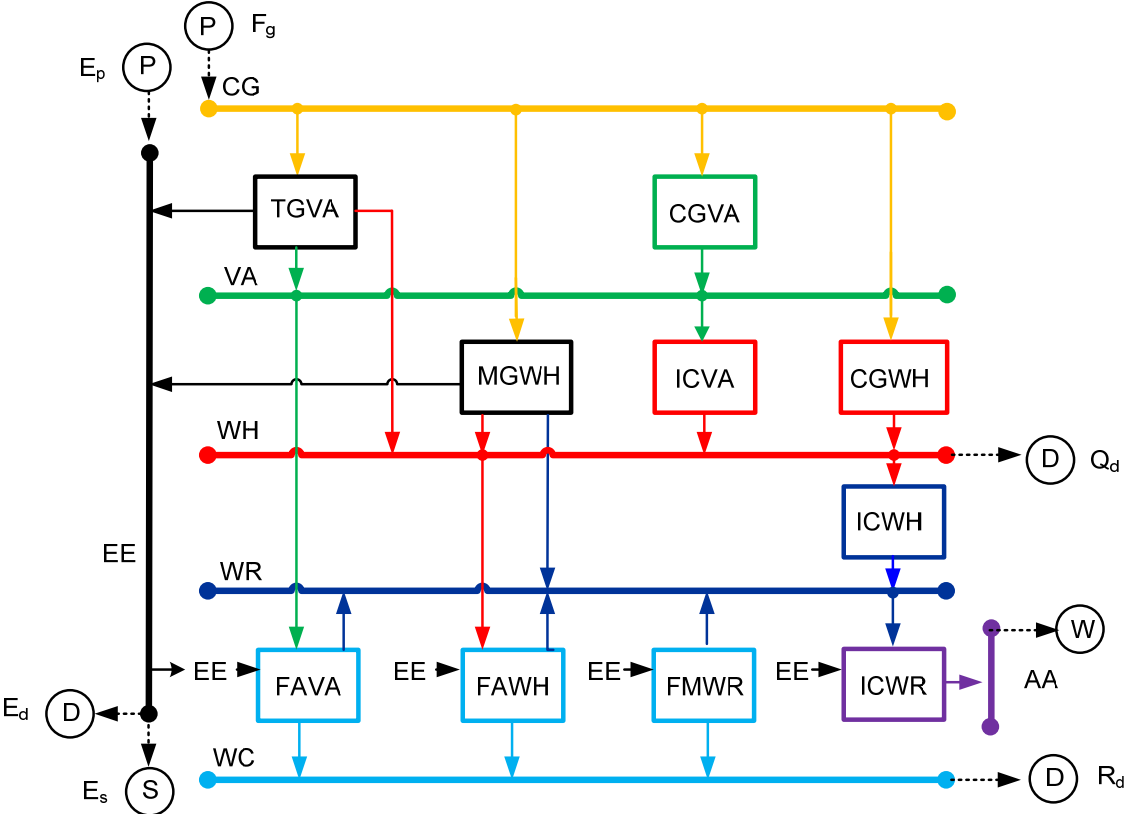


Figure 2

