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Tesis Doctoral

Thermoeconomic and environmental analyses for the synthesis of polygeneration systems in the residential-commercial sector

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D. Miguel Angel Lozano Serrano y D. Luis Mª Serra de Renobales, Profesores del Departamento de Ingeniería Mecánica de la Universidad de Zaragoza,

Hacen constar

Que la memoria titulada ***Análisis termoeconómico y ambiental para la síntesis de sistemas de poligeneración en el sector residencial-comercial (Thermoeconomic and environmental analyses for the synthesis of polygeneration systems in the residential-commercial sector)*** presentada por Dña. Monica Carvalho para optar al grado de Doctor ha sido realizada bajo su dirección de acuerdo con los objetivos y metodología establecidos en su proyecto de tesis.

Zaragoza a 12 de Enero de 2011

Fdo. Miguel Angel Lozano Serrano Fdo. Luis Mª Serra de Renobales

To my sister,

Frances

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Thermoeconomic and environmental analyses for the synthesis of polygeneration systems in the residential-commercial sector

Abstract

The residential-commercial sector, mainly constituted of buildings, represents one of the dominant energy consuming sectors in industrialized societies. For this reason, the energy needs of buildings (electricity, domestic hot water, thermal loads of heating and cooling) should be met in an efficient way by advanced systems, such as trigeneration systems. This thesis develops methodologies and procedures of analysis, synthesis, and design of trigeneration systems for the specific case of the residential-commercial sector. Such methodologies include the investigation of rational criteria for cost allocation in multiproduct complex systems submitted to energy market prices and variable energy demands. Energy demands vary seasonally as well as throughout the day, leading to several optimal operation conditions that combine the possibilities of purchasing or selling electricity and/or wasting the excess of cogenerated heat. An explicit incorporation of environmental considerations in the analysis is also carried out, which requires the development of new thermoeconomic analysis procedures. Initially, this thesis considers simple trigeneration systems, seeking clarity of concepts. Allocation proposals are made for these simple systems, considering the apportionment of economic costs and environmental loads. Then more realistic and complex trigeneration systems are considered as the focus shifts to the specific case of a medium size hospital located in Zaragoza, Spain. A Mixed Integer Linear Programming model (MILP) is developed, which incorporates technical data from commercially available equipment and local economic/environmental conditions to determine the optimal configuration and operation modes for the energy supply systems throughout an entire representative year. Optimal solutions are obtained from economic (minimization of annual cost) and environmental (minimization of annual CO_2 emissions and Eco-Indicator 99 points) viewpoints. A multiobjective optimization addresses conflictive objective functions and transfers the judgment on the trade-offs involved to the decision maker. Lastly, several sensitivity analyses are carried out to evaluate the effects of the most volatile parameters on the configuration and operation of complex trigeneration systems. Overall, this thesis provides a fresh approach to the rational and efficient design and use of polygeneration systems in the residential-commercial sector.

Análisis termoeconómico y ambiental para la síntesis de sistemas de poligeneración en el sector residencial-comercial

Resumen

El sector residencial-comercial, constituido básicamente por edificios, representa uno de los sectores dominantes en el consumo de energía de las sociedades desarrolladas. Sus necesidades energéticas: electricidad, agua caliente sanitaria, cargas térmicas de calefacción y refrigeración, etc., deberían ser cubiertas de manera eficiente con sistemas avanzados como los sistemas de trigeneración. Esta tesis desarrolla métodos y procedimientos de análisis, síntesis, y diseño de sistemas de trigeneración para el caso específico del sector residencial-comercial. Estas metodologías incluyen la investigación de criterios racionales para la asignación de costes en sistemas complejos con múltiples productos, sometidos a precios energéticos de mercado y que atienden demandas energéticas variables. Las demandas varían según la estación, e incluso durante el día, lo que da lugar a diferentes modos óptimos de operación que combinan la posibilidad de compra o venta de electricidad y de despilfarro de parte del calor cogenerado. También se incorporan explícitamente consideraciones ambientales en el análisis, lo que ha requerido el desarrollo de nuevos procedimientos de análisis termoeconómico. Inicialmente, esta tesis considera sistemas simples de trigeneración, buscando claridad en los conceptos. Se han hecho nuevas propuestas de reparto de costes económicos y cargas ambientales para sistemas simples de trigeneración. A continuación, se han considerado sistemas de trigeneración más realistas y complejos, tomando como ejemplo un hospital de tamaño medio ubicado en Zaragoza, España. Se ha desarrollado un modelo en programación lineal entera mixta (MILP) incorporando datos técnicos de equipos comerciales y condiciones económicas/ambientales locales para determinar tanto la configuración óptima como los modos óptimos de operación de los sistemas de suministro de energía a lo largo de un año representativo. Las soluciones óptimas se obtienen desde puntos de vista económico (minimización del coste anual) y ambiental (minimización de emisiones anuales de CO_2 y del Eco-Indicador 99). Se culmina con una optimización multiobjetivo que aborda la cuestión de las funciones objetivo en conflicto y traslada al analista el juicio sobre los compromisos involucrados. Se realizan varios análisis de sensibilidad para verificar los efectos de los parámetros más influyentes en la configuración y operación de los sistemas complejos de trigeneración. En conjunto esta tesis presenta una perspectiva actual para el diseño y utilización racional y eficiente de sistemas de poligeneración en el sector residencial-comercial.

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Nomenclature and acronyms

AA	Ambient air
AB	Auxiliary boiler
AC	Absorption chiller
ACF	Annual cash flows generated by the system [€/y]
Alpha	Ratio between local electricity CO_2 emissions and natural gas CO_2 emissions
B	Parameter that distributes heat from the cogeneration module
BCHP	Buildings Cooling, Heat and Power
c, C	Cost [€/y]
CCHP	Combined Cooling, Heat and Power
CHCP	Combined Heat, Cooling and Power
CG	Natural gas
CGVA	Steam boiler
CGWH	Hot water boiler
CHP	Combined Heat and Power
CI(i)	Investment cost of the equipment of technology i [€]
CM	Cogeneration module
CO_2	Carbon dioxide
$CO_2I(i)$	CO_2 emissions of the production of each piece of technology i [kg CO_2]
Cons(j,d,h)	Consumption of utility j in the period (d,h) [MW]
COP	Coefficient of performance
(d,h)	Period concerning (day, hour)
d	Discount of the combined production compared to separate production
D	Demand
D(j,d,h)	Demand of utility j in the period (d,h) [MW]
DALY	Disability-Adjusted Life Years [DALY]
DAM	Damage category value [DALY, PDF·m^2·y, or MJ surplus]
df	Damage factor [DALY/kg, PDF·m^2·y/kg, or MJ surplus/kg]
DHW	Domestic Hot Water
E, EE	Electricity
EC	Mechanical chiller
EEE	Equivalent Electrical Efficiency [%]
E/E	Egalitarian perspective

EI-99	Eco-indicator 99
EM	Relative to CO_2 emissions
EMIS	Environmental Management Information System
F	Consumption of fuel by equipment [MW]
fam	Amortization and maintenance factor [y^{-1}]
fam_e	Environmental amortization factor [y^{-1}]
FAVA	Double effect absorption chiller
FAWH	Single effect absorption chiller
fcr	Capital recovery factor [y^{-1}]
fic	Indirect costs
fmo	Maintenance and operating costs [y^{-1}]
FMWR	Mechanical chiller
G (node)	Relative to the distribution of the purchased natural gas
GHG	Greenhouse gases
GT	Gas Turbine
h	Sampling period [hour]
H/H	Hierarquist perspective
HC	Operation variable cost [€/h]
HEC	Operation variable emissions [kg CO_2/h]
HES	Operation variable EI-99 Single Score [points/h]
i	Relative to technology *i*
I/I	Individualist perspective
IC (node)	Relative to the distribution of evacuated heat by the cooling tower
ICE	Internal Combustion Engine
ICVA	Steam-hot water heat exchanger
ICWH	Hot water-cooling water heat exchanger
ICWR	Cooling tower
II	Initial investment [€]
IM	Impact category [DALY, PDF·m^2·y, or MJ surplus]
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return [%]
ISO	International Organization for Standardization
iyr	Interest rate [%]

j	Relative to utility *j*
KTU(i,j)	Absolute value of the production coefficient
L	Waste/Loss
L(j,d,h)	Waste of utility j in the period (d,h) [MW]
LCA	Life Cycle Assessment or Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
LHV	Lower Heating Value [MJ/kg]
lim	Limit
LNG	Liquefied Natural Gas
LPG	Liquiefied Petroleum Gas
MFN	Material Flow Network
MGWH	Gas engine + hot water recovery system
MJ surplus	Additional energy that will be needed in the future to extract resources [MJ surplus]
MILP	Mixed integer linear programming
MIP	Mixed integer programming
NA	Not applicable
nd(d)	Number of representative days per year
NIN(i)	Number of pieces of equipment installed for technology i
NIN_BIG(i)	Maximum limit for the number of equipment
NOP(i,d,h)	Number of pieces of equipment of technology i operating in the period (d,h)
NPV	Net Present Value [€]
ny	Number of years to consider the investment [y]
nyr	Equipment lifetime [y]
p	Market price [€/kWh]
P	Purchase
P(j,d,h)	Purchase of utility j in the period (d,h) [MW]
P_{nom}(i)	Nominal power of the equipment for technology i [MW]
PAF	Potentially Affected Fraction of species [PAF·m^2·y]
PDF	Potentially Disappeared Fraction [PDF·m^2·y]
PES	Primary Energy Savings [%]
PIN(i)	Installed power for each technology i [MW]
POP(i,d,h)	Production of technology i in the period (d,h) [MW]

PP	Payback period [y]
Prod(j,d,h)	Production of utility j in the period (d,h) [MW]
PVC	Polyvinyl chloride
Q	Heat
QA (node)	Relative to the distribution of heat from auxiliary boiler
QC (node)	Relative to the distribution of cogenerated heat
QD (node)	Relative to the heat demand output
QR (node)	Relative to the heat input of the absorption chiller
QW (node)	Relative to heat waste by the cogneration module
R	Cooling
r	Unit cost of waste heat (accompanied by subscript $_{ql}$) [€/kWh]
S	Sale
S(j,d,h)	Sale of utility j in the period (d,h) [MW]
SS	Environmental impact, in terms of EI-99 Single Score [points]
SSI	EI-99 Single Score of the production of each piece of technology i [points]
t(d,h)	Annual operation hours [y]
T	Temperature
TGVA	Gas turbine + heat recovery boiler
UHI	Urban Heat Island
VA	High temperature steam
W	Work
WC	Chilled water
WH	Hot water
WR	Cooling water
X(d,h)	Quantity concerning operational strategy
X(i,j,d,h)	Energy flow of utility j interchanged with technology i in the period (d,h) [MW]
y	Year [y]
YIN(i)	Binary variable 1/0 indicating that technology i is/is not installed
YTUC(i,j)	Binary variable 1/0 indicating that technology i consumes/does not consume utility j
YTUP(i,j)	Binary variable 1/0 indicating that technology i produces/does not produce utility j
YUD(j)	Binary variable 1/0 indicating the possibility of demand of utility j
YUP(j)	Binary variable 1/0 indicating the possibility of purchase of utility j
YUS(j)	Binary variable 1/0 indicating the possibility of sale of utility j

YUW(j)	Binary variable 1/0 indicating the possibility of waste of utility j
z	Prices, emissions, environmental loads per unit flow [€/kWh, kg CO_2/kWh, or points/kwh]

Greek letters

α_w	Electrical efficiency of cogeneration module
α_q	Thermal efficiency of cogeneration module
β	Unit cost of products [€/kWh]
Δ	Period
$\in$	Constraint utilized in the multiobjective optimization
η_q	Thermal efficiency of boiler
η_{ec}	Efficiency reference value for the separate production of electricity
η_{qc}	Efficiency reference value for the separate production of heat
λ	Marginal costs [€/kWh]
π	Market prices (reference) [€/kWh]
θ	Carnot factor
σ	Normalization factors [1/DALY,1/ PDF·m^2·y, or 1/MJ surplus]
ζ	Weighting factors

Subscripts

0	Ambient
a	Relative to the auxiliary boiler
aaicr	Relative to the ambient air of the cooling tower
abs	Relative to absorption chiller
c	Cogenerated
cc	Cogenerated useful
cg	Relative to natural gas boiler
cgcg	Natural gas input of natural gas boiler
cgmg	Natural gas input to gas engine
cgd	Relative to the auxiliary heat that attends the heat demand

cgf	Relative to the auxiliary heat that attends the cooling demand
d	demand
da	Relative to heat produced in the auxiliary boiler that attends heat demand
dc	Relative to heat produced in the cogeneration module that attends heat demand
dm	Damage category
e	Electricity
ed, eed	Electricity demand
eeabs	Electricity input to absorption chiller
eefm	Electricity input to mechanical chiller
eeicr	Electricity input to cooling tower
eemg	Electricity produced by gas engine
ep	Electricity purchased
er	Electricity input of mechanical chiller
es	Electricity sold to the grid
fa	Relative to fuel of the auxiliary boiler
fc	Relative to fuel of the cogeneration module
fix	Fixed (relative to equipment)
fm	Relative to the mechanical chiller
g	Relative to natural gas
h	Relative to hierarquist perspective
ich	Relative to the hot water-cooling water heat exchanger
icr	Relative to the cooling tower
ic	Impact category
inf	inferior
k	Relative to substances in the Life Cycle Inventory
l	Waste/loss
mg	Relative to the gas engine
mgc	Cogenerated useful work
mgd	Cogenerated work that attends the heat demand
mgf	Cogenerated work that attends the cooling demand
mgl	Heat waste by gas engine
nom	Nominal
ope	Operation

p	Purchase
ra	Heat produced in the auxiliary boiler attending cooling demand
rc	Heat produced in the cogeneration module attending cooling demand
rd	Cooling demand
re	Cooling output of mechanical chiller
ref	Reference
rq	Cooling output of absorption chiller
q	Relative to heat input to the absorption chiller
qa	Heat produced by auxiliary boiler
qc	Cogenerated heat
qcc	Cogenerated useful heat
qd	Heat demand
qda	Heat produced in the auxiliary boiler that attends heat demand
qdc	Heat produced in the cogeneration module that attends heat demand
ql	Waste/loss
qr	Heat input in absorption chiller
qra	Heat produced in the auxiliary boiler attending cooling demand
qrc	Heat produced in the cogeneration module attending cooling demand
r	Input to chillers
rd	Cooling demand
s	Sale
sup	Superior
tot	Total
wc	Cogenerated work
wcc	Cogenerated useful work
wcd	Cooling demand
wcabs	Cooling output from absorption chiller
wcfm	Cooling output from mechanical chiller
whabs	Heat input to absorption chiller
whd	Heat demand
whcg	Relative to heat from natural gas boiler
whcgd	Heat from natural gas boiler that attend heat demand
whcgf	Heat from natural gas boiler that attend cooling demand

whmg	Heat from gas engine
whmgl	Heat waste from gas engine
whmgc	Cogenerated useful heat from gas engine
whmgd	Heat from gas engine that attends heat demand
whmgf	Heat from gas engine that attends cooling demand
wrabs	Heat evacuated from absorption chiller
wrfm	Heat evacuated from mechanical chiller
wrich	Heat from hot water-cooling water heat exchanger
wricr	Heat evacuated by cooling tower
wrmg	Heat evacuated from gas engine

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CHAPTER I

INTRODUCTION

Polygeneration systems have important socioeconomical benefits related to its efficient use of energy resources and the enhanced economic competitiveness of the products obtained. Recognizing the growing demand for energy services in buildings (electricity, hot water, heating and cooling), the proposal of this thesis is to develop procedures for the synthesis of polygeneration systems in the residential-commercial sector.

Polygeneration is defined as the concurrent production of two or more energy services and/or manufactured products that, benefiting from the energy integration of the processes in its equipment, extracts the maximum thermodynamic potential of the resources consumed. The optimal configuration for a polygeneration system remains a complex problem throughout the years in the residential-commercial sector, because of the wide variety of technology options for the provision of energy services, great diurnal and annual fluctuations in energy consumption, and temporal variations in energy prices. Additionally, incorporation of environmental information into design decisions and allocation of production costs to consumers are controversial aspects of polygeneration systems that have great potential for further investigation. Furthermore, an appropriate allocation of economic costs and environmental loads to the final products will provide the consumers with correct indications on the rational, efficient and environmentally-friendly consumption of energy services. Widespread acceptance of polygeneration systems is highly dependent on the optimization of technology and rational allocation of costs to the products obtained. If consumers assess that cost allocation was fair, their buy-in is more likely to occur.

The primary motivation underlying the proposal of trigeneration systems in the commercial-residential sector is to increase the efficient use of natural resources by combining different technologies and energy resources while attending to varied energy service demands. This thesis aims to aid in overcoming barriers that hinder the consolidation of a more efficient and rational use of energy in the residential-commercial sector. The analyses carried out herein will hopefully enhance the dissemination and translation of knowledge to promote an increase in utilization of trigeneration technologies.

The methodological assumption of this thesis is that the combined application of thermoeconomic analysis, optimization techniques based on integer programming, and environmental impact assessment by applying the technique of Life Cycle Analysis (LCA) will allow for: (1) proposal and selection of configurations for the efficient and sustainable energy supply of buildings, (2) identification of the number and size of the equipment, (3) elucidation of the most suitable operational strategies throughout a year, and (4) allocation of the fair share of production costs and environmental loads among consumers.

1.1 POLYGENERATION IN THE RESIDENTIAL-COMMERCIAL SECTOR

As the desire for high quality of life intensifies worldwide, the demand for comfort increases in parallel with a higher degree of environmental conscience. In general, meeting such comfort demands in buildings leads to greater consumption of energy services (for example, an increment in the use of air conditioning), which is offset by environmental concern regarding consumption of fossil fuels and more rational use of energy. Polygeneration systems have been emerging based on this need for environmentally-friendly comfort.

Presently, the energy consumption of buildings in developed countries comprises 20-40% of total energy use, which is greater than industry and transportation figures in the European Union (EU) and USA (Perez-Lombard *et al.*, 2008). European research projects (CHOSE, 2001; TRIGEMED, 2003; Lamers, 2008) agree on the significant technical and socioeconomical potential of implementing trigeneration in the residential-commercial sector of countries in the Mediterranean area. In these countries, the need for heating is restricted to a few winter months, limiting the application of cogeneration[1] systems thus far. However, there is a significant need for cooling during the summer period. By combining cogeneration and heat-driven absorption chillers, the energy demand covered by cogeneration could be extended into the summer months to match cooling loads (Cardona & Piacentino, 2003; Chicco & Mancarella, 2006) via trigeneration[2]. Polimeros (1981), Horlock (1987), Sala (1994), and Petchers (2003) present many aspects of energy management and distributed generation in co- and tri- generation systems.

The residential-commercial sector (according to Eurostat, the Final Energy Consumption Sector: Households and Services) is a major energy consumer in Europe and around the globe (Manage energy, 2005) and often referred to as the tertiary sector. Advantages of trigeneration systems in buildings have been demonstrated in literature, as the improved use of fuel is associated with

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[1] Cogeneration is often referred to as CHP: Combined Heat and Power.

[2] Trigeneration is often referred to as CCHP: Combined Cooling, Heating and Power, or CHCP: Combined Heat, Cooling and Power. In buildings, the acronym BCHP: Buildings Cooling, Heating and Power is another option.

economic savings and sparing of the environment, as less fuel is consumed and consequently less pollution is generated (Maglorie *et al.*, 2002; Chicco & Mancarella, 2008).

Recognition of buildings as important energy consumers (and consequently polluters) is not yet sufficiently widespread in Spain. In fact, final energy consumption in the residential-commercial sector is 27% in Spain, which is a considerable portion of the total (EU, 2010). However, despite the obvious impact that polygeneration systems could have on this number, they are undoubtedly underutilized in Spain (Serra *et al.*, 2009), reaching only 10% penetration in installed power in buildings (IDAE, 2010).

Polygeneration is a fully developed technology that is well introduced in the industrial sector and has a long history of use in many types of industry, particularly in pulp and paper, petroleum and chemical industries. In recent years, the greater availability and choice of suitable technologies means that polygeneration can become an attractive and practical proposition for a wider range of applications. Owing to its unquestionable advantages, polygeneration is starting to be successfully used in the residential-commercial sector.

Opportunities for savings offered by polygeneration are often not fully exploited in buildings of the residential-commercial sector for the following reasons: (1) difficulty in establishing a suitable configuration for the energy supply system due to sizeable seasonal fluctuations in the consumption and wide variety of technology options (cogeneration/no cogeneration, gas turbine/gas engine, boiler/heat pump, mechanical chiller/absorption chiller), (2) low technical training or absence of staff responsible for energy management, (3) multiple users of energy services believe that individual supply provides greater security, (4) lack of stable legal framework, and (5) decision makers (architects, engineers, building developers and contractors) are not the final consumers of the energy supply system. Polygeneration has been proved to be successful when the owner of the system is also the final consumer (in airports and shopping centers, for example), perhaps because the long-term interests are considered in decision-making.

Until Spain joined the European Union, it could also be argued that the legislative framework was not favorable, but the scenario has changed. In 1993, Council Directive 93/76/EEC (1993) - regarding the limitation of CO_2 emissions through the improvement of energy efficiency in buildings - explicitly recognized the important contribution of buildings to the total environmental emission of CO_2 and the potential for remediation. Directive COM 2002/91/EC (2002) - on the energy performance of buildings - mandated that new buildings with a total usable space area over 1000 m^2 consider the technical, environmental, and economic feasibility of alternative energy systems, such as cogeneration, before the commencement of construction.

Following this, Directive COM 2004/8/EC (2004) promoted cogeneration based on a useful heat demand in the internal energy market. This directive favored microcogeneration systems (<50 kWe) and small-scale cogeneration (<1000 kWe), promoting such cogeneration technologies in the tertiary sector. In Spain, RD 616/2007 (2007) (transposition of COM 2004/8/EC in Spanish legislation) created a stable framework for extensive promotion and public support of cogeneration.

In 2010, Directive 2010/31/EU (a recast of Directive 2002/91/EC, on the energy performance of buildings) was adopted to strengthen the energy performance requirements and streamline some of its provisions. In particular, the Directive's energy performance requirements will now apply to refurbishment projects irrespective of size, rather than only for new buildings greater than 1000 m^2. Moreover, the Directive 2010/31/EU also establishes the goal that all new buildings (both commercial and residential) should be *nearly-zero energy buildings*[3] by 2020. For all new public sector buildings, the deadline for reaching *nearly-zero energy* status is 2018.

The residential-commercial sector includes residential buildings, office buildings, hotels, restaurants, shopping centers, schools, universities and hospitals, among others. These buildings vary in size, technical standard, building age and equipment. Energy demands in buildings depend on climatic conditions, architectonic features, and occupancy. The intricacies involved in developing energy systems for residential-commercial buildings are therefore obvious. In recent years, the analysis and design tools for energy systems have undergone important developments. Particularly, the synthesis and design of trigeneration systems in the residential-commercial sector has become increasingly elaborate, with numerous possibilities for energy sources and technological options. This increase in complexity allows for more flexible systems but at the same time increases difficulties when designing the trigeneration system itself.

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[3] A *nearly-zero energy building* is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources.

In the case of residential buildings, the design of systems can pose a significant technical challenge because of the potential non-coincidence of thermal and electrical loads and presence of multiple decision makers. Such unique challenge reinforces that ultimate penetration of polygeneration will depend on the type of building considered. Predictably stable businesses (unlikely to go out of business or even to shut down temporarily, such as hospitals and shopping centers) are suitable for polygeneration applications. Hospitals are good candidates for trigeneration systems because of their high energy requirements (heat for domestic hot water and space heating, cooling and electricity) compared to other commercial buildings as well as their need for high power quality and reliability.

Hospital facilities are investments intended to last many decades and highly depend on energy to function, thus selecting the best option for energy supply is paramount. Proper medical care of patients in a defined space demands utmost cleanliness and dependably stable internal climate. Bathing patients and frequently washing hands requires that clean hot water is always available. Hot water and steam are also required for additional services such as meals, sterilization of equipment and washing textiles. Although lighting of common spaces is the major consumer of electrical energy, electricity also fulfils a crucial role in life-support systems and operating theaters. Furthermore, electricity is used to power productivity-enhancing equipment such as patient lifts, adjustable beds and elevators. Communication systems for data handling and information exchange all run on electricity. The energy supply in a hospital is so important that its permanent availability must be ensured (Klimstra, 2006). Consequently, hospital environments have been frequently used as case studies in polygeneration literature (Ziher & Poredos, 2006; Arcuri *et al.*, 2007; Mavrotas, 2008; Piacentino & Cardona, 2008).

1.2 OPTIMIZATION/SYNTHESIS OF TRIGENERATION SYSTEMS

Cogeneration was first used by industry in the early 1900s to supply both electrical and thermal needs in an efficient manner. Industrial polygeneration has since become well established, with a long history of success and well known arrangements and benefits. Compared to other economic sectors, the industrial sector has the oldest, largest, and greatest number of polygeneration systems (Kreith & Goswami, 2007). The industrial sector (especially continuously processing chemical plants) is so dominant because facilities often operate continuously, have simultaneous electrical and thermal requirements, and already have a power plant and operating staff.

However, cogeneration in the residential-commercial sector has achieved limited penetration despite the success of industrial installations and strong evidence on the viability of polygeneration as a form of generating heat, cooling and electricity to meet the demands in the residential-commercial sector. Unique difficulties arise in the synthesis of energy supply systems for the residential-commercial sector due to the variability of the energy demands, variability of the energy prices, and legal restrictions. However, these difficulties cannot be seen as insurmountable barriers. For instance, existing optimization techniques widely utilized for the synthesis of energy supply systems in the industrial sector will be utilized/extrapolated herein and consequently extend the capacity of these techniques to the residential-commercial sector. Examples of optimization of cogeneration systems in industrial environments can be found in Sala & González (1988a,b).

In order to maximize benefits, the optimal design of trigeneration plants for buildings needs to address two fundamental issues: (1) synthesis of the plant configuration (*e.g.*, number and capacity of equipment for each type of technology employed) and (2) operational planning (*e.g.*, strategy for operational state of the equipment, energy flow rates, purchase/sale of electricity) (Yokoyama *et al.*, 1994; Lozano *et al.*, 2010). Although operational planning is the only concern for existing plants, both issues are inseparable for new plants. The variability of energy demands in buildings requires a design methodology that builds flexible utility systems which operate efficiently (thermodynamic target) and are capable of adjusting to different conditions (combinatorial challenge) (Shang & Kokossis, 2005).

Apart from heuristic methods, there are two main traditional approaches to synthesize an energy supply system: thermodynamic and optimization (Serra *et al.*, 2009). One example of the latter is mathematical programming, which will be explored below. The thermodynamic approach uses thermodynamic analysis to decrease the loss of available energy to a minimal and has the advantages of providing a comprehensive understanding of the characteristics of the system and requiring simpler calculations when compared to other approaches. For example, Nishio *et al.* (1980) developed a thermodynamic approach to steam-power system design, and Chou & Shih (1987) proposed a thermodynamic design procedure for the synthesis of plant utility systems. Commonly used thermodynamic methodologies for analyzing thermal energy systems are thermoeconomic analysis and pinch analysis. Thermoeconomic analysis has been used to obtain valid cost estimates for internal flows and final products (Lozano & Valero, 1993a; Ensinas *et* *al.*, 2007) and pinch analysis has been used in thermal integration of cogeneration systems (Puigjaner, 1997; Teopa *et al.*, 2005).

Unfortunately, thermodynamic methods alone do not provide a common framework for solving different classes of problems in a systematic manner (Kim & Han, 2001) and are not suited for simultaneous optimization of many different structures (Tveit *et al.*, 2006). Biegler & Grossmann (2004) provide a good overview of mathematical programming and its application to process design and process system engineering. Binary/Integer variables and continuous variables are required. Mixed Integer Programming (MIP) involves variables restricted to binary and/or integer values, for example counts (pieces of equipment), decisions (yes-no), or logical relations (if equipment A is in operation then equipment B is shut-down). MIP programming has very broad applications, and has been used by industries for production planning, sequencing processes, distribution and logistics problems, refinery planning, power plant scheduling, and process design. While this list is by far not complete (refer to Kallrath, 2000), it reflects the typical applications that mathematical programming could have in industries and businesses.

MIP captures the complexity of trigeneration systems in a synthesis problem and consists of three major steps (Grossmann *et al.*, 2000). The first step is the development of a *representation of alternatives* (superstructure of technologies and utilities). The second step is the formulation of a *mathematical program* that represents all possible options of operation through discrete variables and utilizes continuous variables for the representation of flows and funds (physic, economic, environmental). The third step is the *resolution* of the mathematical program from which the optimal solution is determined. This approach utilizes powerful mathematical algorithms to solve an optimization problem, which can include changes to the process parameters, process structure, and logical constraints. Significant advances and fine-tuning have occurred in this approach, which offers the possibility of developing tools to support the exploration of alternatives and optimization (Papoulias & Grossmann, 1983; Iyer & Grossmann, 1998; Bruno *et al.*, 1998).

The previously described legal panorama in Spain and Europe and the advances in optimization techniques stimulated efforts towards the analysis of trigeneration systems design and operation in the residential-commercial sector. The synthesis of energy systems implies searching for a design that minimizes or maximizes an objective function, such as economic cost, environmental load, or 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 economic markets and demand conditions, and operate optimally. The reviews by Hinojosa *et al.* (2007) and Chicco and Mancarella (2009) summarize the characteristics of optimization methods for polygeneration systems presented in recent publications, including time scale, objective function, and solution method.

Focusing on the criteria adopted to the design of trigeneration systems in the residential-commercial sector, a purely economic standpoint has been taken by the majority of optimization studies. Cardona *et al.* (2006) economically optimized the operation of the trigeneration system installed in the Malpensa airport, in Italy. Ziher & Poredos (2006) focused on the economics of a trigeneration system and optimization of cooling production in a hospital in Slovenia. Arcuri *et al.* (2007) presented the optimal operation of a trigeneration system that maximized annual economic returns in an Italian hospital. Li *et al.* (2008) optimized the operation of a trigeneration system in China to achieve minimum cost. Mavrotas (2008) presented an optimization study focusing on the annual cost and degree of demand satisfaction in Greece. Casisi *et al.* (2009) optimized configuration and operation of cogeneration systems installed in six public buildings in Italy. Sugiartha *et al.* (2009) obtained economic benefits when optimizing the operation of a trigeneration system in a supermarket located in the United Kingdom.

Environmental concerns have been a growing issue when planning energy supply systems. The need to consider the environment as an additional design factor arises due to an ever-increasing environmental conscience worldwide and stricter requirements to reduce the environmental impact of modern society. A purely environmental viewpoint has also been the focus of optimization studies specifically targeting polygeneration in buildings. Fumo *et al.* (2009) minimized primary energy consumption and CO_2 emissions separately in the operation of trigeneration systems located in buildings in the USA. Cho *et al.* (2009) presented an optimization of the operation of trigeneration systems in different climate conditions based on primary energy consumption and CO_2 emissions. Mago & Chamra (2009) optimized the operation of polygeneration systems considering primary energy consumption and CO_2 emissions. Wang *et al.* (2010) maximized primary energy savings and minimized pollutant emissions in the operation of a trigeneration system in a hotel in China.

In general, the configuration and operating conditions of a system yielding the best economy are pushed into a range where environmental loads are *higher* than the least otherwise possible. Multiobjective optimizations tackle the issue of conflicting objective functions (such as environment and economy), finding a 'balanced' optimal solution. Wang *et al.* (2008) presented a multicriteria optimization for a trigeneration system in a residential building in China, considering both technological and economical aspects. Kavvadias & Maroulis (2010) carried out an optimization of the operation of a trigeneration system in a hospital in Greece, considering economical and environmental aspects. Costs and CO_2 emissions were utilized in the operational optimization of the trigeneration system accomplished by Ren *at al.* (2010) at a university campus in Japan.

This thesis aims to provide guidelines for designing trigeneration systems by simultaneously optimizing the configuration and operational strategy of a trigeneration system meeting the energy demands of a medium size hospital, thus enhancing and taking previous studies to a next level of applicability. Specifically, this thesis will propose an integrated energy-planning framework based on Mixed Integer Linear Programming (MILP) to determine the optimal configuration and operation of a trigeneration system to be installed in a hospital. In single-objective optimizations, the total annual cost and total annual environmental loads will be separately considered, and several sensitivity analyses will be carried out to verify the effects of the most volatile parameters. This thesis will also present a computationally-intensive multiobjective optimization procedure that considers the total annual cost and total annual environmental loads (CO_2 emissions or Eco-indicator 99 points) involved in the design and operation of trigeneration systems. Note that all equipment considered herein is commercially available, which further enriches the applicability of results.

1.3 THERMOECONOMIC ANALYSIS

Thermoeconomics combines economic and thermodynamic analysis with the purpose of revealing opportunities of energy and cost savings when designing and operating energy conversion systems (El-Sayed & Evans, 1970; El-Sayed & Gaggioli, 1989; El-Sayed, 2003; Serra *et al.*, 2009). Thermoeconomics was first developed during the 1960s and the name was coined by M. Tribus (El-Sayed, 1999). Gaggioli (1983) further refined thermoeconomics to handle energy-intensive systems in general, with the objective of explaining the cost formation process of internal flows and products of energy systems.

Thermoeconomics has been used to support the design, synthesis and operation of energy systems by providing crucial information not available through conventional analyses. By revealing the relationship between thermodynamics and economics in the design of a system, thermoeconomics enhances knowledge and provides appropriate tools to understand cost interactions (Tsatsaronis, 2007). Thermoeconomic methods are powerful tools for the analysis (Lozano & Valero, 1993b; Gonzalez *et al.*, 2003; Wang & Lior, 2007; Deng *et al.* 2008), diagnosis (Lozano *et al.*, 1994; Arena & Borchiellini, 1999; Reini & Taccani, 2004; Verda & Borchiellini, 2007; Zhang *et al.*, 2007) and optimization (Frangopoulos, 1987; von Spakovsky & Evans, 1990a; Lozano *et al.*, 1996; Dentice & de Rossi, 1998; El Sayed, 2003; Sahoo, 2008) of such energy conversion systems.

Unit costs express the amounts of resources consumed to obtain a flow and are used by cost accounting theories as the basis for rational price assessment. In thermoeconomic analysis, the unit costs of internal flows and products of a system are calculated for each stream (*i.e.*, for each material and energy stream) in the overall system with the support of cost balances and auxiliary equations. Cost balances and auxiliary equations are rational carriers of the essential information needed for optimal system design. Obtaining unit costs of internal flows and products of energy systems are cornerstones of several thermoeconomic approaches that have been presented in literature (El Sayed & Tribus, 1983; Tsatsaronis & Winhold, 1985; Frangopoulos, 1987; von Spakovsky & Evans, 1990b; Lozano & Valero, 1993a; Lazzaretto & Tsatsaronis, 2006). Unit costs allow us to follow the cost formation process throughout the system, from energy resources to final products.

Marginal costs have important information for design and operation optimization of energy systems (Ranade & Robert, 1987; Frangopoulos, 1987; von Spakovsky & Evans, 1990a; Hui, 2000; Quelhas *et al.*, 2006). Marginal cost knowledge is predictive, beginning with a known value of the unit cost and if the system evolves according to specified conditions, it is possible to predict the final unit cost (Serra *et al.*, 1995).

The issue of cost allocation emerges when there is a system producing different products. This is important since the manner in which cost allocation is made will not only affect the cost of the products but also the consumers. Proposals for cost allocation criteria have been made in El-Nashar (1992); Neil (1999); Hamed *et al.* (2006); Lozano *et al.* (2009a); Lozano *et al*. (2009b) and Díaz *et al.* (2010), and should be selected depending on the objective of the analysis. However, existing studies have mainly focused on systems isolated from their economic environments and with local consumption of products, including all cogenerated heat.

In order to promote rational and efficient energy services production and consumption, a rational distribution of cost to the product must consider the nature of the optimal operation mode, which is determined by the economic environment and the variable energy demands of the system (Lozano *et al.*, 2009a). A fair cost-and-benefit apportionment will contribute to the acceptance of the more complex but more efficient trigeneration systems by users, which is essential for the success of such systems when they are oriented to multiple users.

This thesis aims to innovate by concurrently considering a trigeneration system and interactions with the environment through the purchase and sale of electricity. Thermoeconomic cost accounting will take the study of trigeneration systems described in the previous section a step further by: (1) providing a rational basis for pricing products, (2) determining the actual cost of internal flows and products, and (3) forming a foundation for operating decisions and its evaluation. Linking thermoeconomics to the optimization of trigeneration systems will solve the issue of explaining the cost formation process and reveal the optimal operation when external conditions change (demands or operation mode, for example). In such changing conditions, the information provided by marginal costs is useful to conduct operation towards optimal conditions and express the additional consumption of resources needed to produce one more unit of a product.

This thesis will address complex problems that have not been fully confronted until now, such as allocation methods for trigeneration systems regarding costs and environmental loads. Different allocation methods will be tested herein, showing how and to what extent applicability is valid since existing methods do not consider interaction with the environment or production of cooling. In addition, through a detailed examination of the operation modes of a trigeneration system, a judicious allocation proposal will be made, providing better insight on the characteristics of a trigeneration system. The allocation proposal will not only provide a solution to the problem of distribution of cost, but will also analyze the consequences of such allocation.

The proposal will obtain product costs that are reasonable and in accordance with the design objective of the system of providing product costs inferior to those of separate production.

Considering the scenario in which the consumers of the energy services are the owners of the trigeneration system designed, the allocation proposal assumes that the consumers will receive credits (in the form of a discount) for what was saved as a result of an efficient production MoreoverThe useful products of cogeneration are taken into account, and the cogenerated heat is disaggregated into a fraction that meets the heat demand directly and a fraction that is utilized to drive the absorption chiller (producing cooling). This proposal not only will shed light on the cost formation process but will also help inform the consumers of trigeneration systems on the costs associated with the consumption of each energy service. Such cost information can be very useful for the introduction of strategies to improve the operation of productive systems as well as consumption patterns and resource conservation, thus contributing to the development of a more sustainable economy (IPCC, 2007).

1.4 LIFE CYCLE ANALYSIS

Rising environmental conscience worldwide and stricter requirements to reduce the environmental impact of modern society have emphasized the need to consider environmental loads/impacts as a design factor in energy supply systems. The Life Cycle Analysis (LCA) is a tool that provides a more global perspective of environmental loads and has the potential to fulfill the need for an adequate design tool for energy supply systems (Guinée, 2002). 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 environmental emissions. The *life cycle* or *cradle-to-grave* impacts include those resulting from extraction of raw materials, fabrication of the product, transportation or distribution of the product to the consumer, use of the product by the consumer, and disposal or recovery of the product after its useful life.

Thermoeconomic analysis techniques and LCA are both based on the premise that all of the resources required for producing a good or service need to be accounted for. LCA can therefore be considered an adequate environmental design tool for energy supply systems as it can compare alternative technical proposals for the same issue and identify the most favorable for the environment. Incorporating sustainable development into the design and planning process should strive towards the following: (1) increased efficiency of energy and materials; (2) reduction of unit cost of final products; and (3) reduction of environmental burden.

Thermoeconomics is usually applied to industrial plants and the limits of the system are those of the associated plant. However, there is no constraint that impedes widening the limits of analysis to include the well or the mine from where the natural resources were extracted. Thus, merging thermoeconomics and LCA methodologies provides a global perspective of a complex system via an integrated analysis of energy, economics and environment. Generally, the analyzed system in LCA is treated as a *black box* from which only its inputs and outputs are measurable, without further knowledge of the inner structure. Applying the philosophy of thermoeconomics opens this *black box* and unravels the process of environmental burden formation, which is where the importance of combining thermoeconomics with LCA lies.

Thermoeconomics and LCA complement each other well - LCA evaluates consumption of natural resources and generation of environmental impacts, while thermoeconomic analysis tracks/distributes environmental burden within the productive system. There is a spatial/temporal connection between these methodologies: thermoeconomics deals with what occurs in the system, inside the limits of the productive system, in the length of time during which the process occurs; while LCA accounts for the generation of environmental burden throughout the system's life cycle, measuring the inputs and outputs of the system. This thesis will demonstrate that LCA can and has been logically and practically combined with thermoeconomic analysis. The result is an ability to take thermoeconomics and LCA – and their tradeoff relationships – into account in product/process design decision making.

Integration of thermoeconomics and LCA was carried out through the incorporation of environmental information on the usage and consumption of resources into an Environmental Management Information System (EMIS). This combined approach identifies where environmental loads are generated and tracks environmental loads throughout the system, allowing for a more precise understanding of operational activities. The combined methodology allows consumers of trigeneration systems to know the unit environmental loads (equivalent to the thermoeconomic unit costs) that are associated with the consumption of each energy service.

Parallel to the ongoing debate on which is the best cost allocation method for productive systems, this thesis will use different environmental allocation methods to assign environmental loads to each product of the trigeneration system, thus yielding a breakdown of fuel usage attributable to each product and identification of the flaws and limitations of existing methods. A rational environmental allocation proposal will be made, not only exposing the distribution of environmental loads throughout the trigeneration system, but also obtaining energy services with fewer environmental loads than those associated with separate production. Similar to the cost formation process, it will be possible to evaluate the process of formation of the environmental impact linked with consumption of natural resources and distribution of environmental loads throughout the system – *i.e.*, from the input of natural resources to the output of final products and emissions.

Significant progress has been made in accounting for environmental impacts within product evaluation and selection, however, in practice its use in process design and decision-making has not been fully exploited. There are challenging decisions that require trade-offs among conflicting attributes like cost, technical feasibility and environmental impacts. Knowledge of LCA methodologies can aid in setting and coordinating criteria that are indispensable to carry out meaningful multiobjective synthesis/optimization, thus correctly judging trade-offs and avoiding absurd comparisons. A multiobjective optimization will be carried out herein, through the solution of a MILP model, considering simultaneously economic and environmental aspects. Two bi-criteria optimization problems are solved (annual cost/annual CO_2 emissions and annual cost/EI-99 points) in an effort to evaluate the trade-offs involved in the conflictive objectives and support decision-makers in the judgment of solutions obtained.

1.5 OBJECTIVES AND STRUCTURE OF THE THESIS

The goal of this thesis is to (1) unravel the cost formation process and track environmental loads throughout trigeneration systems, while establishing appropriate allocation criteria; and (2) analyze, synthesize, and design trigeneration systems for the residential-commercial sector.

The thesis can be divided into two parts. The first part comprehends Chapters II and III, which introduce a simple trigeneration system, seeking clarity in the comprehension of concepts, followed by exposition and analysis of allocation methods, and presentation of results. In these chapters, only the operational stage is considered.

Chapter II presents a thermoeconomic analysis of a simple trigeneration system interacting with the economic environment. Energy costs of final energy services and internal flows for different operation conditions are determined and the significance of adequate selection of cost assessment criteria is emphasized. Thermoeconomic cost accounting for the simple trigeneration system is accomplished based on three different approaches: (1) marginal costs corresponding to optimal operation, (2) costs obtained when production costs are distributed to the final products according to their market prices, and (3) internal costs corresponding to a thermoeconomic analysis of the operation mode of the system. Different operation modes are highlighted, exposing the relationship between operation modes and marginal costs. A cost allocation proposal is made considering the operation modes, providing better insight on the characteristics of a trigeneration system. In this chapter, it is concluded that a fixed/closed set of auxiliary equations is not appropriate and dampens the richness of the optimal solutions obtained.

Chapter III focuses on the need to consider environmental loads/impacts as an additional design factor in energy supply systems. The concept of Life Cycle Analysis (LCA) is explained and the calculation of costs presented in Chapter II is extended to include an environmental viewpoint, integrating LCA and thermoeconomics. Two environmental criteria were considered: (1) kilograms of CO_2 released in the atmosphere and (2) Eco-indicator 99 Method. The allocation of environmental loads to the internal flows and final products of the simple trigeneration system is carried out by applying algebra and rules similar to those used in thermoeconomic analysis for the evaluation of internal costs. Different allocation criteria are discussed, culminating in an environmental load allocation proposal.

The second part of the thesis encompasses Chapters IV, V, and VI and presents more realist trigeneration systems, with extensive options for equipment that meet specific energy demands of a medium size hospital and more complex interactions between equipment and energy flows. In these chapters, synthesis and design problems are solved.

Chapter IV provides detailed calculations of energy services demands (including size of hospital, distribution of calendar, climatic data, and specific consumption indices) and explains the superstructure of the energy supply system (equipment and operation principles). This chapter also presents data on the availability of energy resources and their purchase/sale tariffs, current legal requirements for operating a cogeneration system in Spain, and environmental loads due to interchanged flows and installed equipment. Chapter IV establishes the data used in the optimizations carried out in Chapter V and VI.

Chapter V develops an optimization model using Mixed Integer Linear Programming (MILP) to (1) determine the type, number and capacity of the equipment for trigeneration systems installed in buildings and (2) establish the optimal operation for different plant components on an hourly basis throughout one year. Firstly, the objective function takes into account an economic point-of-view by minimizing the total annual cost (€/y). Secondly, the objective function takes into consideration an environmental viewpoint through the minimization of the annual kilograms of CO_2 released (kg CO_2/y) or the annual Eco-indicator 99 Single Score (points/y). The cost allocation criterion proposed in Chapter II is applied with success to a complex system. Chapter V also addresses the issue of conflictive objectives in a multiobjective optimization, with the analysis of the trade-offs involved in the simultaneous consideration of economic and environemntal viewpoints.

Chapter VI presents sensitivity analyses for the optimal configurations obtained in Chapter V. The first set of sensitivity analyses was carried out by varying the amortization and maintenance factor and then the natural gas price. The second set of sensitivity analyses verified the effect of legal constraints regarding minimum self-consumption and time-of-delivery feed-in tariffs on the optimal economic energy supply system. Sensitivity analysis of electricity sources is studied in the environmental optimals by varying the source of electricity in Spain and then varying international sources of natural gas and electricity. Geographic analysis considered a variation in the location of the system in Spain, which results in different energy service demands and different electricity sources.

Chapter VII presents a summary of the results and main conclusions of the thesis, followed by contributions and future research objectives.

CHAPTER II

THERMOECONOMIC ANALYSIS OF SIMPLE TRIGENERATION SYSTEMS

Chapter II presents a thermoeconomic analysis of a trigeneration system interacting with the economic environment. One of the main difficulties in calculating the costs of internal flows and products in trigeneration systems in buildings is the continuous variation of energy services (demands and prices). Demands vary seasonally as well as throughout a day and as a consequence there are different operation conditions which combine the possibility of buying or selling electricity and/or wasting the excess of heat cogenerated. The aim is to determine the energy costs of final energy services and internal flows for different operation conditions. That is, to determine the process of cost formation considering different operation modes and variable conditions. Fuel prices and purchase and sale electricity tariffs must be known in order to accomplish the necessary economic analysis. The importance of selecting appropriate cost assessment criteria is highlighted. Such criteria should account for different operation modes and the market structure, in order to promote rational and efficient energy services production and consumption.

Thermoeconomic cost accounting of simple trigeneration systems is accomplished based on three different approaches: (1) marginal costs corresponding to optimal operation, (2) costs obtained when production costs are distributed to the final products according to their market prices, and (3) internal costs corresponding to a thermoeconomic analysis of the operation mode of the system. The costs obtained with the mentioned approaches provide different information to be used in different applications and circumstances, as explained in this Chapter.

2.1 SIMPLE TRIGENERATION SYSTEM

A simple trigeneration system basically consists of a cogeneration module and an absorption chiller. The cogeneration module includes a prime mover (gas turbine, reciprocating engine, etc.) to convert the fuel energy to shaft power, an alternator to transform mechanical power to electrical power, and a heat recovery system. The absorption chiller can produce cooling from the recovered heat. Trigeneration plants become distinguishable by the different additional equipment incorporated (Petchers, 2003; Wu & Wang, 2006). The simple trigeneration system defined by Figure 2.1 also includes a mechanical chiller driven by electricity and an auxiliary boiler.

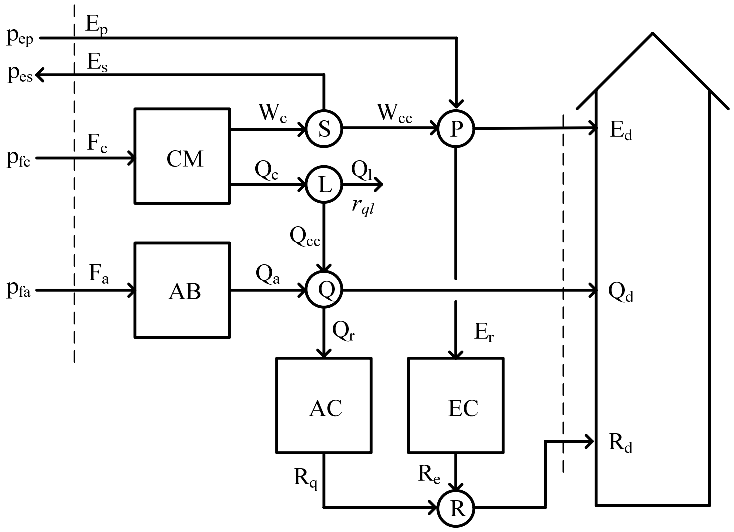

Figure 2.1 Simple trigeneration system.

The purpose of the trigeneration system is to meet the demand of different energy services (electricity, E_d; heat, Q_d; and cooling, R_d) of a consumer center. The simple trigeneration system consists of the following productive units: a cogeneration module CM (providing heat, Q_c, and work, W_c), an auxiliary boiler AB (providing heat, Q_a), an absorption chiller AC (providing cooling, R_q, and driven by heat, Q_r) and a mechanical chiller EC (providing cooling, R_e, and driven by electricity, E_r). F_c and F_a refer to the fuel utilized by the cogeneration module and the auxiliary boiler, respectively.

The prices of the fuel consumed by the cogeneration module and the boiler are, respectively, p_{fc} and p_{fa}. The demands will always be met either by the trigeneration system productive units or with the help of purchased electricity from the electric grid (E_p at a price p_{ep}). It is also possible that a fraction of the cogenerated heat could be wasted (Q_l at a unit cost r_{ql}) or that cogenerated electricity could be sold to the market (E_s at a price p_{es}). Wasted heat permits the operation of the cogeneration module to match the demand of the consumer center or to realize profits by selling surplus cogenerated electricity to the market.

Table 2.1 shows technical data for the productive units in a specific case of the trigeneration system. All of them can operate either at part load or full load. Table 2.2 presents the prices of the energy flows exchanged with the market. Note that different fuels are consumed by the cogeneration module and auxiliary boiler, and therefore the prices are also different.

Table 2.1 Technical parameters.

Unit	Efficiency coefficient	Nominal capacity (kW)
CM	$\alpha_w \equiv W_c/F_c = 0.35$ $\alpha_q \equiv Q_c/F_c = 0.40$	$W_{c\ nom} = 350$
AB	$\eta_q \equiv Q_a/F_a = 0.80$	$Q_{a\ nom} = 400$
AC	$COP_q \equiv R_q/Q_r = 0.625$	$R_{q\ nom} = 250$
EC	$COP_e \equiv R_e/E_r = 5.0$	$R_{e\ nom} = 250$

Table 2.2 Energy prices (€/kWh).

p_{ep}	p_{es}	p_{fc}	p_{fa}
0.100	0.080	0.025	0.020

2.2 OPTIMAL OPERATION MODEL

In a competitive energy market scenario, the profitability of the operation of simple trigeneration systems depends on the capacity and performance of the installed technologies, fuel and electricity prices (subject to high variability and volatility), and demanded quantities of energy services (with great daily and seasonal variation). For a given demand several operating conditions are possible.

To obtain the optimal operation state, a linear programming model was solved. The economic analysis considered that the only significant variable costs were electricity and fuel, and that cogenerated heat could be wasted without cost, *i.e.*, $r_{ql} = 0$. The objective function to be minimized was the operation variable cost (HC, in €/h):

$$HC = p_{fc} \cdot F_c + p_{fa} \cdot F_a + p_{ep} \cdot E_p - p_{es} \cdot E_s + r_{ql} \cdot Q_l \tag{2.1}$$

Which was subject to the following restrictions:

Capacity limits

cCM: $W_c \leq W_{c\ nom}$ (2.2)

cAB: $Q_a \leq Q_{a\ nom}$ (2.3)

cAC: $R_q \leq R_{q\ nom}$ (2.4)

cEC: $R_e \leq R_{e\ nom}$ (2.5)

Equipment efficiency

eCMw: $\alpha_w \cdot F_c - W_c = 0$ (2.6)

eCMq: $\alpha_q \cdot F_c - Q_c = 0$ (2.7)

eAB: $\eta_q \cdot F_a - Q_a = 0$ (2.8)

eAC: $COP_q \cdot Q_r - R_q = 0$ (2.9)

eEC: $COP_e \cdot E_r - R_e = 0$ (2.10)

Balance equations

S: $W_c - W_{cc} - E_s = 0$ (2.11)

P: $W_{cc} + E_p - E_d - E_r = 0$ (2.12)

L: $Q_c - Q_{cc} - Q_l = 0$ (2.13)

Q: $Q_{cc} + Q_a - Q_d - Q_r = 0$ (2.14)

R: $R_q + R_e - R_d = 0$ (2.15)

Demand constraints (here the demands of the energy services for Example ExC$_1$ are shown)

ED: $E_d = 400$ (2.16)

QD: $Q_d = 400$ (2.17)

RD: $R_d = 400$ (2.18)

Results were obtained by utilizing the computer application Lingo (Lindo systems, 2008), which uses an algebraic language to formulate programming models and optimization algorithms to solve them. Given the energy demands to be satisfied, Lingo solved the previous model and determined the feasible operation state with the minimum operation variable cost. The Lingo model can be found in the CD that accompanies the thesis.

The model described by Equations (2.1) – (2.18) could be more complex by considering more detailed operation conditions, *e.g.*, minimum capacity limits of the productive units or cost of heat dissipation. However, increasing the complexity of the model would not provide more relevant conclusions and would hide, to some extent, the clarity of the analysis. In other words, the model and the examples considered are simple (as stated in the title of the chapter) but clearly structured to allow for the making of interesting analyses and conceptual interpretations.

It is worthwhile to comment that the operation states have been determined from an economic viewpoint. The single-objective optimization of processes can be performed from several perspectives and consequently using different bases to construct objective functions. This will be discussed in Chapter III.

2.3 OPERATION MODES

Table 2.3 Operation modes.

	$E_p > 0$ and $E_s = 0$	$E_p = 0$ and $E_s = 0$	$E_p = 0$ and $E_s > 0$
$Q_a > 0$ and $Q_l = 0$	**C_1**	**C_4**	**C_7**
$Q_a = 0$ and $Q_l = 0$	C_2	C_5	C_8
$Q_a = 0$ and $Q_l > 0$	**C_3**	C_6	**C_9**

Table 2.4 Energy flows and variable cost.

		ExC_1	**ExC_3**	**ExC_4**	**ExC_7**	**ExC_9**
E_d	kW	*400*	*400*	*330*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*	*100*
E_p	kW	**100**	**50**	0	0	0
E_s	kW	0	0	0	**130**	**150**
F_c	kW	1000	1000	1000	1000	1000
F_a	kW	300	0	250	250	0
W_c	kW	350	350	350	350	350
Q_c	kW	400	400	400	400	400
W_{cc}	kW	350	350	350	220	200
E_r	kW	50	0	20	20	0
Q_l	kW	0	**140**	0	0	**140**
Q_{cc}	kW	400	260	400	400	260
Q_a	kW	**240**	0	**200**	**200**	0
Q_r	kW	240	160	0	0	160
R_q	kW	150	100	0	0	100
R_e	kW	250	0	100	100	0
Objective HC	€/h	**41.00**	**30.00**	**30.00**	**19.60**	**13.00**
Operation mode		**C_1**	**C_3**	**C_4**	**C_7**	**C_9**

The resulting feasible operation states can be classified into 9 different operation modes, based on the values of purchased electricity (E_p), sold electricity (E_s), auxiliary heat (Q_a) and waste heat (Q_l). These operation modes correspond to different demand of the energy services of the consumer center and are shown in Table 2.3. A summary of results (demand, flows, and hourly cost) obtained with Lingo for five examples ExC$_1$, ExC$_3$, ExC$_4$, ExC$_7$ and ExC$_9$ that correspond to different operation modes (C$_1$, C$_3$, C$_4$, C$_7$ and C$_9$) is presented in Table 2.4. For each different example, the minimum cost of satisfying the energy service demand of the consumer center is reached in a different operation mode, which exchanges energy flows at market prices and utilizes the productive capacity of the installed equipment.

Figures 2.2, 2.3, 2.4, 2.5 and 2.6 show the energy flows associated with examples ExC$_1$, ExC$_3$, ExC$_4$, ExC$_7$ and ExC$_9$.

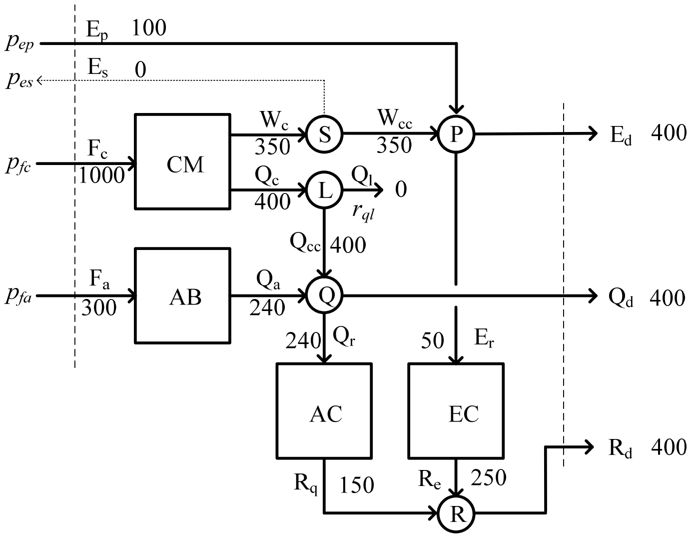

Figure 2.2 Energy flows for example ExC$_1$.

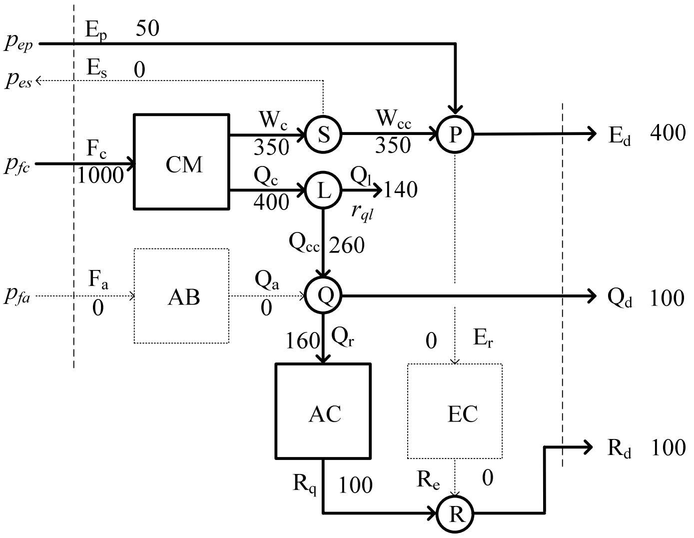

Figure 2.3 Energy flows for example ExC_3.

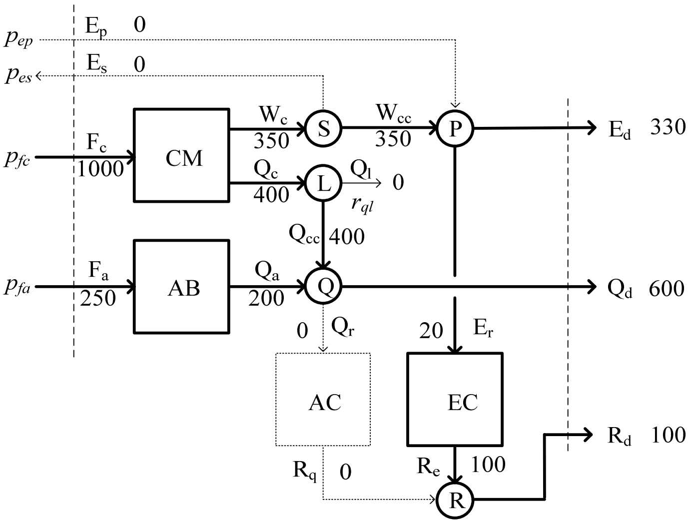

Figure 2.4 Energy flows for example ExC_4.

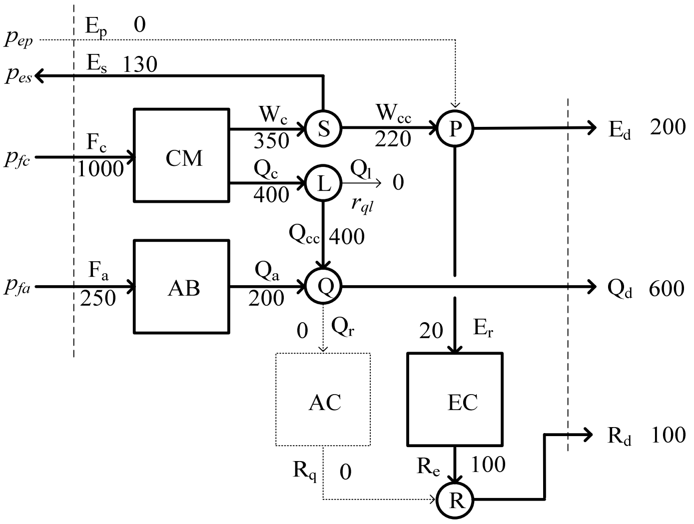

Figure 2.5 Energy flows for example ExC_7.

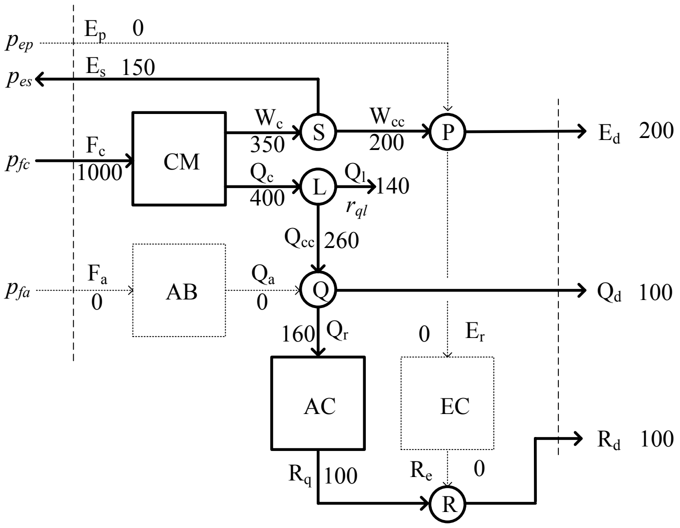

Figure 2.6 Energy flows for example ExC9.

With the technical parameters and energy prices presented in Table 2.2, it is interesting to operate the cogeneration module at full load to produce electricity even if a fraction of heat is wasted. The system takes advantage of the production of electricity from a cheaper fuel source to not only meet the electricity demand but also profit by selling surplus cogenerated electricity to the grid. However, from an environmental viewpoint, the concept of wasting heat is not friendly; it could even be considered a potential threat to the climate (Nordell and Gervet, 2009). Waste heat plays an important role in affecting the urban thermal environment, ambient air quality, and other attributes of the urban climate system, resulting in the Urban Heat Island (UHI) phenomenon (Fan and Sailor, 2005).

The following sections substantiate three different approaches to determine the cost of internal flows and products: (1) analysis of marginal costs, (2) valuation of products applying market prices, and (3) internal costs calculation.

2.4 MARGINAL COSTS

The Lingo solution report for the model presented in the previous section also gives a dual price figure for each constraint. If a constraint expresses the produced quantity of a flow, then its dual price can be interpreted as the marginal cost of this flow. Dual prices are also called shadow prices, because they indicate how much one is willing to pay for an additional unit of a specific resource. Marginal costs in particular have important information for the operational optimization of energy systems. Table 2.5 shows the marginal costs for the final products of the five examples shown in Table 2.4.

Table 2.5 Marginal cost of final products (€/kWh).

	λ_{Ed}	λ_{Qd}	λ_{Rd}
ExC_1	0.100	0.025	0.040
ExC_3	0.100	0	0
ExC_4 (E_d R_d +)	0.100	0.025	0.020
ExC_4 (E_d R_d -)	0.080	0.025	0.016
ExC_7	0.080	0.025	0.016
ExC_9	0.080	0	0

More specifically, marginal costs represent the amount by which the objective function would increase as the constant term of the constraints is increased by one unit. Marginal costs, in general, are not conservative, *i.e.*,

$$HC \neq \lambda_{Ed} \cdot E_d + \lambda_{Qd} \cdot Q_d + \lambda_{Rd} \cdot R_d \tag{2.19}$$

and as a consequence are not appropriate for cost assessment. However, marginal costs are important (1) to identify which operation constraint could be changed to improve the solution, and (2) to react automatically when external operational circumstances (prices of resources and product demands) change (Lozano et al., 2009c). Therefore, marginal costs contain the information associated with the operation costs of the system for each operation mode.

2.4.1 Marginal costs and operation modes

Figure 2.7 graphically explains the direction (origin) of the marginal costs obtained for the final products in example ExC_1; that is, how the equipment will operate to produce an additional unit of the final products. The cogeneration module operates at full load and electricity is purchased; therefore, if an additional unit of electricity is required, it can only be obtained by purchasing it from the electric grid at a price of $\lambda_{Ed} = p_{ep}$. The additional heat will be produced by the auxiliary boiler, to attend to the extra unit of heat demand ($\lambda_{Qd} = p_{fa}/\eta_q$) or produce cooling through the absorption chiller ($\lambda_{Rd} = (p_{fa}/\eta_q)$ /COP_q).

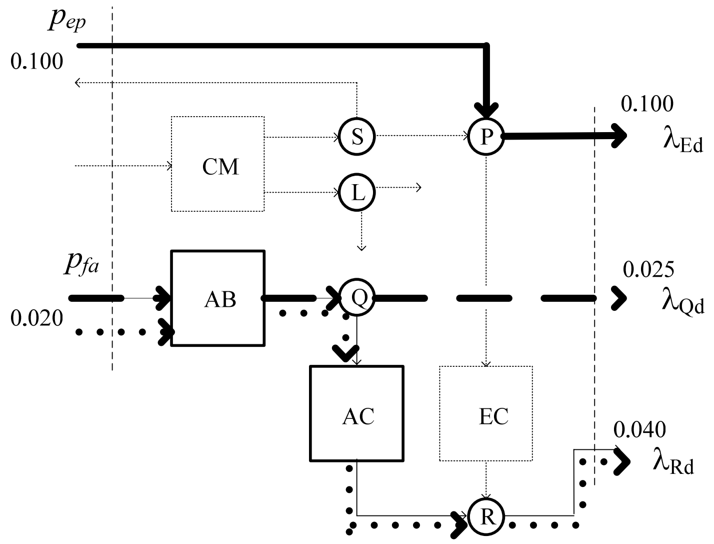

Figure 2.7 Marginal costs for ExC_1.

Figure 2.8 depicts the marginal costs obtained for the final products in example ExC_3. In this case, the cogeneration module operates at full load and electricity is purchased; therefore, if an additional unit of electricity is required, it can only be obtained by purchasing it from the electric grid at a price of $\lambda_{Ed} = p_{ep}$. A part of the cogenerated heat is wasted ($Q_l > 0$), but it could be utilized at no cost ($\lambda_{Qd} = \lambda_{Rd} = 0$) to satisfy directly the additional demand of heat or indirectly, through the absorption chiller, the additional cooling demand.

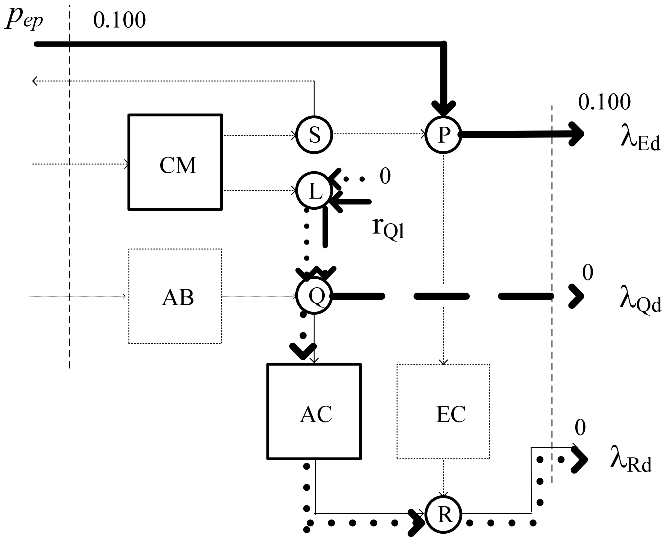

Figure 2.8 Marginal costs for ExC_3.

Figures 2.9 and 2.10 explain the marginal costs for example ExC_4, in which $E_p = E_s = 0$. As can be seen in Figure 2.9, if an additional unit of electricity is required, it must be obtained through the purchased electricity ($\lambda_{Ed} = p_{ep}$), because the cogeneration module is operating at full load. The additional heat will be produced by the auxiliary boiler ($\lambda_{Qd} = p_{fa}/\eta_q$), and the additional cooling will be produced by the mechanical chiller driven by purchased electricity ($\lambda_{Rd} = p_{ep}/COP_e$). Figure 2.10 explains how a decrease in the demand of electricity or cooling allows the sale of surplus electricity to the grid ($\lambda_{Ed} = p_{es}$ and $\lambda_{Rd} = p_{es}/COP_e$, respectively).

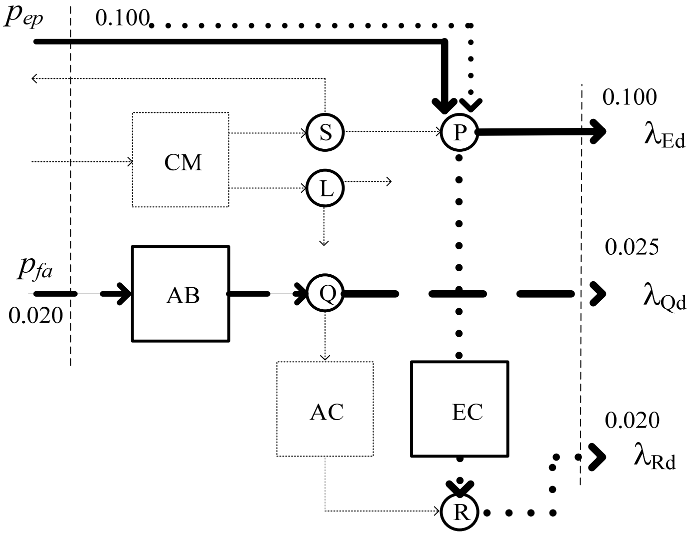

Figure 2.9 Marginal costs for ExC_4 (E_d R_d +).

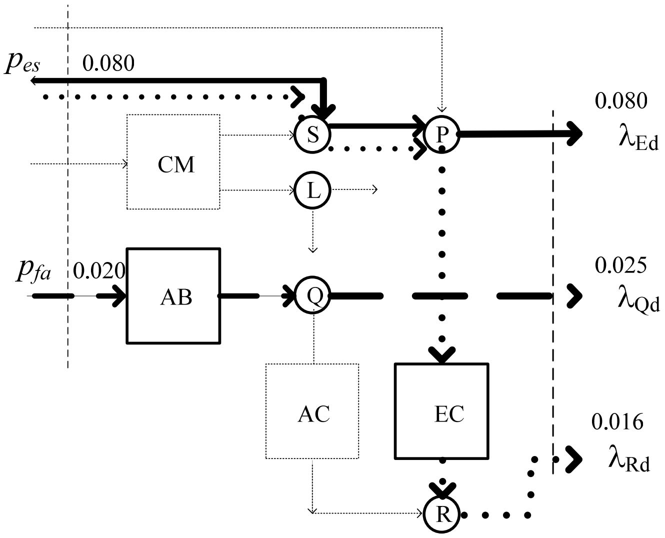

Figure 2.10 Marginal costs for ExC_7 and ExC_4 (E_d R_d -).

Figure 2.10 also explains how the additional demand units will be satisfied in the operation example ExC$_7$, in which surplus electricity is produced and sold to the electric grid. An additional unit of electricity can be consumed if one less unit is sold to the market, therefore the marginal cost is the selling price ($\lambda_{Ed} = p_{es}$). An additional unit of heat will be produced by the auxiliary boiler ($\lambda_{Qd} = p_{fa}/\eta_q$). To produce an additional unit of cooling, 1/COP$_e$ units less of electricity are sold to the market and therefore used to drive the mechanical chiller ($\lambda_{Rd} = p_{es}/COP_e$).

Figure 2.11 depicts the marginal costs obtained for the final products in example ExC$_9$. In this case, the cogeneration module operates at full load and electricity is sold; therefore, if an additional unit of electricity is required, one less unit is sold to the market, therefore the marginal cost is the selling price ($\lambda_{Ed} = p_{es}$). A part of the cogenerated heat is wasted ($Q_l > 0$), but it could be utilized at no cost ($\lambda_{Qd} = \lambda_{Rd} = 0$) to satisfy directly the additional demand of heat or indirectly, through the absorption chiller, the additional cooling demand.

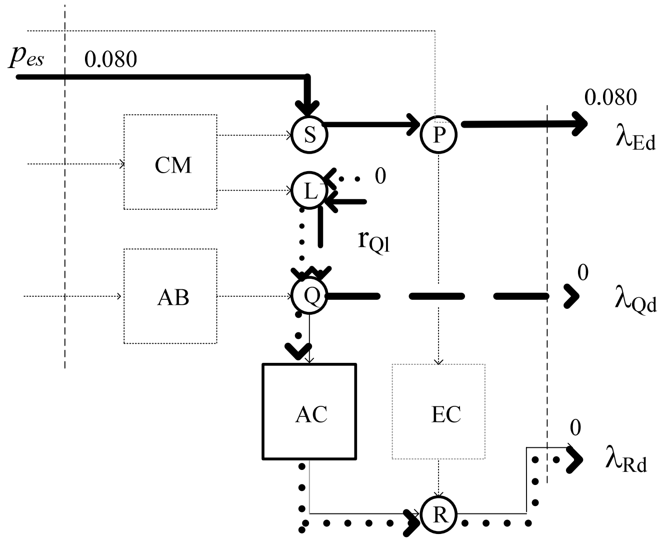

Figure 2.11 Marginal costs for ExC$_9$.

2.4.2 Marginal costs versus variable demands and energy prices

Please note that example ExC$_4$ belongs to the special operation mode C$_4$ ($E_p = 0$, $E_s = 0$) which represents the discontinuity between modes C$_1$ ($E_p > 0$, $E_s = 0$) and C$_7$ ($E_p = 0$, $E_s > 0$). When $Q_d = 600$ kW and $R_d = 100$ kW, and if the electricity demand was precisely $E_d = 330$ kW, the optimal solution would not correspond to either purchase or sale of electricity. Given the market and demand conditions, the cogeneration module is operating at full load in optimal mode; therefore, an increase in the demand or consumption of electricity is covered by purchasing from the electric grid, while a decrease would allow the sale. Since all of the cooling is produced by consuming electricity in the mechanical chiller, an additional unit of cooling implies the purchase of electricity, while a decrease in the demand allows the sale of the electricity not required.

The close relationship that exists between the marginal cost of products and the operation mode of the simple trigeneration system is therefore proven. Table 2.6 and Figure 2.12 show the results corresponding to the optimal operation when the demands of heat and cooling are fixed, Q_d = 600 kW and R_d = 100 kW, and the electricity demand E_d is modified, from 0 to 600 kW. Table 2.6 also presents the variable energy flows (the remaining flows are the same as indicated for ExC_7 in Table 2.4).

Table 2.6 Optimal operation in function of electricity demand (Q_d = 600 kW, R_d = 100 kW).

Operation mode	E_d (kW)	E_s (kW)	E_p (kW)	W_{cc} (kW)	HC (€/h)
C_7	0	330	0	20	3.60
C_7	100	230	0	120	11.60
C_7	200 (ExC_7)	130	0	220	19.60
C_7	300	30	0	320	27.60
C_4	**330 (ExC_4)**	**0**	**0**	**350**	**30.00**
C_1	400 (ExC_1)	0	70	350	37.00
C_1	500	0	170	350	47.00
C_1	600	0	270	350	57.00

In the previous examples the optimal operation corresponded to the full load operation of the cogeneration module, even if wasting part of cogenerated heat. It is more profitable to produce electricity in the cogeneration module at a unit cost of p_{fc}/α_w = 0.0714 €/kWh (lower than p_{es} = 0.080 €/kWh and p_{ep} = 0.100 €/kWh), and therefore the cogeneration module operates at full load to produce electricity. The heat not used to attend to the demands of heat and cooling will be then wasted. This makes the optimization labor somewhat trivial to some extent in this case, as the results presented in Table 2.4 could be determined without solving the optimization model with Lingo.

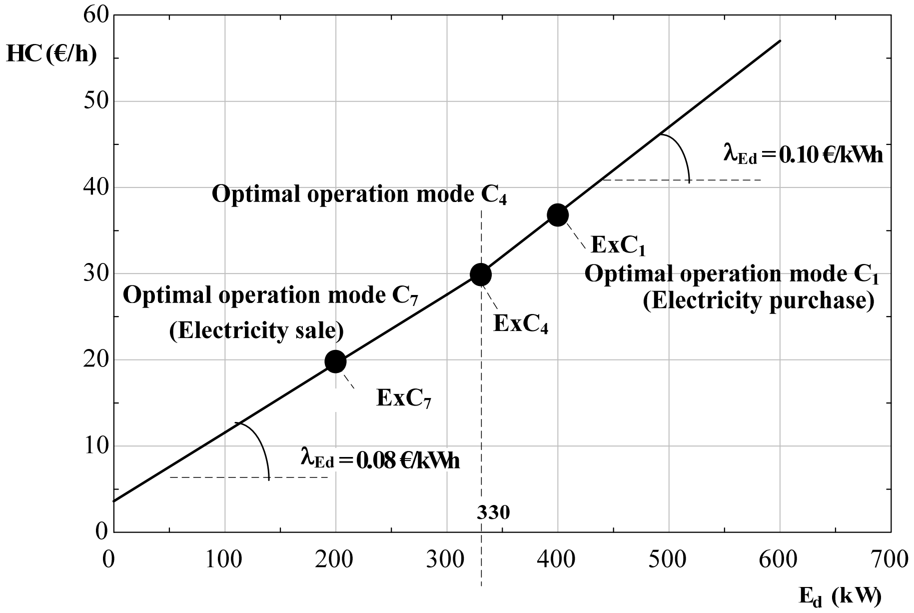

Figure 2.12 Hourly cost versus electricity demand (Q_d = 600 kW, R_d = 100 kW).

Figure 2.13 and Table 2.7 show the variation of minimum operation cost when the price of fuel p_{fc} is increased, being the demand the same as in example ExC_3 (E_d = 400 kW, Q_d = 100 kW and R_d = 100 kW).

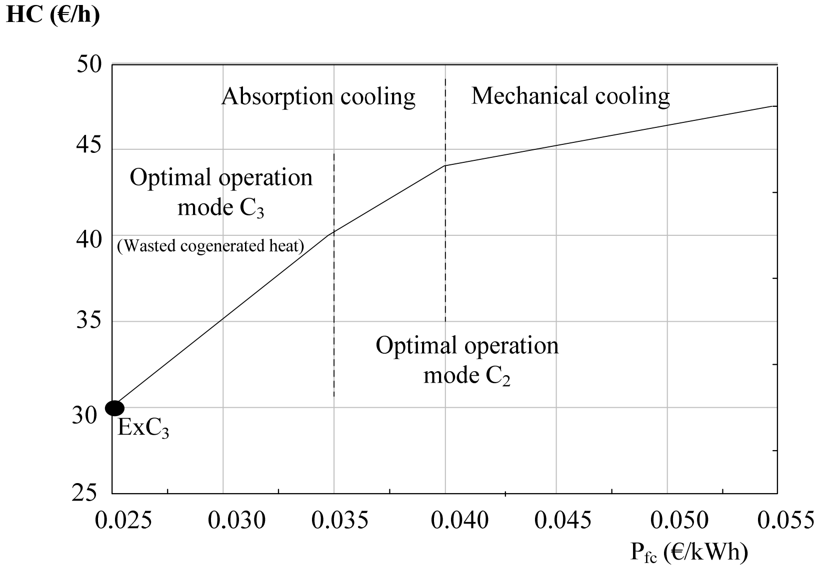

Figure 2.13 Hourly cost versus the price of fuel (E_d = 400 kW, Q_d = 100 kW, R_d = 100 kW).

Table 2.7 Optimal operation in function of the price of fuel

(E_d = 400 kW, Q_d = 100 kW, R_d = 100 kW).

p_{fc} (€/kWh)	Operation mode	W_c (kW)	Q_l (kW)	Q_a (kW)	R_q (kW)	E_p (kW)	HC (€/h)
0.025 (ExC_3)	C_3	350	140	0	100	50	30.00
0.035 -	C_3	350	140	0	100	50	40.00
0.035 +	C_2	227.5	0	0	100	172.5	40.00
0.040 -	C_2	227.5	0	0	100	172.5	43.25
0.040 +	C_2	87.5	0	0	0	332.5	43.25
0.065 -	C_2	87.5	0	0	0	332.5	49.50
0.065 +	C_0	0	0	100	0	420	49.50
0.070	C_0	0	0	100	0	420	50.125

The values in Figure 2.13 and Table 2.7 were obtained utilizing the prices of electricity shown in Table 2.2 (p_{es} = 0.080 €/kWh and p_{ep} = 0.100 €/kWh) and by considering that the difference between the prices of the fuels consumed in the cogeneration module and auxiliary boiler remained constant: $p_{fc} - p_{fa}$ = 0.005 €/kWh. In example ExC_3 electricity was purchased at p_{ep} = 0.100 €/kWh, and therefore only when p_{fc} is higher than $\alpha_w \cdot p_{ep}$ = 0.035 €/kWh it makes sense to consider the possibility of operating the cogeneration module at partial load. In fact, as shown in Figure 2.13 and Table 2.7, when the value of p_{fc} = 0.035 €/kWh is reached, there is no waste of heat and the cogeneration module operates at partial load. But when the fuel cost is additionally increased, being higher than $(\alpha_w + \alpha_q \cdot COP_q/COP_e) \cdot p_{ep}$ = 0.040 €/kWh, the production of cooling utilizing the cogenerated heat is not profitable and the cooling demand is covered by the electrical chiller. Finally, when the fuel cost fulfills the condition $p_{fc} > \alpha_w \cdot p_{ep} + (\alpha_q/\eta_q) \cdot p_{fa}$, cogeneration is not profitable (not even to cover the heat demand) and it is more interesting to produce heat with the auxiliary boiler. This is the case when p_{fc} > 0.065 €/kWh, in which the cogeneration module is not operating.

2.4.3 Marginal cost of internal flows and malfunctions

The marginal costs of the internal flows of the simple trigeneration system can be obtained by interpreting the dual prices corresponding to restrictions (2.2) – (2.15) of the optimization model. Table 2.8 shows the dual prices obtained by Lingo for the linear program, minimizing the operation variable cost corresponding to example ExC_7.

Table 2.8 Dual prices of the restrictions for ExC_7.

Restriction			λ (€/kWh)
Capacity limits			
	cCM	$W_c \le W_{c\,nom}$	- 0.037
	cAB	$Q_a \le Q_{a\,nom}$	0
	cAC	$R_q \le R_{q\,nom}$	0
	cEC	$R_e \le R_{e\,nom}$	0
Equipment efficiency			
	eCM_w	$\alpha_w \cdot F_c - W_c = 0$	0.043
	eCM_q	$\alpha_q \cdot F_c - Q_c = 0$	0.025
	eAB	$\eta_q \cdot F_a - Q_a = 0$	0.025
	eAC	$COP_q \cdot Q_r - R_q = 0$	0.016
	eEC	$COP_e \cdot E_r - R_e = 0$	0.016
Balance equations			
	S	$W_c - W_{cc} - E_s = 0$	0.080
	P	$W_{cc} + E_p - E_d - E_r = 0$	0.080
	L	$Q_c - Q_{cc} - Q_l = 0$	0.025
	Q	$Q_{cc} + Q_a - Q_d - Q_r = 0$	0.025
	R	$R_q + R_e - R_d = 0$	0.016
Demand constraints			
	E_D	$E_d = 200$	0.080
	Q_D	$Q_d = 600$	0.025
	R_D	$R_d = 100$	0.016

According to the optimization theory, if f(x) is the objective function of the program and g(x) = b is an active restriction at the optimal point, the dual price λ of the restriction is interpreted as the derivative of the objective function f regarding the parameter b of the active restriction. That is

$$\lambda = \delta f^{*}/\delta b \qquad (2.20)$$

The super-index * in Equation (2.20) expresses that $f^{*}(b)$ corresponds to the trajectory of the value of the objective function for the optimal solutions when b varies. In this optimization problem of the operation of a simple trigeneration system, f is the hourly cost HC in €/h, and all the restrictions g express energy flows in kW; therefore, the dual prices are expressed in €/kWh. A few examples of interpretation of dual prices are shown next.

Restriction (2.2) cCM: $W_c \leq W_{c\ nom}$ corresponds to the cogeneration module, and in example ExC$_7$ is the only active capacity restriction in the optimum. Rewriting restriction (2.2) in the form g(x) = b, results cCM: $W_c = 350$, being 350 kW the nominal production of the motor. If for any reason (variation in environmental conditions, degradation of lubricating oil, etc.) the electricity production capacity of the engine decreases by 2 kW, the hourly cost would increase by approximately 0.074 €/h:

$$\Delta HC^* \cong \lambda_{cCM} \cdot \Delta b_{cCM} = -\,0.037 \cdot (-2) = 0.074 \qquad (2.21)$$

The interpretation is that the cogeneration module would produce 2 kW less electricity and 2.29 kW less heat ($2 \cdot \alpha_q/\alpha_w$). The decrease in fuel consumption by the motor creates savings of 0.143 €/h ($2 \cdot p_{fc}/\alpha_w$), but a decrease of 0.160 €/h ($2 \cdot p_{es}$) in the sale of electricity. The heat is produced by the boiler at a cost of 0.057 €/h ($2.29 \cdot p_{fa}/\eta_q$). The resulting total cost is therefore 0.074 (0.160 + 0.057 − 0.143).

Restriction (2.8) eAB: $\eta_q \cdot F_a - Q_a = 0$ corresponds to the production of the auxiliary boiler. If because of poor insulation, 5 kW of the produced heat is lost, the restriction should be written as eAB: $\eta_q \cdot F_a - Q_a = 5$, meaning that the boiler would increase its consumption of fuel to compensate such a loss. From the shadow price of the restriction, the cost can be estimated as 0.125 €/h:

$$\Delta HC^* \cong \lambda_{eAB} \cdot \Delta b_{eAB} = 0.025 \cdot 5 = 0.125 \qquad (2.22)$$

Finally, it was observed that the shadow prices of the restrictions corresponding to the energy balances can be immediately interpreted as the marginal costs of the demanded energy services.

2.5 VALUATION BASED ON MARKET PRICES

When an external reference is imposed on value products, for example market prices π (Table 2.9), then the unit costs of products β will be assigned based on such a reference.

Table 2.9 Market prices (€/kWh).

π_e	π_q	π_r
0.100	0.030	0.050

The hourly cost to obtain the final products of the trigeneration system when considering reference prices is

$$HC_{ref} = \pi_e \cdot E_d + \pi_q \cdot Q_d + \pi_r \cdot R_d \quad (2.23)$$

In a trigeneration system properly designed and operated, there will be cost savings in production when compared to the same quantity of products obtained at market prices. As a consequence, the discount d defined as

$$d \equiv (HC_{ref} - HC)/HC_{ref} = 1 - HC/\ HC_{ref} \quad (2.24)$$

will be positive ($d > 0$).

A fair criterion to distribute the production costs HC among the final product consumers is that all of them receive the discount derived from the combined production, so the costs savings when compared to the separate obtaining of products are equally shared. Therefore the following unit cost will be assigned to the products:

$$\beta_i = \pi_i\ (1 - d) \quad (2.25)$$

Production costs HC are thereby distributed to final products according to the economic value of those products. Table 2.10 displays the costs, obtained for the final products of the simple trigeneration system in examples ExC_1, ExC_3, ExC_7 and ExC_9, which are different from the marginal costs shown in Table 2.5.

Table 2.10 Cost of final products.

		ExC_1	ExC_3	ExC_7	ExC_9
HC	€/h	41.00	30.00	19.60	13.00
HC_{ref}	€/h	72.00	48.00	43.00	28.00
Discount	-	0.4306	0.3750	0.5442	0.5357
β_{Ed}	€/kWh	0.0569	0.0625	0.0456	0.0464
β_{Qd}	€/kWh	0.0171	0.0187	0.0137	0.0139
β_{Rd}	€/kWh	0.0285	0.0312	0.0228	0.0232

Note that costs based on market prices are always conservative

$$HC = \beta_{Ed} \cdot E_d + \beta_{Qd} \cdot Q_d + \beta_{Rd} \cdot R_d \tag{2.26}$$

but marginal costs, in general, are not.

2.6 THERMOECONOMIC COST ACCOUNTING

The conservation of costs, as a first principle, is common to all thermoeconomic approaches (all costs from resources consumed in a production unit must be charged to its useful products). Cost balances are explicitly formulated and external resources used in the production process are valued at the prices at which they were purchased. Figure 2.14 shows the analyzed trigeneration system, with internal and product flows and costs.

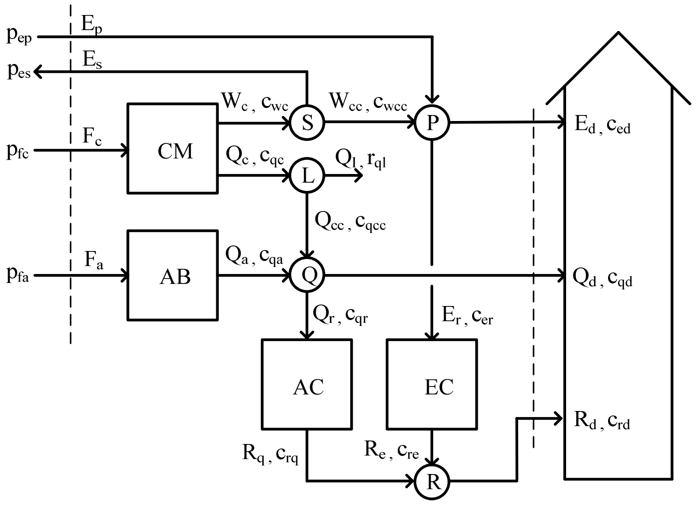

Figure 2.14 Simple trigeneration system with costs and flows.

Applying the condition of cost conservation to the trigeneration system in Figure 2.14, the following system of linear equations was obtained:

CM: $p_{fc}\cdot F_c = c_{wc}\cdot W_c + c_{qc}\cdot Q_c$ (2.27)

AB: $p_{fa}\cdot F_a = c_{qa}\cdot Q_a$ (2.28)

AC: $c_{qr}\cdot Q_r = c_{rq}\cdot R_q$ (2.39)

EC: $c_{er}\cdot E_r = c_{re}\cdot R_e$ (2.30)

S: $c_{wc}\cdot W_c = c_{wcc}\cdot W_{cc} + p_{es}\cdot E_s$ (2.31)

P: $c_{wcc}\cdot W_{cc} + p_{ep}\cdot E_p = c_{er}\cdot E_r + c_{ed}\cdot E_d$ (2.32)

L: $c_{qc}\cdot Q_c + r_{ql}\cdot Q_l = c_{qcc}\cdot Q_{cc}$ (2.33)

R: $c_{rq}\cdot R_q + c_{re}\cdot R_e = c_{rd}\cdot R_d$ (2.34)

Q: $c_{qcc}\cdot Q_{cc} + c_{qa}\cdot Q_a = c_{qr}\cdot Q_r + c_{qd}\cdot Q_d$ (2.35)

Considering that the operation state of the plant is known (see Table 2.4), then all energy flows, market prices for fuel and electricity (see Table 2.2 for p_{fc}, p_{fa}, p_{ep}, p_{es}) and the unit price entailing waste heat (here it was considered that $r_{ql} = 0$) are also known; consequently, there are 12 unit costs of internal flows and final products to be calculated: c_{wc}, c_{wcc}, c_{er}, c_{ed}, c_{qc}, c_{qcc}, c_{qa}, c_{qr}, c_{qd}, c_{rq}, c_{re}, and c_{rd}. As the system is described using 9 equations with 12 unknowns, 3 auxiliary costing equations are needed. The development of generally applicable rules for the formulation of auxiliary costing equations has been a subject of discussion among the different thermoeconomic approaches. An accepted rule, either explicitly or implicitly, is that the unit cost of several flows obtained from a homogeneous flow is the same. Applying this rule to branching points **P** and **Q,** two more auxiliary equations were obtained:

P: $c_{er} = c_{ed}$ (2.36)

Q: $c_{qr} = c_{qd}$ (2.37)

Note that this rule cannot be applied to branching points **S** and **L**. In **S** the system is interacting with the economic environment and E_s is the sold electricity, the cost of which is set by its market price P_{es}. In **L**, Q_l is the wasted heat which is not consumed and no cost should be assessed ($r_{ql} = 0$).

The third auxiliary costing equation must define how production costs in the cogeneration module are attributed to its products: heat and work. The fundamental problem of costs allocation can be formulated as follows (Lozano & Valero, 1993a): Given a system whose limits have been defined and a level of aggregation that specifies the subsystems which constitute it, how to obtain the cost of all flows becoming interrelated in such structure.

2.6.1 Simple allocation methods

Different allocation proposals of costs to electricity and heat products of a cogeneration module are found in literature (Pavlenco & Englesson, 1980; El-Nashar, 1992; Lucas, 2000; Gochenour, 2003, among others). However, such proposals focus on the immediate products of the cogeneration module, Q_c and W_c (Figure 2.15), not accounting for possible different interactions with other pieces of equipment or with the cogeneration module's environment (different destinations or uses of W_c and Q_c).

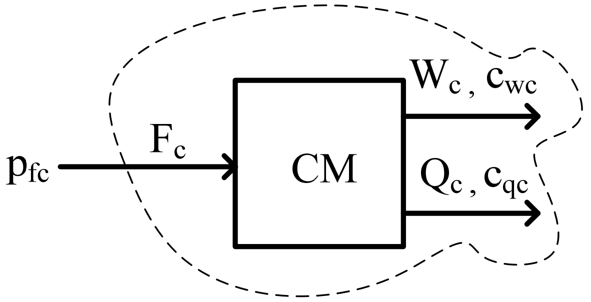

Figure 2.15 Control volume of simple allocation methods.

With this simple control volume, Equation (2.27) will distribute $p_{fc} \cdot F_c$ between $c_{wc} \cdot W_c$ and $c_{qc} \cdot Q_c$. Such an approach is valid to assess costs to the immediate products of the cogeneration module only.

However, when considering different equipment, activities, and options included in the trigeneration system, the assignment of unit costs should rather consider the products of the cogeneration module that are consumed (W_{cc} and Q_{cc}). In this way, adding Equations (2.27), (2.31) and (2.33) yields that $p_{fc} \cdot F_c$ - $p_{es} \cdot E_s$ + $r_{ql} \cdot Q_l$ will be distributed between $c_{wcc} \cdot W_{cc}$ and $c_{qcc} \cdot Q_{cc}$, accounting for interactions of the system with the environment, through possible sale of electricity ($p_{es} \cdot E_s$) and waste heat ($r_{ql} \cdot Q_l$) (Figure 2.16).

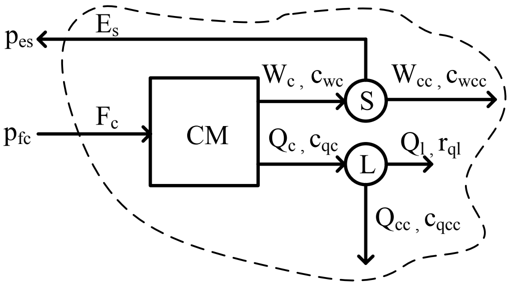

Figure 2.16 Control volume of simple allocation methods, accounting for the interaction of the cogeneration module with the environment.

Therefore some simple allocation proposals (which considered initially W_c and Q_c) were taken to a higher level, by considering W_{cc} and Q_{cc}. In this way the benefits of selling electricity and the inefficiency of wasting heat are both distributed between heat and electricity internally consumed.

A Allocation based on energy. The fractions of the costs allocated to electricity and heat productions are assessed in proportion to the energy content of the cogenerated work and heat:

$$\frac{c_{qcc}}{c_{wcc}} = 1 \tag{2.38a}$$

B Allocation based on exergy. The first proposal for using exergy as a criterion for cost allocation was presented in 1932 by Keenan (*apud* Lozano & Valero, 1993a). The fractions of the costs allocated to electrical and heat productions are assessed in proportion to the exergy content of the cogenerated work and heat:

$$\frac{c_{qcc}}{c_{wcc}} = \theta_{qc} \tag{2.38b}$$

θ_{qc} is the Carnot factor $(1 - T_0/T_c)$ corresponding to the cogenerated heat. Operating conditions were considered to be $T_0 = 298$ K and $T_c = 373$ K, therefore obtaining $\theta_{qc} \approx 0.20$.

C Fuel Chargeable to Power (FCP). This approach subtracts the primary energy needed in a standard boiler to produce heat from the primary energy of the cogeneration plant to obtain an allocation of primary energy to the electricity produced, *i.e.*, $c_{qcc} = c_{qa} = p_{fa} / \eta_q$ which yields

$$\frac{c_{qcc}}{c_{wc}} = \frac{W_c}{\eta_q F_c \left(\frac{p_{fc}}{p_{fa}} \right) - Q_{cc}} \qquad (2.38c)$$

where η_q is the thermal efficiency of the auxiliary boiler of the system ($\eta_q = 0.80$).

D Allocation based on the economic value. In this context, it is proposed that the assignment of unit costs to the products of the cogeneration module that are consumed (*i.e.*, W_{cc} and Q_{cc}) be proportional to the cost of its alternative production. For electricity, cost of separate production is the price of purchasing electricity from the grid (p_{ep} = 0.100 €/kWh), and for heat, cost of separate production is that of producing heat in the auxiliary boiler ($c_{qa} = p_{fa}/\eta_q$ = 0.025 €/kWh). However, this allocation method is *enhanced* by acknowledging the operation mode of the system in the consideration of electricity (p_{ep} or p_{es}) (Lozano *et al.*, 2009a). The auxiliary equation proposed for operation modes C_1 and C_3, in which electricity is purchased from the grid (at a price p_{ep}), was:

C_1 and C_3:

$$\frac{c_{qcc}}{c_{wcc}} = \frac{c_{qa}}{p_{ep}} \qquad (2.39)$$

For operation modes C_7 and C_9, in which part of the electricity produced was sold to the grid (at a price p_{es}), the proposed auxiliary equation was:

C_7 and C_9:

$$\frac{c_{qcc}}{c_{wcc}} = \frac{c_{qa}}{p_{es}} \qquad (2.40)$$

Table 2.11 shows the unit costs of internal flows and final products of the analyzed trigeneration system for the four examples analyzed.

Table 2.11 Unit costs, c (€/kWh), of internal flows and final products of the analyzed trigeneration system.

	Method A				Method B			
	ExC$_1$	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**
c_{ed}	0.0481	0.0484	0.0235	0.0283	0.0674	0.0669	0.0487	0.0516
c_{qd}	0.0302	0.0410	0.0240	0.0283	0.0166	0.0124	0.0148	0.0103
c_{rd}	0.0241	0.0656	0.0047	0.0452	0.0184	0.0199	0.0097	0.0165
c_{es}	--------	--------	0.0800	0.0800	--------	--------	0.0800	0.0800
c_{wc}	0.0333	0.0410	0.0445	0.0504	0.0581	0.0622	0.0603	0.0638
c_{qc}	0.0333	0.0266	0.0235	0.0184	0.0116	0.0081	0.0097	0.0067
c_{wcc}	0.0333	0.0410	0.0235	0.0283	0.0581	0.0622	0.0487	0.0516
c_{er}	0.0481	--------	0.0235	--------	0.0674	--------	0.0487	--------
c_{qcc}	0.0333	0.0410	0.0235	0.0283	0.0116	0.0124	0.0097	0.0103
c_{qa}	0.0250	--------	0.0250	--------	0.0250	--------	0.0250	--------
c_{qr}	0.0302	0.0410	--------	0.0283	0.0166	0.0124	--------	0.0103
c_{rq}	0.0483	0.0656	--------	0.0452	0.0266	0.0199	--------	0.0165
c_{re}	0.0096	--------	0.0047	--------	0.0135	--------	0.0097	--------

	Method C				Method D			
	ExC$_1$	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**
c_{ed}	0.0556	0.0587	0.0209	0.0325	0.0654	0.0652	0.0423	0.0462
c_{qd}	0.0250	0.0250	0.0250	0.0250	0.0181	0.0151	0.0171	0.0144
c_{rd}	0.0219	0.0400	0.0042	0.0400	0.0190	0.0241	0.0085	0.0231
c_{es}	--------	--------	0.0800	0.0800	--------	--------	0.0800	0.0800
c_{wc}	0.0429	0.0529	0.0429	0.0529	0.0556	0.0602	0.0563	0.0607
c_{qc}	0.0250	0.0163	0.0250	0.0163	0.0139	0.0098	0.0132	0.0094
c_{wcc}	0.0429	0.0529	0.0209	0.0325	0.0556	0.0602	0.0423	0.0462
c_{er}	0.0556	--------	0.0209	--------	0.0654	--------	0.0423	--------
c_{qcc}	0.0250	0.0250	0.0250	0.0250	0.0139	0.0151	0.0132	0.0144
c_{qa}	0.0250	--------	0.0250	--------	0.0250	--------	0.0250	--------
c_{qr}	0.0250	0.0250	--------	0.0250	0.0181	0.0151	--------	0.0144
c_{rq}	0.0400	0.0400	--------	0.0400	0.0289	0.0241	--------	0.0231
c_{re}	0.0111	--------	0.0042	--------	0.0131	--------	0.0085	--------

From the values shown in Table 2.11 it can be noted that the unit cost of c_{ed} is lower than the costs of purchased (or sold electricity) – $p_{ep} = 0.100$, $p_{es} = 0.080$. However, the unit cost of c_{qd} is not always lower than and the cost of the heat produced in the auxiliary boiler – $c_{qa} = 0.025$ (see values for method A). Neither is the unit cost of c_{rd} always lower than the cost of cooling through the mechanical chiller (p_{ep} / COP_e = 0.100 / 5 = 0.020 for ExC_1 and ExC_3 and p_{es} / COP_e = 0.080 / 5 = 0.016 for ExC_7 and ExC_9).

Simple methods commonly found in literature were taken to a higher level by considering that the aggregation level of the analysis accounted for the products of the cogeneration system that were consumed. Method A is an allocation according to the amounts of energy forms; however, method A leads to energetic efficiencies of power and heat production mutually equal and the same as the total efficiency of the cogeneration plant. Method B leads to better results as the costs for the final products are always lower than those of separate production. Method C attributes all advantages of cogeneration to power production, as it allocates costs based on that thermal efficiency of heat production in the cogeneration process is approximately the same as that in a separate process. Method D starts from the principle that production costs should be distributed among the final product consumers and that all consumers of heat and power should receive the same discount derived from the combined production compared to the cost of obtaining the energy services separately. The rationale behind Method D will be expanded to include the production of cooling.

2.6.2 Proposal of allocation method – method E

Considering the scenario in which the consumers of the energy services are the owners of the trigeneration system, all operation costs should be allocated to the consumers of the energy services who are benefitting from a more efficient production. Moreover, the benefits should be shared in an equitable form among all consumers (owners). Furthermore, not only a fair apportionment of the costs among the energy services produced is required, but also a clear economic benefit, with respect to the conventional energy supply system in which electricity is purchased from the grid, heat is produced in a conventional boiler, and cooling is produced in a mechanical chiller.

In order to gain insight on the production of cooling, distribution of heat produced in the cogeneration module and auxiliary boiler should be explained. The heat produced in the auxiliary boiler (Q_a) and the cogeneration module (Q_{cc}) can be used for covering the heat demand of the consumer center (Q_d) and/or the heat required for driving the absorption chiller

(Q_r). The simple trigeneration system scheme is re-organized to allow the tracking of heat produced by the cogeneration module and auxiliary boiler (Figure 2.17).

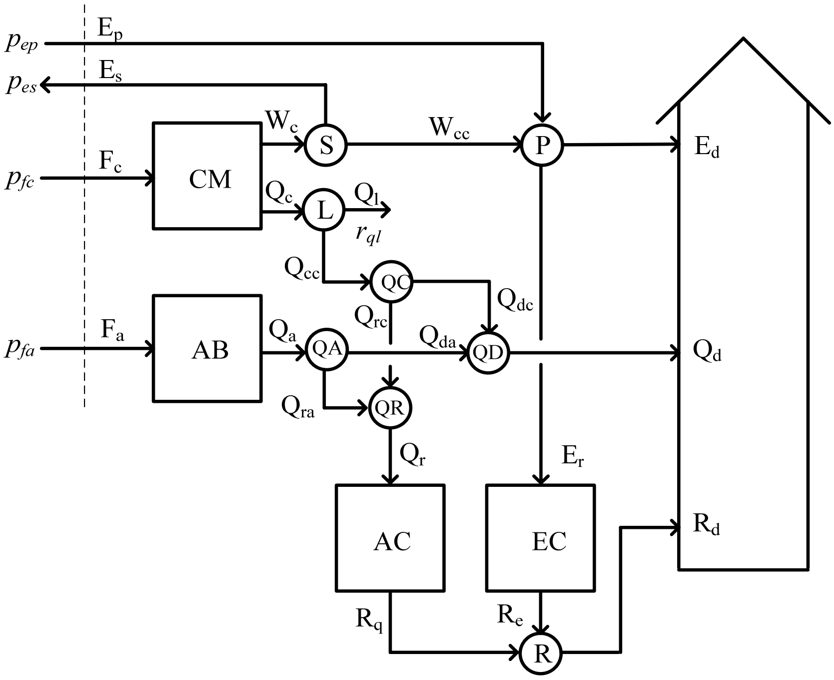

Figure 2.17 Re-organization of simple trigeneration system.

There is no priority or technical limitation in this respect as the cogeneration module is able to independently provide, when required, heat to the consumer center or the absorption chiller, which similarly occurs with the auxiliary boiler. Furthermore, the heat produced is proportionally distributed to the consumer center and the absorption chiller according to the total heat demanded by them. The distribution of heat produced in the cogeneration module to the consumer center and/or the absorption chiller is expressed mathematically through the definition of the following parameter:

$$B = \frac{Q_d}{Q_d + Q_r} \tag{2.41}$$

Heat produced in the cogeneration module is distributed as follows:

$$Q_{dc} = B \cdot Q_{cc} \tag{2.42}$$

$$Q_{rc} = (1 - B) \cdot Q_{cc} \tag{2.43}$$

And the heat produced in the auxiliary boiler is distributed as follows:

$$Q_{da} = B \cdot Q_a \tag{2.44}$$

$$Q_{ra} = (1 - B) \cdot Q_a \tag{2.45}$$

Table 2.12 shows the additional energy flows for the re-organized trigeneration system.

Table 2.12 Additional energy flows for the re-organized trigeneration system.

		ExC$_1$	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**
Q_d	kW	400	100	600	100
Q_r	kW	240	160	0	160
B		0.6250	0.3846	1	0.3846
Q_{cc}	kW	400	260	400	260
Q_{dc}	kW	250	100	400	100
Q_{rc}	kW	150	160	0	160
Q_a	kW	240	0	200	0
Q_{da}	kW	150	0	200	0
Q_{ra}	kW	90	0	0	0

This productive structure yields a new equation system, constituted of Equations (2.27) – (2.34) plus the following equations:

QA: $$c_{qa} \cdot Q_a = c_{qda} \cdot Q_{da} + c_{qra} \cdot Q_{ra} \tag{2.46}$$

QC: $$c_{qcc} \cdot Q_{cc} = c_{qdc} \cdot Q_{dc} + c_{qrc} \cdot Q_{rc} \tag{2.47}$$

QR: $$c_{qrc} \cdot Q_{rc} + c_{qra} \cdot Q_{ra} = c_{qr} \cdot Q_r \tag{2.48}$$

QD: $$c_{qdc} \cdot Q_{dc} + c_{qda} \cdot Q_{da} = c_{qd} \cdot Q_d \tag{2.49}$$

There are 16 unit costs of internal flows and final products to be calculated: c_{wc}, c_{wcc}, c_{er}, c_{ed}, c_{qc}, c_{qcc}, c_{qa}, c_{qr}, c_{qd}, c_{rq}, c_{re}, c_{rd}, c_{qdc}, c_{qrc}, c_{qda} and c_{qra}. The system is described using 12 equations with 16 unknowns, so 4 auxiliary costing equations are needed.

Considering that the unit cost of several flows of the final products or internally consumed obtained from a homogeneous flow is the same, and applying this rule to branching points **P** and **QA,** two auxiliary equations were obtained:

P: $c_{er} = c_{ed}$ (2.50)

QA: $c_{qda} = c_{qra}$ (2.51)

Such considerations are not suitable in the case of cogenerated heat, in which different discounts should be applied to the cogenerated heat covering the heating demand and to the cogenerated heat covering the cooling demand via absorption chiller. In branching point QA, the heat produced in the auxiliary boiler is distributed, which is produced with the same cost than conventional heat and it does not make sense to apply any discount. Branching points S and L present specific features in which the cost of some output flows are known and additional auxiliary equations are not required. In S the system is interacting with the economic environment and E_s is the sold electricity, the cost of which is set by its market price. In L, Q_l is the wasted heat which is not consumed and therefore no cost should be assessed.

The last two auxiliary equations consider that production costs are distributed among the consumers of the final products and all of them must receive the same discount derived from the combined production in proportion to the cost of obtaining the energy services separately by conventional systems. The heat used for covering the heat demand, Q_{dc}, is receiving a discount with respect to the production of heat in a conventional boiler, and the heat used for cooling, Q_{rc}, is receiving a discount with respect to the conventional production of cooling via mechanical chiller. For operation modes C_1 and C_3 the discount d is:

$$1 - d = \frac{c_{wcc}}{p_{ep}} = \frac{c_{qdc}}{c_{qa}} = \frac{\dfrac{c_{qrc}}{COP_q}}{\dfrac{p_{ep}}{COP_e}} \tag{2.52}$$

Which yields two equations:

$$\frac{c_{wcc}}{p_{ep}} = \frac{c_{qdc}}{c_{qa}} \tag{2.53a}$$

$$\frac{c_{wcc}}{p_{ep}} = \frac{\dfrac{c_{qrc}}{COP_q}}{\dfrac{p_{ep}}{COP_e}} \tag{2.53b}$$

For operation modes C_7 and C_9, in which part of the electricity produced was sold to the grid (at a price p_{es}), the discount d is:

$$1 - d = \frac{c_{wcc}}{p_{es}} = \frac{c_{qdc}}{c_{qa}} = \frac{\dfrac{c_{qrc}}{COP_q}}{\dfrac{p_{es}}{COP_e}} \tag{2.54}$$

Which yields two equations:

$$\frac{c_{wcc}}{p_{es}} = \frac{c_{qdc}}{c_{qa}} \tag{2.55a}$$

$$\frac{c_{wcc}}{p_{es}} = \frac{\dfrac{c_{qrc}}{COP_q}}{\dfrac{p_{es}}{COP_e}} \tag{2.55b}$$

Table 2.13 shows the unit costs of internal flows and final products obtained applying the assessment criteria proposed with Equations (2.53) and (2.55) for the four different examples.

From the values shown in Table 2.14 it can be noted that the unit cost of the final products – c_{ed}, c_{qd} and c_{rd} - are lower than the costs of the purchased or sold electricity ($p_{ep} = 0.100$, $p_{es} = 0.080$), the cost of the heat produced in the auxiliary boiler ($c_{qa} = 0.025$) and the cost of the cooling produced in a mechanical chiller ($p_{ep}/COP_e = 0.100/5 = 0.020$ for ExC_1 and ExC_3 and $p_{es}/COP_e = 0.080/5 = 0.016$ for ExC_7 and ExC_9). The proposed cost assessment rules defined by equations (2.53) and (2.55) provide cost values consistent with the objective of equitably sharing the benefits among all the consumers (owners), while also obtaining a clear economic benefit with respect to the conventional energy supply system.

In the four cases analyzed herein, the cogeneration module is operating at full load. Consequently, the marginal cost of the electricity produced reflects the cost of covering the increased demand with the electricity purchased (operation modes C_1 and C_3) or sold (operation modes C_7 and C_9). In the case of heat, there are two possible situations: a) operation modes C_1

and C_7, in which the heat demand is higher than the maximum production of the cogeneration module operating at full load, leading to a marginal cost of heat produced that corresponds to the cost of producing heat in the auxiliary boiler; b) operation modes C_3 and C_9, in which heat waste occurs and the corresponding marginal cost is zero.

Table 2.13 Unit costs, c (€/kWh), of internal flows and final products for method E.

		$ExC_{1\,(2.53)}$	$ExC_{3\,(2.53)}$	$ExC_{7\,(2.55)}$	$ExC_{9\,(2.55)}$
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
λ_{ed}	€/kWh	0.1000	0.1000	0.0800	0.0800
λ_{qd}	€/kWh	0.0250	0	0.0250	0
λ_{rd}	€/kWh	0.0400	0	0.0160	0
c_{ed}	€/kWh	0.0673	0.0679	0.0423	0.0517
c_{qd}	€/kWh	0.0184	0.0158	0.0172	0.0162
c_{rd}	€/kWh	0.0168	0.0127	0.0085	0.0104
c_{wc}	€/kWh	0.0580	0.0633	0.0563	0.0639
c_{qc}	€/kWh	0.0118	0.0071	0.0132	0.0066
c_{wcc}	€/kWh	0.0580	0.0633	0.0423	0.0517
c_{er}	€/kWh	0.0673	--------	0.0423	--------
c_{qcc}	€/kWh	0.0118	0.0110	0.0132	0.0102
c_{qa}	€/kWh	0.0250	--------	0.0250	--------
c_{qr}	€/kWh	0.0139	0.0079	--------	0.0065
c_{rq}	€/kWh	0.0222	0.0127	--------	0.0104
c_{re}	€/kWh	0.0135	--------	0.0085	--------
c_{qdc}	€/kWh	0.0145	0.0158	0.0132	0.0162
c_{qrc}	€/kWh	0.0072	0.0079	--------	0.0065
c_{qda}	€/kWh	0.0250	--------	0.025	--------
c_{qra}	€/kWh	0.0250	--------	--------	--------
Discount d		0.4203	0.3671	0.4710	0.3532

Comparing the marginal costs of the final products with the corresponding unit costs (Table 2.13) of the final products it can be seen that the unit costs are always lower than marginal costs (originating from conventional production), except when marginal costs are zero. This lower unit cost is a consequence of the higher efficiency (with an associated lower cost) of energy production of the trigeneration system compared to the conventional option of purchasing electricity from the grid, producing heat in an auxiliary boiler, and producing cooling via mechanical chiller. When some heat is wasted, the marginal cost of the demanded heat and cooling is zero (in operation modes C_3 and C_9 cooling is produced only by the absorption chiller). The unit cost of producing heat in the cogeneration module is not zero but is lower than the production of heat in the auxiliary boiler.

The previous information is quite relevant and indicates that unit cost values are consistent with the marginal cost values in the cases analyzed.

In example ExC_3 the cogeneration module is operating at full load. There is some heat wasted because the heat demand (direct, Q_d = 100 kW plus indirect, Q_r = 160 kW by absorption chiller) is lower than the heat produced in the cogeneration module; some electricity is purchased from the grid because the electricity demand (400 kW) is higher than the maximum power produced by the cogeneration module (350 kW). c_{ed} increases (when compared to ExC_1) reflecting the waste of heat. However, the consumption of waste heat is promoted (by lowering c_{qd} and c_{rd}) in order to reduce its amount, and as a consequence increase the efficiency of the entire system. Wasting heat is negatively reflected in the unit costs of c_{wcc} and c_{wc}, and positively reflected in c_{qc} and c_{qcc} (which are lower).

In example ExC_7, the cogeneration module is operating at full load. Some electricity is sold to the grid (E_s = 130 kW) because the electricity demand (E_d = 200 kW plus E_r = 20 kW) is lower than the electricity produced in the cogeneration module (W_c = 350 kW). The profit realized with the sale of electricity is correctly reflected in lower costs for final products (compared to those of ExC_1). However, internal costs increase as is the case of c_{qc} and c_{qcc}, which are higher with respect to ExC_1. c_{wcc} benefits from the sale of electricity, which is reflected in a very low cost compared to that of ExC_1. The comment can be extended to example ExC_9 in which some heat is also wasted.

Analyzing the unit costs corresponding to example ExC_9, in which the cogeneration module is also operating at full load with the sale of electricity and waste of heat, the previous comments are reinforced. Cost assessment with Equation (2.55) promotes the usage of the waste heat produced in the cogeneration module (lowering its cost when compared to ExC_7). Similar comments to those presented for operation mode C_7 can be made with respect to the obtained cost values and the indications provided with respect to the electricity consumption, where its lower cost promotes its consumption and at the same time reduces the benefits obtained from the sale of electricity. Internal costs reflect the same tendency shown previously: c_{wc} and c_{wcc} increase with the waste of heat (compared to ExC_7), but q_c and q_{cc} have lower costs.

With equations (2.53) and (2.55) the benefits of selling electricity and the penalties of wasting heat are assessed to the entire cogeneration module. This is particularly clear in example ExC_9, in which it is economically profitable to sell electricity and waste heat. The benefit of selling electricity is a consequence of the more economical operation of the cogeneration system as a whole, even in operation mode C_9 in which some heat is wasted. Therefore, the benefits as well as the penalties of the system are reflected in all energy services produced in the cogeneration module.

2.7 CONCLUSIONS

This chapter showed the characteristics of different operation modes of a simple trigeneration system. The linear programming model developed allowed for the determination of the optimal operation mode corresponding to the minimum variable cost. The results corresponding to different demands of energy services and operation modes were presented and analyzed. It has been shown how thermoeconomic analysis allows us: (1) to explain the reason for the optimal production mode; (2) to obtain the marginal cost of internal flows and final products; (3) to unravel the marginal cost formation process of products; and finally (4) to evaluate the economic impact of changes in the demand or operational condition of the equipment. Thermoeconomic analysis can also aid in the development of effective methodologies for the design of new plants (as will be shown in Chapter V of this thesis) and the retrofit of existing plants to new demand and market price conditions.

The findings would not change by considering a more complex model of the trigeneration system. A greater sophistication of the model, using non linear production restrictions and binary variables limiting both the minimum load of the productive units and the on/off status, would provide more precise results but in general, the above conclusions prevail.

The costs obtained with the approaches mentioned provided different information that is useful in different applications. The dual prices obtained in the optimization process were interpreted as marginal costs of internal flows and products and are useful to react automatically when external operational circumstances change, *i.e.*, energy demands. Costs based on market prices are a fair criterion to distribute production costs among final product consumers, so that all of them receive the same discount from the market price. Internal costs permit the following of the cost formation process throughout the system, from the energy resources to final products.

This chapter included a proposal of internal cost assessment criteria for trigeneration systems. Although the situation of trigeneration systems providing energy services to the buildings' sector is common, there is a lack of detailed studies on the analysis and assessment of energy and thermoeconomic costs to the internal flows and final products in this type of systems. The proposal considers that production costs are distributed among the consumers of the final products and all of them receive a discount derived from the combined production, in proportion to the cost of obtaining the energy services separately by conventional systems. The heat used for covering the heat demand receives a discount with respect to the production of heat in a conventional boiler, and the heat used for cooling receives a discount with respect to the conventional production of cooling via mechanical chiller.

The importance of selecting appropriate cost assessment criteria for a trigeneration system operating in different modes is emphasized. These cost assessment criteria are dependent on the physical structure of the system itself and on its different operation modes, as well as on the economic environment and market structure. Appropriate cost assessment criteria are essential to promote rational and efficient energy services production and consumption. Specific attention was focused on the interaction of the trigeneration system with the economic environment, which clearly influenced the cost assessment definitions.

CHAPTER III

ENVIRONMENTAL ANALYSIS OF SIMPLE TRIGENERATION SYSTEMS

Chapter III introduces the rise of environmental conscience worldwide and stricter requirements to reduce the environmental impact of modern society as catalysts for a focused need to consider environmental loads/impacts as an additional design factor in energy supply systems. The concept of Life Cycle Analysis (LCA) is explained, along with the reasons for utilizing carbon dioxide (CO_2) emissions to quantify the environmental loads. In order to broaden environmental considerations in the impact assessment, the Eco-indicator 99 (EI-99) method was also utilized.

Calculation of costs presented in Chapter II is extended to an environmental viewpoint, considering the kilograms of CO_2 released in the atmosphere and EI-99 points. Different allocation criteria are discussed. The allocation of environmental loads to the internal flows and final products of the trigeneration system was carried out by applying algebra and rules similar to those used in thermoeconomic analysis for the evaluation of internal costs. For such, environmental information was incorporated into an Environmental Management Information System (EMIS). It was possible to evaluate the process of formation of the environmental impact associated with the consumption of natural resources and generation of emissions in the system, from the input of natural resources to the output of the final products and emissions. As a result, the flow analysis of individual production steps specific to operation took the work presented in Chapter II a step further, allowing for the study of operational activities more precisely by implementing environmental information.

3.1 LIFE CYCLE ANALYSIS

Climate change represents one of the greatest environmental, social, and economic threats facing the planet. For different sectors of human activities, a number of key technologies and practices are currently commercially available that could contribute to climate change mitigation. The pressing need to address sustainability in the built environment is being emphasized by external pressures such as environmental and resource concerns, rising energy prices, indoor environmental quality concerns, global warming, and energy security. While economies transition from carbon-based to other forms of more sustainable energy, engineers are and will be challenged to meet an ever-increasing tide of regulations and demands (ASHRAE, 2009).

Less carbon-intensive technologies that generate electricity from renewable or less polluting energies, such as natural gas when compared to coal or oil, have experienced an increase in their share within the technological *mix* of the electricity sector in Spain. In fact, both government and electricity sector predict that the production quota of these less carbon-intensive technologies will only increase in the next few years. However, climate change mitigation strategies should include not only the correct selection of available primary energy, but also an improvement in the efficiency of the technologies employed in heating and cooling. Co- and tri- generation technologies are mentioned in the Climate Change Mitigation Report as options to mitigate greenhouse gas emissions in buildings (Levine *et al.*, 2007).

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. According to the United States' Environmental Protection Agency (EPA, 2006), the environmental impact of products and processes has become a key issue; such an impact is being analyzed using pollution prevention strategies and environmental management systems to improve environmental performance. One such tool is LCA, which estimates the cumulative environmental impact resulting from all stages in the product life cycle and includes environmental impacts often overlooked by more traditional analyses (*e.g.*, raw material extraction, material transportation, and ultimate product disposal). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of a product or process and a more accurate picture of the true environmental trade-offs in product and process selection (Curran, 1996).

A framework for LCA has been standardized by the International Organization for Standardization (ISO) in the ISO 14040 series (ISO 14040, 2006; ISO 14044, 2006). This LCA framework consists of the following elements: (1) Goal and Scope definition, which specifies the goal and intended use of the LCA and delineates the assessment (system boundaries, function and flow, required data quality, technology and assessment parameters); (2) Life Cycle Inventory analysis (LCI), which includes the collection of data on inputs and outputs for all processes in the product system; (3) Life Cycle Impact Assessment (LCIA), which translates inventory data on inputs and outputs into indicators about the product system's potential impacts on the environment, human health, and availability of natural resources; and (4) Interpretation, the phase where the results of the LCI and LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis are performed to qualify the results and conclusions.

3.1.1 CO_2 emissions

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 CO_2 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, CO_2 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.

CO_2 emissions were selected to quantify the environmental loads because global heating and the associated climate change are one of the main medium- and long- term identified threats, with great consequences on a global scale (Levine *et al.*, 2007).

SimaPro (2008) is a specialized LCA tool and was utilized to calculate the impact associated with the operation of the system (consumption of utilities). This was possible because SimaPro includes several inventory databases with thousands of processes and the most important impact assessment methods. SimaPro is also used to calculate the impact associated with the production and final disposal of each piece of equipment of a trigeneration system (explained in Chapter IV). Databases were utilized in the LCI to obtain CO_2 emission values.

3.1.2 Eco-indicator 99

There are different available LCIA methods that utilize different environmental criteria and therefore evaluate and assess different environmental aspects. Basically the methods can be divided into midpoint or endpoint approaches. Examples of midpoint evaluation methods are EDIP97 (Wenzel *et al.*, 1997) and CML2001 (Guinée, 2001); examples of internationally renowned endpoint evaluation methods are Eco-indicator-99 (EI-99) (Goedkoop & Spriensma, 2001) and Swiss Ecoscarcity Method (BUWAL, 1998). In endpoint approaches, the different impact categories are weighted and quantified according to a specific defined objective, *i.e.*, oriented toward evaluation of a specific damage on human health, ecosystem quality or resources. Endpoint indicators, also called damage-oriented indicators, are generally considered more understandable to the decision makers (Bare *et al.*, 2000).

Eco Indicator-99 was selected because it is widely used in LCA, incorporating relevant environmental burdens into different impact categories that allow the evaluation of damages to human health, ecosystem quality, and resources. In addition, results obtained using EI-99 can be aggregated into an easily understandable number (Single Score), which, from a computational perspective, is suitable for integration into an optimization model (Chapter V). Methodologies developed for the analysis of energy systems must take into account not only energy use (consumption) and financial resources expended (economics), but the scarcity both present and future of all resources used as well as any pollution and degradation of the environment which may occur (Frangopoulos & von Spakovsky, 1993).

The EI-99 method considers the values of eleven impact categories, which are added into three damage categories (Figure 3.1), weighted, and then aggregated into an index (the Single Score) that represents the overall environmental load in points. One point represents one thousandth of the annual environmental load of one average European inhabitant. The higher the EI-99 Single Score, the higher the environmental impact of this component/process along its operational life. The LCIA phase provides a system-wide perspective of environmental and resource issues for the products (outputs).

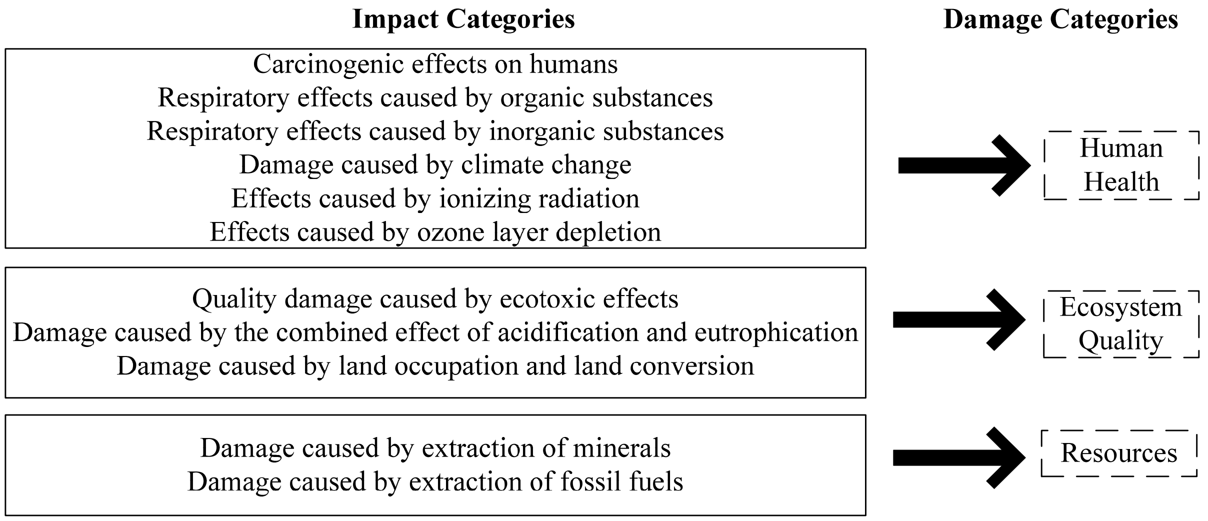

Figure 3.1 Impact and damage categories for Eco-indicator 99.

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 (Goedkoop *et al.*, 2000).

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 (Sonnemann *et al.*, 2003). 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 (Lopez *et al.*, 2006). 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 (Goedkoop *et al.*, 2000). Toxicity is measured by the Potentially Affected Fraction of species (PAF, in PAF·m^2·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 PDF·m^2·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 (Goedkoop *et al.*, 2000).

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 (Sonnemann *et al.*, 2003). 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 (Goedkoop *et al.*, 2000).

In order to account for the subjectivity of the impact assessment procedure, EI-99 presents three different perspectives that lead to three different results, each with its own set of impact perceptions, normalizing factors and weights (Egalitarian, Hierarchist, and Individualist). A perspective is a consistent description of the perceptual screen through which people interpret the world, and which guides them in acting. Different perspectives are reflected by different choices concerning structural uncertainties, which can lead to contradictory results (as will be shown in Section 3.3.5). The Individualist perspective assumes a short-term time perspective, includes substances only if there is complete proof regarding their effect, assumes changes to be recoverable by technological and economic development, and asserts fossil fuels cannot be depleted. The Egalitarian perspective is long-term and includes substances when there is any indication regarding their effect, assumes damages cannot be avoided and may lead to catastrophic effect, and assumes fossil fuels cannot be substituted (Cozzi & Ohji, 2009).

The Hierarchist perspective was selected for the damage model herein because of its balanced time perspective, as a consensus among scientists determined inclusion of environmental effects (Goedkoop *et al.*, 2000), and for its strong-held belief in preventing environmental problems through regulation (Hauschild, 2005). Table 3.1 shows the contributions of Human Health, Ecosystem Quality and Resources of each perspective to the final value of EI-99 Single Score (Goedkoop *et al.*, 2000).

Table 3.1 Relative contributions of Human Health, Ecosystem Quality and Resources to the final value of EI-99 Single Score, considering different cultural perspectives.

	Hierarquist perspective (H/H)	Egalitarian perspective (E/E)	Individualist perspective (I/I)
Human Health	40%	30%	55%
Ecosystem Quality	30%	50%	25%
Resources	30%	20%	20%

Figure 3.2 was built utilizing data from Goedkoop *et al.* (2000) and shows the relative contribution of the eleven impact subcategories considered in the three damage categories to the overall result of the Single Score (Hierarchist perspective, 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.

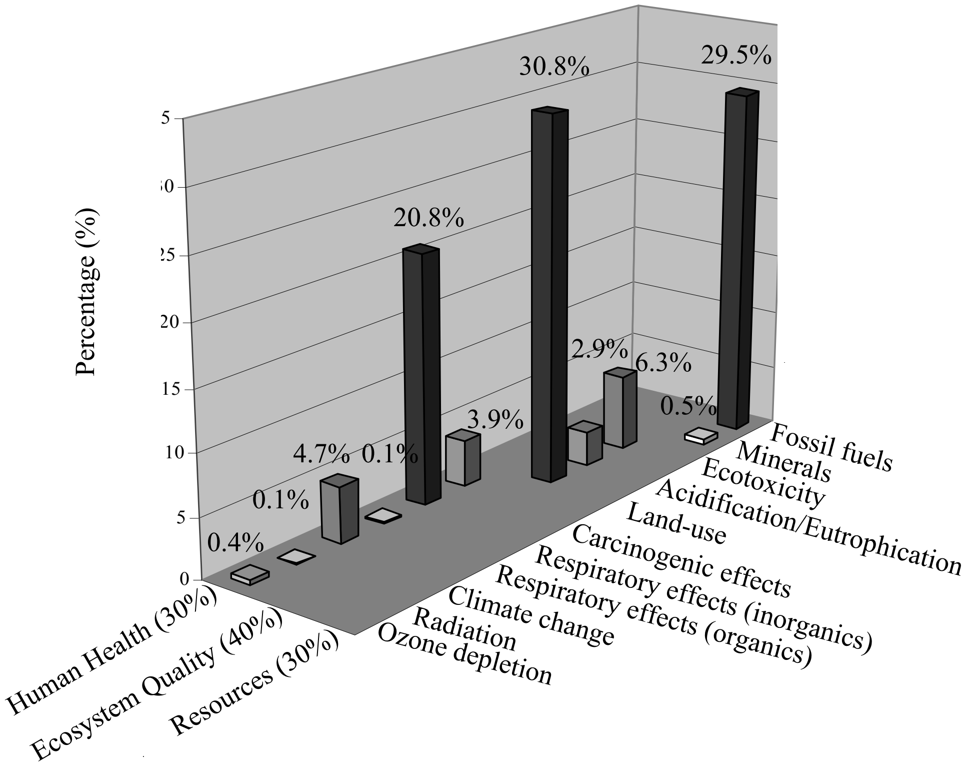

Figure 3.2 Relative contributions of impact categories to the European damage (H/H).

Section 3.3.5 will explicit the high weight of the category Resources in the EI-99 Single score, when considering the H/H perspective. EI-99 uses anticipated added environmental impacts on human health and ecosystems (because of decreased future ore grades) as a measure of the environmental impact of abiotic resource extraction. Abiotic resources are the product of past biological processes (coal, oil and gas) or of physical/chemical processes (deposits of metal ores).

Steen (2006) discusses that abiotic resource depletion in itself is not a well-defined concept and differs somewhat from, for example, global warming and acidification in that the subjective elements stand out more strongly. The concept of resources is highly dependent on the presence of a user, the needs and skill of the user, expectations about the future and perceptions about what constitutes the depletion problem. Many LCIA approaches mix scarcity as such with the difficulty of extraction, which can be viewed as double counting as the effects thereof, such as high-energy demand, are accounted for in other categories (Brent & Hietkamp, 2006). There are different ideas about which time perspective to apply. If only keeping in mind the next decades, the resource problem is one among others; however, when considering thousands of years, the problem becomes enormous (Steen, 2006).

Müller-Wenk (1998) argues that the problem with abiotic resources is rather that the reserve quantities in accessible deposits with high concentration could sensibly go back within a time horizon of 100 or 1000 years, so that future generations would have to live with lower concentrations and correspondingly higher extraction efforts. If abiotic resources are considered to be scarce, the relevant question for a weighting model should therefore focus on the resource concentrations available in 100 or 1000 years from now, and less on the average crustal concentration which will *never* be used for actual mining. Damage for resources would then be more than two orders of magnitude less (Steen, 2006). There is a broad consensus that impact category indicators in LCIA should represent significant environmental issues, but there seems to be less consensus on how significant the problem of abiotic resource depletion is (Ayres, 1998), and to what extent it should be on the agenda of LCIA (Steen, 2006).

The idea of having a global perspective on environmental impact (using EI-99) is important in order to account for all possible environmental issues of concern to which LCI results may be assigned to. From a designer’s point of view, a single indicator that evaluates the environmental impact in such a way that it can be incorporated directly into a decision problem, along with other design considerations, is an ideal situation.

Using one method consistently to compare different potential products coupled with a liberal use of common sense, will indicate with reasonable certainly which of the alternative designs being considered is the most environmentally friendly (Tarr, 2007).

3.2 ENVIRONMENTAL LOADS OF FUELS AND ELECTRICITY

In order to take the work presented in Chapter II a step further by incorporating environmental information, SimaPro was utilized to calculate the environmental loads associated with the consumption of resources. The system interacted with the economic environment (market) through the purchase of natural gas, fuel oil, and electricity from the grid, as well as through the sale of cogenerated electricity to the grid.

LCA analyzes the environmental impacts associated with a process or product from ‘the cradle to the grave’, which begins with the gathering of raw materials from the earth to create the product/service and ends at the point when all materials are returned to the earth (SAIC, 2006). Regarding natural gas, special care was taken to correctly identify the natural gas supplied to a user in Spain. It was considered that the gas comes from Algeria, is transported in Liquefied Natural Gas (LNG) carriers, also including pipeline transportation to the user and controlled burning. The fuel oil burned in the boiler included average transportation and controlled burning. The electricity supplied by the Spanish electric grid was also properly characterized and characterized accordingly to the single-fuel contributors.

3.2.1 Natural gas

Natural gas was characterized by utilizing the related emissions of combustion of natural gas, from the IDEMAT database (IDEMAT, 2001), and the total aggregated system inventory for a natural gas consumer in Spain, from the Ecoinvent database (Ecoinvent, 2007). It was considered that the natural gas originates from Algeria, was transported to Spain in LNG carriers, and transported to the final user through pipelines (utilizing an average distance). The CO_2 emissions associated with the consumption of natural gas in Spain were obtained by utilizing SimaPro, calculated as $EM_{fc} = 0.272$ kg CO_2 per kWh of consumed natural gas. The Single Score obtained when utilizing the EI-99 method (H/H) was $SS_{fc} = 0.0378$ points per kWh consumed. Detailed calculation of EI-99 Single Score is presented in Appendix I.

Figure 3.3 shows the contributors to the total CO_2 emissions of natural gas: related emissions of combustion of natural gas (Energy gas I), with a contribution of 89%, and the total aggregated system inventory for a natural gas user in Spain (Natural gas, at consumer), which includes gas field exploration, natural gas production, long distance transport, distribution and local supply, responsible for 11% of final CO_2 emissions. The cut-off setting[4] was set at 1% (default for the entire study), and the cut-off threshold[5] for displaying processes in the tree was set at 5% (default for the entire study), although all processes are shown for this specific example.

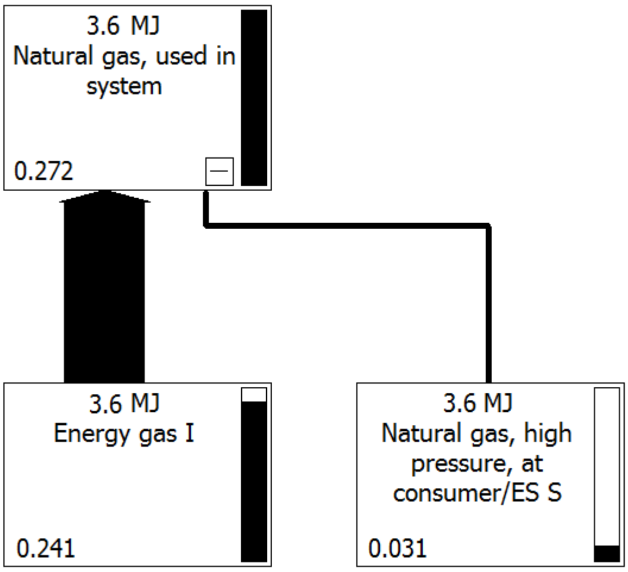

Figure 3.3 Visualization tree for CO_2 emissions of combustion of natural gas (kg/kWh).

Table 3.2 shows the EI-99 Single Score (total and contribution of each damage category) and CO_2 emissions for 1 kWh of consumed natural gas.

Table 3.2 EI-99 (H/H) Single Score (points/kWh) and CO_2 emissions (kg CO_2/kWh) per damage category, for 1 kWh of consumed natural gas.

	Eco-Indicator 99 (H/H) 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)	$2.49 \cdot 10^{-3}$	$3.92 \cdot 10^{-4}$	$3.49 \cdot 10^{-2}$	**$3.78 \cdot 10^{-2}$**	**$2.72 \cdot 10^{-1}$**

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[4] Process trees contain many processes that do not contribute in a quantitatively relevant degree to the system. A cut-off setting is quantified in relation to the percentage of environmental impacts that will be excluded via the cut-off.

[5] The cut-off threshold for displaying processes is for visualization purposes only; the cut-off threshold does not reveal processes that contribute with less than a fixed percentage although they were computed in calculations.

According to Table 3.2, the *Resources* category was the category with highest contribution to the total EI-99 Single Scores. 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 (Dones *et al.*, 2007). With respect to CO_2 emissions, the highest contribution corresponded to natural gas combustion.

3.2.2 Fuel oil

Fuel oil was characterized by copying the process *Light fuel oil, burned in industrial furnace 1 MW/RER U* from the Ecoinvent database (Ecoinvent, 2007), and excluding equipment. The final process (*Light fuel oil, inventory + combustion*) included the inventory module *Light fuel oil, at regional storage/RER U* (extraction, production at refinery and transportation from refinery to an average European end user) and related emissions of controlled burning. The CO_2 emissions associated with the consumption of fuel oil were obtained by utilizing SimaPro, calculated as EM_{fa} = 0.305 kg CO_2 per kWh of consumed fuel oil. The Single Score obtained when utilizing the EI-99 method (H/H) was SS_{fa} = 0.0257 points per kWh consumed.

Table 3.3 shows the EI-99 (H/H) Single Score (total and contribution of each damage category) and CO_2 emissions for 1 kWh of consumed fuel oil.

Table 3.3 EI-99 Single Score (points/kWh) and CO_2 emissions (kg CO_2/kWh) per damage category, for 1 kWh of consumed fuel oil.

	Eco-Indicator 99 (H/H) Single Score (points/kWh)				CO_2 emissions
	Human Health	Ecosystem Quality	Resources	TOTAL EI-99 SS	kg CO_2/kWh
Fuel oil consumed (1 kWh)	$2.75\cdot10^{-3}$	$1.37\cdot10^{-3}$	$2.16\cdot10^{-2}$	$\mathbf{2.57\cdot10^{-2}}$	$\mathbf{3.05\cdot10^{-1}}$

Differently from the case of natural gas (where two processes had to be added), there existed a single process that accounted for the aggregated inventory and combustion of fuel oil. The related emissions of combustion of fuel oil are not explicitly shown in the visualization tree in Figure 3.4, but account for 87% of final CO_2 emissions and are embedded in the wide arrow that connects *Light fuel oil, at regional storage/RER U* to the output process *Light fuel oil, inventory + combustion*.

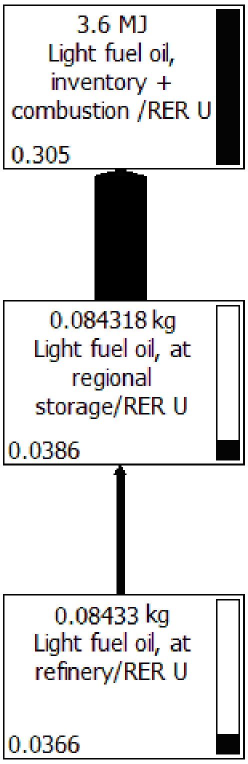

Figure 3.4 Visualization tree for CO_2 emissions of consumption of fuel oil (kg/kWh).

3.2.3 Electricity

The CO_2 emissions associated with the local electricity (Spanish electricity mix) were also calculated by SimaPro, utilizing the Ecoinvent database and considering the following contributors to the mix: 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 (REE, 2007a). The average CO_2 emissions associated with electricity in Spain in 2007 was EM_e = 0.385 kg CO_2 per kWh consumed. The single score obtained when utilizing EI-99 (H/H) was SSe = 0.0226 pts per kWh consumed.

Table 3.4 shows the EI-99 Single Scores and CO_2 emissions for the different contributors to the electricity mix in Spain. The final value was obtained by multiplying each contributor by its corresponding proportion. Values in Table 3.3 were obtained from the Ecoinvent database, which provides environmental loads associated with the production of electricity at each specific power plant.

Table 3.4 EI-99 Single Score and CO_2 emissions 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[6]	$2.97\cdot10^{-2}$	$3.66\cdot10^{-3}$	$7.50\cdot10^{-3}$	$4.09\cdot10^{-2}$	1.02
Natural gas in combined cycle[7]	$2.58\cdot10^{-3}$	$2.80\cdot10^{-4}$	$3.55\cdot10^{-2}$	$3.84\cdot10^{-2}$	$3.98\cdot10^{-1}$
Nuclear[8]	$7.64\cdot10^{-4}$	$9.45\cdot10^{-5}$	$3.85\cdot10^{-4}$	$1.24\cdot10^{-3}$	$7.10\cdot10^{-3}$
Hydraulic[9]	$1.76\cdot10^{-4}$	$5.61\cdot10^{-5}$	$1.38\cdot10^{-4}$	$3.70\cdot10^{-4}$	$3.60\cdot10^{-3}$
Eolic[10]	$6.42\cdot10^{-4}$	$6.43\cdot10^{-4}$	$1.42\cdot10^{-3}$	$2.71\cdot10^{-3}$	$1.70\cdot10^{-2}$
Fuel-gas[11]	$1.62\cdot10^{-2}$	$4.31\cdot10^{-3}$	$6.49\cdot10^{-2}$	$8.55\cdot10^{-2}$	$6.46\cdot10^{-1}$
Others[12]	$1.37\cdot10^{-3}$	$2.62\cdot10^{-4}$	$1.15\cdot10^{-2}$	$1.31\cdot10^{-2}$	$1.32\cdot10^{-1}$
Spanish electricity mix (1 kWh)	$8.83\cdot10^{-3}$	$1.17\cdot10^{-3}$	$1.26\cdot10^{-2}$	**$2.26\cdot10^{-2}$**	**$3.85\cdot10^{-1}$**

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 CO_2 emissions. However, when applying the EI-99 method with the hierarquist perspective (H/H), 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; SimaPro, 2008) 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

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

[7] 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%.

[8] 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%).

[9] Hydraulic: 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%.

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

[11] 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%.

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

Score). Hydraulic energy generation has an almost insignificant contribution (0.21%). Figure 3.5 depicts the visualization tree for the Spanish mix.

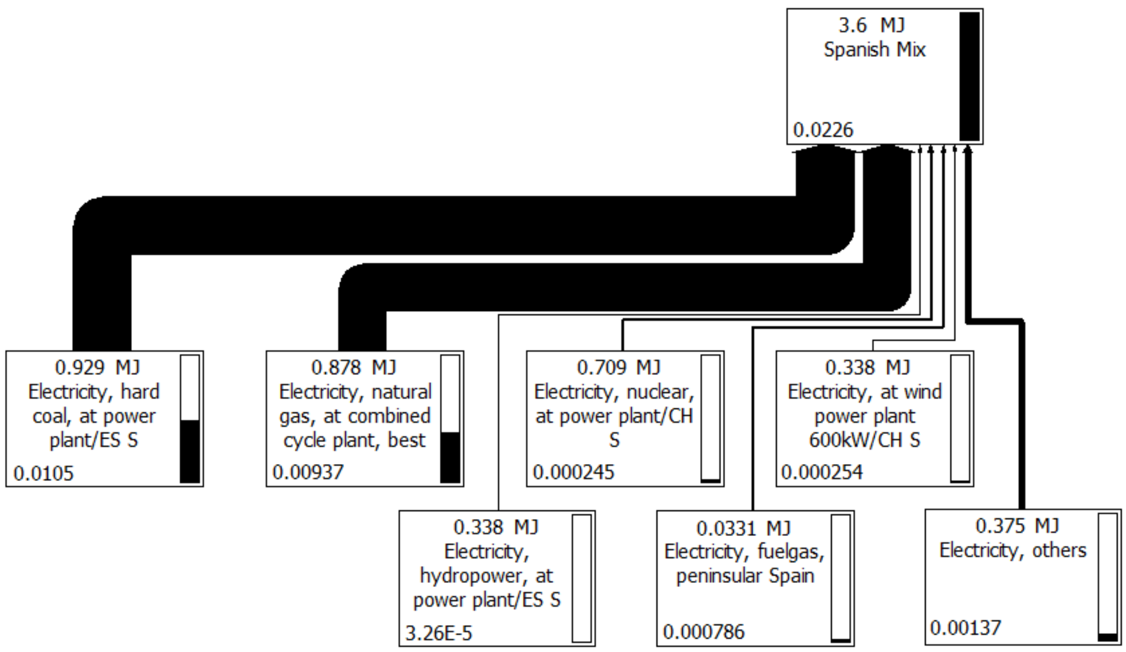

Figure 3.5 Visualization tree for the Electricity mix in Spain (EI-99 points/kWh).

3.3 ENVIRONMENTAL OPTIMALS

In order to minimize the environmental impact associated with the operation of trigeneration systems, environmental loads (CO_2 emissions and EI-99 Single Score) should be considered as the objective function in the optimization of such systems.

Therefore, a methodology similar to that utilized in Chapter II (economic optimization followed by cost accounting) was applied for consistency.

3.3.1 CO_2 minimization

Figure 3.6 shows the analyzed trigeneration system, with internal and product flows and emissions.

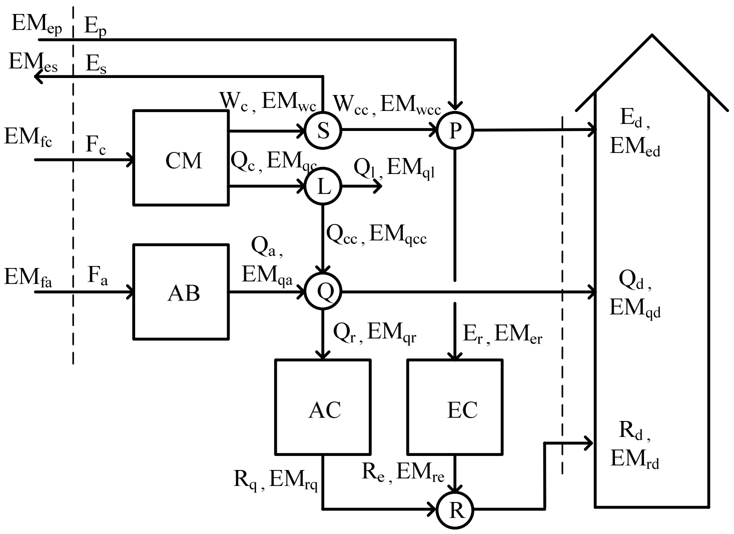

Figure 3.6 Simple trigeneration system with emissions and flows.

A linear programming model was solved in order to obtain the optimal operation mode from an environmental viewpoint. The environmental analysis considered that the only significant variable environmental loads were electricity, natural gas and fuel oil, and that cogenerated heat could be wasted without environmental burden, *i.e.*, $EM_{ql} = 0$. The objective function to be minimized was the operation variable emissions (HEC, in kg CO_2/h):

$$HEC = EM_{fc} \cdot F_c + EM_{fa} \cdot F_a + EM_{ep} \cdot E_p - EM_{es} \cdot E_s + EM_{ql} \cdot Q_l \qquad (3.1)$$

Cogenerated electricity sold to the grid was considered to have the same environmental load as that of electricity purchased from the grid ($EM_{es} = EM_{ep}$). The concept of avoided emissions is presented as the emissions avoided elsewhere with the production of electricity by the cogeneration module, consequently avoiding the purchase of electricity from the grid.

Equation (3.1) is subject to restrictions of capacity limit and equipment efficiency as well as balance equations, previously presented in Equations (2.2) – (2.15) in Chapter 2. Results were also obtained by utilizing the computer application Lingo. Given the energy demands to be satisfied, according to the different operation modes, Lingo solved the previous model and determined the feasible operation mode with the minimum operation variable emissions.

As a consequence, when utilizing the same energy demands of Chapter 2, the following energy flows were obtained (Table 3.5), considering the CO_2 emissions of natural gas $EM_{fc} = 0.272$ kg

CO_2/kWh, CO_2 emissions of fuel oil EM_{fa} = 0.305 kg CO_2/kWh, CO_2 emissions of electricity $EM_{ep} = EM_{es}$ = 0.385 kg CO_2/kWh, and the objective, HEC.

Table 3.5 Energy flows and total CO_2 emissions considering the Spanish electricity mix.

		ExEC$_1$	**ExEC$_3$**	**ExEC$_7$**	**ExEC$_9$**
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
E_p	kW	**100**	**332.50**	0	**132.50**
E_s	kW	0	0	**130**	0
F_c	kW	1000	250	1000	250
F_a	kW	300	0	250	0
W_c	kW	350	87.50	350	87.50
Q_c	kW	400	100	400	100
W_{cc}	kW	350	87.50	220	87.50
E_r	kW	50	20	20	20
Q_l	kW	0	0	0	0
Q_{cc}	kW	400	100	400	100
Q_a	kW	**240**	**0**	**200**	**0**
Q_r	kW	240	0	0	0
R_q	kW	150	0	0	0
R_e	kW	250	100	100	100
Objective HEC	kg CO_2/h	**402.00**	**196.01**	**298.20**	**119.01**
Operation mode		**C$_1$**	**C$_2$**	**C$_7$**	**C$_3$**

There was no way of implementing waste of heat with the aforementioned demands. Operation states and modes differ from those obtained in the economic optimization (Table 2.4), with exception of ExEC$_1$, which presented the same operation mode and state than ExC$_1$.

With the demands of ExC$_3$ (E_d = 400, Q_d = 100, R_d = 100), the cogeneration module operated at part load. Consultation of Table 2.3 indicated that the operation mode obtained with these demands was C$_2$ ($E_p > 0$, $E_s = 0$; $Q_a = 0$, $Q_l = 0$).

Considering the demands E_d = 200, Q_d = 600, R_d = 100, the cogeneration module operates at full load and the purchase of electricity was not allowed. There was sale of cogenerated electricity. The operation mode was C$_7$ ($E_p = 0$, $E_s > 0$; $Q_a > 0$, $Q_l = 0$), the same operation state obtained for ExC$_7$ in Chapter II.

When the demands were changed to those of ExC_9, purchase of electricity occurred and the cogeneration module operated at part load. Again, there was no waste heat and the operation mode was C_3 ($E_p > 0$, $E_s = 0$, $Q_a = 0$, $Q_l = 0$).

3.3.2 EI-99 minimization

The trigeneration system is the same as presented in Figure 3.6, changing CO_2 emissions to EI-99 points. This environmental analysis considered that the only significant variable Single Scores were electricity, natural gas and fuel oil, and that cogenerated heat could be wasted without penalty, *i.e.*, $SS_{ql} = 0$. The objective function to be minimized was the operation variable Single Score (HES, in points/h):

$$HES = SS_{fc} \cdot F_c + SS_{fa} \cdot F_a + SS_{ep} \cdot E_p - SS_{es} \cdot E_s + SS_{ql} \cdot Q_l \qquad (3.2)$$

Cogenerated electricity sold to the grid (SS_{es}) was considered to have the same environmental loads as those of electricity purchased from the grid. The concept of avoided environmental loads is presented as the environmental loads avoided elsewhere with the production of electricity by the cogeneration module, consequently avoiding the purchase of electricity from the grid.

Equation (3.2) is subject to restrictions of capacity limit and equipment efficiency as well as balance equations, previously presented in Equations (2.2) – (2.15) in Chapter 2.

Results were also obtained by utilizing the computer application Lingo. Given the energy demands to be satisfied, according to the different operation modes, Lingo solved the previous model and determined the feasible operation mode with the minimum operation variable Single Score (Table 3.6), with EM_{fc} = 0.0378 points/kWh, EM_{fa} = 0.0257 points/kWh, $SS_{ep} = SS_{es}$ = 0.0226 points/kWh, and the objective, HES.

There was no way of implementing waste of heat with the aforementioned demands. Operation states and modes differ from those obtained in the economic optimization (Table 2.4), being also different from those obtained in the CO_2 emissions minimization.

Table 3.6 Energy flows and EI-99 loads considering the Spanish electricity mix.

		$ExSC_1$	**$ExSC_3$**	**$ExSC_7$**	**$ExSC_9$**
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
E_p	kW	**240**	**420**	**45**	**220**
E_s	kW	0	0	0	0
F_c	kW	600	0	500	0
F_a	kW	500	125	500	125
W_c	kW	210	0	175	0
Q_c	kW	240	0	200	0
W_{cc}	kW	210	0	175	0
E_r	kW	50	20	20	20
Q_l	kW	0	0	0	0
Q_{cc}	kW	240	0	200	0
Q_a	kW	**400**	**100**	**400**	**100**
Q_r	kW	240	0	0	0
R_q	kW	150	0	0	0
R_e	kW	250	100	100	100
Objective HES	points/h	**40.95**	**12.70**	**32.77**	**8.18**
Operation mode		**C_1**	**C_0**	**C_1**	**C_0**

With the demands of ExC_1, the cogeneration module operated at part load. Operation mode was still C_1, however, with a different operation state. The auxiliary boiler operated at full load. With the demands of ExC_3, the cogeneration module did not operate, and electricity was purchased from the grid. This special operation mode was classified as C_0 because the cogeneration module was not in service.

Considering the demands of ExC_7 ($E_d = 200$, $Q_d = 600$, $R_d = 100$), the cogeneration module operated at part load, and electricity was purchased from the grid. The operation mode was C_1 ($E_p > 0$, $E_s = 0$, $Q_a > 0$, $Q_l = 0$). The auxiliary boiler operated at part load.

When the demands were changed to those of ExC_9 ($E_d = 200$, $Q_d = 100$ and $R_d = 100$), special operation mode C_0 occurred again. The cogeneration module was not in service and the boiler operated at part load.

3.3.3 Analysis

The results obtained with the environmental minimizations presented very different results when compared with economic minimization. Economic minimization always suggested the cogeneration module operated at full load, even if wasting part of cogenerated heat. However, environmental minimizations suggested the cogeneration module operate at part load or even not operate at all. The starting point for operation at full load of the cogeneration module can be set as:

$$z_{fc} \cdot F_c \leq z_{ep} \cdot W_c \tag{3.3}$$

where z can be prices, emissions, or environmental loads per flow unit (€/kWh, kg CO_2/kWh, or points/kWh). Equation (3.3) can be rewritten as $z_{fc} \leq z_{ep} \cdot \alpha_w$. Therefore when this relationship is fulfilled, the cogeneration module is operating at full load. Note that the demands of ExC_1 led to an operation of the cogeneration module because of the high cooling demand, which could not be met with the mechanical chiller only and therefore required the operation of the absorption chiller. For the demands of ExC_7, the cogeneration module operates because of production limitations of the auxiliary boiler. For CO_2 emissions, $z_{ep} \cdot \alpha_w$ yields 0.135, which is not greater than 0.272 and therefore the cogeneration module does not operate at full load. For EI-99 points, the relationship yields 0.0079, also indicating that the cogeneration module should not operate at full load.

There is also a starting point for shutting down the cogeneration module, when it is not interesting to operate the equipment at all:

$$z_{fc} \cdot F_c \geq z_{ep} \cdot W_c + z_a \cdot Q_c \tag{3.4}$$

where $z_a = z_{fa}/\eta_q$. Equation (3.4) can be simplified to $z_{fc} \geq z_{ep} \cdot \alpha_w + z_a \cdot \alpha_q$. For CO_2 emissions, the result of the right side of the expression yields $z_{fc} \leq 0.288$ (because z_{fc} = 0.272 kg CO_2/kWh). Non-fulfillment of this expression indicates that the cogeneration module should be operating (even if at part load). However, for EI-99 points, the expression yields $z_{fc} \leq 0.0208$, because z_{fc} = 0.0378 points/kWh and therefore the cogeneration module must not operate. Table 3.7 summarizes the starting points for operation at part load or full load of the cogeneration module.

It should be noted that the cogeneration module often operates because existing equipment are not capable of meeting heat and/or cooling loads.

Table 3.7 Operational state of the cogeneration module, considering the Spanish electricity mix.

Cogeneration module operational state	CO_2 emissions	EI-99 points
Full load operation	$z_{fc} \leq 0.135$	$z_{fc} \leq 0.0079$
Part load operation	$\mathbf{0.135 < z_{fc} < 0.288}$	$0.0079 < z_{fc} < 0.0208$
Not in service	$z_{fc} \geq 0.288$	$\mathbf{z_{fc} \geq 0.0208}$

The environmental minimizations also revealed a trend of cooling production via mechanical chiller. The production of cooling utilizing cogenerated heat is not interesting (and consequently the cooling demand is covered by the mechanical chiller) when:

$$z_{fc} \geq (\alpha_w + \alpha_q \cdot COP_q/COP_e) \cdot z_{ep} \tag{3.5}$$

$z_{fc} \geq 0.154$ kg CO_2/kWh for CO_2 emissions and $z_{fc} \geq 0.00904$ points/kWh for EI-99 points; both relationships are true and expose the adequacy of operating the mechanical chiller instead of utilizing cogenerated heat via absorption chiller.

3.3.4 Effect of the origin of electricity

The changes implied in changing the origin of electricity purchased from the grid will be studied in this section. The electricity mix was changed (utilizing values from Table 3.2), considering that all electricity originated from a single-fuel representative coal power plant (EM_{ep}=1.020 kg CO_2/kWh). Operation states from Table 2.4 were achieved including waste heat.

A summary of results (demand, flows, and hourly environmental loads) obtained with Lingo for four examples $ExECC_3$, $ExECC_4$, $ExECC_7$ and $ExECC_9$ that correspond to different operation modes (C_1, C_3, C_7 and C_9) is presented in Table 3.8, considering EM_{fc} = 0.272 kg CO_2/kWh, EM_{fa} = 0.305 kg CO_2/kWh, $EM_{ep} = EM_{es}$ = 1.020 kg CO_2/kWh, and the objective, HEC.

With the change of fuel, $z_{fc} \leq z_{ep} \cdot \alpha_w$ results in $z_{fc} \leq 0.357$ (full load operation of cogeneration module), and the condition presented by Equation (3.3) is now fulfilled. It is interesting to operate the cogeneration module with EM_{ep} = 1.020 kg CO_2/kWh, even if a part of cogenerated heat is wasted. On the supply side, purchasing electricity with at least 0.777 kg CO_2/kWh would result in operating the cogeneration module at full load.

Table 3.8 Energy flows and variable emissions considering a coal power plant.

		ExECC$_1$	**ExECC$_3$**	**ExECC$_7$**	**ExECC$_9$**
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
E_p	kW	**100**	**50**	0	0
E_s	kW	0	0	**130**	**150**
F_c	kW	1000	1000	1000	1000
F_a	kW	300	0	250	0
W_c	kW	350	350	350	350
Q_c	kW	400	400	400	400
W_{cc}	kW	350	350	220	200
E_r	kW	50	0	20	0
Q_l	kW	0	**140**	0	**140**
Q_{cc}	kW	400	260	400	260
Q_a	kW	**240**	0	**200**	0
Q_r	kW	240	160	0	160
R_q	kW	150	100	0	100
R_e	kW	250	0	100	0
Objective HEC	kg CO_2/h	**465.50**	**323.00**	**215.65**	**119.00**
Operation mode		**C$_1$**	**C$_3$**	**C$_7$**	**C$_9$**

Following the same methodology, the electricity mix was changed in the EI-99 minimization (utilizing values from Table 3.2), considering that 100% of the electricity originated from a single-fuel representative coal power plant (SS_{ep} = 0.0409 points/kWh). However, operation modes with waste heat could not be obtained, yielding energy flows as seen in Table 3.9 (with SS_{fc} = 0.0378 points/kWh, SS_{fa} = 0.0257 points/kWh, SS_{ep} = SS_{es} = 0.0409 points/kWh, and the objective, HES).

Table 3.9 Energy flows and EI-99 loads considering a coal power plant.

		ExSCC$_1$	**ExSCC$_3$**	**ExSCC$_7$**	**ExSCC$_9$**
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
E_p	kW	**240**	**420**	**45**	**220**
E_s	kW	0	0	0	0
F_c	kW	600	0	500	0
F_a	kW	500	125	500	125
W_c	kW	210	0	175	0
Q_c	kW	240	0	200	0
W_{cc}	kW	210	0	175	0
E_r	kW	50	20	20	20
Q_l	kW	0	0	0	0
Q_{cc}	kW	240	0	200	0
Q_a	kW	**400**	**100**	**400**	**100**
Q_r	kW	240	0	0	0
R_q	kW	150	0	0	0
R_e	kW	250	100	100	100
HES	points/h	**45.35**	**20.39**	**33.59**	**12.21**
Operation mode		**C$_1$**	**C$_0$**	**C$_1$**	**C$_0$**

Equation (3.4) is fulfilled $z_{fc} \geq z_{ep} \cdot \alpha_w + z_a \cdot \alpha_q$, yielding $z_{fc} \geq 0.0272$, therefore indicating that the cogeneration module should not operate. On the supply side, a fuel with at least 0.1080 points/kWh is required for the cogeneration module to operate at full load. No contributor to the Spanish electricity mix was found with such high environmental loads to carry out this analysis.

Previously, when the CO_2 emissions associated with electricity purchased from grid were raised, considering a single-fuel coal power plant, full cogeneration was obtained. It becomes apparent that the utilization of natural gas is penalized with such high EI-99 points for Resources up to a point where there is no single-fuel power plant in the Spanish mix with sufficient high emissions to compensate for utilization of natural gas in the cogeneration module. Table 3.10 summarizes the operational states for the cogeneration module considering a coal power plant.

Table 3.10 Operational state of the cogeneration module, considering a coal power plant.

Cogeneration module operational state	CO_2 emissions	EI-99 points
Full load operation	$\mathbf{z_{fc} \leq 0.357}$	$z_{fc} \leq 0.0143$
Part load operation	$0.510 < z_{fc} < 0.357$	$0.0272 < z_{fc} < 0.0143$
Not in service	$z_{fc} \geq 0.510$	$\mathbf{z_{fc} \geq 0.0272}$

3.3.5 Effect of different EI-99 perspectives

Cultural perspectives were switched in the calculation of the EI-99 Single Score for natural gas, fuel oil and Spanish electricity mix to verify the changes implied. A great difference in values was observed when comparing Single Scores for the utilization of natural gas and fuel oil. The values obtained for natural gas, Spanish electricity mix, and fuel oil were, respectively, SS_{fci} = 0.0045, SS_{ei} = 0.0220, and SS_{fai} = 0.0073 points/kWh in the Individualist perspective (I/I), and SS_{fce} = 0.0225, SS_{ee} = 0.0248, and SS_{fai} = 0.0160 points/kWh in the Egalitarian perspective (E/E). By applying these values to Equations (3.4) and (3.5) the operational state of the cogeneration module can be predicted (Table 3.11), where the cogeneration module operates at full load in the Individualist perspective and does not operate in the Egalitarian and Individualist perspectives.

Table 3.11 Operational state of the cogeneration module, considering the Spanish electricity mix and different cultural perspective in EI-99.

Cogeneration module operational state	(H/H)	(E/E)	(I/I)
Full load operation	$x_{fc} \leq 0.0079$	$x_{fc} \leq 0.0087$	$\mathbf{x_{fc} \leq 0.0077}$
Part load operation	$0.0079 < x_{fc} < 0.0208$	$0.0087 < x_{fc} < 0.0167$	$0.0077 < x_{fc} < 0.0114$
Not in service	$\mathbf{x_{fc} \geq 0.0208}$	$\mathbf{x_{fc} \geq 0.0167}$	$x_{fc} \geq 0.0114$

The EI-99 Single Score for the Spanish electricity mix did not present significant variation when changing cultural perspectives, and always presented fewer points than electricity from fossil fuels. Such results are in accordance with Dones & Heck (2006), which state that average European fossil systems have in general the worst environmental performance under all three perspectives, with the exception of natural gas for the Individualist (not accounted for). If LCA as an instrument fits better with one of the perspectives than the others, it would have been enough to develop a framework just for that one (Hofstetter, 2000). However, Jørgensen (1996) has argued that theoretically all three active perspectives have a very positive attitude towards LCA.

This generally positive attitude towards LCA justifies the approach that LCA, one way or another, has to cope with these different value orientations if it is to be used in the future by all the perspectives. The issue of selecting a cultural perspective remains an open question that requires further research. Such a low value for the utilization of natural gas and fuel oil by the Individualist perspective lies in the fact that the Individualist is an optimist, who thinks that technical problems to environmental solutions will allow us to continue and expand the present lifestyle in the future. The choice of the Hierarchist perspective did not allow for the establishment of several different operation states, but is still considered to provide the desirable results, which should be the closest to a scientists' point of view (representing the view of the *average scientist*, therefore following the IPCC assessment reports (Laleman *et al.*, 2010)).

3.4 ENVIRONMENTAL LOADS ACCOUNTING

Thermoeconomic analysis combines economic and thermodynamic analysis by implementing the concept of cost, an economic property, to a thermodynamic analysis. The basic tool of thermoeconomic analysis is the cost, understood as the amount of resources consumed for obtaining a piece of equipment, a flow or a commodity. Hence, the cost of a flow in a plant represents the amount of resources that have to be supplied to the overall system to produce this flow. Thermoeconomic methodologies are usually based on the costs of the mass and energy flows of the plant, and can be expressed in monetary, environmental or other units.

Both thermoeconomic analysis techniques and LCA are based on the accounting of the resources required for producing a good or service. Thermoeconomics is usually applied to industrial plants and the limits of the system are those of the plant. There is no constraint that impedes the widening of the limits of analysis to the well or the mine from where the natural resources were extracted. Thus, both methodologies can be combined providing an integrated energy, economic and environmental analysis with a global perspective of a complex system. Some authors have already proposed and developed research in exergy-life cycle assessment (Cornelissen & Hirs, 2002; Hau, 2002) and others have already proposed the combination of thermoeconomic analysis with Life Cycle Assessment (González *et al.*, 2003; Tsatsaronis, 2007; Serra *et al.*, 2007).

Typically, analyses of environmental loads consider only the inputs and outputs of a productive system to calculate the total environmental burden (the system is regarded as a black box). However, knowledge on distribution of environmental loads was very important, which would take Chapter II (cost distribution and analysis) *a step further*, considering also an environmental perspective (distribution and analysis of environmental burden)[13].

3.4.1 Umberto software for material and energy flow analysis

The Umberto software is an Environmental Management Information System (EMIS) and has been specifically designed for analyzing the distribution of material and energy resources throughout a productive system. Even if a Material Flow Network (MFN) can provide data on the level of material and energy flows, it is necessary to extend the networks because life cycle assessments require a representation of the entire life cycle of products and services, including raw material extraction, distribution, use phase, and waste disposal (Möller, 2010). Such an extension is interesting for companies, as the concept of resource productivity is a new administrative approach to deal with sustainability challenges (Porter & van der Linde, 1995).

Through the inclusion of environmental information on the usage and consumption of resources into this software, the MFN approach was able to demonstrate the environmental loads associated with each flow of the system. Additionally, integrated models of energy flows facilitated a better understanding of the assignation of environmental and economic costs to the internal and final products of the trigeneration system.

The initial concept of MFN focused on absolute material and energy flows of companies and supply chains, and was not really in line with LCA, which is another means-end analysis instrument and there are parallels to the different perspectives between accountants and engineers. Surprisingly, the ideas around MFN have led to a new framework for material and energy flow-based cost accounting, supporting the engineering of complex production structures and their economic evaluation (Möller, 2010). In MFN, the term *material* refers to substances

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[13] The environmental scope of this study and consequent use of Environmental Management Information Systems (EMIS) fomented a research stay in Berlin to develop in-depth knowledge in environmental analysis of trigeneration systems through the use of the Umberto software (Umberto, 2006). This research stay took place at the Umberto Competence Centre at the University of Applied Sciences of the Hochschule für Technik und Wirtschaft Berlin (HTW Berlin), under supervision of Prof. Volker Wohlgemuth. The 3-month work plan focused on providing instruction and training in Umberto as well as analyzing allocation criteria for environmental loads. The research project was titled *Instruction, training and investigation in environmental modeling with Umberto – Analysis of the distribution of energy and environmental impacts in trigeneration systems.*

and energy, meaning there is virtually no distinction between substances and energy. MFN can be applied to systems of any size or even to a specific stage of production.

According to Wohlgemuth *et al.* (2006), the most attractive feature of MFN is the possibility to combine the compilation of eco-balances for a company, industrial plant, or production process with an analysis of material flows associated with given products or services. An advantage of the MFN approach resides in its gradual modeling approach, starting from a very basic model of few processes with simple specifications, the model can be extended step by step to include further processes, sites, more complex specifications, costs, etc. (Viere *et al.*, 2010).

Umberto software allows the visualization of processes, units and flows, carrying out mass and energy balances and analyzing from an environmental point of view the loads/emissions generated. Petri Nets and double-entry bookkeeping and cost accounting are the basis of Umberto software, allowing the setup of complex systems and also a combined material, energy and inventory calculation. Material Flow Networks consist of transitions, places and arrows (directed graphs).

Using a diagram notation, *transitions* are shown in Umberto software as squares, indicating the location of material or energy transformations. *Places* types are *input*, *output*, and *connection*, being represented by circles. *Input and output* connect the material flow network with its environment. *Connection* is represented by two concentric circles, and is utilized to connect transitions (link from the output of one process to the input of the next process). *Arrows* link places and transitions, and thus create the actual network structure. The functional unit was the production of the demanded energy services during one hour of operation of the different alternatives.

3.4.2 Umberto model of simple trigeneration system

Figure 3.7 shows the simple trigeneration system (scheme in Figure 2.1) modeled in Umberto, followed by the main features of the model.

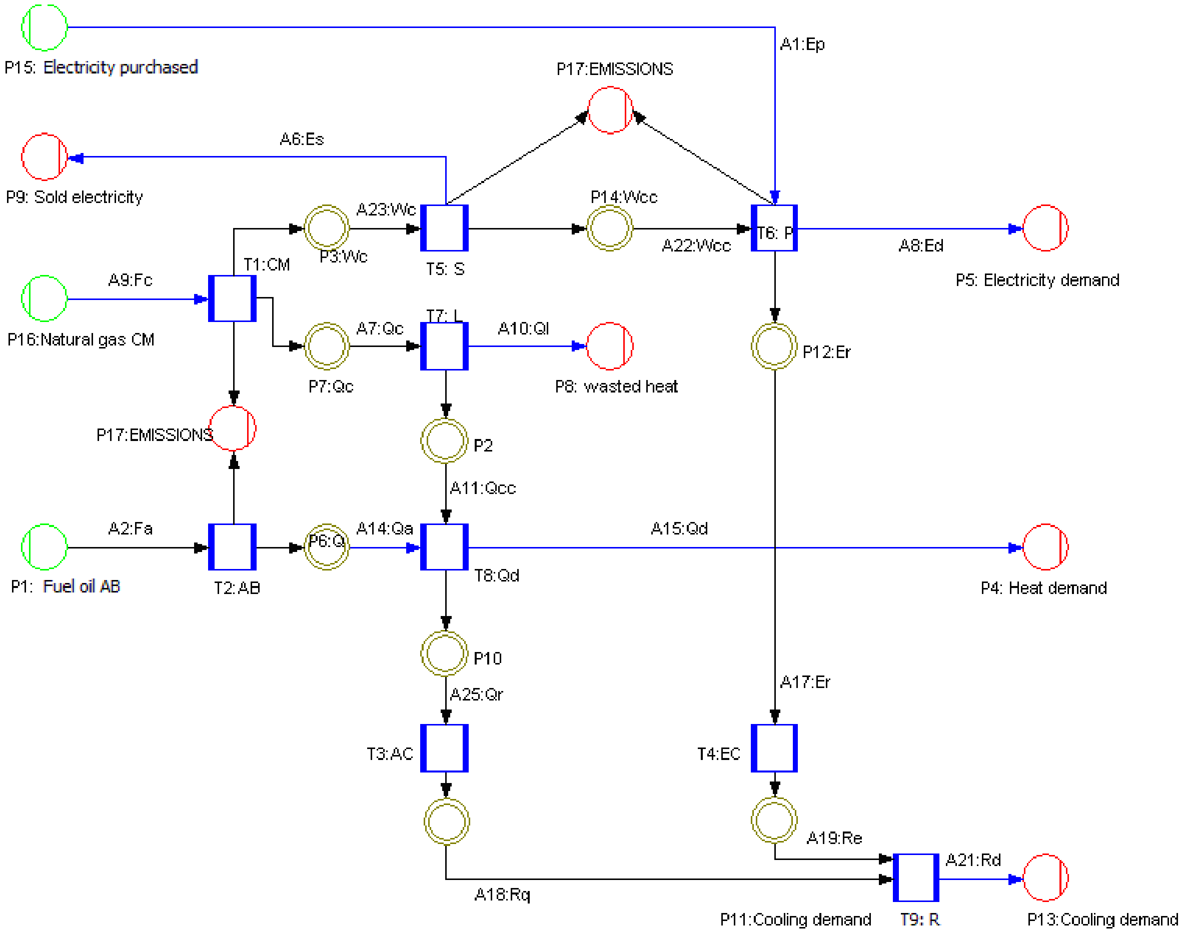

Figure 3.7 Umberto model of simple trigeneration system.

There are special types of places: input and output places representing the boundaries of the balance and acting as bridges to the environment, and connection places which can only distribute flows and not act as storages, *i.e.*, their inventories are always zero or constant.

According to the MFN formalism, places and transitions always alternate in the network. Thus a transition can never be directly linked to another transition; a place has to be interposed. If no storage occurs between two processes, the transitions can be linked by a connection place, represented by two concentrical circles.

The inputs of the simple trigeneration system (Figure 3.7, green circles) were the consumption of fuel by the cogeneration module (F_c) and auxiliary boiler (F_a), and the electricity purchased from the grid (E_p).

The outputs of the system (red circles in Figure 3.7) were the demands of electricity (E_d), heat (Q_d), and cooling (R_d). Freedom was available to the consumer to decide how the system operated, to minimize costs or environmental impacts; wasted heat permitted the operation of the cogeneration module to match the demand of the consumer center and the sale of surplus autogenerated electricity permitted to realize profit. Therefore two more outputs of the system were waste heat (Q_l) and the autogenerated electricity sold to the grid (E_s).

The output place *Emissions* accounted for the environmental loads originating from the consumption of natural gas in CM, fuel oil in AB, and from the purchase/sale of electricity from/to the grid. The two emissions outputs seen in Figure 3.7 are duplicate places. If an arrow leads to a place far away, the graphical display might become incomprehensible. Therefore the emissions place was duplicated and the copy was positioned in the vicinity of transition P. All emissions go into the atmosphere, but Umberto software tracks the contribution of each transition to account for its share of emissions.

Each piece of equipment was modeled as a transition (blue rectangles in Figure 3.7). A slightly more complex but more flexible method to specify transitions was applied, utilizing expressions to describe the relationships between input and output flows of a transition, making it possible to model non-linear transitions. To guarantee that the network could be calculated in both directions, the user-defined functions also considered the inverse form. Table 2.1 showed the technical parameters of the equipments, which established the relationship between inputs and outputs of each transition.

Branching and merging points S (Sale), L (Waste heat), P (Purchase), Q (Heat node), and R (Refrigeration node) were also modeled as transitions. Branching and merging points can be interpreted as decision points, in which possibilities are reflected. Point S refers to the possibility of selling autogenerated electricity to the grid; point L refers to the possibility of wasting part of the cogenerated heat; point P refers to the possibility of purchasing electricity from the grid; point Q refers to the possibility of operating the auxiliary boiler, and point R adds the contributions of the chillers to satisfy the refrigeration demand.

3.4.3 Umberto assistant

The objective of building an assistant was to transfer the philosophy/methodology utilized in energy cost analysis (thermoeconomics) to the evaluation of environmental loads. According to Gaggioli (1983), the objective of thermoeconomics is to explain the cost formation process of internal flows and products of energy systems. The costs obtained with thermoeconomics can be used to diagnose the operation and to control the production of existing plants, and in addition, improve the processes and synthesis of new systems.

Chapter II emphasized the importance of selecting appropriate cost assessment criteria for a trigeneration system operating in different modes. These cost assessment criteria were dependent on the physical structure of the system itself and on its different operation modes. The latter were, in turn, dependent on the environment and market conditions.

Costs can be understood as the amount spent (according to the consumption of resources) in order to obtain a flow (or commodity). However, the concept of cost can involve different magnitudes, as for example, environmental loads. Environmental costs can be understood as a category of cost (according to the generation of environmental loads in order to obtain a flow).

For the implementation of the environmental allocation method based on thermoeconomics, an assistant was created in Umberto software. The assistant performed calculations of environmental loads of internal flows and products after network calculation.

The new functions and extensions were implemented within the menu structure, utilizing structural language XML with code/logic J#. The assistant was an application that collected data of the calculated flows to carry out cost accounting. The assistant was necessary because Umberto calculates flows and costs simultaneously, and the implementation of thermoeconomic equations required the flows to be previously calculated.

The assistant contained initially equations (2.27-2.37 and 2.39 or 2.40, depending on operation mode) and was validated with economic costs (correctly reproducing thermoeconomic cost results published in Lozano *et al*., 2009a and previously exposed in Chapter II, Section 2.6.1, Table 2.11). By changing ‘market prices’ to ‘environmental loads’, the assistant turned to an environmental perspective, giving the assistant flexibility to support calculations regarding environmental loads or economic costs. The assistant model can be found in the CD that accompanies this thesis.

Balances were formulated and external resources used in the production process were valued by the environmental burden caused. Balance equations (2.27) – (2.35) were changed to:

CM: $EM_{fc} \cdot F_c = EM_{wc} \cdot W_c + EM_{qc} \cdot Q_c$ (3.6)

AB: $EM_{fa} \cdot F_a = EM_{qa} \cdot Q_a$ (3.7)

AC: $EM_{qr} \cdot Q_r = EM_{rq} \cdot R_q$ (3.8)

EC: $EM_{er} \cdot E_r = EM_{re} \cdot R_e$ (3.9)

S: $EM_{wc} \cdot W_c = EM_{wcc} \cdot W_{cc} + EM_{es} \cdot E_s$ (3.10)

P: $EM_{wcc} \cdot W_{cc} + EM_{ep} \cdot E_p = EM_{er} \cdot E_r + EM_{ed} \cdot E_d$ (3.11)

L: $EM_{qc} \cdot Q_c + EM_{ql} \cdot Q_l = EM_{qcc} \cdot Q_{cc}$ (3.12)

R: $EM_{rq} \cdot R_q + EM_{re} \cdot R_e = EM_{rd} \cdot R_d$ (3.13)

Q: $EM_{qcc} \cdot Q_{cc} + EM_{qa} \cdot Q_a = EM_{qr} \cdot Q_r + EM_{qd} \cdot Q_d$ (3.14)

Considering that the operation state of the plant was known, then all energy flows, environmental loads for fuel and electricity and the environmental load entailing waste heat are also known. Here it was considered that $EM_{ql} = 0$ because the objective was to assess all environmental loads to useful final products. Consequently, there are 12 unit environmental loads of internal flows and final products to be calculated: EM_{wc}, EM_{wcc}, EM_{er}, EM_{ed}, EM_{qc}, EM_{qcc}, EM_{qa}, EM_{qr}, EM_{qd}, EM_{rq}, EM_{re}, and EM_{rd}. As the system is described using nine equations with 12 unknowns, three auxiliary equations are again needed. It was considered that the unit environmental load of several flows obtained from a homogeneous flow is the same. Applying this rule to branching points **P** and **Q,** two more auxiliary equations were obtained:

P: $EM_{er} = EM_{ed}$ (3.15)

Q: $EM_{qr} = EM_{qd}$ (3.16)

The third auxiliary equation must define how the environmental loads generated in the cogeneration module be attributed to its products: heat and work. Allocation itself only makes sense when the resulting energy products are used to obtain different market products. If all of them were used in a process yielding a single product, allocation would not be necessary, since this product would finally have associated all the environmental burdens of the system's life cycle.

3.4.4 Simple allocation methods

Different allocation methods of environmental loads to electricity and heat products (third auxiliary equation for the analyzed system) are found in literature.

However, the main issue found during the utilization of such simple methods focuses on the immediate products of the cogeneration module, Q_c and W_c (Figure 3.8), not accounting for possible different destinations or uses of Q_c and W_c.

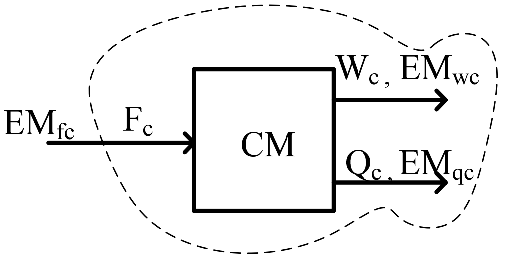

Figure 3.8 Control volume of simple allocation methods.

With this simple control volume, Equation (3.8) will distribute $EM_{fc} \cdot F_c$ between $EM_{wc} \cdot W_c$ and $EM_{qc} \cdot Q_c$. Such an approach is valid to assess costs to the immediate products of the cogeneration module only. However, when considering the possibility that part of the electrical power is sold to the electrical network, it is necessary to separate loads corresponding to different flows (González *et al.*, 2003).

Therefore when considering different equipment, activities, and options included in the trigeneration system, the assignment of unit costs should rather consider the products of the cogeneration module that are consumed (W_{cc} and Q_{cc}). In this way, adding Equations (3.6), (3.10) and (3.12) yields that $EM_{fc} \cdot F_c - EM_{es} \cdot E_s + EM_{ql} \cdot Q_l$ will be distributed between $EM_{wcc} \cdot W_{cc}$ and $EM_{qcc} \cdot Q_{cc}$, accounting for interactions of the system with the environment, through possible sale of electricity ($EM_{es} \cdot E_s$) and waste heat ($EM_{ql} \cdot Q_l$) (Figure 3.9).

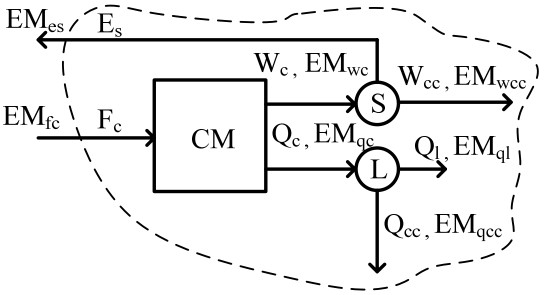

Figure 3.9 Control volume of simple allocation methods, accounting for the interaction of the cogeneration module with the environment.

Therefore a few simple allocation methods (Phylipsen *et al.*, 1998), which considered initially W_c and Q_c were taken to a higher level, by considering W_{cc} and Q_{cc}:

A Allocation based on energy. The fractions of the environmental loads allocated to electrical and heat productions are assessed in proportion to the energy content of the cogenerated work and heat:

$$\frac{EM_{qcc}}{EM_{wcc}} = 1 \tag{3.17a}$$

B Allocation based on exergy. The fractions of the environmental loads allocated to electrical and heat productions are assessed in proportion to the exergy content of the cogenerated work and heat:

$$\frac{EM_{qcc}}{EM_{wcc}} = \theta_{qc} \tag{3.17b}$$

θ_{qc} is the Carnot factor $(1 - T_0/T_c)$ corresponding to the cogenerated heat. Operating conditions were considered to be $T_0 = 25ºC$ and $T_c = 100ºC$, therefore obtaining $\theta_{qc} \approx 0.20$.

C Fuel Chargeable to Power. Many consultants in the cogeneration area utilize this *Fuel Chargeable to Power* method (Rosen, 2008), in which it is considered that the heat is produced in a conventional manner and the remainder of the fuel is allocated to the electricity produced by the cogeneration module. $EM_{qcc} = EM_{qa} = EM_{fa} / \eta_q$, which yields:

$$\frac{EM_{qcc}}{EM_{wc}} = \frac{W_c}{\eta_q F_c \left(\frac{EM_{fc}}{EM_{fa}} \right) - Q_{cc}} \tag{3.17c}$$

where η_q is the thermal efficiency of the auxiliary boiler ($\eta_q = 0.80$).

D Allocation based on separate production. This method allocates environmental loads to electricity and heat in proportion to their separate production whilst acknowledging the operation mode, in coherency with was proposed in (Carvalho *et al.*, 2010a). The economic minimization considered market prices and this environmental minimization will consider the environmental loads.

C₁ and C₃:

$$\frac{EM_{qcc}}{EM_{wcc}} = \frac{EM_{qa}}{EM_{ep}} \tag{3.18}$$

C₇ and C₉:

$$\frac{EM_{qcc}}{EM_{wcc}} = \frac{EM_{qa}}{EM_{es}} \tag{3.19}$$

EM_{ep} being the environmental loads corresponding to electricity purchased from the Spanish electricity mix, and EM_{qa} the environmental loads associated with the heat produced in the auxiliary boiler. Equation (3.18) can be applied directly to all operation examples, as it was previously established that EM_{ep}=EM_{es}.

Tables 3.12 and 3.13 show the unit environmental loads allocated to the internal flows and final products for the four most common allocation methods found in literature.

Table 3.12 CO_2 emissions (kg CO_2/kWh) for methods A and B considering EM_{ep}= 1.020 kg CO_2/kWh.

	Method A				Method B			
	$ExECC_1$	**$ExECC_3$**	**$ExECC_7$**	**$ExECC_9$**	**$ExECC_1$**	**$ExECC_3$**	**$ExECC_7$**	**$ExECC_9$**
EM_{ed}	0.5087	0.5177	0.2248	0.2587	0.7187	0.7195	0.4647	0.4722
EM_{qd}	0.3696	0.4459	0.2770	0.2587	0.2220	0.1353	0.1890	0.0944
EM_{rd}	0.2854	0.7134	0.0450	0.4139	0.2231	0.2165	0.0929	0.1511
EM_{es}	-----	-----	1.0200	1.0200	-----	-----	1.0200	1.0200
EM_{wc}	0.3627	0.4459	0.5202	0.5850	0.6326	0.6766	0.6709	0.7070
EM_{qc}	0.3627	0.2898	0.2248	0.1682	0.1265	0.0880	0.0929	0.0614
EM_{wcc}	0.3627	0.4459	0.2248	0.2587	0.6326	0.6766	0.4647	0.4722
EM_{er}	0.5087	-----	0.2248	-----	0.7187	-----	0.4647	-----
EM_{qcc}	0.3627	0.4459	0.2248	0.2587	0.1265	0.1353	0.0929	0.0944
EM_{qa}	0.3813	-----	0.3813	-----	0.3813	-----	0.3813	-----
EM_{qr}	0.3696	0.4459	-----	0.2587	0.2220	0.1353	-----	0.0944
EM_{rq}	0.5914	0.7134	-----	0.4139	0.3553	0.2165	-----	0.1511
EM_{re}	0.1017	-----	0.0450	-----	0.1437	-----	0.0929	-----

Table 3.13 CO_2 emissions (kg CO_2/kWh) for methods C and D considering EM_{ep}= 1.020 kg CO_2/kWh.

	Method C				Method D			
	$ExECC_1$	**$ExECC_3$**	**$ExECC_7$**	**$ExECC_9$**	**$ExECC_1$**	**$ExECC_3$**	**$ExECC_7$**	**$ExECC_9$**
EM_{ed}	0.4922	0.5597	-0.0595	0.0994	0.6502	0.6597	0.3773	0.4004
EM_{qd}	0.3812	0.3812	0.3812	0.3812	0.2702	0.2273	0.2211	0.1497
EM_{rd}	0.2903	0.6100	-0.0119	0.6100	0.2434	0.3638	0.0755	0.2395
EM_{es}	-----	-----	1.0200	1.0200	-----	-----	1.0200	1.0200
EM_{wc}	0.3414	0.4939	0.3414	0.4939	0.5445	0.6083	0.6160	0.6660
EM_{qc}	0.3812	0.2478	0.3812	0.2478	0.2035	0.1478	0.1410	0.0973
EM_{wcc}	0.3414	0.4939	-0.0595	0.0994	0.5445	0.6083	0.3773	0.4004
EM_{er}	0.4922	-----	-0.0595	-----	0.6502	-----	0.3773	-----
EM_{qcc}	0.3812	0.3812	0.3812	0.3812	0.2035	0.2273	0.1410	0.1497
EM_{qa}	0.3813	-----	0.3813	-----	0.3813	-----	0.3813	-----
EM_{qr}	0.3812	0.3812	-----	0.3812	0.2702	0.2273	-----	0.1497
EM_{rq}	0.6100	0.6100	-----	0.6900	0.4323	0.3638	-----	0.2395
EM_{re}	0.0984	-----	-0.0119	-----	0.1300	-----	0.0755	-----

From an environmental viewpoint, the purpose of installing a trigeneration system is to provide environmentally friendlier energy services. It can be seen that the unit CO_2 emissions of EM_{ed} are always lower than the environmental loads of purchased (or sold) electricity – EM_{ep}=EM_{es}=1.020 kg CO_2/kWh. EM_{qd} are not always lower than the emissions of heat produced by the auxiliary boiler, EM_{qa}=0.381 kg CO_2/kWh (see Q_d values for method A). And finally, all methods fail in that EM_{rd} values are not lower than the emissions of cooling produced by the mechanical chiller ($EM_{mec} = EM_{ep} / COP_e = 1.020/5 = 0.204$ kg CO_2/kWh).

The waste of heat is not correctly reflected in the unit emissions of Q_d, when comparing $ExECC_1$ and $ExECC_3$ in method A and C. The waste of heat should lower the emissions of heat and cooling via absorption chiller, promoting its consumption and therefore reducing its amount. In $ExECC_1$ and $ExECC_3$, the values of EM_{qd} and EM_{rd} increase when the correct indication would be to reduce. Method C is insensitive to the waste of heat in $ExECC_3$, as the values of EM_{qd} remain the same as those of $ExECC_1$. Method C also provides negative values for $ExECC_7$.

Allocation based on energy does not take energy quality and its real value into account, and for this reason the same environmental loads per energy unit are assigned to power and thermal energy. When the exergy criterion is applied, the indicator value associated with electrical power is multiplied by five compared to the energy criterion. In the allocation of emissions based on incremental fuel consumption in terms of energy calculation, thermal efficiency of heat production in the cogeneration process is the same as that in a separate process. The results found by using the Fuel Charge to Power method are strongly dependent on the thermal efficiency of the auxiliary boiler, and this method is unfair in terms of distribution of emissions.

The allocation method can influence whether the consumer will consume products of the trigeneration system, and the choice of one method over another will depend on the objective of the study. Methods A - C can, to various degrees, produce final emissions that would lead consumers of heat or electricity to wrongly to believe that they were consuming lower carbon supplies than from non-CHP alternatives or vice versa. After studying nine methods to allocate emissions to heat and electricity, Pout & Hitchin (2005) recommended that the method adopted should be to set the cogeneration carbon intensities to be proportional to those of the alternative supplies (general principle of Method D). This also dealt satisfactorily with comparisons with renewable alternatives but is not independent of the context, that is, the alternative sources of heat or electricity. The principle supporting Method D will be expanded to include the alternate production of cooling.

3.4.5 Proposal of allocation method - method E

The allocation of energy and other environmental interventions is a key issue. Many companies, government agencies, and researchers have struggled with the question of how to allocate emissions and environmental impacts for a system that has multiple products and multiple inputs (Huppes & Schneider, 1994; Rosen, 2008).

Considering the scenario in which the consumers of the energy services are the owners of the trigeneration system, all operation emissions should be allocated to the consumers of the energy services who are benefitting from a more efficient production. Moreover, the reductions in emissions should be shared in an equitable form among all consumers (owners). Furthermore, a fair apportionment of the emissions among the energy services produced is required, with respect to the conventional energy supply system in which electricity is purchased from the grid, heat is produced in an auxiliary boiler, and cooling is produced in a mechanical chiller.

In order to gain insight on the production of cooling, distribution of heat produced in the cogeneration module and auxiliary boiler should be explained. The heat produced in the auxiliary boiler (Q_a) and the cogeneration module (Q_{cc}) can be used for covering the heat demand of the consumer center (Q_d) and/or the heat required for driving the absorption chiller (Q_r). The simple trigeneration system scheme is re-organized to allow the tracking of heat produced by the cogeneration module and auxiliary boiler (Figure 3.10).

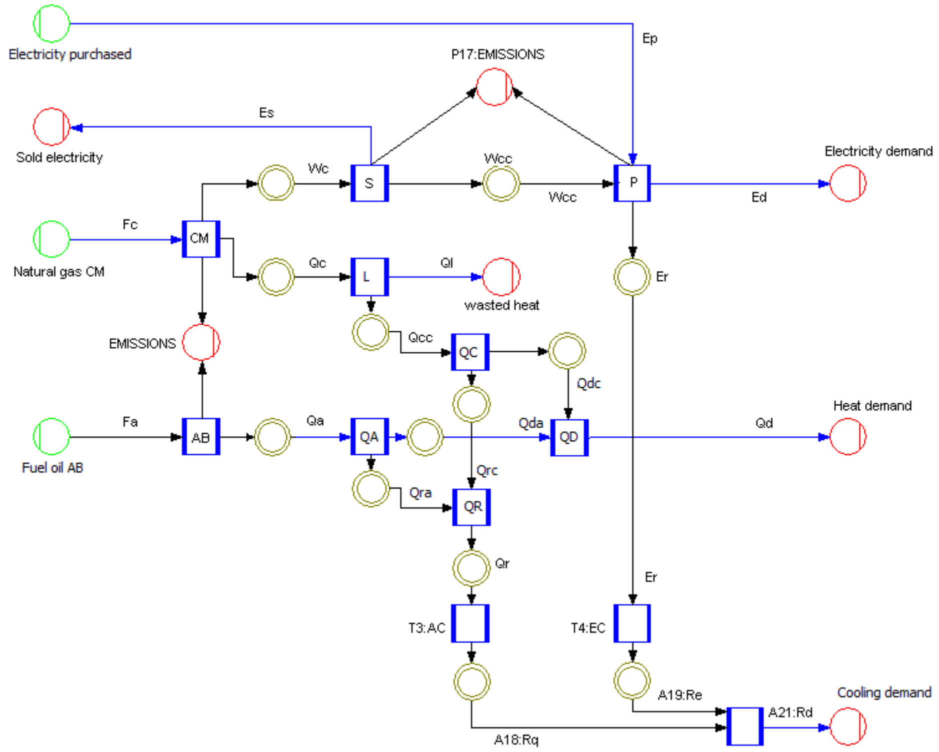

Figure 3.10 Re-organization of simple trigeneration system.

There is no priority or technical limitation in this respect as the cogeneration module is able to independently provide, when required, heat to the consumer center or the absorption chiller, which similarly occurs with the auxiliary boiler. Furthermore, the heat produced is proportionally distributed to the consumer center and the absorption chiller according to the total heat demanded by them. The distribution of heat produced in the cogeneration module to the consumer center and/or the absorption chiller was expressed mathematically through the definition of parameter B in Chapter II:

$$B = \frac{Q_d}{Q_d + Q_r} \tag{3.20}$$

Heat produced in the cogeneration module is distributed as follows:

$$Q_{dc} = B \cdot Q_{cc} \tag{3.21}$$

$$Q_{rc} = (1 - B) \cdot Q_{cc} \tag{3.22}$$

And the heat produced in the auxiliary boiler is distributed as follows:

$$Q_{da} = B \cdot Q_a \tag{3.23}$$

$$Q_{ra} = (1 - B) \cdot Q_a \tag{3.24}$$

Table 3.14 shows the additional energy flows for the re-organized trigeneration system.

Table 3.14 Additional energy flows for the re-organized trigeneration system.

		ExECC$_1$	**ExECC$_3$**	**ExECC$_7$**	**ExECC$_9$**
Q_d	kW	400	100	600	100
Q_r	kW	240	160	0	160
B		0.6250	0.3846	1	0.3846
Q_{cc}	kW	400	260	400	260
Q_{dc}	kW	250	100	400	100
Q_{rc}	kW	150	160	0	160
Q_a	kW	240	0	200	0
Q_{da}	kW	150	0	200	0
Q_{ra}	kW	90	0	0	0

This new productive structure yields the following equation system, constituted of Equations (3.3) – (3.13) plus the following equations:

QA: $EM_{qa} \cdot Q_a = EM_{qda} \cdot Q_{da} + EM_{qra} \cdot Q_{ra}$ (3.25)

QC: $EM_{qcc} \cdot Q_{cc} = EM_{qdc} \cdot Q_{dc} + EM_{qrc} \cdot Q_{rc}$ (3.26)

QR: $EM_{qrc} \cdot Q_{rc} + EM_{qra} \cdot Q_{ra} = EM_{qr} \cdot Q_r$ (3.27)

QD: $EM_{qdc} \cdot Q_{dc} + EM_{qda} \cdot Q_{da} = EM_{qd} \cdot Q_d$ (3.28)

There are now 16 unit environmental loads of internal flows and final products to be calculated: EM_{wc}, EM_{wcc}, EM_{er}, EM_{ed}, EM_{qc}, EM_{qcc}, EM_{qa}, EM_{qr}, EM_{qd}, EM_{rq}, EM_{re}, EM_{rd}, EM_{qdc}, EM_{qrc},

EM_{qda} and EM_{qra}. The system is described using 12 equations with 16 unknowns, and therefore 4 auxiliary equations are needed.

Considering that the environmental load of several flows of the final products or internally consumed obtained from a homogeneous flow is the same, and applying this rule to branching points **P** and **QA,** two auxiliary equations were obtained:

P: $c_{er} = c_{ed}$ (3.29)

QA: $c_{qda} = c_{qra}$ (3.30)

Note that this consideration is not suitable in the case of cogenerated heat, in which a *reduction in emissions* should be applied to the cogenerated heat covering the heating demand and to the cogenerated heat covering the cooling demand via absorption chiller. In branching point QA, the heat produced in the auxiliary boiler is distributed, which is produced at the same environmental load than conventional heat and therefore there is no *reduction*. Branching points S and L present specific features in which the environmental loads of some output flows are known and additional auxiliary equations are not required. In S the system is interacting with the economic environment and E_s is the sold electricity, the cost of which is set by its market price. In L, Q_l is the waste heat which is not consumed and no cost should be assessed.

The last two auxiliary equations must consider that production emissions are distributed among the consumers of the final products and all of them receive the same *reduction* derived from the combined production in proportion to the emissions of obtaining the energy services separately by conventional systems. The heat used for covering the heat demand, Q_{dc}, is receiving a *reduction* with respect to the production of heat in a conventional boiler, and the heat used for cooling, Q_{rc}, is receiving a *reduction* with respect to the conventional production of cooling via mechanical chiller. For all operation modes the discount d is:

$$1 - d = \frac{EM_{wcc}}{EM_{ep}} = \frac{EM_{qdc}}{EM_{qa}} = \frac{\dfrac{EM_{qrc}}{COP_q}}{\dfrac{EM_{ep}}{COP_e}} \tag{3.31}$$

Which yields two equations:

$$\frac{EM_{wcc}}{EM_{ep}} = \frac{EM_{qdc}}{EM_{qa}} \tag{3.32a}$$

$$\frac{EM_{wcc}}{EM_{ep}} = \frac{\dfrac{EM_{qrc}}{COP_q}}{\dfrac{EM_{ep}}{COP_e}} \tag{3.32b}$$

Please note that the same auxiliary equations are utilized for all operation modes, as there is no distinction between EM_{ep} and EM_{es}. Table 3.15 shows the unit emissions of internal flows and final products obtained applying the assessment criteria proposed by Equation (3.32) for the four different examples (EM_{fc} = 0.272 kg CO_2/kWh, EM_{fa} = 0.305 kg CO_2/kWh, and EM_{ep} = 1.020 kg CO_2/kWh).

Analysis of Table 3.15 shows that the unit emissions of the final products are lower than those of conventional/separate production. EM_{ed} is lower than the emissions of electricity (EM_{ep} = EM_{es} = 1.020 kg CO_2/kWh), EM_{qd} is lower than the emissions associated with heat produced in the auxiliary boiler (EM_{qa} = 0.381) and EM_{rd} is lower than the emissions of cooling produced in a mechanical chiller (EM_{ep}/COP_e = 1.020/5 = 0.204 kg CO_2/kWh). The proposed assessment rule defined by Equations (3.32) provides emission values consistent with the objective of sharing the benefits (reduction in emissions) in an equitable form among all consumers.

In the examples analyzed, the cogeneration module is operating at full load. As a consequence, the marginal emissions of the electricity produced reflect the cost of covering the increased demand with the electricity purchased (operation modes C_1 and C_3) or sold (operation modes C_7 and C_9). In the case of heat there are two situations: a) operation modes C_1 and C_7, in which the heat demand is higher than the maximum production of the cogeneration module operating at full load, and as a consequence the marginal emissions of heat corresponds to the emissions of producing heat in the auxiliary boiler; b) operation modes C_3 and C_9, in which heat waste occurs, and the corresponding marginal emission is zero.

Table 3.15 Unit CO_2 emissions (kg CO_2/kWh) for method E in the re-organized trigeneration system with EM_{ep}= 1.020 kg CO_2/kWh.

		$ExECC_1$	$ExECC_3$	$ExECC_7$	$ExECC_9$
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
λC_{ed}	kg CO_2/kWh	1.0200	1.0200	1.0200	1.0200
λC_{qd}	kg CO_2/kWh	0.3810	0	0.3810	0
λC_{rd}	kg CO_2/kWh	0.6100	0	0.2040	0
EM_{ed}	kg CO_2/kWh	0.6844	0.7117	0.3773	0.4624
EM_{qd}	kg CO_2/kWh	0.2804	0.2496	0.2211	0.1728
EM_{rd}	kg CO_2/kWh	0.1989	0.1335	0.0755	0.0925
EM_{wc}	kg CO_2/kWh	0.5885	0.6677	0.6160	0.7013
EM_{qc}	kg CO_2/kWh	0.1651	0.0958	0.1410	0.0663
EM_{wcc}	kg CO_2/kWh	0.5885	0.6677	0.3773	0.4624
EM_{er}	kg CO_2/kWh	0.6844	-----	0.3773	-----
EM_{qcc}	kg CO_2/kWh	0.1651	0.1473	0.1410	0.1020
EM_{qa}	kg CO_2/kWh	0.3813	-----	0.3813	-----
EM_{qr}	kg CO_2/kWh	0.1889	0.0835	-----	0.0578
EM_{rq}	kg CO_2/kWh	0.3023	0.1335	-----	0.0925
EM_{re}	kg CO_2/kWh	0.1369	-----	0.0755	-----
EM_{qdc}	kg CO_2/kWh	0.2200	0.2496	0.1410	0.1728
EM_{qrc}	kg CO_2/kWh	0.0736	0.0835	-----	0.0578
EM_{qda}	kg CO_2/kWh	0.3813	-----	0.3813	-----
EM_{qra}	kg CO_2/kWh	0.3813	-----	-----	-----
Discount d		0.4230	0.3454	0.6301	0.5467

Comparing the marginal emissions of the final products with the corresponding unit emissions of the final products (Table 3.15) it can be seen that the unit costs are always lower than marginal emissions, except when marginal emissions are nill. This is a consequence of the higher efficiency (with lower emissions associated) of energy production of the trigeneration system with respect to the conventional option of purchasing electricity from the grid, producing heat in an auxiliary boiler, and producing cooling in a mechanical chiller via purchased electricity. When some heat is wasted, the marginal cost of the demanded heat and cooling is zero (in operation modes C_3 and C_9 cooling is produced only by the absorption chiller). The unit emission of producing heat in the cogeneration module is not zero but is lower than the production of heat in the auxiliary boiler.

The previous information is quite relevant and indicates that, in the cases analyzed, unit emission values are consistent with the marginal cost values.

Comparison of unit emissions between examples $ExECC_1$ and $ExECC_3$ will give indications on what occurs when some heat is wasted. EM_{wc} and EM_{wcc} increase their value in $ExECC_3$, reflecting the inefficiency of wasting heat; however, EM_{qc} and EM_{qcc} lower their value to promote consumption of waste heat. Consequently, EM_{ed} has a higher value and EM_{qd} and EM_{rd} present lower values in $ExECC_3$.

The comparison between examples $ExECC_1$ and $ExECC_7$ gives indications on the behavior of the system when electricity is sold to the grid. EM_{wc} presents a higher value and EM_{wcc} presents a lower value. The sale of electricity with lower emissions (but evaluated as having higher emissions) consequently lowers the cost of EM_{wcc}. The benefits of the sale of electricity are positively reflected on the values of EM_{qc} and EM_{qcc}, and ultimately on the final emissions of E_d, Q_d and R_d, which are lower.

In $ExECC_9$, EM_{ed} increases reflecting the waste of heat, but with sale of electricity, EM_{ed} is still environmentally sounder than EM_{ep}. The sale of electricity benefits all final energy services, resulting in lower emission values when comparing $ExECC_3$ and $ExECC_9$. Internal flows too, are lower in $ExECC_9$. When comparing $ExECC_7$ and $ExECC_9$, it can be seen that EM_{ed} and EM_{rd} increase, reflecting the inefficiency of wasting heat. EM_{rd} increases in this case because production of cooling occurs via mechanical chiller. EM_{qc} and EM_{qcc} have lower values, resulting in a lower value for EM_{qd} which should promote consumption of otherwise wasted heat. EM_{wc} and EM_{wcc} have increased values which were translated into higher emissions for R_d and E_d. The benefits as well as the penalties of the system were reflected in all energy services produced in the cogeneration module.

The EMIS Umberto software efficiently supported data management, modeling of material flows, and proved to be a useful tool, allowing the tracking of environmental impacts associated with each output. Umberto software successfully answered the question on what emissions were caused by the current inventory strategy for the trigeneration system, while considering different approaches to the allocation issue.

The combination of Umberto with LCA databases and thermoeconomic analysis can provide the consumers with information on the environmental loads associated with the consumption of each energy service (electricity, heat, cooling).

3.5 CONCLUSIONS

Different allocation methods bring very different results, confirming the controversy as to what was the most appropriate allocation method and what was most logic in different situations. Research on allocation of emissions and environmental burden will allow the environmental benefits of properly designed and operated cogeneration technologies to be better understood and exploited (Rosen & Dincer, 2001; Abusoglu & Kanoglu, 2009).

Effective environmental related strategies connect the reduction of emissions with a system's operational strategy (consumption of resources). Therefore the usage of EMIS and LCA tools could be promoted to (1) analyze the distribution of material and energy resources throughout a productive system, (2) allow an emission-efficient economy to develop; (3) identify the most environmentally beneficial among competing technologies, and (4) serve the numerical registration and interpretation of environmental effects.

The allocation proposal for trigeneration systems considers that environmental loads of the cogeneration module are distributed among the consumers of the final products, who all receive the benefit of reduced emissions derived from the combined production. Such reductions are evaluated in proportion to the emissions associated with obtaining each energy service separately via conventional systems.

By incorporating environmental information on the usage and consumption of resources into Umberto software, the approach of MFN gave insight on the environmental loads associated with each flow of the system. Thus, the consumers of a productive system will know the environmental loads, as well as the economic cost, associated with the consumption of each product (either internal or final). This information can be very useful for the introduction of strategies oriented to changes and improvements in the design and operation of productive systems as well as in consumption patterns and resource conservation, contributing to the development of a more sustainable economy (IPCC, 2007).

CHAPTER IV

SYNTHESIS OF TRIGENERATION SYSTEMS - DATA -

Chapter IV establishes the scenario that will be utilized in the optimization models of Chapter V. The idea behind operating a trigeneration system is that a cogeneration module, jointly with an absorption chiller, satisfies the base thermal demand for the different services (heat and cooling), while conventional units (boiler and mechanical chiller) are utilized in an auxiliary way to make up for the demand peaks. Therefore, supply is guaranteed and the installation is reliable, since the existence of conventional equipment assures the satisfaction of the thermal demand (although sometimes partially). The residual heat flows that are not used must be evacuated to the environment through the use of cooling towers or other devices, which are therefore important elements of trigeneration plants.

The design of trigeneration systems for buildings should consider various factors: (1) different energy services demand profiles; (2) tariffs and energy prices; (3) investment costs and performance of different components; and (4) legal constraints on energy efficiency and environmental protection. Daily and seasonal variations of heating and cooling demands are factors that exert the most influence on the appropriate structure (number of boilers, cogeneration modules and cooling towers, type and number of refrigerators, thermal energy storage capacity, etc.) of the energy supply system. A structure can only be selected when consideration is given to the optimal operation of the system's different components on an hour-by-hour basis throughout the year. An analysis involves many feasible configurations with different operation modes, thus resulting in a complex and difficult problem.

The first aspect that will determine whether trigeneration is a valid option is the energy demand. It is necessary to verify that along with electricity demands, the building requires heat demands in winter and cooling demands in warmer weather (when heat demands decrease). Knowledge on energy demands will allow for establishment of a monthly, daily and hourly distribution profile of the demands, as well as the number of operating hours for the system.

The second aspect to account for is a global vision of the equipment that constitute trigeneration systems, at economic and environmental levels, also considering appropriate process integration in order to select appropriate equipment that will satisfy energy demands.

The third aspect is the availability of energy resources. Specifically, it is necessary to refer to the fuel that will be used to drive the system. The most common situation is that trigeneration systems incorporate natural gas engines (with complementary production by auxiliary boilers), and therefore it is necessary to confirm whether the geographic zone of the building counts with adequate pipelines for the provision of natural gas. It is also convenient to know the concrete situation of the electric grid. Although a trigeneration system can operate in an autonomous and independent manner (as an island), it may result beneficial to establish a link with the electric grid to sell surplus self-generated electricity and realize profits. In this case it is advisable to verify if the system is capable of maintaining an Equivalent Electrical Efficiency of at least 55% (for the example of natural gas engines), as the sale of electricity can only occur between the limits established by Spanish legislation.

Finally, it is also important to establish the economic and legal scenario in which the trigeneration system will be installed and operated. Therefore investment, installation and maintenance costs for each piece of equipment should be known as well as tariffs for the purchase of natural gas and purchase/sale of electricity. The issue of legal conditions should also be included into the synthesis model and the operation restrictions. In the case of Spain, the design of cogeneration plants is restricted by legal constraints on the Special Regime for electricity production.

In summary, Chapter IV establishes the framework that will be utilized in the optimization models of Chapter V, where trigeneration systems will be synthesized on the basis of different objective functions.

4.1 ENERGY DEMANDS

A systematic approach for the selection of an appropriate energy supply system requires a detailed knowledge of heat, cooling, and electricity loads (Noren & Pyrko, 1998; Basulto, 2006; Kalina, 2006; Pedersen, 2008). Special attention must be given as estimated energy demand patterns affect significantly the economic and energy saving characteristics of trigeneration systems.

Hospitals are good candidates for trigeneration systems because of their high energy requirements compared to other commercial buildings as well as their need for high power quality and reliability. Consequently, hospital environments have been frequently used as case studies in polygeneration literature (Ziher & Poredos, 2006; Arcuri *et al.*, 2007; Piacentino &

Cardona, 2008; Mavrotas, 2008; among others). The trigeneration system syntheses carried out in Chapter V consider a medium size hospital with 500 beds, located in Zaragoza (Spain). The energy demands considered were heat, cooling, and electricity. The heat load included heat for domestic hot water (DHW) and for heating. Steam demand could also have been considered, to attend laundry and sterilization necessities. However, the current trend is to eliminate such a service, subcontracting an external company, and for this reason steam demand was not considered in this investigation.

In order to establish the energy demands for the hospital, a study period of one year was considered, 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 Sánchez (2003), which estimated monthly, daily, and hourly profiles of the representative days based on the size of the hospital and its geographical location in Spain. Demand data for a hospital in Zaragoza are given on a daily basis in Table 4.1. Complete hourly demands for a hospital located in Zaragoza are given in Appendix II.

The annual electricity consumption of the hospital was E_d = 3250 MWh, the cooling demand was R_d = 1265 MWh, and the heat requirements (DHW + heating) were Q_d = 8059 MWh. Energy demand fluctuations with respect to the time of day are shown in Figures 4.1 and 4.2, respectively, for the days of maximum demands of heat (January, working day) and cooling (July, working day).

Table 4.1 Hospital energy demands

Day Type	Number of days/y	Heat demand		Cooling demand		Electricity demand	
		Total kWh/day	Mean kW	Total kWh/day	Mean kW	Total kWh/day	Mean kW
JAN W	20	**50,007**	**2084**	0	0	9411	392
JAN F	11	39,547	1648	0	0	7802	325
FEB W	20	42,365	1765	0	0	9411	392
FEB F	8	33,709	1405	0	0	7802	325
MAR W	18	32,814	1367	0	0	9411	392
MAR F	13	26,411	1100	0	0	7802	325
APR W	21	25,149	1048	0	0	9411	392
APR F	9	20,556	857	0	0	7802	325
MAY W	22	14,224	593	0	0	9411	392
MAY F	9	12,209	509	0	0	7802	325
JUN W	21	5319	222	4312	180	9411	392
JUN F	9	4873	203	3294	137	7802	325
JUL W	23	3429	143	**20,170**	**840**	9411	392
JUL F	8	3429	143	15,411	642	7802	325
AUG W	20	3429	143	18,235	760	9411	392
AUG F	11	3429	143	13,931	580	7802	325
SEP W	22	5658	236	1412	59	9411	392
SEP F	8	5132	214	1079	45	7802	325
OCT W	22	17,542	731	0	0	9411	392
OCT F	9	14,723	613	0	0	7802	325
NOV W	20	36,253	1511	0	0	9411	392
NOV F	10	29,039	1210	0	0	7802	325
DEC W	21	47,332	1972	0	0	9411	392
DEC F	10	37,504	1563	0	0	7802	325
		MWh/y	kW	MWh/y	kW	MWh/y	kW
Year	365	8059	920	1265	144	3250	371

W = Working day, F=Holiday/Weekend day

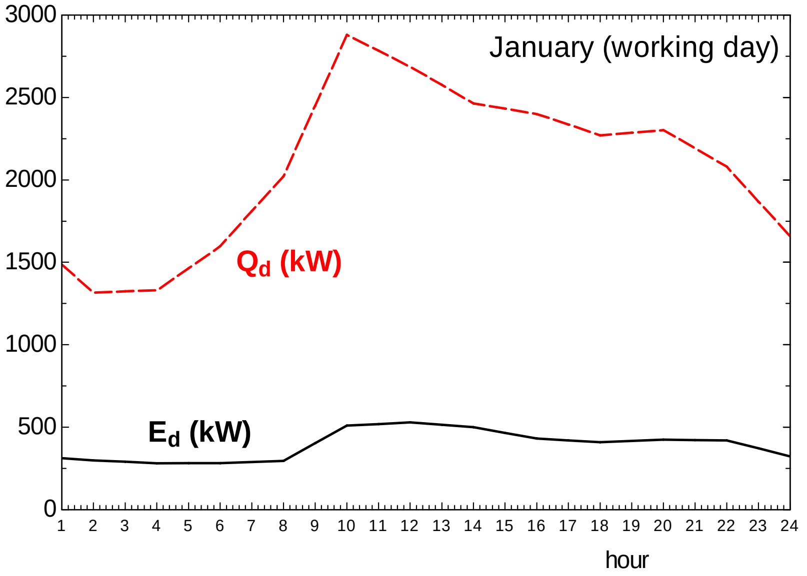

Figure 4.1 Hourly energy demand pattern for a representative working day in January (E_d = electricity demand, Q_d = heat demand).

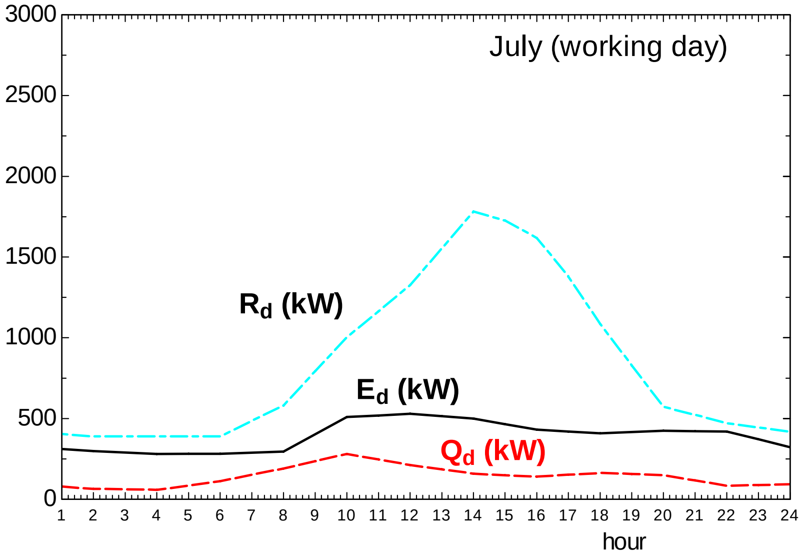

Figure 4.2 Hourly energy demand pattern for a representative working day in July (E_d = electricity demand, Q_d = heat demand, R_d = cooling demand).

4.2 SUPERSTRUCTURE OF THE SYSTEM

To solve the fundamental issue of synthesizing the configuration of a system, a reducible structure (known as superstructure) was created to embed all feasible process options and interconnections for the optimal design structure (Horii *et al.*, 1987; Iyer & Grossmann, 1998;

Bruno *et al*., 1998; Yokoyama *et al.*, 2002). Initially, redundant features were built into the superstructure to ensure that all features that could be part of an optimal solution were included. According to Smith (Smith, 2005), this approach has a number of advantages: (1) Many different design options can be considered at the same time; (2) The complex multiple trade-offs usually encountered in energy supply systems design can be handled; and (3) The entire design procedure can be automated and is capable of producing designs quickly and efficiently. Nevertheless, there are also a number of difficulties (Smith, 2005): (1) The approach will fail to find the optimal structure embedded somewhere within the superstructure (Therefore, the more options included, the more likely it will be that the optimal structure was included); (2) If the individual equipments are represented accurately, the resulting mathematical model will be extremely large and the optimization problem becomes more difficult to solve; and (3) The greatest drawback is that the design engineer is removed from the decision making. Thus, the many intangibles in design which are difficult to include in the mathematical formulation cannot be taken into account satisfactorily.

In summary, the superstructure must include all feasible process options and connections, based on appropriate process integration (Klemeš & Friedler, 2010). 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 Serra *et al.* (2009). Furthermore, Ryan (2004) 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 Teopa *et al.* (2005).

Selection of equipment took into account input/output utility flows based on appropriate energy process integration. The superstructure shown in Figure 4.3 is proposed considering heat and power sources (gas turbine, gas engine, steam boiler, hot water boiler, to among others). Also considered were the requirements - temperature, heat, power, and cooling - of (1) the energy services demanded by the consumer center; and (2) different pieces of equipment. Technical production coefficients of equipment were evaluated prior to the inclusion in the superstructure.

The superstructure of a trigeneration system that satisfies energetic demands of heat (DHW 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.

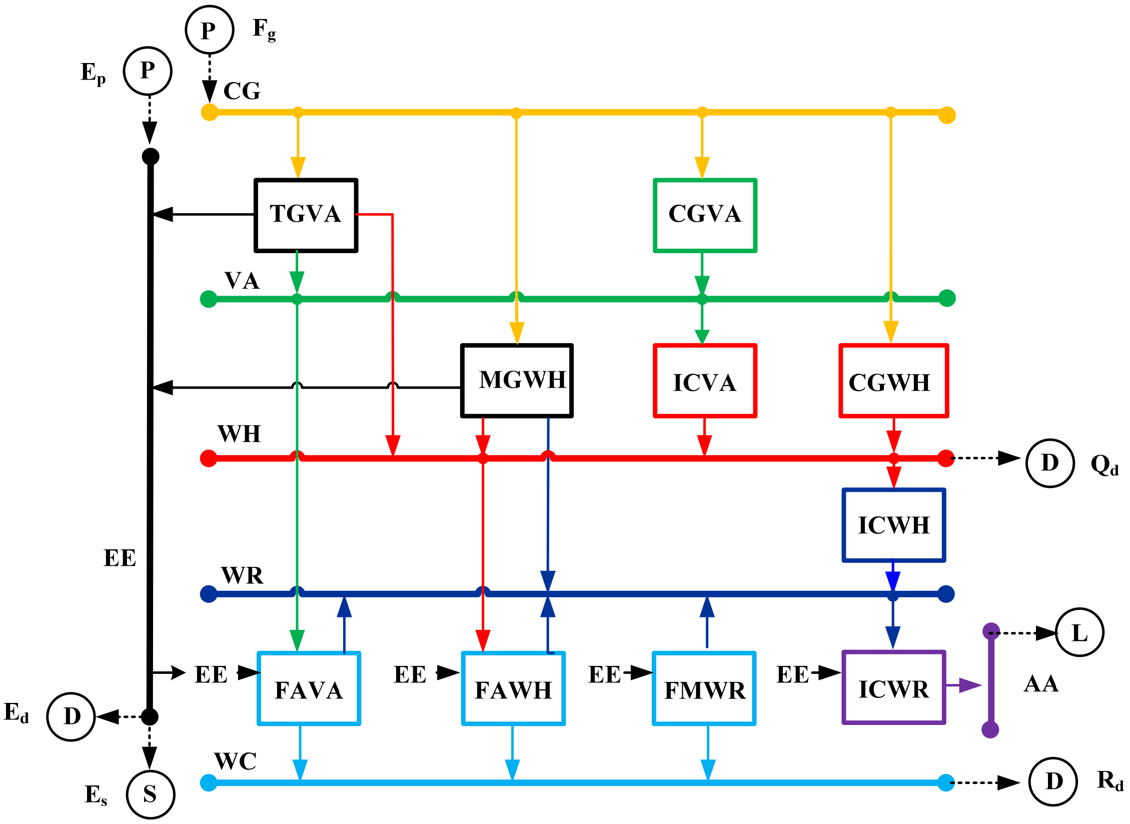

Figure 4.3 Superstructure of the energy supply system.

The available utilities were CG (natural gas), VA (high temperature steam, 180ºC), WH (hot water, 90ºC), WR (cooling water, t_0 + 5ºC), AA (ambient air, t_0), WC (chilled water, 5ºC), and EE (electricity). D, S, P and L refer to, respectively, demand, sale, purchase and waste/loss of a utility. E_d, Q_d and R_d are the demands of electricity, heat, and cooling, respectively. F_g refers to the consumption of natural gas, while E_p and E_s refer to electricity purchased from the grid and self-generated electricity sold to the grid, respectively.

4.3 EQUIPMENT

The types of selected technologies will optimally fit together and the size or nominal power of the equipment must be proportionate to energy demands. 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.

4.3.1 Technical data

4.3.1.1 TGVA, Gas turbine cogeneration module

Turbine Saturn 20 was selected, from Solar Turbines (Caterpillar Company). The most important parameters are:

Power output: 1.210 MW
Fuel input: 4.916 MW
Exhaust mass flow: 6.5 kg/s
Exhaust temperature: 511 ºC

Figure 4.4 shows a picture from the equipment catalog (left) and the energy flows for the turbine (right). The main flow was considered to be electricity (coefficient 1). To produce 1 MW of electricity (EE), 4.06 MW of natural gas (CG) will be consumed, producing also 1.83 MW of steam (VA) and recovering 0.53 MW of hot water (WH).

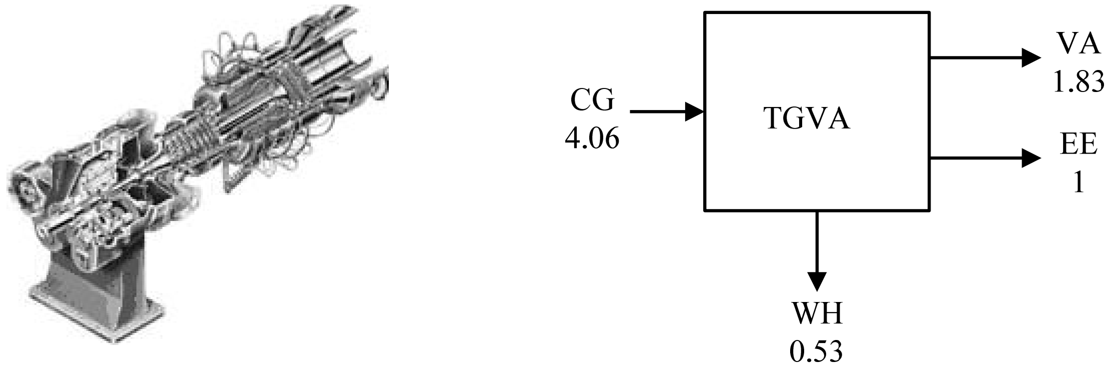

Figure 4.4 Gas turbine (left) and its technical production coefficients (right).

4.3.1.2 CGVA, Steam boiler

Vitomax 200 HS model M237 was selected and its important technical parameters are:

Useful thermal power: 0.750 MW
Steam production: 1150 kg/h
Design pressure: 11 bar
Inlet water temperature: 102 ºC

Figure 4.5 shows a picture from the equipment catalog (left) and the energy flows for the boiler (right). The main flow was considered to be steam (coefficient 1). To produce 1 MW of steam (VA), there will be a consumption of 1.25 MW of natural gas (CG).

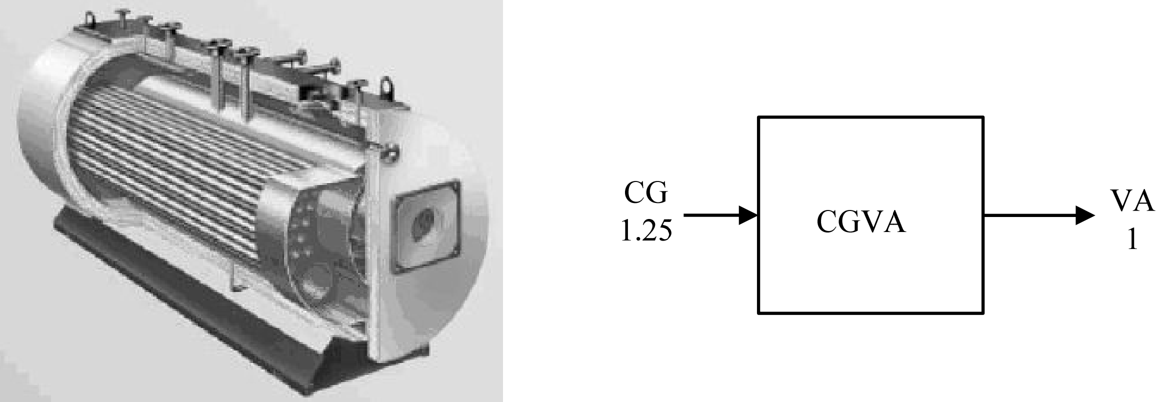

Figure 4.5 Steam boiler (left) and its technical production coefficients (right).

4.3.1.3 MGWH, Gas engine cogeneration module

Engine TCG 2016 V12 from Deutz was selected and the most important parameters are:

Electrical power: 0.580 MW
Fuel consumption: 1.422 MW
Exhaust mass flow wet: 3239 kg/h
Exhaust temperature: 467ºC
Exhaust cooled to 120°C : 0,348 MW
Jacket water heat: 0,208 MW
Intercooler LT heat: 0,118 MW

Figure 4.6 shows a picture from the equipment catalog (left) and the energy flows for the gas engine (right); 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%).

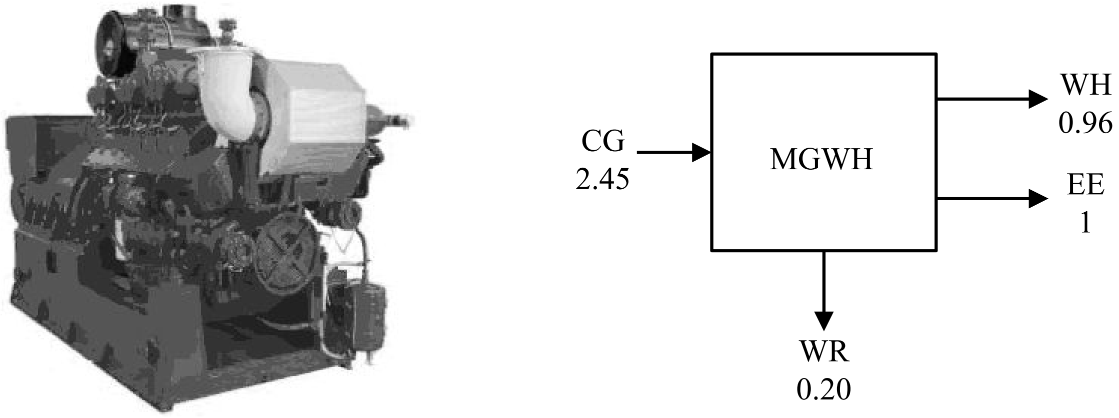

Figure 4.6 Gas engine (left) and its technical production coefficients (right).

4.3.1.4 CGWH, Hot water boiler

The hot water boiler selected was Thermital THE-Q model 575. The most important parameter was:

Useful thermal power: 0.532 MW

Figure 4.7 shows a picture from the equipment catalog (left) and the energy flows for the hot water boiler (right). Considering that the main flow is hot water (coefficient 1), in the production of 1 MW of hot water (WH), 1.08 MW of natural gas (CG) will be consumed.

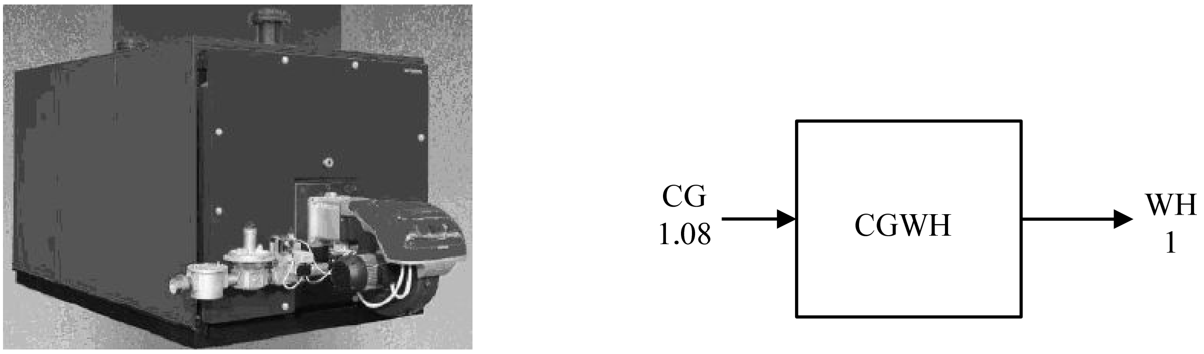

Figure 4.7 Hot water boiler (left) and its technical production coefficients (right).

4.3.1.5 ICVA, Steam-hot water heat exchanger

Equipment SEDICAL SB-3E/50 was selected and its most important parameter was:

Useful thermal power: 0.400 MW

Figure 4.8 shows a picture from the equipment catalog (left) and the energy flows for the heat exchanger (right). The main flow was considered to be hot water. To produce 1 MW of hot water (WH), 1 MW of steam (VA) is consumed.

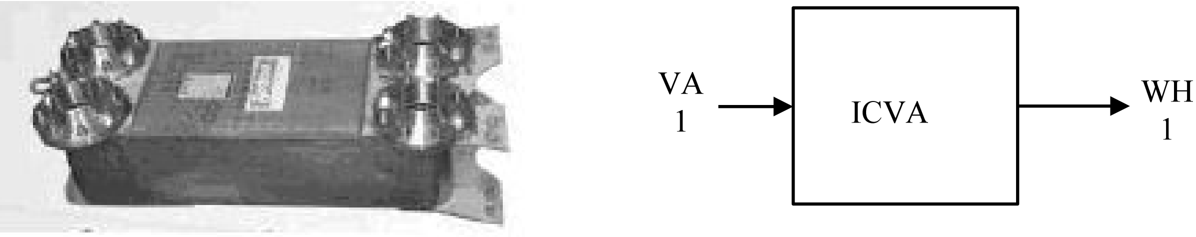

Figure 4.8 Steam-hot water heat exchanger (left) and its technical production coefficients (right).

4.3.1.6 ICWH, Hot water-cooling water heat exchanger

Equipment SEDICAL UFX-12/35 was selected and the most important parameter is:

Useful thermal power: 0.400 MW

Figure 4.9 shows a picture from the equipment catalog (left) and the energy flows for the ICWH heat exchanger (right). Hot water was considered to be the main flow; to evacuate 1 MW of heat to cooling water (WR), 1 MW of hot water (WH) was needed.

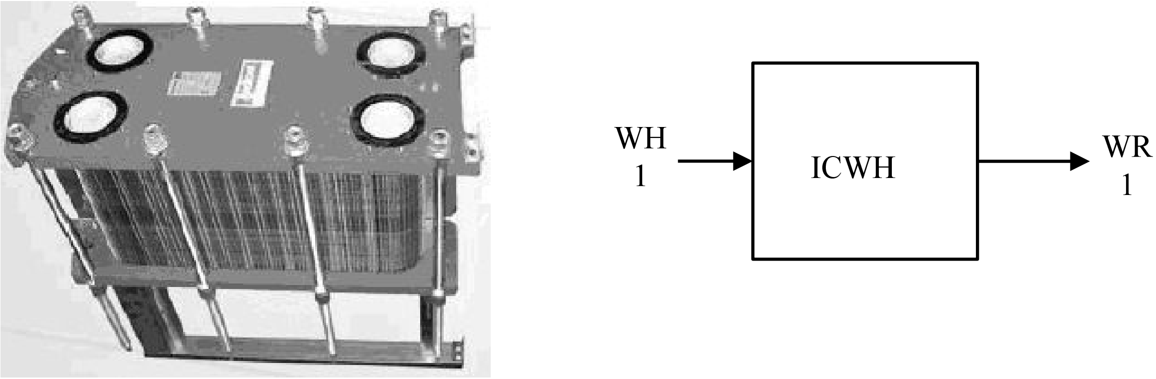

Figure 4.9 Hot water-cooling water heat exchanger (left) and its technical production coefficients (right).

4.3.1.7 FAVA, Double effect absorption chiller

Absorption chiller ABTF-380 from Trane was selected and the most important parameters were:

Capacity: 1.266 MW
COP: 1.20

Figure 4.10 shows a picture from the equipment catalog (left) and the energy flows for the double effect absorption chiller (right). The main flow was considered to be chilled water. To produce 1 MW of chilled water (WC), 0.01 MW of electricity (EE) and 0.83 MW of steam (VA) will be consumed, evacuating 1.83 MW of heat to cooling water (WR).

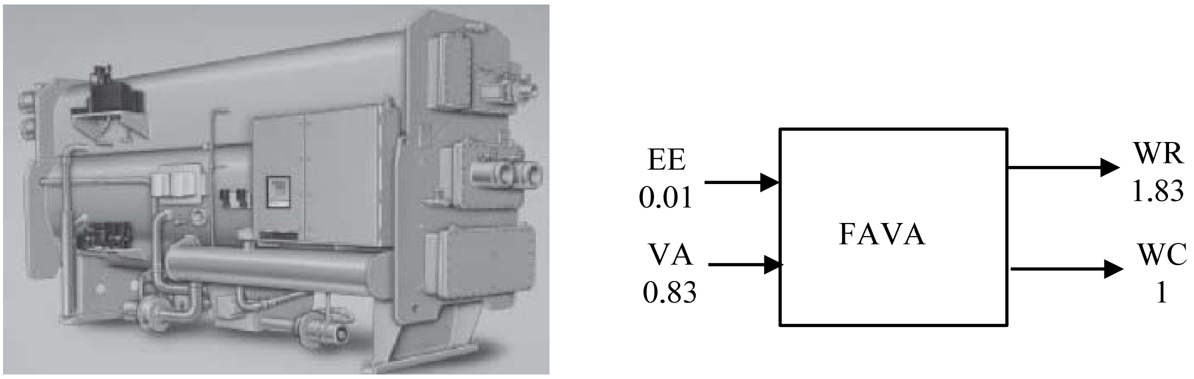

Figure 4.10 Double effect absorption chiller (left) and its technical production coefficients (right).

4.3.1.8 FAWH, Single effect absorption chiller

The selected equipment was THERMAX Prochill model 14S and the most important parameters are:

Capacity: 0.493 MW
COP: 0.60

Figure 4.11 shows a picture from the equipment catalog (left) and the energy flows for FAWH (right). The main flow was considered to be chilled water; to produce 1 MW of chilled water (WC), 0.01 MW of electricity (EE) and 1.50 MW of hot water (WH) are consumed, evacuating 1.50 MW of heat to cooling water (WR).

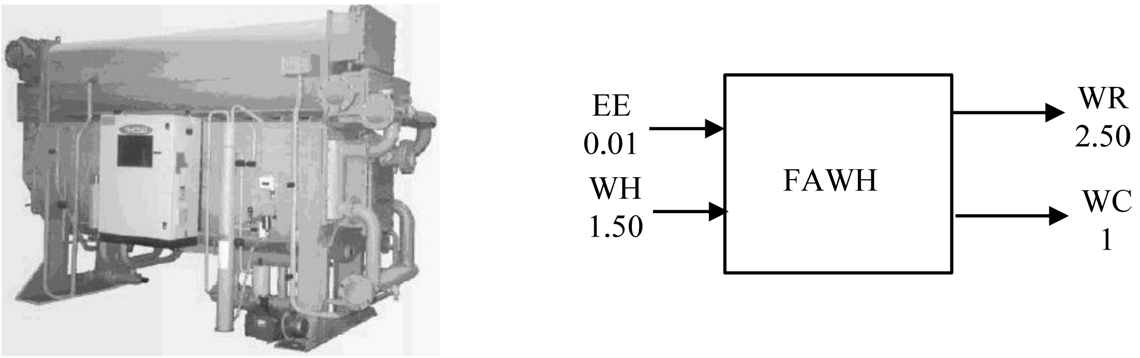

Figure 4.11 Single effect absorption chiller (left) and its technical production coefficients (right).

4.3.1.9 FMWR, Mechanical chiller

Ciatesa's HydroCiat LW – LWP model 2150BX was selected and the most important parameters are:

Capacity: 0.492 MW
COP: 4.47

Figure 4.12 shows a picture from the equipment catalog (left) and the energy flows for the mechanical chiller (right). The main flow was considered to be chilled water; to produce 1 MW of chilled water (WC), 0.23 MW of electricity (EE) will be consumed, evacuating 1.23 MW of heat to cooling water (WR).

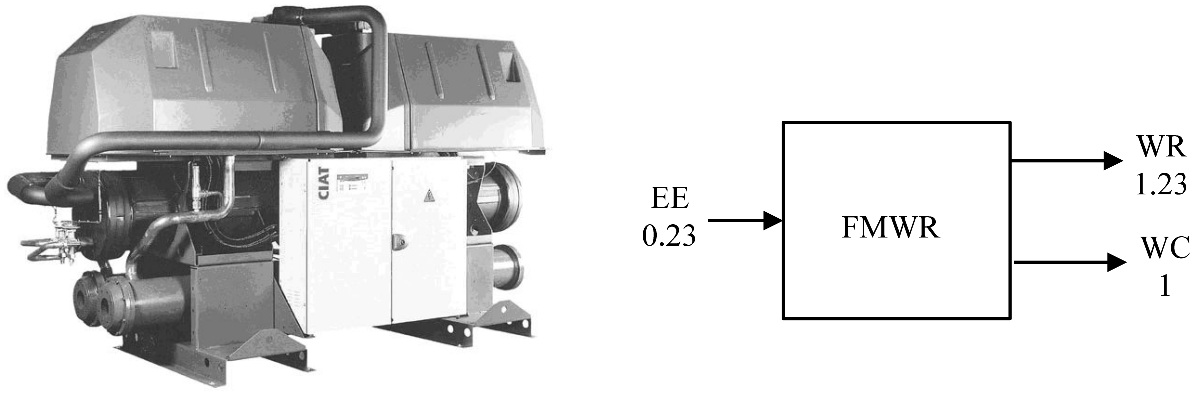

Figure 4.12 Mechanical chiller (left) and its technical production coefficients (right).

4.3.1.10 ICWR, Cooling tower

The cooling tower selected was MARLEY NC8302F1 and the most important parameters for this study are:

Cooling power: 1.000 MW
Water flow: 143,800 kg/h

Figure 4.13 shows a picture from the equipment catalog (left) and the energy flows for the cooling tower (right). Heat evacuated to ambient air was considered to be the main flow. To evacuate 1 MW of heat to ambient air (AA), 0.02 MW of electricity (EE) and 1 MW of cooling water (WR) are consumed.

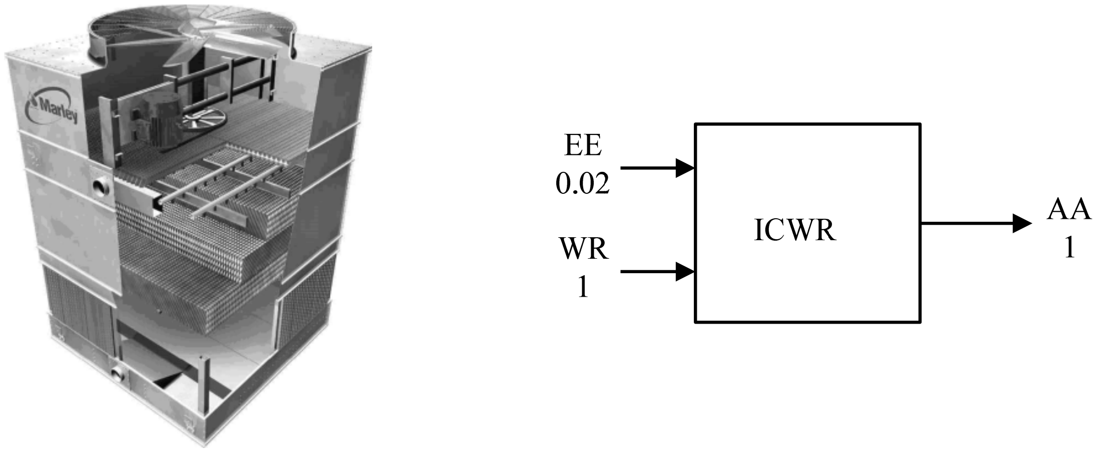

Figure 4.13 Cooling tower (left) and its technical production coefficients (right).

Table 4.2 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. P_{nom} being the nominal power of the equipment, it was considered that the production coefficients were constant and independent from the production $P \leq P_{nom}$ of the equipment at a given moment.

The data shown in Table 4.2 was obtained from equipment catalogs and consultations with manufacturers.

Table 4.2 Selected equipment and matrix of production coefficients

	Selected equipment		Utility *j*						
Technology *i*	Cost CI (10^3 €)	Nominal Power P_{nom} (MW)	CG	VA	WH	WR	AA	WC	EE
TGVA	1 530	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

4.3.2 Economic data

CI_i in Table 4.2 is the investment cost of the selected equipment of technology *i*, obtained from the catalog price and multiplied by a simple module factor which took into account transportation, installation, connection, insulation, etc. (Brown, 2000; Zogg, 2002; Goldstein, 2003; Seider, 2004). The total plant cost was obtained by adding indirect costs, including engineering and supervision expenses, legal expenses, contractor's fees and contingencies, which were assumed to be equal to 15% of the equipment investment costs (fic = 0.15).

The capital recovery factor fcr multiplied by the total plant cost gives the cost of servicing the required capital (Horlock, 1987). Assuming that the interest rate iyr and the equipment lifetime nyr are the same for all types of equipment, the capital recovery factor is given by:

$$\mathrm{fcr} = \frac{\mathrm{iyr} \cdot (1 + \mathrm{iyr})^{\mathrm{nyr}}}{(1 + \mathrm{iyr})^{\mathrm{nyr}} - 1} \qquad (4.1)$$

Considering the life time of the plant to be 15 years and an interest rate of 0.10 y^{-1} (reasonable for the present economic circumstances in Spain), an annual capital recovery factor of 0.13 y^{-1} was obtained. Annual maintenance and operating costs, different from energy costs, were considered to be 7% of the total plant cost (fmo = 0.07 y^{-1}). The factor fam took into account both maintenance and capital recovery factors:

$$\text{fam} = \text{fmo} + \text{fcr} \tag{4.2}$$

4.3.3 Environmental data

The CO_2 emissions and EI-99 Single Score (Hierarchist perspective, H/H) associated with the production of each type of technology were calculated utilizing SimaPro (2008) following the same procedure explained in Section 3.2 and Appendix I.

Data on the material composition and manufacturing of the equipment were obtained from consultation with the manufacturers and incorporated into SimaPro through IDEMAT (2001), Ecoinvent (2007), and ETH-ESU (Frischknecht & Jungbluth, 2004) 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 (Directive 2005/55/EC). The following assumptions were also made: (1) 100% of materials was landfilled (worst case scenario, with no recycling), (2) any oil or fluid was considered as an emission into the soil, and (3) gases (R134a, for example) were considered to be discharged into the atmosphere. The next sections present the characterization for each equipment, as implemented in SimaPro.

4.3.3.1 TGVA, Gas turbine cogeneration module

9080 kg of steel, from IDEMAT;
500 kg of aluminium, from IDEMAT;
9080 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
500 kg of aluminium product manufacturing, average metal working/RER S, from Ecoinvent;
2874 tkm[14] of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

---

[14] tkm refers to total transport in ton per kilometers. The final weight is multiplied by the distance traveled.

4.3.3.2 CGVA, Steam boiler

1000 kg of cast iron, from ETH-ESU;
1850 kg of steel, from IDEMAT;
50 kg of aluminium, from IDEMAT;
1850 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
50 kg of aluminium product manufacturing, average metal working/RER S, from Ecoinvent;
1000 kg of metal product manufacturing, average metal working/RER S, from Ecoinvent;
870 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.3 MGWH, Gas engine cogeneration module

5700 kg of steel, from IDEMAT;
10940 kg of oil, used in system (Heavy fuel oil, burned in refinery furnace/kg/RER S), from Ecoinvent (Initial load plus operation consumption, according to manufacturer);
5700 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
1710 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.4 CGWH, Hot water boiler

850 kg of steel, from IDEMAT;
25 kg of aluminum, from IDEMAT;
850 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
25 kg of aluminum product manufacturing, average metal working/RER S, from Ecoinvent;
263 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.5 ICVA, Steam-hot water heat exchanger

360 kg of steel, from IDEMAT;
360 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
108 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.6 ICWH, Hot water-cooling water heat exchanger

760 kg of steel, from IDEMAT;
760 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
228 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.7 FAVA, Double effect absorption chiller

3700 kg of iron alloy, from IDEMAT;
10044 kg of steel, from IDEMAT;
10044 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
3700 kg of metal product manufacturing, average metal working/RER S, from Ecoinvent;
4123 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.8 FAWH, Single effect absorption chiller

9000 kg of steel, from IDEMAT;
9000 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
2700 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.9 FMWR, Mechanical chiller.

2000 kg of steel, from IDEMAT;
500 kg of copper, from IDEMAT;
1000 kg of PVC high impact, from ETH-ESU;
20 kg of aluminium, from IDEMAT;
135 kg of production of R134a (Refrigerant R134a, at plant/RER S), from Ecoinvent (A loss of 5% per year during 15 years, into the atmosphere was considered);
360 kg of lubricating oil, at plant/RER S, from Ecoinvent (9 refills were considered);
2000 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
500kg of copper product manufacturing, average metal working/RER S, from Ecoinvent;
1000 kg of injection moulding/RER S, from Ecoinvent;
20 kg of aluminium product manufacturing, average metal working/RER S, from Ecoinvent.
1056 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

4.3.3.10 ICWR, Cooling tower

3500 kg of steel, from IDEMAT;
1605 kg of PVC high impact ETH S, from ETH-ESU,
3500 kg of steel product manufacturing, average metal working/RER S, from Ecoinvent;
1605 kg of injection moulding/RER S, from Ecoinvent;
1532 tkm of transport, lorry 16-32t, EURO5/RER S, from Ecoinvent.

Table 4.3 summarizes the technologies and their associated main material composition, CO_2 emissions, CO_2I, and the Single Score (H/H) obtained by applying EI-99, SSI.

Table 4.3 Technologies, main material composition, CO_2 emissions, EI-99 Single Score (H/H).

Technology	Main material composition (kg)	CO_2I (kg CO_2)	SSI (points)
TGVA	9080 kg steel, 500 kg aluminum	80,500	8700
CGVA	1000 kg cast iron, 1850 kg steel, 50 kg aluminum	15,810	1420
MGWH	5700 kg steel	37,350	4030
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

4.4 GAS AND ELECTRICITY RATES

Section 3.2 presented the calculation of CO_2 emissions and EI-99 Single Score for the fuels and electricity available to the trigeneration system.

Since 2003, when gas and electricity markets in Spain were liberalized, consumers can freely choose a supplier and leave the regulated-rate system or remain connected to the old regulated market. Herein, the regulated-rate system was considered for calculations.

This investigation considered a constant purchase cost of p_g = 0.025 €/kWh for natural gas (RMITC 7575/2007), which includes taxes and the distribution of fixed costs throughout the estimated annual consumption (Table 4.4).

Table 4.4 Regulated natural gas rate.

Rate	Supply Pressure bar	Maximum consumption MWh/y	Fixed cost (€/month)/(kWh/day)	Variable cost €/kWh
2.4	4 < P < 60	30 000 < EC < 100 000	0.048	0.021

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 (RD 1634/2006) was utilized throughout the studied year. However, there is a supplement that discriminates the price of electricity by time 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 (RD 1634/2006). Final electricity price, p_{ep}, was 0.095 €/kWh for off-peak hours, and 0.130 €/kWh for on-peak hours. Table 4.5 and 4.6 show, respectively, the regulated electricity rate selected for this study and the electricity cost with hourly differentiation.

Table 4.5 Regulated electricity rate.

Rate	Supply voltage kV	Power cost (€/month)/kW	Energy cost €/kWh
1.1	< 36	2.272	0.078

Table 4.6 Electricity cost (€/kWh) with hourly differentiation in two periods.

Annual period	Months	On-peak (+ 37%)		Off-peak	
		Time	Cost	Time	Cost
Summer	4 to 9	11 to 14	1.37·0.095	15 to 24 and 1 to 10	0.095
Winter	10 to 3	10 to 13	1.37·0.095	14 to 24 and 1 to 9	0.095

Cogeneration plants operate in Spain under different economic regimes, depending on the applicable Royal Decree. Older regimes were replaced by Royal Decree 661/2007 (2007). This RD indicates that the plant operator can: (1) Feed electricity to the grid at a regulated feed-in tariff; or (2) Sell energy to the free market receiving an additional premium on top of the market price. The tariff and premium depends on the group to which the installation belongs, determined by its power output and the fuel used. For Subgroup a.1.1, which refers to cogeneration installations utilizing natural gas, the tariffs and premiums covered by RD 661/2007 are given in Table 4.7. In addition to the tariffs and premiums shown in the table, cogeneration units can receive several supplements, such as for reactive power, for efficiency, and for delivery in on-peak hours. In agreement with the 2006 Spanish law for cogeneration systems (RDL 7/2006), internal self-consumption is not mandatory.

In order to qualify for such payment, the Equivalent Electrical Efficiency (EEE) of the CHP plant should be equal or higher to what was fixed in RD 661/2007, depending on the type of cogeneration technology used and fuel consumed. EEE is calculated on an annual basis with the equation:

$$\mathrm{EEE} = \frac{E_c}{F_c - \frac{Q_c}{0.9}} \tag{4.3}$$

where E_c is the cogenerated electricity, F_c is the consumption of primary energy measured by the fuel's Lower Heating Value (LHV), and Q_c is the cogenerated useful heat. The EU Cogeneration Directive (Directive 2004/8/EC) discriminates positively microcogeneration (<50 kWe) and small-scale cogeneration (<1000 kWe) systems, contributing to potentiate the implementation of such technologies in the residential and tertiary sectors. A discount of 10% in the minimum EEE is applied for these systems.

The sale price of electricity was obtained from Table 4.7; considering the energy demand for the hospital and the nominal power of the cogeneration modules selected, the 1 000-2 000 kW power range was the most appropriate. Therefore the price for sold electricity p_{es} was 0.077 €/kWh.

Table 4.7 Regulated minimum equivalent electrical efficiency and feed-in tariff.

Maximum capacity (kW)	Classification UE	GT EEE (%)	ICE EEE (%)	Tariff (€/kWh)	Premium (€/kWh)
0 - 50	Micro - cogeneration	53.1%	49.5%	0.1204	NA
50 - 500	Small scale cogeneration	53.1%	49.5%	0.1204	NA
500 - 1000	Small scale cogeneration	53.1%	49.5%	0.0988	NA
1000 - 10000	Cogeneration	59.0%	55.0%	0.0772	0.027844
10000 - 25000	Cogeneration	59.0%	55.0%	0.0731	0.022122
25000 - 50000	Cogeneration	59.0%	55.0%	0.0692	0.019147

GT: Gas Turbine, ICE: Internal Combustion Engine, NA: Not applicable

4.5 CONCLUSIONS

The existence of the great number of options for the supply of energy services in urban districts and in large buildings (which may differ in technical, economic, and/or environmental performances) created the growing need for energy planning models.

The following activities were necessary to establish the base scenario for the optimization model of Chapter V: firstly, the annual energy services demands were estimated and expressed on an hourly basis by two representative days per month. Secondly, a superstructure for the energy supply system was created to match the energy demand requirements of the hospital with the commercially available energy vectors. The superstructure was composed of all types of equipment that were considered as candidates for inclusion in the energy supply system. Types and sizes of these equipments were previously selected taking into account a good match between the equipment and the energy demand patterns. Each piece of equipment was a commercially available technology, and was characterized in economic and environmental terms. Thirdly, energy prices were determined and legal conditions imposed to feed the surplus autogenerated electricity into the grid at a regulated feed-in tariff, were included. Fuels and electricity were previously characterized in environmental terms in Chapter III.

Once all information is collected and on the basis of a decision criterion, it will be verified whether trigeneration technology is the most adequate to satisfy the energy requirements of the building through an optimization model.

CHAPTER V

SYNTHESIS OF TRIGENERATION SYSTEMS - APPLICATION -

Chapter IV prepared the basis for a more complex study on trigeneration systems, which considered not only the operational aspect but also the design/synthesis of complex systems.

Chapter V develops an optimization model using Mixed Integer Linear Programming (MILP) to determine the type, number and capacity of the equipment in trigeneration systems to be installed in a building as well as to establish the optimal operational strategy on an hourly basis throughout one year.

Starting from the superstructure defined in Chapter IV, an energy supply system was optimized considering specific demands of a hospital located in Zaragoza, Spain. Firstly, the objective function took into account only an economic point of view through the minimization of the annual total cost (€/y). Secondly, the objective function took into consideration only an environmental viewpoint through the minimization of the annual kilograms of CO_2 released (kg CO_2/y) or the annual Eco-indicator 99 Single Score (points/y).

In the design of trigeneration plants for buildings, two fundamental issues should be addressed (Yokoyama, 1994; Serra *et al.*, 2009), *i.e.*, the synthesis of the plant configuration (number and capacity of equipment for each type of technology employed) and the operational planning (strategy concerning operational state of the equipment, energy flow rates, purchase/selling of electricity, etc.). For existing plants the operational strategy is the only concern, but for new plants these issues are not independent.

This chapter proposes a methodology for the synthesis of energy supply systems in buildings, based on the comparison of annual balances for all feasible different plant configurations contained in a superstructure. MILP techniques were utilized (Nemhauser, 1999; Williams, 1999; Schrage, 2006), which have been applied to the optimization of cogeneration and trigeneration systems (Beihong, 2006; Oh, 2007; Seo, 2008). The MILP model for the multiperiod synthesis and operational planning problem was characterized by binary variables for the selection of technologies, by integer variables for the determination of the number of units installed, and by continuous variables for the representation of energy, economic and environmental flows.

The MILP model was implemented in the Lingo modeling language and optimizer. Lingo is a commercial software package for solving optimization problems that uses the branch and bound solver to enforce any integer restrictions contained in a model. The advanced capabilities of Lingo such as cut generation, tree reordering, advanced heuristic and presolve strategies were used as needed. The branch and bound solver will, in turn, call upon the linear solver, which uses the revised simplex method with product form inverse.

Chapter V presents an extension of the cost accounting method proposed in Chapter II, in an application considering a more complex trigeneration system. Multiobjective optimization is also approached, considering economic and environmental viewpoints simultaneously.

5.1 ECONOMIC OPTIMIZATION

Investment in trigeneration systems always competes with other projects (cogeneration or conventional supply energy systems) that can prove themselves more economically successful. The total annual cost required satisfying the demands of heat, cooling, and electricity was used in this subsection as an economic evaluation criterion. Such cost is constituted of two components: investment and maintenance costs (fixed) and operational costs (variable). The investment costs included the purchase and installation of the equipment required for the energy supply system, to be amortized in a specific period. The operational costs included the consumption of gas by boilers and cogeneration modules as well as the purchase of electricity from the electric grid. The profit realized by the sale of autogenerated electricity to the grid must be subtracted from the operational costs. To complete the economic analysis, the planning horizon - which is the lifetime of the project - and other financial parameters such as interest rates must be known.

5.1.1 Mathematical model

The model represented the superstructure containing all configuration/operation alternatives and the conditions of demand, prices, etc. expressed in Chapter IV and could be solved in a few minutes. Figure 5.1 shows the superstructure of the energy supply system considered in the model.

As explained in Chapter IV, the superstructure accounts 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).

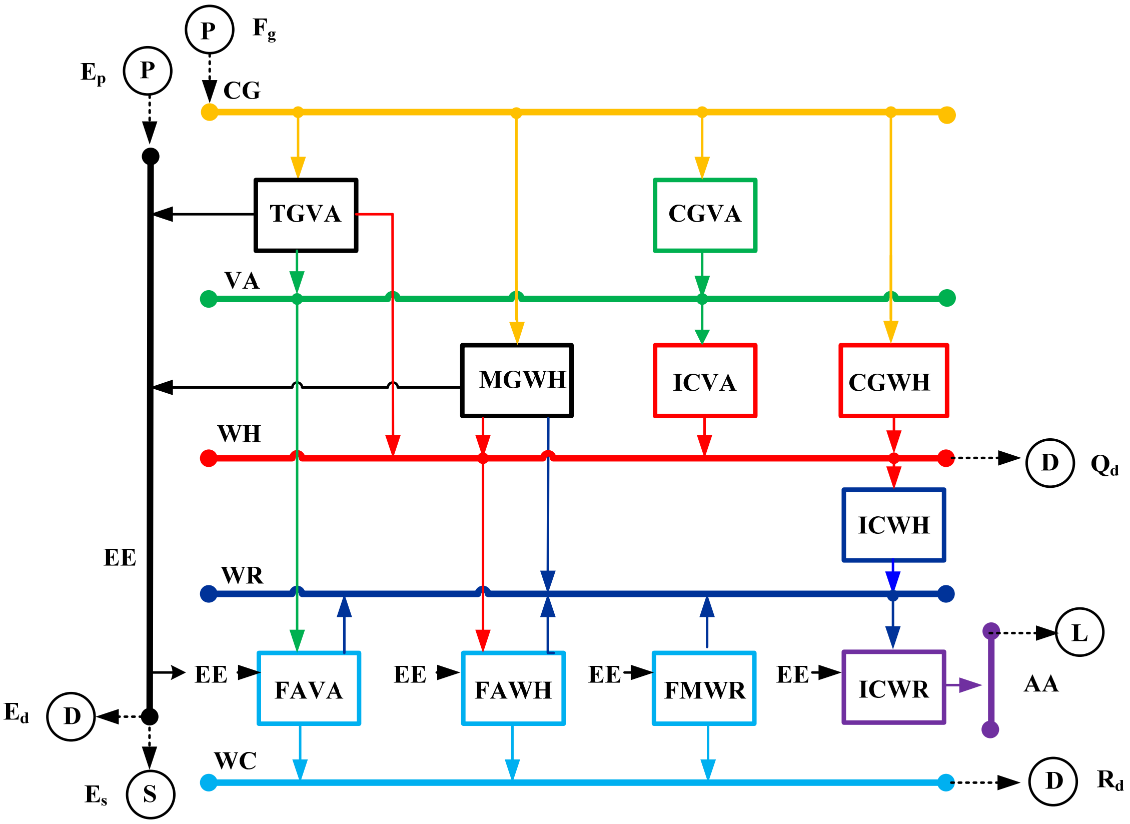

Figure 5.1 Superstructure of the energy supply system.

The available utilities were CG (natural gas), VA (high temperature steam, 180ºC), WH (hot water, 90ºC), WR (cooling water, t_0 + 5ºC), AA (ambient air, t_0), WC (chilled water, 5ºC), and EE (electricity). D, S, P and L refer to, respectively, demand, sale, purchase and waste/loss of a utility. E_d, Q_d and R_d are the demands of electricity, heat, and cooling, respectively. F_g refers to the consumption of natural gas, while E_p and E_s refer to electricity purchased from the grid and self-generated electricity sold to the grid, respectively.

The solution of the model included the most convenient configuration of the system and all energy and economic flows for the operation periods considered for the year. The corresponding model in simple algebraic language is described below. The Lingo model can be found in the CD that accompanies this thesis.

5.1.1.1 Objective function

The objective of the synthesis problem is to minimize the total annual cost C_{tot}

$$\text{Min } C_{tot} = C_{fix} + C_{ope} \tag{5.1}$$

which includes the annual fixed cost C_{fix} and the annual energy cost C_{ope}. The annual fixed cost is expressed by

$$C_{fix} = fam \cdot (1+fic) \cdot \Sigma_i \, NIN(i) \cdot CI(i) \tag{5.2}$$

where NIN(i) and CI(i) are, respectively, the number of pieces of equipment installed and the initial capital cost of each piece of equipment for technology i, with the factors fam and fic defined previously in Chapter IV (fam = 0.20 y^{-1} and fic = 0.15).

The installed power PIN(i) for each technology i is given by

$$PIN(i) = NIN(i) \cdot P_{nom}(i) \tag{5.3}$$

$$NIN(i) \leq YIN(i) \cdot NIN\_BIG(i) \quad \text{with} \quad YIN(i) \in \{0,1\} \tag{5.4}$$

where $P_{nom}(i)$ is the nominal power of the equipment (found in Table 4.2), YIN(i) is a binary variable 0/1 indicating that the technology i is not/is installed, NIN(i) is the number of equipment installed, and NIN_BIG(i) is a maximum limit for the number of equipment.

In order to formulate the operational planning problem for the energy supply system considered in this study, it was assumed that the annual energy demands were given a priori, dividing the year into representative days and each representative day into h sampling time intervals with the identical period of $\Delta t = 24/h$ (refer to Section 4.1 for more details). In the following formulation, a quantity X concerning operational strategy is designated by X(d,h) at the hth sampling time interval of the dth representative day of the year. If nd(d) is the number of d type days per year, the annual operational hours for the hth sampling time on the dth representative day will be

$$t(d,h) = nd(d) \cdot \Delta t = nd(d) \cdot (24/h) \tag{5.5}$$

Please note that in this study h = 24 and d = 24. The annual energy cost is then expressed by

$$C_{ope} = \Sigma_d \Sigma_h c_e(d,h)\cdot t(d,h) \tag{5.6}$$

where $c_e(d,h)$ is the hourly energy charge which is mainly composed of natural gas and electricity charges (data from Section 4.4: p_g = 0.025 €/kWh, pe_p = 0.095 €/kWh off-peak, pe_p = 0.130 €/kWh on-peak, and pe_s = 0.077 €/kWh):

$$c_e(d,h) = p_g\cdot F_g(d,h) + p_{ep}(d,h)\cdot E_p(d,h) - p_{es}\cdot E_s(d,h) \tag{5.7}$$

Operation is subject to capacity limits, production restrictions, and balance equations.

5.1.1.2 Capacity limits

For each period (d,h)

For each technology i

$$POP(i,d,h) \le PIN(i) \tag{5.8}$$

where POP(i,d,h) is the production of technology i in the period (d,h).

5.1.1.3 Production restrictions

For each period (d,h)

For cogeneration modules i = MGWH or TGVA

$$POP(i,d,h) = NOP(i,d,h)\cdot P_{nom}(i) \quad \text{with} \quad NOP(i,d,h) \in \{0,1,\ldots,NIN(i)\} \tag{5.9}$$

For each technology i

For each utility j

$$X(i,j,d,h) = KTU(i,j)\cdot POP(i,d,h) \tag{5.10}$$

where X(i,j,d,h) is the energy flow of utility j interchanged by technology i in the period (d,h) and KTU(i,j) is the absolute value of the production coefficient given in Table 4.2. Restriction

(5.9) imposes that the cogeneration modules in service operate at full load. This is a common practice to facilitate the operation of the system and does not entail excessive costs.

5.1.1.4 Balance equations

For each period (d,h)

For each utility j

$$\mathrm{Prod}(j,d,h) - \mathrm{Cons}(j,d,h) + P(j,d,h) - S(j,d,h) - W(j,d,h) - D(j,d,h) = 0 \quad (5.11)$$

$$\mathrm{Prod}(j,d,h) = \Sigma_i X(i,j,d,h)\cdot \mathrm{YTUP}(i,j) \quad \text{with} \quad \mathrm{YTUP}(i,j) \in \{0,1\} \quad (5.12)$$

$$\mathrm{Cons}(j,d,h) = \Sigma_i X(i,j,d,h)\cdot \mathrm{YTUC}(i,j) \quad \text{with} \quad \mathrm{YTUC}(i,j) \in \{0,1\} \quad (5.13)$$

$$P(j,d,h) \le \mathrm{YUP}(j)\cdot(\mathrm{Cons}(j,d,h) + D(j,d,h)) \quad \text{with} \quad \mathrm{YUP}(j) \in \{0,1\} \quad (5.14)$$

$$S(j,d,h) \le \mathrm{YUS}(j)\cdot \mathrm{Prod}(j,d,h) \quad \text{with} \quad \mathrm{YUS}(j) \in \{0,1\} \quad (5.15)$$

$$L(j,d,h) \le \mathrm{YUW}(j)\cdot \mathrm{Prod}(j,d,h) \quad \text{with} \quad \mathrm{YUW}(j) \in \{0,1\} \quad (5.16)$$

$$D(j,d,h) \le \mathrm{YUD}(j)\cdot(\mathrm{Prod}(j,d,h) + P(j,d,h)) \quad \text{with} \quad \mathrm{YUD}(j) \in \{0,1\} \quad (5.17)$$

where Prod(j,d,h), Cons(j,d,h), P(j,d,h), S(j,d,h), L(j,d,h), and D(j,d,h) are, respectively, the production, consumption, purchase, sale, waste, and demand of utility j in the period (d,h). YTUP(i,j) is 1 when the production coefficient given in Table 4.2 is positive, i.e., when technology i produces utility j. YTUC(i,j) is 1 when the production coefficient given in Table 4.2 is negative, i.e., when technology i consumes utility j. Production Prod and Consumption Cons correspond to internal utility flows whereas Purchase P, Sale S, Waste L, and Demand D are the interchanges of utilities between the energy supply system and the environment. Binary variables YUP(j), YUS(j), YUW(j) and YUD(j) indicate, respectively, the possibility of such interchanges.

5.1.1.5 Other conditions

A condition was introduced in the mathematical model so that gas engines and gas turbines could not be installed simultaneously

$$\mathrm{YIN(TGVA)} + \mathrm{YIN(MGWH)} \le 1 \quad (5.18)$$

In order to comply with regulation, additional conditions must be imposed. If cogeneration exists and there is the possibility of selling surplus electricity to the grid, the equivalent electric efficiency in annual base must exceed specific limits (55% for gas engines and 59% for gas turbines)

$$\mathrm{EEE} \geq 0.59 \cdot \mathrm{YIN(TGVA)} + 0.55 \cdot \mathrm{YIN(MGWH)} \tag{5.19}$$

Furthermore, other conditions can be imposed concerning the permission to sell/purchase electricity, the permission to waste heat, etc. By assigning values to the binary variables YIN(i) and NIN_BIG(i) corresponding to technology i, the configuration alternatives offered by the superstructure can be restricted. For example, the possibility of cogeneration could be excluded by imposing

$$\mathrm{YIN(TGVA)} + \mathrm{YIN(MGWH)} = 0 \tag{5.20}$$

trigeneration could be excluded by imposing

$$\mathrm{YIN(FAVA)} + \mathrm{YIN(FAWH)} = 0 \tag{5.21}$$

and to design a trigeneration system capable of operating autonomously and independently from the electric grid (as an island)

$$\mathrm{YUP(EE)} + \mathrm{YUS(EE)} = 0 \tag{5.22}$$

5.1.2 Results

Given the situation defined by the complete set of conditions and the model, the following results were obtained.

5.1.2.1 Reference system

Configuration of a reference system was obtained when excluding the possibility of cogeneration by means of Equation (5.20). The optimal energy supply system that satisfied the condition of minimal total annual cost is shown in Figure 5.2, in which electricity was bought directly from the grid to attend the demand of electricity as well as the cooling demand with 4 compression chillers. The heat was produced by 6 hot water boilers. Table 5.1 displays the system’s structure and relevant annual energy and monetary flows for the reference system.

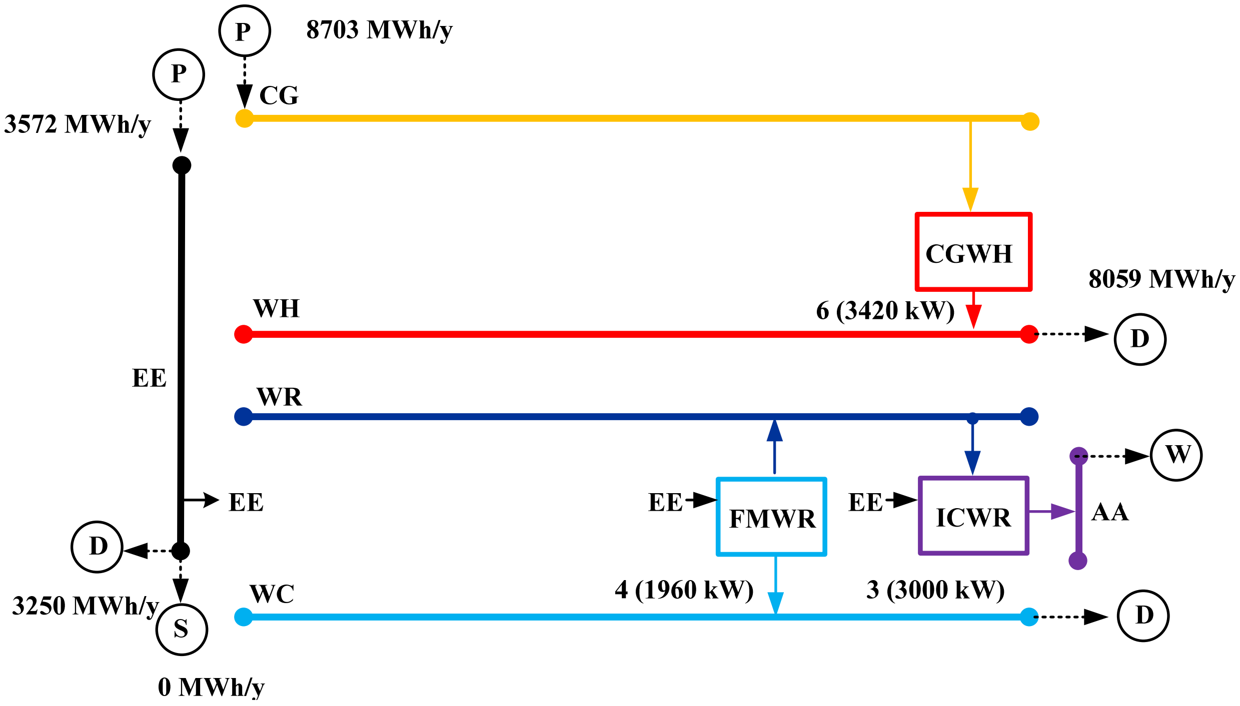

Figure 5.2 Structure and annual operation of the reference system.

Table 5.1 Reference system results.

	Reference system	
System Composition	Number	Installed power
Steam boilers	0	
Hot water boilers	6	3420 kW
Heat exchangers VA→ WH	0	
Heat exchangers WH→ WR	0	
Double effect absorption chillers	0	
Single effect absorption chillers	0	
Mechanical chillers	4	1960 kW
Cooling towers	3	3000 kW
Natural gas (total) MWh/y	8703	
Purchased electricity MWh/y	3572	
Cost of equipment €/y	219,650	
Cost of natural gas €/y	217,582	
Cost of electricity €/y	366,951	
Total annual cost €/y	804,184	

5.1.2.2 Optimal economic system

The following results were obtained by solving the mathematical model, using the Lingo software, to minimize the total annual cost. There was total freedom of selecting technologies, except for Equation (5.18), and the cogeneration legal restriction given by Equation (5.19) was fulfilled. For this case, the minimal cost was obtained by installing three gas engines, three hot water boilers, four hot water-cooling water heat exchangers, one single effect absorption chiller, three mechanical chillers, and three cooling towers, as shown in Figure 5.3. Table 5.2 displays the system's structure and relevant annual energy and monetary flows for the optimal economic system.

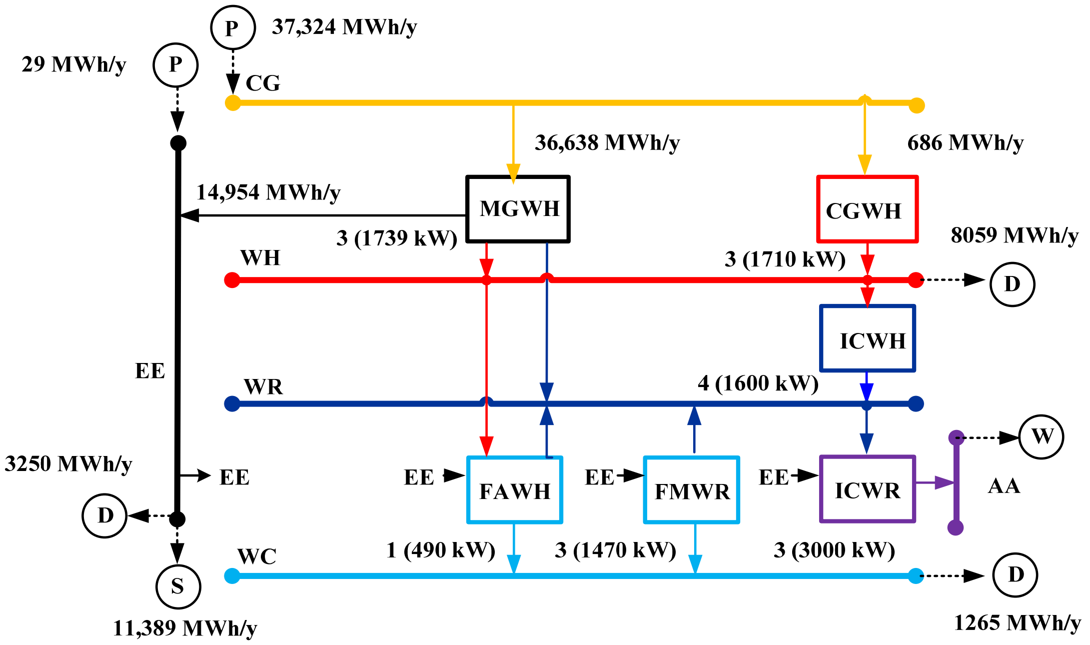

Figure 5.3 Structure and annual operation of the optimal economic system.

Electricity was supplied to users by operating the gas engine cogeneration modules and by purchasing a small quantity of electricity from an outside electric power company. Electricity was used to drive the mechanical chillers and auxiliary machinery in this system. Hot water for DHW, space heating, and to drive the single effect absorption chiller was supplied by the cogeneration modules and gas-fired boilers. Surplus not consumed cogenerated heat was disposed of through hot water-cooling water heat exchangers. Cold water for space cooling was supplied by the single effect absorption chiller and vapor compression chillers.

Table 5.2 Optimal economic system results.

	Optimal economic system	
System composition	Number	Installed power
Gas turbines	0	
Gas engines	3	1739 kW
Steam boilers	0	
Hot water boilers	3	1710 kW
Heat exchangers VA→ WH	0	
Heat exchangers WH→ WR	4	1600 kW
Double effect absorption chillers	0	
Single effect absorption chillers	1	490 kW
Mechanical chillers	3	1470 kW
Cooling towers	3	3000 kW
Natural gas (total) MWh/y	37,324	
Purchased electricity MWh/y	29	
Sold electricity MWh/y	11,389	
Natural gas (cogeneration) MWh/y	36,638	
Cogenerated work MWh/y	14,954	
Cogenerated useful heat MWh/y	8602	
Primary Energy Savings %	10.01	
Equivalent electrical efficiency %	55.22	
Cost of equipment €/y	510,830	
Cost of natural gas €/y	933,092	
Cost of electricity €/y	3207	
Profit with the sale of electricity €/y	- 876,960	
Total annual cost €/y	570,169	

5.1.3 Energy efficiency

Equivalent Electrical Efficiency (EEE) of the system was calculated according to what was fixed in RD 661/2007:

$$\mathrm{EEE} = \frac{E_c}{F_c - \frac{Q_{cc}}{0.9}} = 55.22\% \tag{5.23}$$

where E_c is the generated electricity, F_c is the consumption of primary energy, and Q_{cc} is the cogenerated useful heat. All values refer to annual operation.

The Primary Energy Savings (PES) provided by cogeneration was calculated in accordance with the EU Cogeneration Directives (Directives 2004/8/EC and 2007/74/EC):

$$PES = 1 - \frac{F_c}{\left(\frac{E_c}{\eta_{ec}}\right) + \frac{Q_{cc}}{\eta_{qc}}} = 10.01\% \tag{5.24}$$

where $\eta_{ec} = 0.48$ and $\eta_{qc} = 0.90$ are the efficiency reference values given in the Official Journal of the EU (EU, 2007) for the separate production of electricity and heat, respectively. All values refer to annual operation.

Detailed flows and operation modes of the economic optimal can be found in Appendix III.

5.1.4 Economic efficiency

Table 5.3 summarizes the economic aspects of the reference and optimal economic systems.

Table 5.3 Reference system compared to the economic optimal system.

	Reference system	Optimal system
Total plant cost €	1,098,250	2,554,150
Cost of natural gas €/y	217,582	933,092
Cost of electricity €/y	366,951	3207
Profit with the sale of electricity €/y	0	- 876,960
Total annual energy cost €/y	584,533	59,339

There was an increase (1,455,900 €) in invested capital, but a considerable annual profit in energetic turnover was observed: with trigeneration, 525,194 €/y will be saved.

Decisions on investment, which take time to mature, have to be based on the returns which that investment will make. Often, it would be good to know what the present value of the future investment is, or how long it will take to mature (give returns). In order to assess the feasibility of investing in trigeneration, some capital budgeting techniques should be used to evaluate the project.

Of the several methods available to evaluate investments, the economic optimal system was evaluated by the payback period (static method) and the internal rate of return (dynamic method). The payback period (PP) is the number of years required for the invested capital to be exceeded by the resulting benefits.

$$\mathrm{PP} = \frac{\text{Investment}}{\text{Annual benefit}} \tag{5.25}$$

By investing in trigeneration, when compared to the reference system, the payback period of the additional investment is approximately 2 years and 9 months. The explanation behind PP is that the shorter the payback period, the greater the liquidity, and the less risky the project. Advantages of the method include computational simplicity, it is easy to understand and handles investment risk effectively (Zutter, 2009).

With dynamic methods the time factor is also taken into consideration. Net Present Value (NPV) calculates all incomes and outcomes in the economic lifetime of the project with respect to the value at the beginning of the project, and was the criterion utilized in the economic optimal.

$$\mathrm{NPV} = \text{-}\mathrm{II} + \sum_{j=1}^{ny} \frac{\mathrm{ACF_j}}{(1+\mathrm{iyr})^{ny}} \tag{5.26}$$

Where II is the initial investment, ACF are the annual cash flows generated by the system, ny is the number of years to consider the investment and iyr is the type of interest. When $\mathrm{ACF_j}$ are constant,

$$\mathrm{NPV} = \text{-}\mathrm{II} + \frac{\mathrm{ACF}}{\mathrm{fam}} \rightarrow \mathrm{NPV}\cdot\mathrm{fam} = \mathrm{ACF} - \mathrm{fam}\cdot\mathrm{II} \tag{5.27}$$

Which shows that Equation (5.27) was the economic criterion utilized in the objective function.

Investment in trigeneration was evaluated by the Internal Rate of Return (IRR). IRR is the discount rate that generates a zero NPV for a series of future cash flows.

$$0 = -\mathrm{II} + \sum_{j=1}^{ny} \frac{\mathrm{ACF_j}}{(1+\mathrm{IRR})^{ny}} \Rightarrow \mathrm{IRR} \tag{5.28}$$

When $\mathrm{ACF_j}$ is constant, Equation (5.28) can be treated as a geometric progression and hence:

$$0 = -\mathrm{II} + \frac{\mathrm{ACF}\ \left[(1+\mathrm{IRR})^{ny} - 1\right]}{\mathrm{IRR}\ (1+\mathrm{IRR})^{ny}} \tag{5.29}$$

IRR gives information on how rates have to go in order to eliminate the present value of trigeneration. IRR = 35.70% and considering that for energy efficiency projects a worthwhile margin is between 7-13%, investment in trigeneration is again considered to be profitable.

5.1.5 Cost assessment

This section presents an application of the equations shown in Section 2.6.2 (allocation method proposal) to obtain unit costs of internal flows and products in simple trigeneration systems. It will be shown how the concepts can be adapted to approach more complex systems. Figure 5.4 depicts the production scheme of the economic optimal, where CG refers to natural gas, WH refers to hot water, WC refers to chilled water, WR refers to cooling water, EE refers to electricity and AA refers to ambient air. The technologies depictes in Figure 5.4 are CGWH (hot water boiler), MGWH (gas engine), ICWH (hot water-cooling water heat exchanger), FAWH (single effect aborption chiller), and FMWR (mechanical chiller).

Following the procedure described in Chapter II, the system allows for tracking of heat produced by the cogeneration module and auxiliary boiler, and the four new energy flows were calculated by adapting parameter B from Chapter II (Equation 2.42):

$$\mathrm{B} = \frac{\mathrm{WH_d}}{\mathrm{WH_d} + \mathrm{WH_{abs}}} \tag{5.30}$$

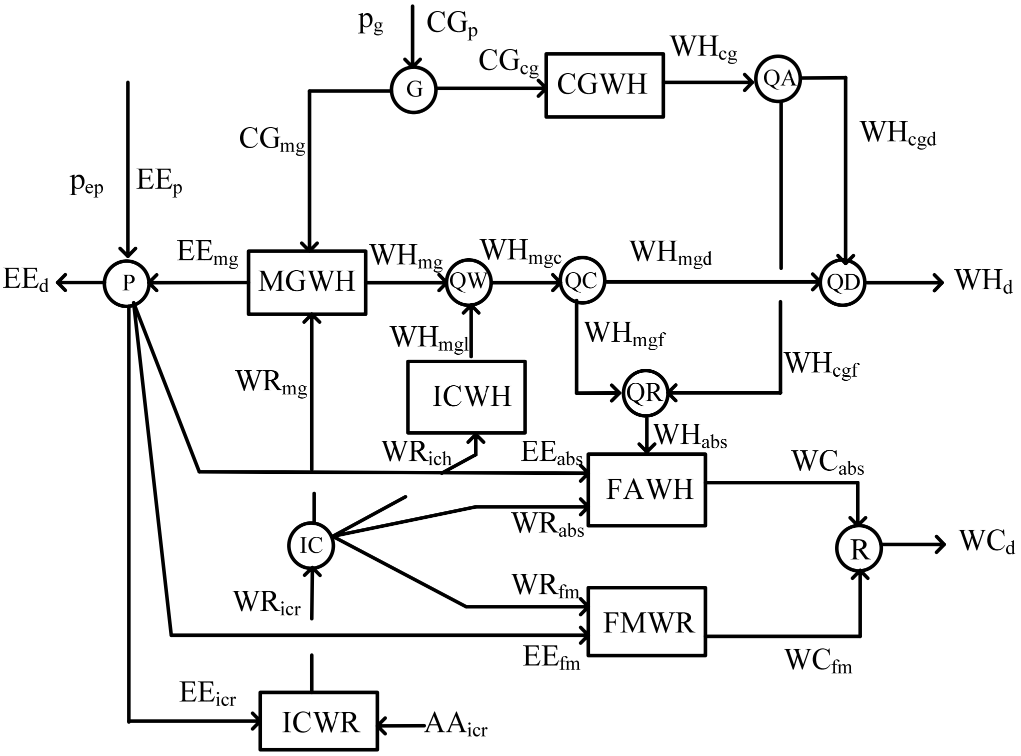

Figure 5.4 Internal and product flows of the economic optimal system.

Yielding that heat produced in the cogeneration module was distributed as follows:

$$WH_{mgd} = B \cdot WH_{mgc} \tag{5.31}$$

$$WH_{mgf} = (1 - B) \cdot WH_{mgc} \tag{5.32}$$

And the heat produced in the auxiliary boiler is distributed as follows:

$$WH_{cgd} = B \cdot WH_{cg} \tag{5.33}$$

$$WH_{cgf} = (1 - B) \cdot WH_{cg} \tag{5.34}$$

Given that the energy flows are known, costs balances are formulated:

MGWH: $$c_{cgmg} \cdot CG_{mg} + c_{wrmg} \cdot WR_{mg} = c_{eemg} \cdot EE_{mg} + c_{whmg} \cdot WH_{mg} \tag{5.35}$$

CGWH: $$c_{cgcg} \cdot CG_{cg} = c_{whcg} \cdot WH_{cg} \tag{5.36}$$

FAWH: $$c_{whabs} \cdot WH_{abs} + c_{eeabs} \cdot EE_{abs} + c_{wrabs} \cdot WR_{abs} = c_{wcabs} \cdot WC_{abs} \tag{5.37}$$

FMWR: $c_{eefm}\cdot EE_{fm} + c_{wrfm}\cdot WR_{fm} = c_{wcfm}\cdot WC_{fm}$ (5.38)

ICWR: $c_{eeicr}\cdot EE_{icr} + p_{aaicr}\cdot AA_{ic} = c_{wricr}\cdot WR_{ic}$ (5.39)

ICWH: $c_{wrich}\cdot WR_{ich} = c_{whmgl}\cdot WH_{mgl}$ (5.40)

P: $c_{eemg}\cdot EE_{mg} + p_{ep}\cdot EE_{p} = c_{eed}\cdot EE_{d} + c_{eeabs}\cdot EE_{abs} + c_{eefm}\cdot EE_{fm} + c_{eeicr}\cdot EE_{icr}$ (5.41)

G: $p_{g}\cdot CG_{p} = c_{cgmg}\cdot CG_{mg} + c_{cgcg}\cdot CG_{cg}$ (5.42)

QW: $c_{whmg}\cdot WH_{mg} + c_{whmgl}\cdot WH_{mgl} = c_{whmgc}\cdot WH_{mgc}$ (5.43)

QC: $c_{whmgc}\cdot WH_{mgc} = c_{whmgd}\cdot WH_{mgd} + c_{whmgf}\cdot WH_{mgf}$ (5.44)

QA: $c_{whcg}\cdot WH_{cg} = c_{whcgd}\cdot WH_{cgd} + c_{whcgf}\cdot WH_{cgf}$ (5.45)

QD: $c_{whcgd}\cdot WH_{cgd} + c_{whmgd}\cdot WH_{mgd} = c_{whd}\cdot WH_{d}$ (5.46)

QR: $c_{whmgf}\cdot WH_{mgf} + c_{whcgf}\cdot WH_{cgf} = c_{whabs}\cdot WH_{abs}$ (5.47)

IC: $c_{wricr}\cdot WR_{icr} = c_{wrfm}\cdot WR_{fm} + c_{wrabs}\cdot WR_{abs} + c_{wrmg}\cdot WR_{mg} + c_{wrich}\cdot WR_{ich}$ (5.48)

R: $c_{wcfm}\cdot WC_{fm} + c_{wcabs}\cdot WC_{abs} = c_{wcd}\cdot WC_{d}$ (5.49)

The prices for natural gas p_g and purchased electricity p_{ep} are known and there is no tax applied to waste heat, $p_{aaicr} = 0$. There are 25 unit costs of internal flows and final products to be calculated: c_{cgmg}, c_{cgcg}, c_{whcg}, c_{whcgf}, c_{whcgd}, c_{whd}, c_{whmg}, c_{whmgc}, c_{whmgd}, c_{whmgf}, c_{whabs}, c_{wcabs}, c_{eemg}, c_{eed}, c_{eeabs}, c_{eefm}, c_{wcfm}, c_{wcd}, c_{wrfm}, c_{wrabs}, c_{wrmg}, c_{wrich}, c_{whmgl}, c_{eeicr} and c_{wricr}. Cost balances provide 15 equations, and therefore 10 auxiliary costing equations are needed.

Considering that the unit cost of several flows of the final products or internally consumed obtained from a homogeneous flow is the same, and applying this rule to branching points **P**, **G**, **QA** and **IC** eight auxiliary equations were obtained:

P: $c_{eed} = c_{eefm}$ (5.50)

P: $c_{eed} = c_{eeabs}$ (5.51)

P: $c_{eed} = c_{eeicr}$ (5.52)

G: $c_{cgmg} = c_{cgcg}$ (5.53)

QA: $c_{whcgf} = c_{whcgd}$ (5.54)

IC: $c_{wrfm} = c_{wrabs}$ (5.55)

IC: $c_{wrfm} = c_{wrmg}$ (5.56)

IC: $c_{wrfm} = c_{wrich}$ (5.57)

Equation (2.53) was adapted to the production scheme of Figure 5.4, where the three cogenerated consumed products benefit from the same discount d, providing the two auxiliary equations:

$$1 - d = \frac{c_{eemg}}{p_{ep}} = \frac{c_{whmgd}}{c_{whcg}} = \frac{\frac{c_{whmgf}}{COP_q}}{\frac{p_{ep}}{COP_e}} \qquad (5.58)$$

$$\frac{c_{eemg}}{p_{ep}} = \frac{c_{whmgd}}{c_{whcg}} \qquad (5.59)a$$

$$\frac{c_{eemg}}{p_{ep}} = \frac{\frac{c_{whmgf}}{COP_q}}{\frac{p_{ep}}{COP_e}} \qquad (5.59)b$$

Operation for a Working day in July, at 2pm, was chosen as an application example to carry out the internal cost analysis. At that specific time, the Hot Water-Cooling Water heat exchanger (ICWH) is not operational, yielding c_{wrich},WR_{ich}, c_{whmgl}, $WH_{mgl} = 0$ and that $WH_{mg} = WH_{mgc}$ ($c_{whmg} = c_{whmgc}$). Table 5.4 shows the energy flows and unit costs for the trigeneration system, for the specific study case.

The unit cost of the final products – c_{eed}, c_{whd} and c_{wcd} - are lower than the costs of conventional production: c_{eed} is lower than the purchased electricity (p_{ep} = 0.130 €/kWh), c_{whd} is lower than the cost of the heat produced in the auxiliary boiler ($c_{whcg} = p_g/\eta_q$ = 0.025/0.926 = 0.027 €/kWh) and c_{wcd} is lower than the cost of cooling produced in a mechanical chiller (p_{ep}/COP_e = 0.130 / 5 = 0.026 €/kWh) for this specific operation state (a Working day in July, at 2pm). The proposed cost assessment rules defined by equations (2.58) provided cost values that shared a discount of 59.18% among all consumers. There was also a significant economic benefit with respect to the conventional energy supply system.

Table 5.4 Energy flows and unit costs, c (€/kWh), of internal flows and final products for the trigeneration system on a Working day in July, at 2pm.

	Energy flows (kW)		**Unit costs (€/kWh)**
EE_d	499.6	c_{eed}	0.0801
WH_d	158.2	c_{whd}	0.0128
WC_d	1781.4	c_{wcd}	0.0204
EE_p	314.9	p_{ep}	0.1300
EE_s	0	p_{es}	---
CG_{cg}	74.0	c_{cgcg}	0.0250
WH_{cg}	68.5	c_{whcg}	0.0270
WH_{cgd}	17.33	c_{whcgd}	0.0270
WH_{cgf}	51.17	c_{whcgf}	0.0270
CG_{mg}	1421.0	c_{cgmg}	0.0250
WH_{mg}	556.8	c_{whmg}	0.0089
EE_{mg}	580.0	c_{eemg}	0.0531
WR_{mg}	116.0	c_{wrmg}	0.0016
WR_{ich}	0	c_{wrich}	---
WH_{mgl}	0	c_{whmgl}	---
WH_{mgc}	556.8	c_{whmgc}	0.0089
WH_{mgd}	140.9	c_{whmgd}	0.0110
WH_{mgf}	415.9	c_{whmgf}	0.0081
WH_{abs}	467.1	c_{whabs}	0.0102
EE_{abs}	3.1	c_{eeabs}	0.0801
WR_{abs}	778.5	c_{wrabs}	0.0016
WC_{abs}	311.4	c_{wcabs}	0.0201
WR_{fm}	1808.0	c_{wrfm}	0.0016
EE_{fm}	338.1	c_{eefm}	0.0801
WC_{fm}	1470.0	c_{wcfm}	0.0204
WR_{icr}	2703.0	c_{wricr}	0.0016
EE_{icr}	54.1	c_{eeicr}	0.0801
Discount d		0.5918	

5.2 ENVIRONMENTAL OPTIMIZATION

Ever stricter environmental controls are a result of the increase in environmental awareness and energy demand, and companies are searching for ways to move beyond compliance using pollution minimization strategies. The decision on such strategies must consider technology availability, cost-effectiveness, regulatory factors and environmental issues, to among others.

Environmental optimization was carried out based on two criteria: (1) CO_2 emissions and (2) 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. CO_2 emissions were chosen for optimization in this study because they accounted for 77% of total global anthropogenic GHG emissions in 2004 (Rogner *et al.*, 2007). As explained in Chapter III, EI-99 is a global environmental indicator that encompasses several impact categories and was included to broaden the environmental perspective.

5.2.1 Mathematical model

5.2.1.1 CO_2 Objective function

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.

$$\text{Min } CO_{2tot} = CO_{2fix} + CO_{2ope} \tag{5.60}$$

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

$$CO_{2fix} = fam_e \cdot \Sigma_i \, NIN(i) \cdot CO_2I(i) \tag{5.61}$$

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 (Table 4.3). 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}. fam_e expresses the damage imposed on the environment and ecosystems and those who use the environment, and a 5-year safety protection margin was considered in the 15-year system lifetime, yielding a 10-year amortization.

The annual operation impact (CO_{2ope}) associated with the operation of the system was expressed by:

$$CO_{2ope} = \Sigma_d \Sigma_h [EM_g \cdot F_g(d,h) + EM_e \cdot E_p(d,h) - EM_e \cdot E_s(d,h)] \quad (5.62)$$

F_g was the consumption of natural gas, and E_p and E_s were the amount of electricity purchased and sold, respectively. The system boundaries were defined as seen in Figure 5.5, where the autogenerated electricity sold to the grid was evaluated at the same ‘environmental’ cost as the electricity purchased from the grid. The avoided emissions were considered as the difference between the emissions associated with the generation of electricity through the cogeneration module and the emissions associated with purchase from the grid. Emission values considered were EM_g = 0.272 kg CO_2/kWh and $EM_{ep} = EM_{es} = EM_e$ = 0.385 kg CO_2/kWh (Section 3.2). $EM_e \cdot E_s(d,h)$ was considered as the impact avoided elsewhere with the sale of electricity produced by the cogeneration module.

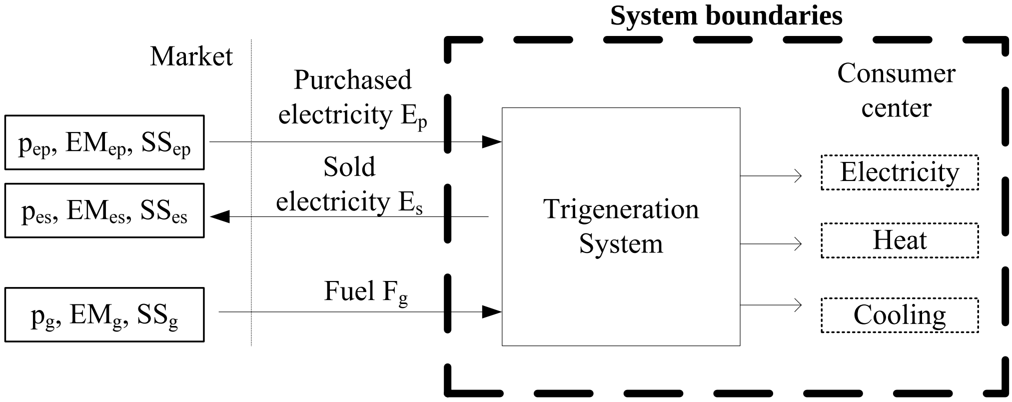

Figure 5.5 System boundaries.

Note that with all objective functions considered, values related to the surplus cogenerated electricity sold to the grid ($EM_e \cdot E_s$, $SS_e \cdot E_s$, $p_{es} \cdot E_s$) are subtracted from annual operation impact and cost.

Operation was subject to capacity limits, production restrictions, and balance equations as previously presented in Equations (5.8)-(5.22).

5.2.1.2 EI-99 Objective function

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 (5.60) – (5.62) were changed to

$$\text{Min } SS_{tot} = SS_{fix} + SS_{ope} \tag{5.63}$$

$$SS_{fix} = fam_e \cdot \Sigma_i \, NIN(i) \cdot SSI(i) \tag{5.64}$$

$$SS_{ope} = \Sigma_d \, \Sigma_h \, [SS_g \cdot F_g(d,h) + SS_e \cdot E_p(d,h) - SS_e \cdot E_s(d,h)] \tag{5.65}$$

Operation was also subject to capacity limits, production restrictions, and balance equations as previously presented in Equations (5.8)-(5.22).

5.2.2 Results

Once the scenario was completely defined by the conditions previously specified (energy demands, economic and environmental evaluations), the following results were obtained with the optimization model. The model was solved by Lingo by freely selecting the technologies to be installed and minimizing the different objective functions considered. Figure 5.6 and Table 5.5 show the results for the optimization of annual CO_2 emissions and annual EI-99 Single Score.

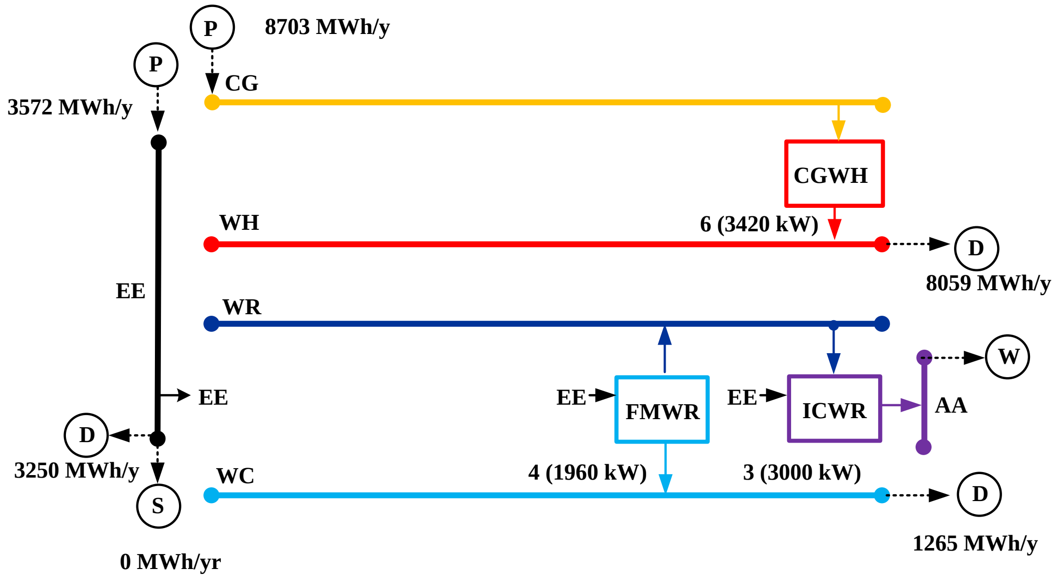

Figure 5.6 Structure of the CO_2 emissions and EI-99 optimizations (identical).

The configuration obtained for the optimal CO_2 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. The configuration is the same as the one presented in Section 5.1.2.1. Detailed flows and operation modes of the environmental optimals can be found in Appendix III.

Table 5.5 Results for annual CO_2 emissions and annual EI-99 optimization.

	Optimal CO_2 system		Optimal EI-99 system	
System Composition	Number	Installed power	Number	Installed power
Gas turbines	-		-	
Gas engines	-		-	
Steam boilers	0		0	
Hot water boilers	6	3420 kW	6	3420 kW
Heat exchangers VA→ WH	0		0	
Heat exchangers WH→ WR	0		0	
Double effect absorption chillers	0		0	
Single effect absorption chillers	0		0	
Mechanical chillers	4	1960 kW	4	1960 kW
Cooling towers	3	3000 kW	3	3000 kW
Natural gas (total) MWh/y	8703		8703	
Purchased electricity MWh/y	3572		3572	
Sold electricity MWh/y	-		-	
Natural gas (cogeneration) MWh/y	-		-	
Cogenerated work MWh/y	-		-	
Cogenerated useful heat MWh/y	-		-	
Primary Energy Savings %	-		-	
Equivalent electrical efficiency %	-		-	
Cost of equipment €/y	219,650		219,650	
Cost of natural gas €/y	217,582		217,582	
Cost of electricity €/y	366,951		366,951	
Profit with the sale of electricity €/y	0		0	
Total annual cost €/y	804,184		804,184	
Environmental load of equipment	43,057 kg CO_2/y		2272 points/y	
Environmental load of purchase of natural gas	2,367,296 kg CO_2/y		328,984 points/y	
Environmental load of purchase of electricity	1,375,264 kg CO_2/y		80,730 points/y	
Environmental benefit of sale of electricity	-		-	
Total environmental load	3,785,617 kg CO_2/y		411,986 points/y	

Cogeneration and trigeneration systems present higher energy and economic efficiency than conventional energy supply systems. However, this does not necessarily represent reduction in emissions, which depends on the local energy supply conditions (Carvalho *et al.*, 2010b; Carvalho *et al.*, 2010c; Meunier, 2002; Chevalier & Meunier, 2005; Chicco & Mancarella, 2008; Mancarella & Chicco, 2008) and therefore the environmental results were not totally unexpected.

The environmental optimization carried out in this work is based on specific environmental criteria. Other Life Cycle Assessment methods focus on different environmental aspects, and very likely would provide a different result. Therefore it is very important to select an objective function that appropriately considers the key aspects related to which the system is going to be optimized.

Table 5.6 shows the environmental loads for the economic optimal (minimal annual cost) obtained in Section 5.1.

Table 5.6 CO_2 emissions and EI-99 Single Score for the economic optimal.

		Economic optimal	Environmental optimal	variation %
CO_2 emissions kg CO_2/y	Emissions of equipment	52,699	43,057	-18.30
	Emissions of purchase of natural gas	10,152,037	2,367,296	
	Emissions of purchase of electricity	11,168	1,375,264	
	Avoided emissions/sale of electricity	4,384,799	-	
	Total annual emissions	5,831,105	3,785,617	-35.08
EI-99 points /y	Environmental load of equipment	3908	2272	-41.86
	Environmental load purchase of natural gas	1,410,835	328,984	
	Environmental load purchase of electricity	656	80,730	
	Avoided load/sale of electricity	257,393	-	
	Total environmental load	1,158,005	411,986	-64.42

A breakdown of the environmental loads of the optimal economic and environmental configurations is shown in Tables 5.7 and 5.8.

Table 5.7 Breakdown of EI-99 Single Score for the economic optimal.

	Impact category	Unit	Total	Natural gas	Electricity	Equipment
Human Health	Carcinogens	points	-17,631	530	-18,482	114
	Resp. organics	points	-0.162	23	-24	286
	Resp. inorganics	points	-23,079	50,002	-74,044	302
	Climate change	points	23,257	42,215	-19,246	95
	Radiation	points	-1208	9	-1220	12
	Ozone layer	points	31	21	-5	85
Ecosystem Quality	Ecotoxicity	points	-3699	462	-4419	191
	Acidification/ Eutrophication	points	3967	12,203	-8354	143
	Land use	points	-541	1929	-2579	414
Resources	Minerals	points	-442	309	-1308	577
	Fossil fuels	points	1,177,354	1,303,132	-127,055	1689
	Total	points	1,158,005	1,410,835	-256,737	3908

Table 5.8 Breakdown of EI-99 Single Score for the environmental optimal.

	Impact category	Unit	Total	Natural gas	Electricity	Equipment
Human Health	Carcinogens	points	6139	124	5811	204
	Resp. organics	points	13	5	7	~ 0
	Resp. inorganics	points	35,488	11,659	23,282	546
	Climate change	points	16,099	9843	6052	204
	Radiation	points	388	2	383	~ 2
	Ozone layer	points	25	5	2	~ 18
Ecosystem Quality	Ecotoxicity	points	1602	108	1389	105
	Acidification/ Eutrophication	points	5524	2845	2627	51
	Land use	points	1332	450	811	71
Resources	Minerals	points	990	72	411	507
	Fossil fuels	points	344,385	303,871	43,866	564
	Total	points	411,986	328,984	80,730	2272

It can be observed that in the case of the economic optimal, the electricity sold to the grid is responsible for a considerable reduction in the final environmental load. In some impact categories the minimum cost solution performs better than the minimum environmental impact solution. In both designs, the main contribution to the overall impact is given by the extraction of fossil fuels followed by climate change. Although with almost triple the annual EI-99 Single Score, the economic optimal has negative values for the impact categories of carcinogens, respiratory inorganics, radiation, ecotoxicity, land use and minerals. These results exposed the complexity of carrying out an environmental optimization, as there are multiple (and sometimes opposite) factors to be considered. This highlights the necessity of establishing and determining with greater precision the environmental loads and impacts, in order to obtain clear indications at the time of making decisions regarding the minimization of environmental loads.

5.3 MULTIOBJECTIVE OPTIMIZATION

Steps towards the design of sustainable energy systems must include tools for simultaneously considering the broad range of criteria linked to the thermodynamic, economic and environmental performance assessment of a system. The increasing need for more efficient systems that are both economically attractive and friendlier to the environment request the development of new criteria and determine new design rules. It is obvious that the design of such a system is associated with conflicting objectives (Kavvadias and Maroulis, 2010), as it is often expensive to utilize environmentally friendly technologies.

Trigeneration systems are usually studied from an economic, energetic or environmental point of view. In the case of multiple objectives, there does not necessarily exist a solution that is best with respect to all objectives because of differentiation between objectives (Sivanandam & Deepa, 2008). A solution may be best in one objective but worst in another. Therefore, there usually exists a set of solutions for the multiple-objective case, which cannot simply be compared with each other. For such solutions, called Pareto optimal[15] solutions or non-dominated solutions, no improvement is possible in any objective function without sacrificing at least one of the other objective functions. The optimal trade-off solutions of certain conflicting objective criteria are valuable for the decision-maker in order to choose the best solution suited to its needs.

5.3.1 Solution method

To compare candidate solutions to the multiobjective problems, the concepts of Pareto dominance and Pareto optimality are commonly used. A solution belongs to the Pareto set if

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[15] The term is named after Vilfredo Pareto, an Italian economist who used the concept in his studies of economic efficiency and income distribution.

there is no other solution that can improve at least one of the objectives without degradation any other objective.

According to (Ngatchou *et al.,*2005), Pareto dominance is used to compare and rank decision vectors: **u** dominates **v** in the Pareto sense means that **f(u)** is better or equal than **f(v)** for all objectives, and there is at least one objective function for which **f(u)** is strictly better than **f(v)**. A solution **a** is said to be Pareto optimal if and only if there does not exist another solution that dominates it. In other words, solution cannot be improved in one of the objectives without adversely affecting at least one other objective. The corresponding objective vector **f(a)** is called a Pareto dominant vector, or non-inferior or non-dominated vector. The set of all Pareto optimal solutions is called the Pareto optimal set. The corresponding objective vectors are said to be on the Pareto front. It is generally impossible to come up with an analytical expression of the Pareto front. Figure 5.7 depicts a Pareto set for a two-objective minimization problem. Potential solutions that optimize f_1 and f_2 are shown on the graph. The Pareto Optimal Front describes the relationship between key performance indicators: annual costs and CO_2 emissions for example.

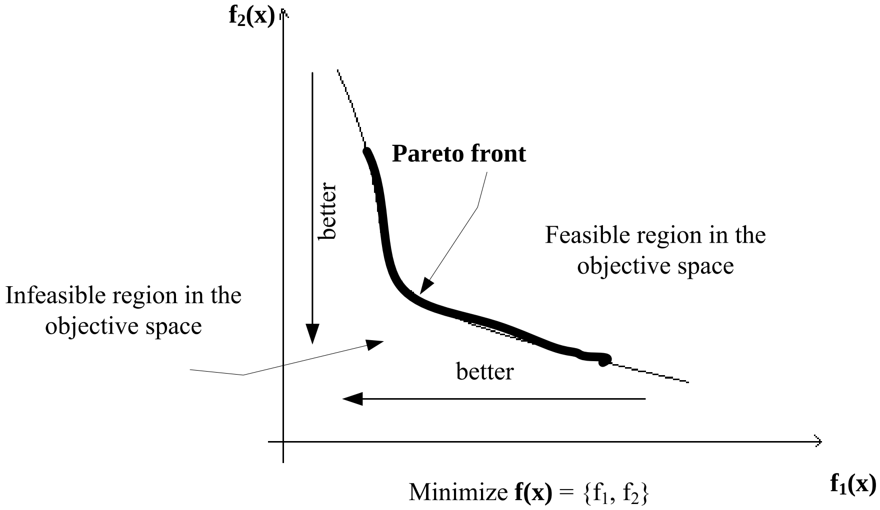

Figure 5.7 Pareto front.

Many methods are available for solving multiobjective optimization problems (Rangaiah, 2009). Some methods involve converting the multiobjective problem into a series of single objective optimization problems. An important question is the role of the decision maker in solving the multiobjective problem. Generating methods with a posteriori analysis of Pareto fronts are preferred (Li *et al.*, 2006; Silva *et al.*, 2008). Among them, the $\in$-constraint has been applied by various authors to similar problems (Hugo & Pistikopoulos, 2005; Gebreslassie *et al.*, 2009). The design task is posed as a bi-criteria programming problem, which can be mathematically expressed as Minimize $\mathbf{f(x)} = \{f_1, f_2\}$. The solution to this problem is given by a set of efficient or Pareto optimal points representing alternative process designs, each achieving a unique combination of environmental and economic performances.

For the calculation of the Pareto optimal points, the ϵ-constraint method was chosen, which is rigorous for convex and non-convex problems. This method is based on formulating an auxiliary model, which is obtained by transferring one of the objectives of the original problem to an additional constraint. This constraint imposes an upper limit on the value of the secondary objective. The problem is repeatedly solved for different values of $\in$ to generate the entire Pareto set; it is a relatively simple technique, yet it is computationally intensive (Ngatchou *et al.,*2005). The problem can be mathematically expressed as:

Min $\mathbf{f_2(x)}$

Subject to $\mathbf{f_1(x)} \leq \in_j$

With $\in_j = \in_1, \in_2, \ldots$

$\mathrm{Lim}_{inf} \leq \in_j \leq \mathrm{Lim}_{sup}$

Where Min $\mathbf{f_2(x)}$ is the economic objective function and Min $\mathbf{f_1(x)}$ is the environmental objective function. If the model is solved for all possible values of $\in$ and the resulting solutions are unique, then these solutions represent the entire Pareto set of solutions of the original multiobjective problem. The extreme points of the interval $[\mathrm{lim}_{inf}, \mathrm{lim}_{sup}]$ within which $\in$ should fall, can be determined by solving each single objective problem separately. The procedure explained by Gebreslassie *et al.* (2009) will be followed in a step-by-step manner.

5.3.2 Economic and CO_2 emissions multiobjective optimization

First step: obtain the first two points of the curve, by optimizing each objective function separately, providing the superior and inferior limits for ϵ. The same optimization model used for economic and environmental optimization was utilized. lim_{sup} = 5,831,105 kg CO_2/y (economic optimal) and lim_{inf} = 3,785,617 kg CO_2/y (environmental optimal) , shown in Figure 5.8. As can be observed in the figure, there is a clear trade-off between both objective functions, since a reduction in the total emissions can only be achieved at the expense of an increase in the total annualized cost. Points A and B are the optimal design solutions with minimum emissions and total annualized cost values, respectively. In the optimal solution A, the total annualized cost is 41% greater than in solution B, whereas in B the emissions generated are 54% greater than in A.

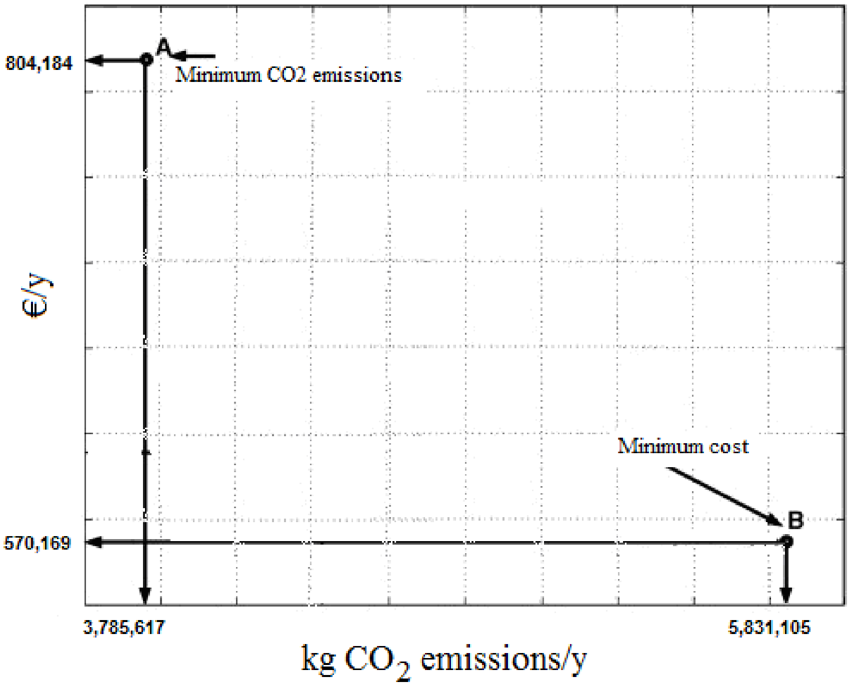

Figure 5.8 Extreme Pareto optimal solutions.

Second step: Interval [lim_{inf}, lim_{sup}] is partitioned into 20 sub-intervals, and the model is solved for each of the limits of these sub-intervals.

It is interesting to point out the fact that the optimization carried out encompasses not only the operational strategy of a system, but also the configuration. The set of optimal solutions is composed of configurations that have been able to adapt their strategy only within a specific range of the Pareto frontier. Figure 5.9 shows the different configurations obtained and their behavior, where E = gas engine, B = hot water boiler, A = single effect absorption chiller, and M = mechanical chiller.

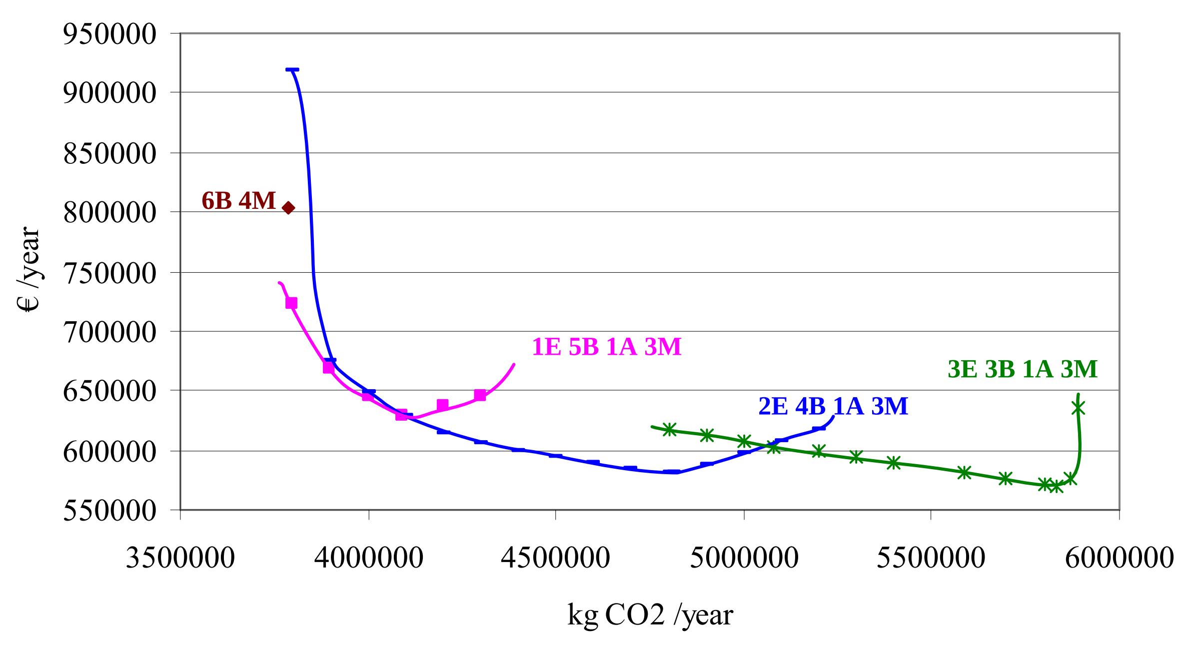

Figure 5.9 Economic and CO_2 emissions multiobjective optimization solutions.

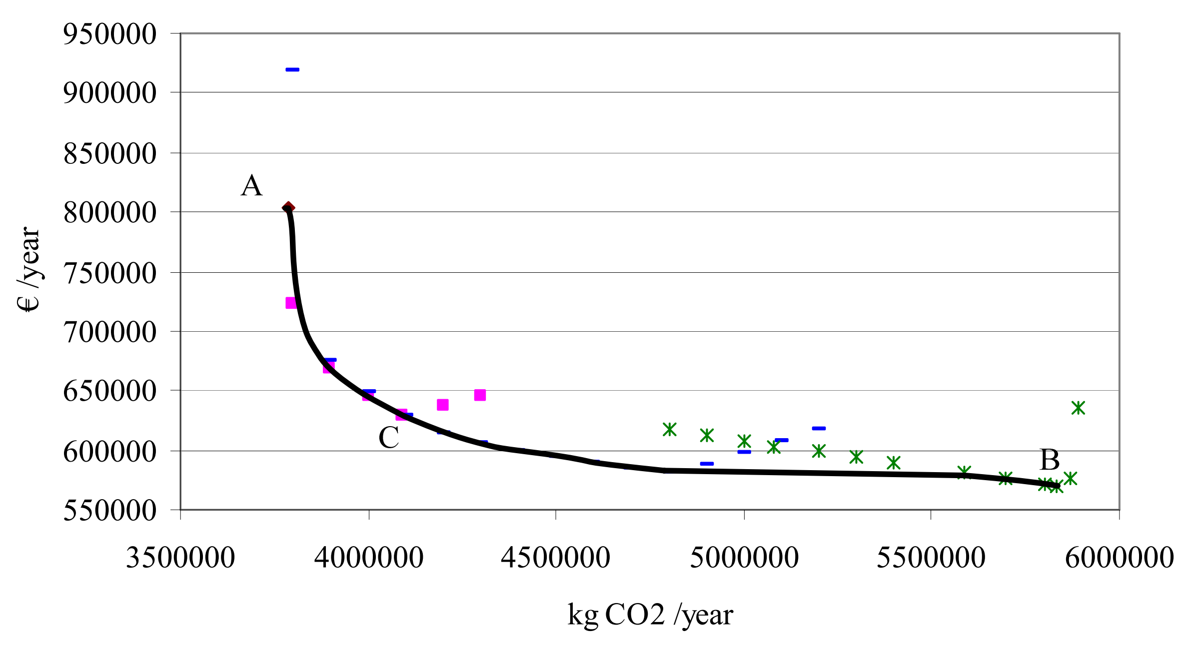

Figure 5.10 Pareto frontier considering the annual cost and annual CO_2 emissions.

Figure 5.10 shows the Pareto frontier obtained. Each point in the Pareto frontier represents a different optimal system (different optimal configuration and/or operation, as both configuration and operational conditions may vary) which operates under an annual CO_2 emissions limit and a set of specific conditions. Furthermore, each trade-off solution involves a different compromise between both criteria.

Significant reductions in costs can be attained if the decision-maker is willing to compromise the environmental performance of the system. Our methodology is intended to promote a more sustainable design of trigeneration by guiding the economic decision-makers towards the adoption of alternatives that cause less environmental impact (Gebreslassie *et al.*, 2009).

Point C (configuration 2E 4B 1A 3M) represents the preferred intermediate Pareto optimal solution in the interval [lim_{inf}, lim_{sup}]. Point C was chosen because it was considered to be a good trade-off between CO_2 emissions and cost, after systematic calculations of decrease in emissions versus increase in cost for each point of the interval [lim_{inf}, lim_{sup}]. Point C represents a pronounced decrease in cost (- 22%) compared to point A and a small sacrifice in CO_2 emissions (+ 9%) compared to point B. Configuration 2E 4B 1A 3M presents a wide range of possible operation modes (blue line in Figure 5.9) and is an adequate option, adaptable to different operational circumstances. Table 5.9 shows the main features of solutions A, B and C.

Analyzing Figure 5.10 and Table 5.9 together and noting that Spanish data for 2007 has the particularity of being the breakpoint for installation of cogeneration (as explained previously in the environmental optimization), the considerable drop in annual cost between point A and point C is due to installation of cogeneration modules and consequent sale of electricity to realize profit. From point A on, the consumption of natural gas and sale of cogenerated electricity is increasing, and the purchase of electricity from the grid is decreasing.

Table 5.9 Optimal solutions A, B and C for economic and CO_2 multiobjective.

	A		**C**		**B**	
System composition	Number	Installed Power	Number	Installed Power	Number	Installed Power
Gas turbines	0		0		0	
Gas engines	0		2	1160 kW	3	1739 kW
Steam boilers	0		0		0	
Hot water boilers	6	3420 kW	4	2280 kW	3	1710 kW
Heat exchangers VA→ WH	0		0		0	
Heat exchangers WH→ WR	0		1	400 kW	4	1600 kW
Double effect absorption chillers	0		0		0	
Single effect absorption chillers	0		1	490 kW	1	490 kW
Mechanical chillers	4	1960 kW	3	1470 kW	3	1470 kW
Cooling towers	3	3000 kW	3	3000 kW	3	3000 kW
Natural gas (total) MWh/y	8703		20,370		37,324	
Purchased electricity MWh/y	3572		203		29	
Sold electricity MWh/y	-		4070		11,389	
Natural gas (cogeneration) MWh/y	-		18,068		36,638	
Cogenerated work MWh/y	-		7375		14,954	
Cogenerated useful heat MWh/y	-		6706		8602	
Primary Energy Savings %	-		20.80		10.01	
Equivalent electrical efficiency %	-		69.50		55.22	
Cost of equipment €/y	219,650		413,195		510,830	
Cost of natural gas €/y	217,582		509,252		933,092	
Cost of electricity €/y	366,951		20,278		3207	
Profit with the sale of electricity €/y	-		- 313,396		- 876,960	
Total annual cost €/y	804,184		629,329		570,169	
Emissions of equipment kg CO_2/y	43,057		47,775		52,699	
Emissions of natural gas kg CO_2/y	2,367,296		5,540,660		10,152,037	
Emissions of electricity kg CO_2/y	1,375,264		78,297		11,168	
Avoided emissions/sale electricity kg CO_2/y	-		- 1,566,980		- 4,384,799	
Total annual emissions kg CO_2/y	3,785,617		4,099,743		5,831,105	

5.3.3 Economic and EI-99 Single Score multiobjective optimization

The first two points of the curve were obtained, by optimizing each objective function separately, providing the superior and inferior limits for $\in$. Lim_{sup} = 1,158,005 points/y (economic optimal) and Lim_{inf} = 411,986 points (environmental optimal). Points A and B are the optimal design solutions with minimum EI-99 points and total annualized cost values, respectively (Figure 5.12). In the optimal solution A, the total annualized cost is 41% greater than in solution B, whereas in B the emissions generated are 181% greater than in A.

The interval [lim_{inf}, lim_{sup}] was partitioned into 20 sub-intervals, and the model was solved for each of the limits of these sub-intervals. Again, the optimal set of solutions obtained is a composition of optimal configurations that adapt their operational strategy until a forced change in configuration occurs, yielding an optimal solution. Figure 5.11 shows the different configurations obtained and their behavior, where E = gas engine, B = hot water boiler, A = single effect absorption chiller, and M = mechanical chiller.

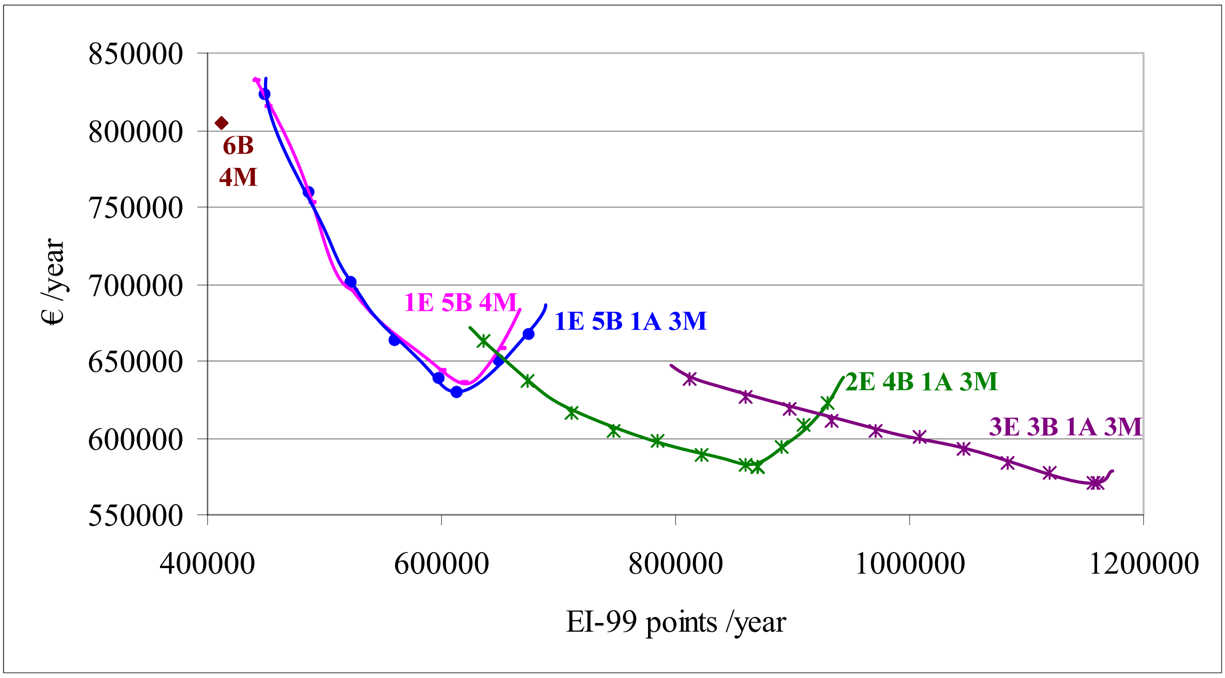

Figure 5.11 Economic and EI-99 Single Score multiobjective optimization solutions.

Figure 5.12 shows the Pareto frontier obtained. Each point in the Pareto frontier represents a different optimal system (optimal configuration and operation, as both configuration and operational conditions may vary) which operates under a set of specific conditions. Furthermore, each trade-off solution involves a different compromise between both criteria.

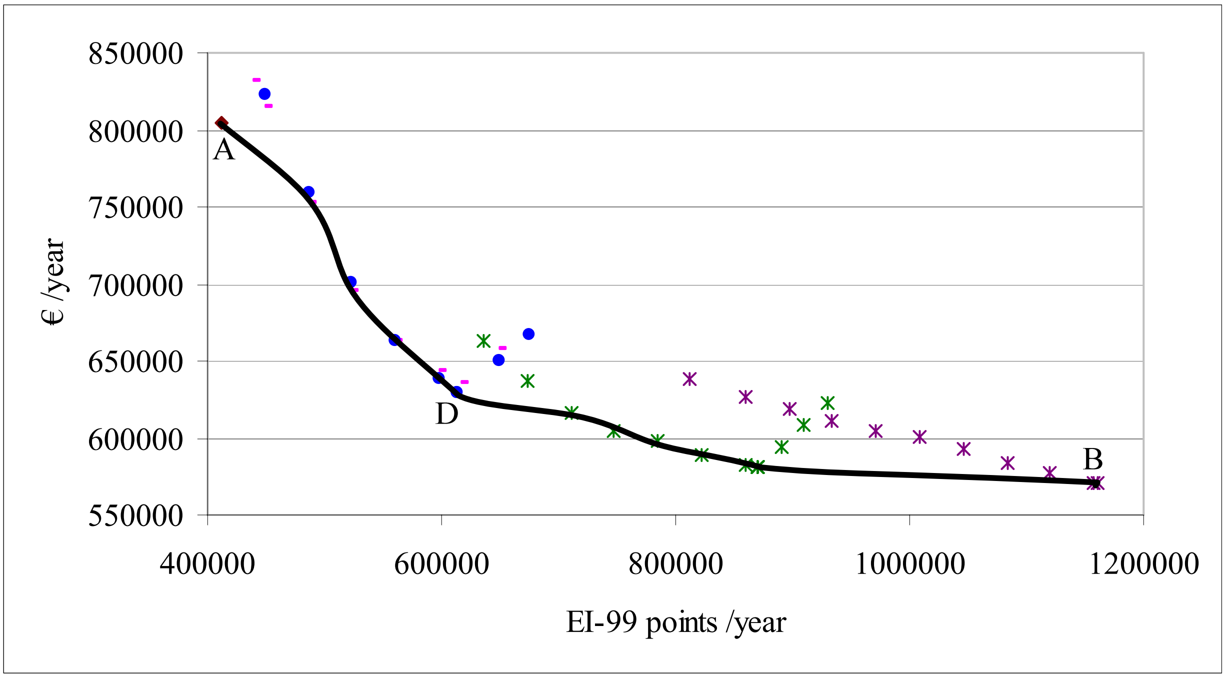

Figure 5.12 Pareto frontier considering the annual cost and annual EI-99 points.

Point D (configuration 1E 5B 1A 3M) represents the preferred intermediate Pareto optimal solution in the interval [lim_{inf}, lim_{sup}], being a good trade-off between EI-99 and cost, after systematic calculations of decrease in points versus increase in cost for each point of the interval [lim_{inf}, lim_{sup}]. Point D represents a pronounced decrease in cost (- 21%) compared to point A and an increase in EI-99 points (+ 45%). Note that limit x-coordinate values of this graph are much more separated than those of Figure 5.10, implying an expected greater increase in EI-99 points when traveling along the Pareto frontier towards minimum cost. Table 5.10 shows the main features of solutions A, B and D.

Similarly to the trend in the economic and CO_2 multiobjective solutions, the consumption of natural gas and sale of cogenerated electricity increase with the increase of EI-99 Single Scores, while purchase of electricity from the grid decreases. The system slowly installs cogeneration modules and removes hot water boilers, while the production of cooling remains almost fixed by one absorption chiller and three mechanical chillers. The number of hot water – refrigeration water heat exchangers oscillated to accommodate restriction on the EI-99 points ([lim_{inf}, lim_{sup}]), and exchangers were added when more heat was wasted. Configuration 1E 5B 1A 3M presents a smaller range of adaptability when compared to configuration 2E 4B 1A 3M in the CO_2 multiobjective optimization.

Table 5.10 Optimal solutions A, B and D for economic and EI-99 multiobjective.

	A		**D**		**B**	
System composition	Number	Installed Power	Number	Installed Power	Number	Installed Power
Gas turbines	0		0		0	
Gas engines	0		1	580 kW	3	1739 kW
Steam boilers	0		0		0	
Hot water boilers	6	3420 kW	5	2280 kW	3	1710 kW
Heat exchangers VA→ WH	0		0		0	
Heat exchangers WH→ WR	0		1	400 kW	4	1600 kW
Double effect absorption chillers	0		0		0	
Single effect absorption chillers	0		1	490 kW	1	490 kW
Mechanical chillers	4	1960 kW	3	1470 kW	3	1470 kW
Cooling towers	3	3000 kW	3	3000 kW	3	3000 kW
Natural gas (total) MWh/y	8703		16,538		37,324	
Purchased electricity MWh/y	3572		226		29	
Sold electricity MWh/y	-		1537		11,389	
Natural gas (cogeneration) MWh/y	-		11,782		36,638	
Cogenerated work MWh/y	-		4809		14,954	
Cogenerated useful heat MWh/y	-		4412		8602	
Primary Energy Savings %	-		21.04		10.01	
Equivalent electrical efficiency %	-		69.91		55.22	
Cost of equipment €/y	219,650		320,045		510,830	
Cost of natural gas €/y	217,582		413,452		933,092	
Cost of electricity €/y	366,951		23,003		3207	
Profit sale of electricity €/y	-		- 118,353		- 876,960	
Total annual cost €/y	804,184		638,148		570,169	
Single Score of equipment points/y	2272		2984		3908	
Single Score of natural gas points/y	328,984		625,140		1,410,835	
Single Score of electricity points/y	80,730		5102		656	
Avoided Single Score/sale electricity points/y	-		- 34,737		257,393	
Total annual Single Score points/y	411,986		598,488		1,158,005	

The choice of one configuration considering economic and environmental viewpoints leads to the choice of configuration 2E 4B 1A 3M, which clearly perfoms better and in a wider range of adaptability in the economic/CO_2 optimization. Note that configuration 2E 4B 1A 3M does not perform significantly worse in the economic/EI-99 optimization (green line in Figure 5.11), as the designer may accept small increases in costs over the economic minimum and still guarantee optimal conditions under small increases in the annual EI-99 Single Score.

5.4 CONCLUSIONS

A mixed integer linear programming model optimized the configuration and operation of a trigeneration system to be installed in a hospital. Three objective functions were considered: the total annual cost (in €/y), annual kilograms of CO_2 emissions (kg CO_2/y), and annual Eco-indicator 99 Single Score (points/y).

Influence of local economic/environmental conditions was verified. The price/environmental loads of energy resources, the price/environmental loads and amortization possibilities of the equipment, the options to sell the surplus electricity to the electric grid, and the possibility that the system helped mitigate climate change (avoiding emissions elsewhere) were all taken into account. No steam demand was considered (outsourcing of laundry and sterilization services).

Interestingly, the 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 total cost. Gas turbine cogeneration modules were not installed. This could mainly be attributed to the lower electric efficiency of gas turbines, greater investment cost per unit of power, as well as elevated associated environmental impact.

The cost assessment rule established in Chapter II for a simple trigeneration system was applied to the economic optimal (a more complex system), yielding cheaper energy services than those that would be provided by conventional devices.

Comparison of economic and environmental optimals showed clearly different structures. Optimal configurations based on conventional equipment (such as hot water boilers, mechanical chillers and cooling towers) were obtained by separately minimizing CO_2 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.

Multiobjective optimization techniques allow the enlargement of the perspective of single-objective energy system analyses and the determination of the complete spectrum of solutions that optimize the design according to more than one objective at a time. As in most practical problems, multiple objectives compete with one another and a unique optimal solution with respect to all of them cannot be identified. The issue of multiobjective optimization was tackled, in the form of a bicriteria programming problem. The same Lingo model of single-objective optimization was adapted for application of the ϵ-constraint method, and the solution of the model provided a set of Pareto optimal design alternatives. Two multiobjective optimizations were carried out, considering economic (annual cost) and environmental viewpoints (represented separately by annual CO_2 emissions and EI-99 points). Solutions close to the environmental minimum were associated with a steep increase in the economic objective. Problems were compared and it was observed that some configurations were more stable along the Pareto frontier. The judgment of the solutions and the trade-offs involved led to the choice of configuration 2E 4B 1A 3M. Significant reductions in the environmental impact could be attained if the economic performance was compromised.

CHAPTER VI

SYNTHESIS OF TRIGENERATION SYSTEMS – SENSITIVITY AND GEOGRAPHIC ANALYSES –

Mathematical programming strives to provide decision makers with both optimal solutions and insight into the underlying problems. An insight into a solution reveals how optimal decisions are affected by information updates on resource availability, demand fluctuations, productions costs or new developments. In linear programming, much of this information can be derived from sensitivity analyses, thereby contributing great strength to the method, computing exactly the effect of changes in data. The sensitivity of a variable illustrates the care that modellers must take to obtain and employ an appropriate value for the variable, but can also signify its importance in relation to its dependency by the model structure (Saltelli *et al.* 1999).

Chapter V presents optimal solutions for a set of established data, and Chapter IV carries out sensitivity analyses for those optimal solutions.

From an economic point of view, the first sensitivity analysis was carried out by varying the amortization and maintenance factor. A second sensitivity analysis varied the price of natural gas.

From the viewpoint of legal constraints in Spain, the sensitivity analyses verified the effect of legal constraints regarding minimum self-consumption and time-of-delivery feed-in tariffs on the optimal economic energy supply system.

Sensitivity analysis to electricity sources was studied in the CO_2 environmental optimals firstly by varying the source of electricity in Spain, and then by varying local market conditions (natural gas and electricity sources).

Geographic analysis considered a variation in the location of the system in Spain, resulting in different energy service demands. Electricity supply conditions were analyzed in the geographic analysis, as some locations of Spain present different electricity mixes.

As no optimal solution obtained presented the installation of gas turbines, steam boilers, steam-hot water heat exchangers, or double effect absorption chillers, these pieces of equipment do not appear in the tables of this Chapter. Figure 6.1 shows the superstructure of the system minus such equipment.

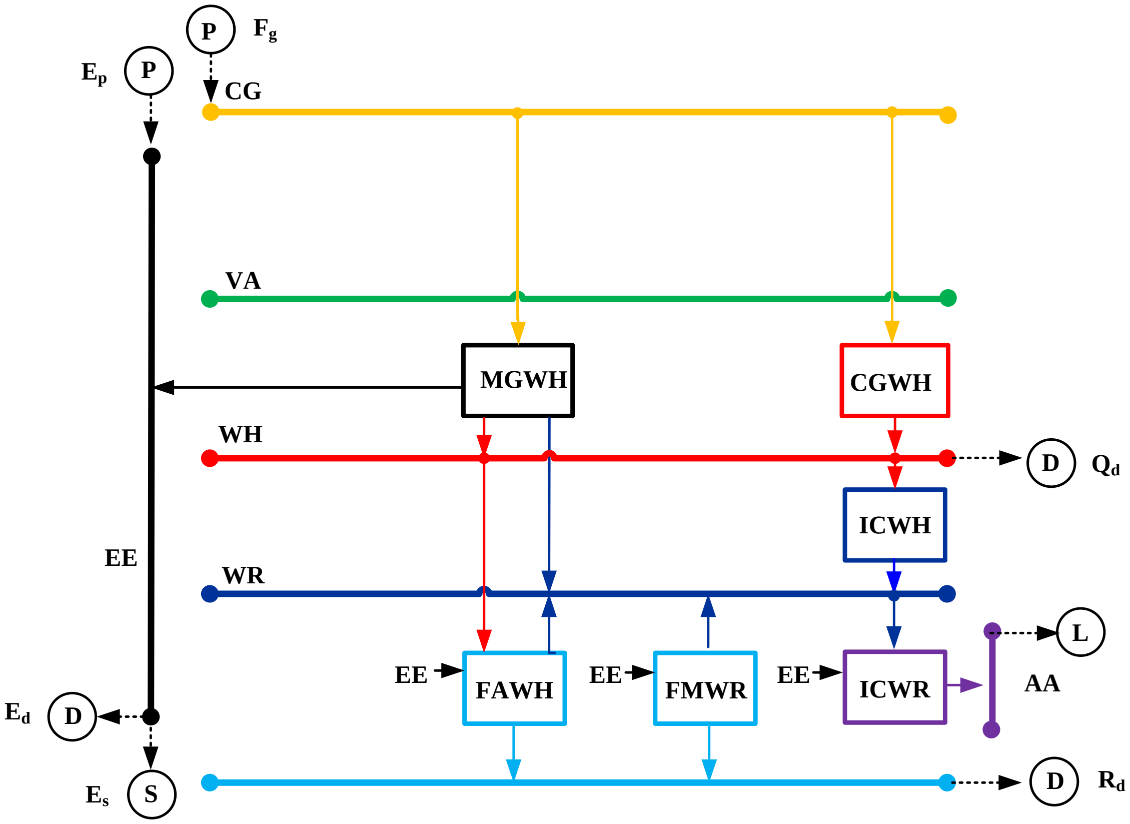

Figure 6.1 Superstructure of the energy supply system used in this Chapter.

6.1 SENSITIVITY TO ECONOMIC FACTORS

Given the energy demand, production coefficients for technologies, and electricity prices, the parameters that could significantly influence the economic optimal system structure and the energy interchanged with the market were the financial conditions and natural gas price. To investigate the influence of these parameters, a sensitivity analysis was carried out by varying the amortization and maintenance factor as well as the natural gas price, starting from the results of the economic optimization previously illustrated in Chapter V.

6.1.1 Sensitivity to amortization and maintenance factor

Firstly, the influence of the amortization and maintenance factor fam was analyzed, varying between 0.10 and 0.30 y^{-1}. Table 6.1 displays the type and number of installed equipment, and annual energy and monetary flows for the optimal design. E stands for gas engines, and A stands for absorption chillers.

Table 6.1 Sensitivity analysis for fam factor.

fam (y^{-1})	0.10	0.15	**0.20**	0.25	0.30
System Composition	E3A2	E3A2	E3A1	E2A1	E2A1
Gas engines	3	3	**3**	2	2
Hot water boilers	3	3	**3**	4	4
Heat exchangers WH→ WR	4	4	**4**	3	3
Single effect absorption chillers	2	2	**1**	1	1
Mechanical chillers	2	2	**3**	3	3
Cooling towers	4	4	**3**	3	3
Natural gas (total) MWh/y	38,028	38,028	**37,324**	26,847	26,847
Purchased electricity MWh/y	0	0	**29**	29	29
Sold electricity MWh/y	11,712	11,712	**11,389**	6620	6620
Natural gas (cogeneration) MWh/y	37,344	37,344	**36,638**	24,741	24,741
Cogenerated work MWh/y	15,242	15,242	**14,954**	10,098	10,098
Cogenerated useful heat MWh/y	9075	9075	**8602**	7288	7288
Primary Energy Savings %	10.74	10.74	10.01	15.08	15.08
Equivalent electrical efficiency %	*55.91*	*55.91*	***55.22***	*60.68*	*60.68*
Cost of equipment €/y	261,165	391,747	**510,830**	520,231	624,278
Cost of natural gas €/y	950,705	950,705	**933,092**	671,163	671,163
Cost of electricity €/y	0	0	**3207**	3207	3207
Profit with the sale of electricity €/y	- 901,838	- 901,838	**- 876,960**	- 509,717	- 509,717
Total annual cost €/y	*310,032*	*440,614*	**570,169**	*684,885*	*788,931*

A trend was observed: as the fam factor increased, the number of cogeneration modules and absorption chillers as well as the sale of electricity decreased. The purchased electricity reached a null value with fam less than 0.20 y^{-1}, when three gas engines and two absorption chillers were installed. With fam = 0.20 y^{-1}, one absorption chiller with one cooling tower were replaced by one mechanical chiller, reducing the investment. With fam greater than 0.20 y^{-1}, a gas engine was eliminated, reducing the inversion but with a consequent reduction in the production of electricity and cogenerated heat. The sale of electricity decreased and it was necessary to install another hot water boiler to supply heat.

6.1.2 Sensitivity to natural gas prices

Secondly, the influence of the natural gas price was analyzed. Table 6.2 displays the type and number of installed equipment for values of p_g between 0.015 and 0.035 €/kWh, and annual energy and monetary flows for the economic optimal.

Table 6.2 Sensitivity analysis for natural gas prices.

p_g (€/kWh)	0.015	0.020	**0.025**	0.030	0.035
System Composition	E3A2	E3A2	**E3A1**	E2A1	E1A1
Gas engines	3	3	**3**	2	1
Hot water boilers	3	3	**3**	4	5
Heat exchangers WH→ WR	4	4	**4**	2	1
Single effect absorption chillers	2	2	**1**	1	1
Mechanical chillers	2	2	**3**	3	3
Cooling towers	4	4	**3**	3	3
Natural gas (total) MWh/y	38,028	38,028	**37,324**	25,977	17,199
Purchased electricity MWh/y	0	0	**29**	29	83
Sold electricity MWh/y	11,712	11,712	**11,389**	6273	1660
Natural gas (cogeneration) MWh/y	37,344	37,344	**36,638**	23,871	12,425
Cogenerated work MWh/y	15,242	15,242	**14,954**	9743	5072
Cogenerated useful heat MWh/y	9075	9075	**8602**	7288	4525
Primary Energy Savings %	10.74	10.74	10.01	15.93	20.32
Equivalent electrical efficiency %	*55.91*	*55.91*	***55.22***	*61.77*	*68.55*
Cost of equipment €/y	522,330	522,330	**510,830**	414,690	320,045
Cost of natural gas €/y	570,423	760,564	**933,092**	779,306	599,155
Cost of electricity €/y	0	0	**3207**	3207	9424
Profit with the sale of electricity €/y	- 901,838	- 901,838	**- 876,960**	- 483,019	- 127,847
Total annual cost €/y	*190,915*	*381,056*	***570,169***	*714,185*	*800,776*

Not much variety was observed in the optimal configurations, and the results were logical in the sense that the operation of the system adapted to the price of natural gas, realizing profit by taking advantage of its low price and selling electricity to the grid.

As the price of natural gas increased, the number of cogeneration modules and absorption chillers as well as the sale of electricity decreased. The purchased electricity reached a null value with p_g less than 0.025 €/kWh, when three gas engines and two absorption chillers were installed. With $p_g = 0.025$ €/kWh, one absorption chiller and one cooling tower were replaced by one mechanical chiller. This reduced the investment but required purchasing electricity externally. With $p_g = 0.030$ €/kWh, one gas engine was eliminated, reducing the inversion but with a consequent reduction in the production of electricity and cogenerated heat. The sale of electricity decreased and it was necessary to install another hot water boiler to supply heat. With $p_g = 0.035$ €/kWh, only one gas engine was installed, the sale of electricity decreased to a reduced value and it was necessary to install another hot water boiler to supply heat.

6.1.3 Structural resilience

Previous analyses considered the design of a new system. However, if the system has already been built, only an operational retrofit will take place. The main optimal economic configuration was maintained, varying firstly fam, and secondly, the price of natural gas. Table 6.3 shows the results for the operational optimal strategy considering the optimal economic configuration with three gas engines, three hot water boiler, four hot water-cooling water heat exchangers, one absorption chiller, three mechanical chillers and three cooling towers (E3A1). Only fam was varied.

Table 6.3 Sensitivity analysis for fam considering a fixed configuration.

fam (y^{-1})	0.10	0.15	**0.20**	0.25	0.30
System Composition					
Gas engines	3	3	**3**	3	3
Hot water boilers	3	3	**3**	3	3
Heat exchangers WH→ WR	4	4	**4**	4	4
Single effect absorption chillers	1	1	**1**	1	1
Mechanical chillers	3	3	**3**	3	3
Cooling towers	3	3	**3**	3	3
Natural gas (total) MWh/y	37,324	37,324	**37,324**	37,324	37,324
Purchased electricity MWh/y	29	29	**29**	29	29
Sold electricity MWh/y	11,389	11,389	**11,389**	11,389	11,389
Natural gas (cogeneration) MWh/y	36,638	36,638	**36,638**	36,638	36,638
Cogenerated work MWh/y	14,954	14,954	**14,954**	14,954	14,954
Cogenerated useful heat MWh/y	8602	8602	**8602**	8602	8602
Primary Energy Savings %	10.01	10.01	**10.01**	10.01	10.01
Equivalent electrical efficiency %	*55.22*	*55.22*	***55.22***	*55.22*	*55.22*
Cost of equipment €/y	255,415	383,122	**510,830**	638,538	766,245
Cost of natural gas €/y	933,092	933,092	**933,092**	933,092	933,092
Cost of electricity €/y	3207	3207	**3207**	3207	3207
Profit with the sale of electricity €/y	- 876,960	- 876,960	**- 876,960**	- 876,960	- 876,960
Total annual cost €/y	*314,754*	*442,462*	**570,169**	*697,877*	*825,584*

Table 6.4 shows the results for the operational optimal strategy considering the same optimal economic fixed configuration E3A1. Only the price of natural gas was varied.

Table 6.4 Sensitivity analysis for natural gas price considering a fixed configuration.

p_g (€/kWh)	0.015	0.020	**0.025**	0.030	0.035
System Composition					
Gas engines	3	3	**3**	3	3
Hot water boilers	3	3	**3**	3	3
Heat exchangers WH→ WR	4	4	**4**	3	1
Single effect absorption chillers	1	1	**1**	1	1
Mechanical chillers	3	3	**3**	3	3
Cooling towers	3	3	**3**	3	3
Natural gas (total) MWh/y	37,338	37,324	**37,324**	37,324	24,218
Purchased electricity MWh/y	27	29	**29**	29	34
Sold electricity MWh/y	11,389	11,389	**11,389**	11,389	6089
Natural gas (cogeneration) MWh/y	36,638	36,638	**36,638**	36,638	23,437
Cogenerated work MWh/y	14,954	14,954	**14,954**	14,954	9566
Cogenerated useful heat MWh/y	8602	8602	**8602**	8602	8241
Primary Energy Savings %	10.01	10.01	**10.01**	10.01	19.42
Equivalent electrical efficiency %	*55.22*	*55.22*	***55.22***	*55.22*	*67.00*
Cost of equipment €/y	510,830	510,830	**510,830**	510,830	510,830
Cost of natural gas €/y	560,064	746,473	**933,092**	1,119,719	847,624
Cost of electricity €/y	2990	3207	**3207**	3207	3731
Profit with the sale of electricity €/y	- 876,960	- 876,960	**- 876,960**	- 876,960	- 468,824
Total annual cost €/y	*196,924*	*383,551*	***570,169***	*756,787*	*893,361*

The data shown in Tables 6.3 and 6.4 suggest that the basic configuration E3A1 is good in terms of optimality and also good in terms of robustness against perturbations of values. Variation of fam did not affect the operational strategy of the system. Variations in operation occurred only for low and high extreme values of the price of natural gas, being the variation only remarkable for p_g = 0.035 €/kWh, when much less natural gas is purchased (and consequently less cogenerated electricity is sold to the grid).

Figure 6.2 shows the behavior of three solutions in response to variations in fam: Conventional (optimal conventional solutions), E3A1 (the aforementioned fixed configuration, data from Table 6.3), and Real (optimal solutions with free choice of equipment, data from Table 6.1).

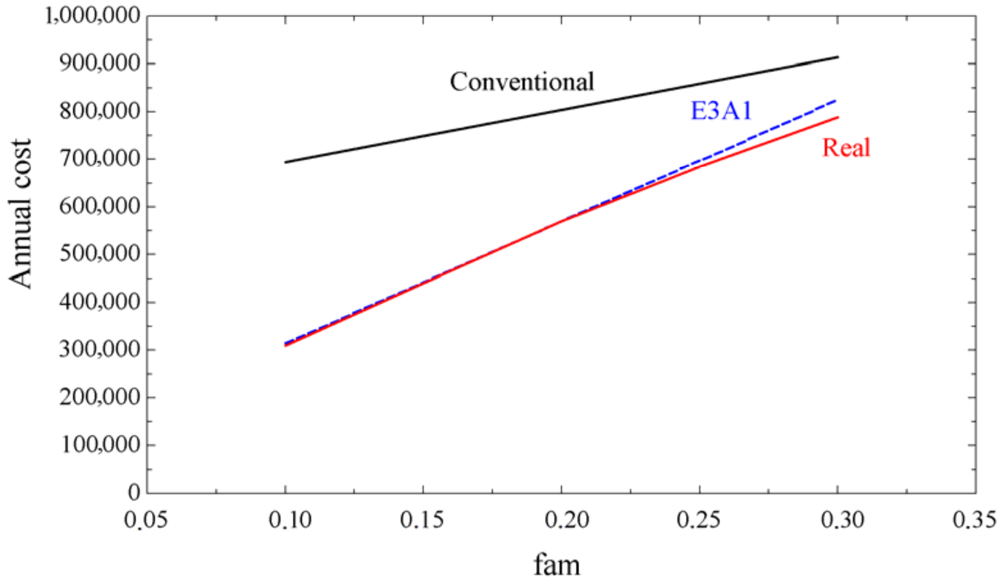

Figure 6.2 Behavior of solutions in response to variations in fam.

Figure 6.3 shows the behavior of the same three solutions in response to variations in the price of natural gas: Conventional (optimal conventional solutions), E3A1 (fixed configuration, data from Table 6.3), and Real (optimal solutions with free choice of equipment, data from Table 6.1).

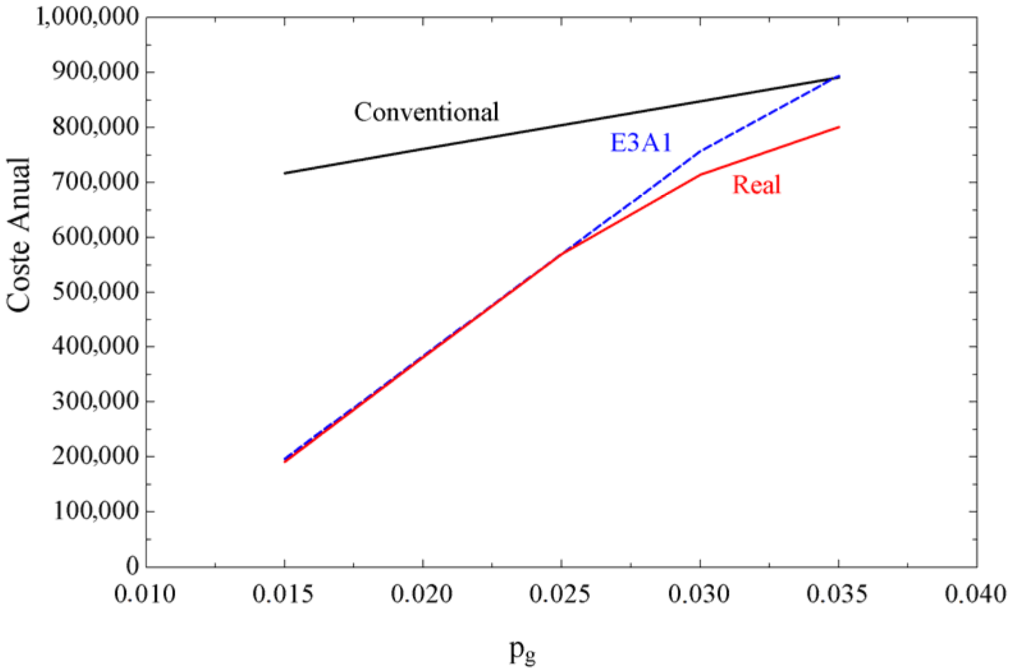

Figure 6.3 Behavior of solutions in response to variations in the price of natural gas.

In many practical optimization tasks, there is a need to search for robust solutions whose value of optimization function is adequate and will not change due to the variation of market conditions. If a solution obtained by the algorithms is sensitive to small perturbations of variables, it may not be appropriate or risky for practical use. With respect to the economic parameters, Figure 6.2 and 6.3 reveal that the E3A1 design is a wise selection, being stable for a wide interval of annual amortization factors and natural gas prices, and behaving closely to the optimal *real* solutions (with free choice of equipment).

6.2 SENSITIVITY TO LEGAL FACTORS

6.2.1 Self-consumption

In the case of Spain, the design of cogeneration plants is restricted by legal constraints on the electricity production in a Special Regime. In recent years, legal restrictions have been modified and the most significant difference has been the mandatory minimum amount of self-consumed electricity. In 1998, the self-consumption had to be higher than 30% of the electricity produced in the cogeneration plant (RD 2818/1998); in 2004 this limit was reduced to 10% (RD 436/2004); and in 2006 this restriction was eliminated (RDL 7/2006).

This section will apply the aforementioned different values (corresponding to the legal restrictions on self-consumption of electricity) to the economic optimization model of Chapter V, yielding three scenarios (S2D0, S1D0 and the standard case S0D0), shown in Table 6.5. The amortization and maintenance factor fam and prices of natural gas and electricity (purchased and sold) were the same for all scenarios (fam = 0.20 y^{-1}, p_g = 0.025 €/kWh, p_{ep} = 0.095 €/kWh, p_{es} = 0.077 €/kWh).

As the real self-consumption of Scenario S0D0 was 23.83%, the same configuration and operation was maintained when the obligation of self-consumption was raised to 10% in Scenario S1D0. However, a slightly different configuration was obtained in Scenario S2D0 when the obligatory self-consumption was 30%. The obligation of a minimum electricity self-consumption of 30% affected significantly the amount of electricity sold to the electric grid (Scenario S2D0: 6620 MWh/y and Scenarios S1D0 and S0D0: 11,389 MWh/y), installing one less gas engine, and one more hot water boiler; on the operation side, less electricity was sold to the grid. Part of the self-consumption can be justified by the operation of mechanical chillers, which would lead to different configurations in localities with lower cooling demands (= less cogeneration).

Table 6.5 Sensitivity analyses for legal constraints on mandatory self-consumption.

SCENARIO	S2D0	S1D0	**S0D0**
Obligation of self-consumption	> 30%	> 10%	**0%**
System Composition	E2A1	E3A1	**E3A1**
Gas engines	2	3	**3**
Hot water boilers	4	3	**3**
Heat exchangers WH→ WR	3	4	**4**
Single effect absorption chillers	1	1	**1**
Mechanical chillers	3	3	**3**
Cooling towers	3	3	**3**
Natural gas (total) MWh/y	26,847	37,324	**37,324**
Purchased electricity MWh/y	29	29	**29**
Sold electricity MWh/y	6620	11,389	**11,389**
Natural gas (cogeneration) MWh/y	24,741	36,638	**36,638**
Cogenerated work MWh/y	10,098	14,954	**14,954**
Cogenerated useful heat MWh/y	7288	8602	**8602**
Electricity self-consumption %	*34.45*	*23.83*	***23.83***
Primary Energy Savings %	*15.08*	*10.01*	***10.01***
Equivalent electrical efficiency %	*60.68*	*55.22*	***55.22***
Cost of equipment €/y	416,185	510,830	**510,830**
Cost of natural gas €/y	671,163	933,092	**933,092**
Cost of electricity €/y	3207	3207	**3207**
Profit with the sale of electricity €/y	- 509,717	- 876,960	**- 876,960**
Total annual cost €/y	*580,839*	*570,169*	***570,169***

6.2.2 Time-of-delivery ratio in the production of electricity

Time-of-delivery feed-in tariffs help create a more efficient electricity system, while providing a means to encourage peak shaving – this can create a number of benefits for electricity customers, grid operators, and society (Langniss *et al.*, 2009). Some countries provide higher payment levels to encourage electricity generation at times of high demand. Because electricity is more valuable during these times, this incentive structure is one way of aligning the feed-in tariff payment structure to be more market-oriented (Klein *et al.,* 2008).

Cogeneration plants operate in Spain under different economic regimes, depending on the applicable Royal Decree. Standard optimizations of Chapter V were regulated by Royal Decree 661/2007 (2007). The regulated feed-in tariff p_{es} = 0.077 €/kWh to feed electricity to the grid differentiated tariffs by time of delivery, but the increase/discount were so similar that it was considered to be constant.

The time-of-delivery[16] differential in the feed-in tariff of electricity produced in a Special Regime considered in this sensitivity analysis will consider that the day is divided into two periods: 16 on-peak hours with an increase in price, and the 8 remaining hours with a discount. Final feed-in electricity price, p_{es}, was calculated as the multiplication of the corresponding tariff (according to group, subgroup, antiquity, and power range, as shown in Table 4.7) by a time-of-delivery factor (increase or discount). The time-of-delivery factor reflects the fact that electricity delivered to the grid during peak times is more valuable than electricity delivered during other times. Table 6.6 shows the electricity feed-in tariffs with hourly differentiation utilized in the sensitivity analyses carried out in this section.

Table 6.6 Electricity feed-in tariff (€/kWh) with hourly differentiation in two periods.

Scenario	Time-of-Delivery Ratio	On-peak		Off-peak	
		Time	Time-of-Delivery factor	Time	Time-of-Delivery factor
A0D0	1.0	8 – 24	1.000	0 – 8	1.000
A0D1	1.5	8 – 24	1.125	0 – 8	0.750
A0D2	2.0	8 – 24	1.200	0 – 8	0.600

Analyses considered a variation in the ratio between the on-peak and off-peak time-of-delivery factors. Standard data utilized in the optimization model did not account for time of delivery and therefore the ratio is 1.00. Ratios of 2.0 and 1.5 were chosen to carry out the sensitivity analyses, following:

$$\text{(On-peak factor)}\cdot p_g\cdot 16 + \text{(Off-peak factor)}\cdot p_g\cdot 8 = p_g\cdot 24 \qquad (6.1)$$

---

[16] Policies that differentiate feed-in tariffs paid to electricity generated by the same technology have also frequently been referred to as *stepped* or *tiered* feed-in tariffs (Couture *et al.*, 2010)

(On-peak factor) / (Off-peak factor) = ratio (6.2)

Two scenarios were calculated with the economic optimization model, and the results are shown in Table 6.7.

Table 6.7 Sensitivity analyses for hourly differentiation in the feed-in tariff.

Scenario	**A0D0**	A0D1	A0D2
Time-of-Delivery ratio	**1.0**	1.5	2.0
System Composition	**E3A1**	E3A1	E4A2
Gas engines	**3**	3	4
Hot water boilers	**3**	3	2
Heat exchangers WH→ WR	**4**	4	5
Single effect absorption chillers	**1**	1	2
Mechanical chillers	**3**	3	2
Cooling towers	**3**	4	4
Natural gas (total) MWh/y	**37,324**	32,812	39,326
Purchased electricity MWh/y	**29**	0	0
Sold electricity MWh/y	**11,389**	9555	12,384
Natural gas (cogeneration) MWh/y	**36,638**	32,110	39,092
Cogenerated work MWh/y	**14,954**	13,106	15,931
Cogenerated useful heat MWh/y	**8602**	8589	9379
Primary Energy Savings %	***10.01***	*12.86*	*10.50*
Equivalent electrical efficiency %	***55.22***	*58.10*	*55.68*
Cost of equipment €/y	**510,830**	516,580	616,975
Cost of natural gas €/y	**933,092**	820,293	983,159
Cost of electricity €/y	**3207**	0	0
Profit with the sale of electricity €/y	**- 876,960**	- 768,094	- 1,067,473
Total annual cost €/y	***570,169***	*568,780*	*532,662*

Scenario A0D2 presented a slight increase in the sale of cogenerated electricity, taking advantage of the 20% increase in the feed-in tariff between 8-24h to realize profit. However, the initial investment in equipment was considerably higher, installing one more gas engine, one less hot water boiler, and switching one mechanical chiller for an absorption chiller. Scenario A0D1 presented the same configuration as the standard case (A0D0) with the addition of one cooling tower, and selling less cogenerated electricity. Operation changes throughout the day, to adapt to delivering electricity to the grid at on-peak times. With the implementation of hourly differentiation, no purchase of electricity from the grid occurred. Interestingly, no significant increase in the sale of electricity was verified.

6.3 SENSITIVITY TO ELECTRICITY SOURCES

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.

The *Alpha* 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 CO_2 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 CO_2 emissions related to combustion of natural gas plus the total aggregated system inventory for a natural gas user. The Alpha factor for the standard Spanish data utilized throughout this thesis is Alpha = 0.385 / 0.272 = 1.42.

This section carries out two sensitivity analyses in which the energy demands for a medium size hospital (500 beds) located in Zaragoza, Spain are maintained: firstly, the source of electricity in Spain is varied, and secondly, the country of the source of electricity and natural gas supply is varied.

6.3.1 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 3.3). Table 6.8 shows the Alpha factors, the configuration of the optimal system, and main flow values as a function of the origin of electricity.

It was previously noted (Table 5.5) that cogeneration was not installed when Spanish natural gas and electricity mix (Alpha = 1.42) were considered. Table 6.8 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.

Table 6.8 Configuration and main flows of the system, in function of the origin of electricity (CO_2 optimal).

	Spanish mix	Natural gas (Combined cycle)	Fuel-gas	Coal
Alpha factor	**1.42**	1.46	2.38	3.75
System Composition	**E0A0**	E3A0	E5A3	E5A4
Gas engines	**0**	3	5	5
Hot water boilers	**6**	3	1	1
Heat exchangers WH→ WR	**0**	1	2	3
Single effect absorption chillers	**0**	0	3	4
Mechanical chillers	**4**	4	1	0
Cooling towers	**3**	3	5	6
Natural gas (total) MWh/y	**8703**	17,148	29,300	42,882
Purchased electricity MWh/y	**3572**	1573	0	0
Sold electricity MWh/y	**0**	3951	8522	13,969
Natural gas (cogeneration) MWh/y	**0**	14,635	29,275	42,879
Cogenerated work MWh/y	**0**	5973	11,949	17,501
Cogenerated useful heat MWh/y	**0**	5732	9784	9953
Primary Energy Savings %	**0**	22.21	18.15	9.77
Equivalent electrical efficiency %	**0**	72.26	64.93	55.00
Emissions of equipment kg CO_2/y	**43,057**	53,848	57,959	58,161
Emissions of natural gas kg CO_2/y	**2,367,296**	4,664,244	7,969,723	11,663,871
Emissions of electricity kg CO_2/y	**1,375,264**	626,166	0	0
Avoided emissions/sale of electricity kg CO_2/y	**0**	- 1,572,353	-5,505,467	- 14,247,966
Total annual emissions kg CO_2/y	**3,785,617**	3,771,904	2,522,215	- 2,525,935

The primary factors that alter CO_2 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 CO_2 emissions associated with the production of electricity in Spain have oscillated between 0.350 and 0.450 kg CO_2/kWh (REE, 2009). The CO_2 emissions associated with the Spanish electricity mix considered in this paper (EM_e=0.385 kg CO_2/kWh) have the particular feature of being the limit value at which cogeneration modules are not installed. When changing the value of Alpha to 1.43 (EM_e=0.390 kg CO_2/kWh), the solution of the model yields an optimal configuration that presents cogeneration modules.

Options to limit the emission of CO_2 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 (REE, 2009)), it can be deduced that combined cycle is a good reference for an environmental analysis of cogeneration and other alternative electricity sources.

6.3.2 International sources of electricity and natural gas

This section analyzes the effects of using different country values for the emissions of CO_2 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 6.9 shows the countries, emission values, and associated Alpha factors indicating the ratio between local electricity CO_2 emissions and natural gas CO_2 emissions. Table 6.10 shows the optimal configurations of the systems and main flows.

Table 6.9 Emissions associated with electricity and natural gas, per country.

Country	CO_2 emissions associated with consumption		Alpha factor
	Electricity (Mix)	Natural gas	
Canada[1]	0.222 kg CO_2/kWh	0.179 kg CO_2/kWh	1.24
Spain	0.385 kg CO_2/kWh	0.272 kg CO_2/kWh	1.42
Japan[2]	0.380 kg CO_2/kWh	0.248 kg CO_2/kWh	1.53
United Kingdom (U.K.)[3]	0.537 kg CO_2/kWh	0.206 kg CO_2/kWh	2.61
United States of America (U.S.A.)[4]	0.603 kg CO_2/kWh	0.191 kg CO_2/kWh	3.15

[1] CANADA (2009); [2] JAPAN (2008); [3] U.K. DEFRA (2008); [4] U.S. EPA (2008), U.S. EIA (2006).

Table 6.10 Configurations of the systems and main flows, per country (CO_2 optimal).

	Canada	**Spain**	**Japan**	**U.K.**	**U.S.A.**
Alpha factor	1.24	1.42	1.53	2.61	3.15
System Composition	E0A0	**E0A0**	E4A0	E5A4	E5A4
Gas engines	0	**0**	4	5	5
Hot water boilers	6	**6**	2	1	1
Heat exchangers WH→ WR	0	**0**	1	3	3
Single effect absorption chillers	0	**0**	0	4	4
Mechanical chillers	4	**4**	4	0	0
Cooling towers	3	**3**	3	6	6
Natural gas (total) MWh/y	8703	**8703**	17,861	42,886	42,886
Purchased electricity MWh/y	3572	**3572**	1544	0	0
Sold electricity MWh/y	0	**0**	4412	13,970	13,970
Natural gas (cogeneration) MWh/y	0	**0**	15,841	42,883	42,883
Cogenerated work MWh/y	0	**0**	6466	17,503	17,503
Cogenerated useful heat MWh/y	0	**0**	6189	9953	9953
Primary Energy Savings %	0	**0**	22.15	9.76	9.76
Equivalent electrical efficiency %	0	**0**	72.13	55.00	55.00
Emissions of equipment kg CO_2/y	43,057	**43,057**	57,278	58,161	58,161
Emissions of natural gas kg CO_2/y	1,557,889	**2,367,296**	4,429,424	8,834,545	8,191,253
Emissions of purchased electricity kg CO_2/y	793,010	**1,375,264**	586,889	0	0
Avoided emissions kg CO_2/y	0	**0**	- 1,676,537	- 7,502,048	- 8,424,087
Total annual emissions kg CO_2/y	2,393,956	**3,785,617**	3,397,053	1,390,658	- 174,674

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. More precisely, cogeneration was installed when the Alpha factor was higher than 1.43 and from 1.91 onwards, absorption chillers were also installed.

6.4 GEOGRAPHIC ANALYSIS

This section considered that a medium size hospital (500 beds) could be located in different climatic zones throughout Spain (energy demands vary as well as Alpha factor).

6.4.1 Climatic conditions and consumption of energy services

The energy needs of heating, domestic hot water, and cooling of a building depend heavily on local climatic conditions and vary considerably throughout the year, suggesting a strong seasonal character.

Distinct geographic locations were chosen to represent the climatic variability in Spain. There are 12 climatic zones in Spain, in function of climate harshness in winter (A, B, C, D, E) and summer (1, 2, 3, 4). Climate harshness combines degree-days and solar radiation of the locality (CTE, 2006). When two localities have the same climate harshness in winter, the heat demands of identical buildings in both localities is approximately the same; similarly, when two localities have the same climate harshness in summer, the cooling demands of identical buildings in both localities is also approximately the same. Combining the five winter divisions with the four divisions for summer would result in 20 different zones, of which only 12 are realistic for Spanish localities. The 12 zones are identified by a letter (winter division) and a number (summer division), as shown in Figure 6.4.

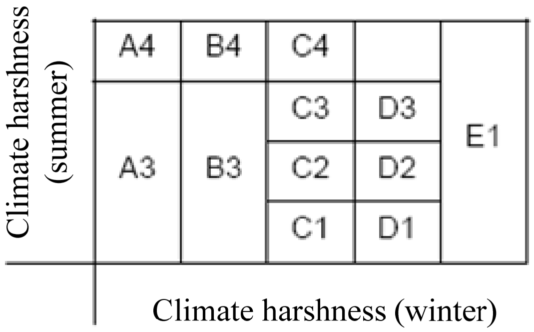

Figure 6.4 Climatic zones in Spain (CTE, 2006).

The following geographic locations were chosen to represent the climatic variability in Spain: Málaga (A3, southern Mediterranean coast), Almería (A4, southern Mediterranean coast), Valencia (B3, eastern Mediterranean coast), Sevilla (B4, southern Spain), Bilbao (C1, northern Atlantic coast), Barcelona (C2, eastern Mediterranean coast), Granada (C3, southern Spain), Cáceres (C4, western central Spain), Lugo (D1, northwestern Spain), Huesca, Zaragoza, and Teruel (D2/D3/D2, northeastern Spain, going from north to south, respectively) and León (E1, northwest Spain). Figure 6.5 shows the location of the selected locations in Spain.

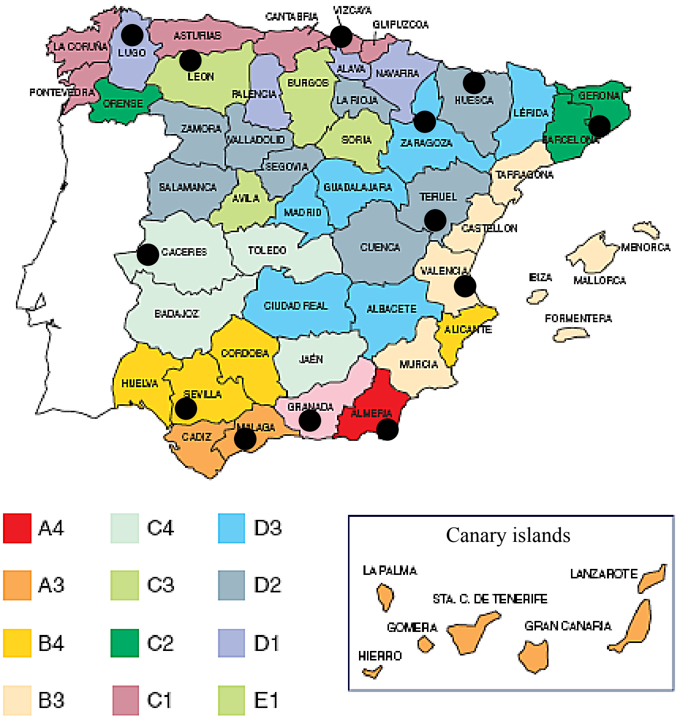

Figure 6.5 Selected locations in Spain (adapted from Construmatica, 2009).

Table 6.11 summarizes the main climatic and geographical information for the selected locations. Data were obtained from the State Meteorological Agency (AEMET, 2009) and from Martín & Olcina (2001).

Table 6.11 Summary of climatic and geographical information for the selected locations.

Locality	Maximum temperature (ºC)[1]	Average temperature (ºC)[1]	Minimum temperature (ºC)[1]	Type of climate	Altitude (m)	Precipitation (mm)
Málaga	22.9	18.0	13.1	Meridional Mediterranean	7	524
Almería	23.1	18.7	14.3	Arid Mediterranean	20	196
Valencia	22.3	17.8	13.4	Mediterranean	11	454
Sevilla	24.9	18.6	12.2	Meridional Mediterranean	26	534
Bilbao	19.1	14.3	9.4	Atlantic Oceanic	39	1195
Barcelona	20.0	15.5	11.1	Mediterranean	6	640
Granada	22.8	15.1	7.5	Mountain Mediterranean	570	357
Cáceres	21.4	16.1	10.8	Meridional Mediterranean	405	523
Lugo	16.8	11.5	6.3	Atlantic Oceanic	444	1084
Huesca	19.0	13.6	8.2	Continental Mediterranean	541	535
Teruel	18.7	11.8	4.9	Mountain Mediterranean	900	373
Zaragoza	20.4	15.0	9.5	Continental Mediterranean	247	318
León	18.1	10.9	7.2	Continental Mediterranean	534	668

[1] Annual average of maximum and minimum daily temperatures (1971-2000).

The procedure described by Sánchez (2003), estimated monthly, daily, and hourly profiles of the representative days based on the size of the hospital and its geographical location in Spain. As many locations presented similar heat/cooling demands, the localities of Lugo, Zaragoza, Cáceres and Málaga were selected for visualization of results in this section. Table 6.12 shows the annual demands for the selected hospital locations.

Table 6.12 Heat, cooling, and electricity demands for the selected hospital locations.

	Heat (MWh/y)	Cooling (MWh/y)	Electricity (MWh/y)
Lugo	10,189	0	3250
Zaragoza	8059	1265	3250
Cáceres	7269	1644	3250
Málaga	5581	1941	3250

6.4.2 Economic and environmental optimals

Once the scenario defined by the model and conditions previously shown was specified, the following results were obtained. The model was solved by Lingo, freely selecting the technologies to be installed and minimizing the different objective functions considered. Table 6.13 shows the results from the CO_2 and EI-99 (H/H) optimization for the different localities considered. Lugo and Zaragoza presented the same configuration for CO_2 and EI-99.

Table 6.13 CO_2 and EI-99 (H/H) optimal for selected geographic locations.

	Málaga CO_2	Málaga EI-99	Cáceres CO_2	Cáceres EI-99	**Zaragoza**	Lugo
System composition	E0A1	E0A0	E0A1	E0A0	**E0A0**	E0A0
Gas engines	0	0	0	0	**0**	0
Hot water boilers	4	4	5	5	**6**	10
Heat exchangers WH→ WR	0	0	0	0	**0**	0
Single effect absorption chillers	1	0	1	0	**0**	0
Mechanical chillers	5	6	4	5	**4**	0
Cooling towers	4	4	3	3	**3**	0
Natural gas (total) MWh/y	6030	6027	7859	7850	**8703**	11,005
Purchased electricity MWh/y	3744	3744	3667	3669	**3572**	3250
Sold electricity MWh/y	0	0	0	0	**0**	0
Natural gas (cogeneration) MWh/y	0	0	0	0	**0**	0
Cogenerated work MWh/y	0	0	0	0	**0**	0
Cogenerated useful heat MWh/y	0	0	0	0	**0**	0
Primary Energy Savings %	0	0	0	0	**0**	0
Equivalent electrical efficiency %	0	0	0	0	**0**	0
Single Score of equipment points/y	3432	3156	2841	2565	**2272**	205
Single Score of natural gas points/y	227,934	227,820	297,070	296,730	**328,984**	415,971
Single Score of electricity points/y	84,620	84,620	82,874	82,909	**80,730**	73,451
Avoided Single Score points/y	0	0	0	0	**0**	0
Total annual Single Score points/y	315,986	315,597	382,785	382,303	**411,986**	489,627
Emissions of equipment kg CO_2/y	59,232	61,884	48,642	51,294	**43,057**	3050
Emissions of natural gas kg CO_2/y	1,640,203	1,639,344	2,137,584	2,135,000	**2,367,296**	2,993,234
Emissions purchased electricity kg CO_2/y	1,441,392	1,441,392	1,411,981	1,412,565	**1,375,264**	1,251,263
Avoided emissions kg CO_2/y	0	0	0	0	**0**	0
Total annual emissions kg CO_2/y	3,140,827	3,142,620	3,598,207	3,598,859	**3,785,617**	4,247,547

The results for the EI-99 optimal and CO_2 optimal suggested the installation of *conventional* equipment for the selected locations, including hot water boilers, mechanical chillers, and cooling towers. Málaga and Cáceres presented different configurations for the environmental optimals: one absorption chiller was replaced by one mechanical chiller when changing the objective function from CO_2 emissions to EI-99 Single Score.

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 (Meunier, 2002; Chevalier & Meunier, 2005; Chicco & Mancarella, 2008; Mancarella & Chicco, 2008).

Table 6.14 shows the results from the economic optimization.

Table 6.14 Economic optimal for the different geographic locations.

	Málaga	Cáceres	**Zaragoza**	Lugo
System composition	E2A1	E3A2	**E3A1**	E2A0
Gas engines	2	3	**3**	2
Hot water boilers	2	2	**3**	8
Heat exchangers WH→ WR	3	4	**4**	3
Single effect absorption chillers	1	2	**1**	0
Mechanical chillers	5	3	**3**	0
Cooling towers	4	4	**3**	2
Natural gas (total) MWh/y	25,499	37,619	**37,324**	27,200
Purchased electricity MWh/y	19	0	**29**	0
Sold electricity MWh/y	6535	11,605	**11,389**	5467
Natural gas (cogeneration) MWh/y	24,839	37,217	**36,638**	21,613
Cogenerated work MWh/y	10,138	15,191	**14,954**	8822
Cogenerated useful heat MWh/y	6855	8880	**8602**	5016
Primary Energy Savings %	13.14	10.35	**10.01**	9.77
Equivalent electrical efficiency %	58.39	55.54	**55.22**	55.00
Cost of equipment €/y	488,635	555,680	**510,830**	271,285
Cost of natural gas €/y	637,476	940,479	**933,092**	680,005
Cost of electricity €/y	2148	0	**3207**	0
Profit with the sale of electricity €/y	- 503,190	- 893,564	**- 876,960**	- 420,992
Total annual cost €/y	625,069	602,596	**570,169**	530,298

In the economic optimal, cogeneration modules, hot water-cooling water heat exchangers, and absorption chillers (where cooling demands existed) were installed for all locations. All systems took advantage of the lower purchase cost of natural gas and realized profit by selling the autogenerated electricity to the electric grid.

6.4.3 Electricity supply conditions

There is a difference between electricity mixes for peninsular Spain, Canary Islands and Melilla and therefore three locations were selected for carrying out an environmental analysis: Málaga (peninsular Spain), Santa Cruz de Tenerife (Canary Islands) and Melilla (north coast of North Africa). The three locations are classified as climatic zone A3.

Santa Cruz is the capital of the Spanish island of Tenerife (largest of the seven Canary Islands in Spain) in the Atlantic Ocean, off the coast of Africa. This island has year-round sunshine and warm weather (average temperature 21.2 ºC), with maximum and minimum temperatures of 24.3 ºC and 18.0 ºC respectively, with an annual precipitation average of 214 mm.

Melilla is an autonomous Spanish city located at the North of Africa, on the Mediterranean coast. Maximum and minimum temperatures are 22.0 ºC and 15.2 ºC respectively, with an average annual temperature of 18.6 ºC and annual precipitation average of 370 mm.

Santa Cruz de Tenerife presents an electricity mix based mainly on fuel-gas (gaseous refinery products, which may include coal gas, syngas, ethane, and propane or LPG), constituted of 66.8% Fuel-gas, 30.1% Natural gas in combined cycle, and 3.1% Eolic (REE, 2007b). The CO_2 emissions for Santa Cruz de Tenerife were EM_e = 0.536 kg CO_2 per kWh consumed (Alpha = 1.97). Melilla also presents an electricity mix dominated by fuel-gas (95.8% Fuel-gas, 4.2% Solid waste, (REE, 2007b)), resulting in CO_2 emissions of EM_e = 0.619 kg CO_2 per kWh consumed (Alpha = 2.28). Table 6.15 shows the annual demands for the different hospital locations.

Table 6.15 Heat, cooling, and electricity demands for the hospital locations.

	Heat (MWh/y)	Cooling (MWh/y)	Electricity (MWh/y)
Málaga	5581	1941	3250
Santa Cruz	3511	2500	3250
Melilla	5852	1893	3250

Table 6.16 shows the Alpha factors, the configuration of the system, and main flow values as a function of the origin of electricity.

The results for the CO_2 optimal previously discussed suggested the installation of *conventional* equipment for peninsular locations. When considering the case of Santa Cruz de Tenerife and Melilla, where the local electricity supply depends highly on fuel-gas (higher emission value and associated global environmental impact), gas engines were installed because of the considerable difference between the impacts of local electricity supplied by the grid and electricity produced by cogeneration modules.

Table 6.16 Configuration and main flows of the system, in function of the origin of electricity (CO_2 optimal).

	Málaga	Santa Cruz	Melilla
Alpha factor	1.42	1.97	2.28
System composition	E0A1	E2A1	E5A4
Gas engines	0	2	5
Hot water boilers	4	1	1
Heat exchangers WH→ WR	0	1	2
Single effect absorption chillers	1	1	4
Mechanical chillers	5	6	3
Cooling towers	4	4	7
Natural gas (total) MWh/y	6030	9260	24,197
Purchased electricity MWh/y	3744	1904	99
Sold electricity MWh/y	0	1450	6443
Natural gas (cogeneration) MWh/y	0	8401	24,112
Cogenerated work MWh/y	0	3429	9841
Cogenerated useful heat MWh/y	0	2911	8093
Primary Energy Savings %	0	19.05	18.25
Equivalent electrical efficiency %	0	66.37	65.09
Emissions of equipment kg CO_2/y	59,232	74,830	85,639
Emissions of natural gas kg CO_2/y	1,640,203	2,518,784	6,581,613
Emissions purchased electricity kg CO_2/y	1,441,392	1,020,288	61,306
Avoided emissions kg CO_2/y	0	-777,204	- 3,988,100
Total annual emissions kg CO_2/y	3,140,827	2,836,698	2,740,458

6.5 CONCLUSIONS

The economic sensitivity analyses carried out by varying firstly fam, starting from the results of the economic optimization, showed that the amortization factor was evidenced as an influent factor when determining the adequate combination of technologies. An investment strategy that allowed smaller amortization factors stimulates the usage of more efficient technologies, with great investments, but with a considerable reduction in the annual energy cost. When varying the price of natural gas, it was observed that as the price of natural gas increased, the number of cogeneration modules and absorption chillers as well as the sale of electricity decreased. Not much variety was observed in the configuration of the optimal solutions in these analyses.

Considering the sensitivity to legal factors, the obligation of self-consumption of a portion of the electricity produced by the cogeneration module has been seen as a restriction in the operation and configuration of the optimal design. In fact, this condition limited the quantity of different units of equipment to install, particularly the number of cogeneration modules. The self-consumption obligation has been a persistent barrier to a wider uptake of cogeneration in Spain. The installation of energy-efficient technologies (cogeneration modules and absorption chillers) was fomented by the most recent legal scenario, in which all electricity produced by cogeneration modules could be sold to the electric grid. Regarding time of delivery differentiation in the feed-in tariff of cogenerated electricity, no significant increase in the sale of electricity was verified. However, it was observed that no purchase of electricity occurred. Differentiating feed-in tariffs according to the time of delivery can create an incentive to match generation more closely to demand. The introduction of a time of delivery differentiation can be seen as a way of making fixed-price feed-in tariff policies more sensitive to market demand – and, therefore, more compatible with competitive electricity markets.

The following environmental sensitivity analyses kept all other values constant and maintained the objective function as the minimization of CO_2 emissions. The ratio between local electricity emissions and natural gas emissions was initially modified by varying the origin of electricity in Spain considering single-fuel representative power plants. The results verified that cogeneration modules were installed when the energy supply was highly dependent on fossil fuels (high ratio between electricity emissions and natural gas emissions). 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). The Alpha factor (ratio between local electricity emissions and natural gas emissions) could be considered the strongest influencing factor when deciding the optimal configuration of a system that minimizes environmental loads.

The substantial impact of the *Alpha* 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. In open market arrangements, consumers can buy electricity from a range of service providers, some offering low carbon and/or renewably-fuelled electricity, yielding different Alpha factors. 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.

Regarding the sensitivity to geographic conditions, the optimal results suggested the installation of conventional equipment and purchase of electricity from the electric grid to attend the demands of cooling and electricity for all locations in peninsular Spain. The optimal solutions of Eco-indicator 99 Single Score and CO_2 emissions were identical for Zaragoza and Lugo. Málaga and Cáceres presented different configurations for the environmental optimals: one absorption chiller was replaced by one mechanical chiller when changing the objective function from CO_2 emissions to EI-99 Single Score. Emissions savings by cogeneration depended highly on the local electricity supply mix that would be substituted through cogeneration. In fact, Santa Cruz de Tenerife and Melilla presented different optimal environmental results from the rest of the locations in peninsular Spain because they are supplied by a different electricity mix (with higher associated CO_2 emissions/Single Score). Cogeneration modules were installed because of the difference in the CO_2 emissions/Single Score between the electricity supplied by the grid and natural gas. The economic optimal results suggested the installation of cogeneration modules, hot water boilers, and absorption chillers for all locations except for Lugo, which did not demand cooling and therefore no cooling equipment was installed. Gas engines were used to benefit from the lower price of natural gas and selling surplus of autogenerated electricity to the grid, minimizing the total annual cost.

CHAPTER VII

CONCLUSIONS

This Chapter summarizes the results and main conclusions of the thesis, followed by a discussion of contributions to current knowledge and future directions.

7.1 SYNTHESIS

The overarching aim of this thesis was to develop methodologies and procedures of analysis, synthesis and design of trigeneration systems, specifically focusing on the residential-commercial sector. Such methodologies included the investigation of rational criteria for cost allocation in multiproduct complex systems, submitted to different operation conditions and experiencing great demands fluctuations not only throughout the year, but also throughout the day. The explicit incorporation of environmental considerations in the analysis was also carried out, which required the development of new analysis procedures.

The thesis was divided into two parts. The first part comprehended Chapters II and III, which introduced a simple trigeneration system and sought clarity in the comprehension of concepts. In these chapters, only the operational stage was considered.

The thermoeconomic analysis of a simple trigeneration system was presented in Chapter II, considering different optimal operation modes corresponding to different variable demands. Cost analysis was carried out by applying three different thermoeconomic approaches: (1) analysis of marginal costs, (2) valuation of products applying market prices, and (3) internal costs calculation. Marginal costs of products proved useful in understanding how to best operate the system when energy demands changed. Costs based on market prices were found to be a fair criterion to distribute production costs among final product consumers when an external reference is imposed on value products. Existing cost assessment rules were tested and analyzed in the calculation of internal costs, culminating in the proposal of a judicious allocation method that considered interactions of the system with the environment and the production of cooling. This innovative approach to allocation methods takes existing studies a step further in complexity. The proposal considered that the cogenerated useful heat could be divided into meeting the heat demand directly and driving the absorption chiller. The new cost allocation method benefitted the consumers of the trigeneration system with a discount proportional to the difference between the cost of obtaining the energy services separately via conventional technologies and the cost from combined production.

Subsequently in Chapter III, thermoeconomic analysis and Life Cycle Analysis (LCA) were combined, allowing for the use of cost accounting in the evaluation of environmental impacts. The LCA approach expanded the limits of the system to consider the consumption of resources, while thermoeconomics allowed for the distribution and tracking of environmental loads. Integration of thermoeconomics and LCA was achieved by incorporating environmental information on the usage and consumption of resources into an Environmental Management Information System (EMIS). The allocation of environmental loads to the internal flows and final products of a simple trigeneration system was carried out by applying algebra and rules similar to those used in thermoeconomic analysis for the evaluation of internal and product costs. Similarly to cost accounting, it was possible to register and track environmental impacts generated in each piece of equipment as well as to assess the cumulative environmental load of each final product and internal flow. Several allocation methods were analyzed to assign environmental loads to each product of a trigeneration system, leading to an innovative environmental allocation proposal. The proposal considered the disaggregation of the cogenerated useful heat, with a fraction meeting the heat demand directly and the other fraction driving the absorption chiller. The allocation proposal was congruent with the objective of providing energy services with fewer emissions than those of separate production.

The increasing number of energy supply options for buildings (which may differ in technical, economic, and/or environmental performance) has caused a growing need for energy planning models in the residential-commercial sector. The second part of the thesis encompassed Chapters IV, V and VI, which presented more realistic and complex trigeneration systems attending to the specific energy service demands of a medium size hospital (500 beds) located in Zaragoza, Spain. More options of commercial equipment were included, presenting more complex interactions between equipment and energy flows. These chapters solved synthesis and design problems.

Chapter IV provided detailed calculations of energy service demands (including considerations for size of hospital, distribution of calendar, climatic data, and specific consumption indices) and explained the superstructure of the energy supply system (available technologies as well as technical and economic characteristics of equipment and operation modes). This chapter also presented data on the availability of energy resources and their purchase/sale tariffs, current legal requirements for operating a cogeneration system in Spain, and environmental loads due to interchanged flows and installed equipment. Chapter IV established the data used in the optimizations carried out in Chapters V and VI.

A Mixed Integer Linear Programming (MILP) model was developed in Chapter V for the multiperiod synthesis and operational planning problem of a trigeneration system, including the following: (1) determining the type, number and capacity of the equipment installed and (2) establishing the optimal operation for the different plant components on an hourly basis throughout a representative year. Single objective optimization considered separately three objective functions: minimization of annual cost, minimization of CO_2 emissions, and minimization of EI-99 points.

Regarding the economic objective function, it was observed that the installation of *energy-efficient technologies* (cogeneration modules and absorption chillers) was beneficial to achieve the minimum annual cost. Unexpectedly, optimal solutions based on *conventional equipment* (hot water boilers and mechanical chillers) were obtained by separately minimizing CO_2 emissions and then EI-99 Single Score for current conditions in Spain. Emissions savings by cogeneration were strongly dependent on the ratio between local electricity emissions and natural gas emissions (*Alpha* factor). This highlighted 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 the MILP model.

The issue of multiobjective optimization was also addressed in Chapter V, where two bicriteria optimizations (minimization of annual cost and CO_2 emissions, and minimization of annual cost and EI-99 points) were carried out. The solution of the MILP model provided sets of Pareto optimal design alternatives, which were analyzed and evaluated based on trade-offs. This detailed analysis highlighted the important role of the decision maker in solving and using their specialized judgment in the multiobjective problem. Significant reductions in the environmental impact could be attained if the economic performance was partially compromised.

Several sensitivity analyses were carried out in Chapter VI to identify the most influential factors on the structure and the operation of trigeneration systems. Economic sensitivity analyses considered the variation of the amortization factor *fam* and natural gas prices. As the *fam* factor increased, the number of installed cogeneration modules and absorption chillers as well as the sale of electricity decreased. Similarly, as the price of natural gas increased (starting from an initial low price), the benefits slowly decreased with a gradual decrease in the sale of electricity to the grid and less cogeneration modules and absorption chillers installed.

Legal-constraint sensitivity analyses verified the effect of minimum self-consumption and time-of-delivery feed-in tariffs on the optimal economic energy supply system. The obligation of a minimum electricity self-consumption of 30% significantly affected the amount of cogenerated elecvtricity and, consequently, the amount of electricity sold to the electric grid, proving that the obligation of self-consumption has been a legal barrier limiting the application of cogeneration in the residential-commercial sector. The introduction of a time-of-delivery differentiation could be seen as a way of making fixed-price feed-in tariff policies more sensitive to market demand and, therefore, more compatible with competitive electricity markets. Operation of the systems changed to adapt to delivering electricity to the grid at on-peak times to realize profit.

Sensitivity analyses of electricity sources were carried out for the environmental optimals by varying the source of electricity in Spain, then considering several international market conditions (alternate countries). Cogeneration modules were installed when the electricity supply was highly dependent on fossil fuels. Geographic analysis considered a variation in the location of the system in Spain, which resulted in different energy service demands and different supplies of electricity. From a purely economic perspective, the optimal configuration for all localities included cogeneration modules. Alternatively, an environmental standpoint yielded an optimal solution strongly dependent on the origin of the electricity supplied by the grid. The great influence exerted by the geographic zone of the hospital (specifically geographic location and availability of utilities in the local market conditions) was proved to be a key factor on the decision of whether to install a trigeneration system that minimized environmental loads.

7.2 CONTRIBUTIONS

Cost analysis for a simple trigeneration system was carried out based on: (1) analysis of marginal costs, (2) valuation of products applying market prices, and (3) internal costs calculation. The costs obtained provided different information that was useful for different applications. An allocation method was proposed, assuming that the cogenerated useful heat can be divided into a fraction to meet the heat demand directly and a fraction to drive the absorption chiller. The proposal benefitted the consumers of electricity, heat and cooling with the same discount when compared to separate production.

LCA and thermoeconomic analysis were integrated into the framework of an Environmental Management Information System (EMIS). This combined approach identified where environmental loads were generated and tracked their distribution to the final products of trigeneration systems. In an attempt to address the ongoing debate, an innovative environmental allocation method was proposed. This is the first step towards the establishment of meaningful environmental allocation criteria in trigeneration systems.

This thesis compiled significant data on trigeneration systems, including: available technologies, technical and economic characteristics of equipment and operation modes, energy resources and their purchase/sale tariffs, current legal requirements in Spain, and environmental loads due to interchanged flows and installed equipment.

Guidelines for the synthesis/design of trigeneration systems in buildings were provided. Such guidelines were applied through the elaboration of a MILP model for the optimization of trigeneration systems in medium size hospitals. For the specific hospital considered, the optimal economic solution corresponded to the installation of gas engines and absorption chillers. Surprisingly, optimal solutions based on *conventional equipment* were obtained by separately minimizing CO_2 emissions and then EI-99 Single Score. Gas turbines were never installed. A bicriteria optimization addressed the issues of conflicting objectives and trade-offs when considering economic and environmental aspects. The role of the decision maker was highlighted in the analysis and judgment of the solutions obtained, where considerable reductions in the environmental impact could be attained if the economic performance was partially compromised.

Extensive sensitivity analyses were carried out to verify the most influential factors on the synthesis/design of trigeneration systems, including economic, legal, energy supply, and geographic factors. The economic optimal configuration was found to be adaptable to a reasonable interval of economic and legal parameters. The ratio between local electricity emissions and natural gas emissions was found to have the highest impact on the optimal environmental system.

7.3 FUTURE DIRECTIONS

The complexity of the optimal synthesis and operation of trigeneration systems for the residential-commercial sector has not been fully covered in this research work. Thus, there are three interesting directions in which this study could be extended in the future.

Regarding possible technologies to incorporate into polygeneration systems, a suggestion is the consideration of thermal energy storage (TES, *i.e.*, hot water and/or chilled water tanks with/without the support of phase change materials). TES can be used to maximize power production during peak hours (where high value electricity is produced), storing eventual surplus heat/cooling energy to reuse it during off-peak hours. TES can also be used to limit the capacity of the installed equipment, leading to the operation of the productive equipment (cogeneration modules and chillers) for longer hours at full-load. Renewable energies (particularly solar thermal with seasonal storage and biomass) should be considered in agreement with new European directives.

Regarding the application of simultaneous environmental and efficiency objectives, an analysis is suggested to support the establishment of reasonable policies (through avenues of support and impositions). It should be important to specify (1) the objectives, (2) the technical developments/applications necessary, and (3) the stimuli used towards the application of (2) to obtain (1). The goal is to provide strategic support to decision makers when conflictive objectives are considered.

Regarding the combination of thermoeconomic analysis and LCA, this thesis presented the first steps towards what can be seen as an extremely fruitful collaboration. The process of visualizing the generation and distribution of environmental loads in productive systems took its first steps here with the application of algebra and rules similar to those used in thermoeconomic analysis for the evaluation of internal costs in trigeneration systems. Tagging energy services to the environmental impact associated with their consumption would give consumers an indication of which energy service to consume to guarantee an efficient and environmentally sound operation of their system.

CAPÍTULO VII

CONCLUSIONES

CAPÍTULO VII

CONCLUSIONES

Este capítulo presenta un resumen de los resultados y conclusiones principales, seguido de las contribuciones y sugerencias para trabajos futuros.

7.1 SÍNTESIS

El objetivo general de esta tesis ha sido el de desarrollar metodologías y procedimientos de análisis, síntesis y diseño de sistemas de trigeneración, para el caso específico del sector residencial-comercial. Estas metodologías han incluido la investigación de criterios racionales para la asignación de costes en sistemas complejos multiproducto, sometidos a diferentes condiciones de operación y experimentando grandes fluctuaciones de demanda, no sólo a lo largo del año, sino también a lo largo del día. Se han incorporado explícitamente las consideraciones ambientales en el análisis, lo que ha requerido el desarrollo de nuevos procedimientos.

La tesis se divide en dos partes. La primera parte comprende los capítulos II y III, que analizan un sistema simple de trigeneración, buscando claridad en la comprensión de los conceptos. En estos capítulos sólo se ha considerado la operación del sistema.

En el capítulo II se ha presentado el Análisis Termoeconómico de un sistema simple de trigeneración, tomando en consideración los diferentes modos de funcionamiento óptimo que se presentan al variar la demanda de servicios energéticos. El análisis de costes se ha llevado a cabo mediante la aplicación de tres enfoques termoeconómicos diferentes: (1) análisis de los costes marginales, (2) valoración de los productos según los precios de mercado, y (3) cálculo de los costes internos. Los costes marginales de los productos han sido útiles para la comprensión de cómo operar mejor el sistema cuando hay cambios en las demandas de energía y otros cambios. Los costes basados en precios de mercado han sido considerados como un criterio justo para distribuir los costes de producción entre los consumidores de productos finales cuando hay un imperativo económico en la distribución. Las reglas publicadas de asignación de costes han sido sometidas a prueba y analizadas en el cálculo de costes internos, culminando en la propuesta de un método nuevo de asignación que considera las interacciones del sistema con el ambiente económico y la producción de frío, llevando los estudios existentes un paso más allá. La propuesta considera que el calor cogenerado útil se divide en una fracción que atiende directamente a la demanda de calor, y una fracción de calor que va a la enfriadora de absorción. El nuevo método de asignación de costes beneficia a los consumidores del sistema de trigeneración con un descuento derivado de la producción combinada y proporcional al coste de obtener por separado, y con tecnologías convencionales, los servicios energéticos consumidos.

Posteriormente, en el capítulo III, la combinación del análisis termoeconómico y del Análisis de Ciclo de Vida (ACV) ha permitido utilizar la contabilidad de costes para la valoración de impactos ambientales. El enfoque del ACV ha ampliado los límites del sistema para considerar el consumo de recursos primarios y la termoeconomía ha permitido la distribución y seguimiento de las cargas ambientales dentro de los límites del sistema. La integración entre termoeconomía y ACV se ha realizado a través de la incorporación de información medioambiental sobre el uso y consumo de recursos en un Sistema de Información y Gestión Ambiental (Environmental Management Information System, EMIS). La asignación de cargas ambientales a los flujos internos y productos finales de un sistema simple de trigeneración se ha efectuado mediante la aplicación de procedimientos algebraicos similares a los utilizados en el análisis termoeconómico para la asignación de costes internos. Al igual que en la contabilidad de costes, se han podido registrar y rastrear los impactos ambientales generados en cada equipo, así como evaluar las cargas ambientales asociadas a cada flujo interno y producto final. Han sido analizados diferentes métodos para el reparto de las cargas ambientales, concluyéndose una propuesta innovadora de asignación de cargas ambientales en sistemas de trigeneración. El método de asignación propuesto ha considerado la desagregación del calor cogenerado útil (una parte atiende directamente a la demanda de calor y la otra parte va a la máquina de absorción). La propuesta de asignación de cargas ambientales es congruente con el objetivo de proporcionar servicios energéticos con menos emisiones que los de la producción por separado.

La existencia de numerosas opciones de suministro de energía para los edificios, que pueden diferir en sus características técnicas, económicas y/o ambientales, ha creado la necesidad de modelos eficaces de planificación del suministro de servicios energéticos en el sector residencial-comercial. En la segunda parte de la tesis, que abarca los capítulos IV, V y VI, se han estudiado sistemas de trigeneración más realistas y complejos, atendiendo a las demandas específicas de servicios energéticos de un hospital de tamaño medio (500 camas), ubicado en Zaragoza, España. Se han contemplado más opciones de equipos comerciales dando lugar a una interacción más compleja entre equipos y flujos energéticos. Estos capítulos resuelven problemas de síntesis y diseño.

El capítulo IV proporciona cálculos detallados de las demandas de servicios energéticos (considerando el tamaño del hospital, el calendario laboral, los datos climáticos, y los índices de consumo específico) y explica la superestructura considerada para el diseño del sistema de suministro de energía (las tecnologías disponibles, las características técnicas y económicas de los equipos, y los modos posibles de operación). En este capítulo también se presentan datos sobre la disponibilidad de los recursos energéticos y sus tarifas de compra/venta, los requisitos legales exigidos en España para el funcionamiento de un sistema de cogeneración dentro del régimen especial de producción eléctrica, y las cargas ambientales debidas a los flujos intercambiados y equipos instalados. El capítulo IV establece los datos utilizados en las optimizaciones realizadas en los Capítulos V y VI.

Un modelo en Programación Lineal Entera Mixta (Mixed Integer Linear Programming, MILP) ha sido desarrollado en el Capítulo V para la síntesis y planificación multiperiodo de la operación de un sistema de trigeneración: (1) determinando el tipo, número y capacidad de los equipos a instalar y (2) estableciendo el modo óptimo de operación para los componentes de la planta, hora a hora a lo largo de un año representativo. La optimización con objetivo único ha considerado por separado tres funciones objetivo: minimización de costes anuales, minimización de emisiones de CO_2, y minimización del ecoindicador EI-99.

En cuanto a la función objetivo económica, se ha observado que la instalación de tecnologías *eficientes* (motores de gas y máquinas de absorción) es beneficiosa para lograr el coste mínimo anual. Sorprendentemente, soluciones óptimas basadas en equipos *convencionales* (calderas y enfriadoras mecánicas) se han obtenido, para las condiciones actuales en España, al minimizar tanto las emisiones de CO_2 como el ecoindicador EI-99. La reducción de emisiones con cogeneración depende significativamente de la relación entre las emisiones que conllevan los suministros locales de electricidad y gas natural (factor *Alpha*). Esto pone de manifiesto la necesidad de una perspectiva que considere las circunstancias locales para determinar la configuración óptima y el funcionamiento de los sistemas de suministro de energía. Estas cuestiones han sido aclaradas aquí merced a la integración de información medioambiental en el modelo de optimización desarrollado.

El tema de la optimización multiobjetivo también ha sido abordado en el capítulo V, partiendo de dos optimizaciones bicriterio (minimización del coste anual *versus* emisiones de CO_2, y minimización del coste anual *versus* ecoindicador EI-99). La solución del modelo MILP proporciona conjuntos de Pareto de alternativas de diseño óptimo, que han sido analizados destacando el papel del decisor en la solución del problema multiobjetivo. Se comprueba que pueden conseguirse sistemas eficientes con reducciones significativas en el impacto ambiental a costa de un pequeño descuento del beneficio económico.

En el Capítulo VI se han realizado varios análisis de sensibilidad, con el fin de examinar los factores que más influyen en la estructura y funcionamiento de los sistemas de trigeneración. El análisis de sensibilidad económica ha considerado las variaciones del factor de amortización *fam* y del precio del gas natural. A medida que el fam aumenta van disminuyendo el número de módulos de cogeneración y enfriadoras de absorción, así como la venta de electricidad. Al aumentar el precio del gas natural, desde un precio inicial bajo, van disminuyendo paulatinamente los beneficios, vendiéndose cada vez menos electricidad a la red e instalándose menos módulos de cogeneración y enfriadoras de absorción.

Los análisis de sensibilidad a las restricciones legales han comprobado los efectos sobre los óptimos económicos del auto-consumo eléctrico mínimo obligatorio y la discriminación horaria en el precio de venta de la electricidad cogenerada. La obligación de un auto-consumo mínimo del 30% limita significativamente la cantidad de electricidad producida y por tanto también la vendida a la red eléctrica, lo que demuestra que ha sido una barrera legal a la penetración de la cogeneración en el sector residencial-comercial. La introducción de una tarifa con discriminación horaria para la venta de la electricidad cogenerada implica la selección de sistemas de suministro energético mejor adaptados a las condiciones del mercado y, por lo tanto, más rentables con mercados competitivos de electricidad. La operación de los sistemas ha cambiado para adaptarse a la venta de electricidad cogenerada en horas-punta.

Los análisis de sensibilidad a las fuentes de electricidad y gas de los óptimos ambientales se han realizado variando la fuente de electricidad en España y luego considerando diversas condiciones del mercado internacional (diferentes países). Los módulos de cogeneración se instalan cuando el suministro eléctrico es altamente dependiente de los combustibles fósiles. El análisis geográfico ha considerado una variación en la ubicación del hospital en España, lo que da lugar a diferentes demandas de servicios energéticos y diferentes condiciones de suministro de electricidad. Desde una perspectiva puramente económica, la configuración óptima para todas las localidades ha incluido módulos de cogeneración. Por otra parte, desde un punto de vista ambiental, la solución óptima ha dependido en gran medida del origen de la electricidad suministrada por la red. La gran influencia ejercida por la zona geográfica en la que se ubica el hospital (demanda por razones climatológicas y fuentes de los servicios energéticos en el mercado local) ha demostrado ser un factor clave en la decisión de instalar o no sistemas de trigeneración para reducir las cargas ambientales.

7.2 CONTRIBUCIONES

Se ha realizado un análisis termoeconómico de costes en un sistema simple de trigeneración desde tres perspectivas diferentes: (1) análisis de costes marginales, (2) valoración de productos aplicando precios de mercado, y (3) cálculo de costes internos. Los costes obtenidos tienen un significado diferente, y por tanto son útiles para diferentes aplicaciones. Se ha propuesto un método nuevo de asignación de costes, considerando que el calor cogenerado útil se divide en una fracción que atiende directamente a la demanda de calor, y otra fracción que produce frío a través de la máquina de absorción. La propuesta beneficia a los consumidores de calor, frío y electricidad con costes de producción inferiores, y con el mismo descuento, a los de la producción por separado.

El análisis de ciclo de vida y el análisis termoeconómico se han integrado en un Sistema de Información y Gestión Ambiental (Environmental Management Information System, EMIS). Este enfoque combinado identifica donde se generan las cargas ambientales y cómo deben distribuirse entre los productos finales de los sistemas de trigeneración. Nos incorporamos al debate en curso sobre los métodos de asignación de costes ambientales en sistemas energéticos proponiendo un método innovador y paralelo al de asignación de costes termoeconómicos. Este ha sido un primer paso centrado en los sistemas de trigeneración.

Durante la realización de esta tesis se han recopilado datos importantes sobre sistemas de trigeneración: tecnologías disponibles, características técnicas y económicas de equipos y su modo de operación, recursos energéticos disponibles y sus tarifas de compra/venta, requisitos legales vigentes en España, y cargas ambientales debidas a flujos intercambiados y equipos instalados.

Se han dado directrices para la síntesis y diseño de sistemas de trigeneración en edificios. Estas directrices se han aplicado elaborando un modelo MILP para la optimización de sistemas de trigeneración en hospitales de tamaño medio. Para el hospital específico considerado, la solución óptima económica corresponde a la instalación de motores de gas y enfriadoras de absorción. Sorprendentemente, soluciones óptimas basadas en equipos convencionales se han obtenido por separado al minimizar las emisiones de CO_2 y el ecoindicador EI-99. Las turbinas de gas nunca han sido instaladas. Una optimización bicriterio ha permitido abordar el análisis de compromisos entre los objetivos conflictivos: económicos y ambientales. El papel del decisor se ha destacado en el análisis y evaluación de las soluciones obtenidas, comprobándose que pueden lograrse reducciones considerables en el impacto ambiental comprometiendo solo una pequeña parte del beneficio económico.

Se han realizado análisis exhaustivos de sensibilidad para verificar los factores más influyentes en la síntesis y diseño de sistemas de trigeneración, considerando parámetros económicos, restricciones legales, condiciones locales del suministro de energía y factores geográficos. La configuración óptima económica ha resultado ser adaptable a un rango razonable de variación de parámetros económicos y restricciones legales. La relación entre las cargas ambientales locales de electricidad y gas natural tiene la mayor importancia en la selección del sistema de suministro energético correspondiente al óptimo ambiental.

7.3 PERSPECTIVAS FUTURAS

Hay tres direcciones de estudio interesantes para extender el trabajo de esta tesis en el futuro.

En cuanto a las tecnologías a incorporar, se sugiere la consideración del almacenamiento de energía térmica (depósitos de agua caliente y/o agua fría con/sin apoyo de materiales de cambio de fase). Esta se puede utilizar para maximizar la producción de energía en horas-punta (cuando la electricidad es más cara) almacenando el calor excedente para su consumo durante las horas-valle, ó también para limitar la potencia instalada de equipos productores (módulos de cogeneración y enfriadoras) operando más horas a plena carga. Las energías renovables deben ser consideradas de acuerdo con las nuevas directivas europeas, especialmente la solar térmica con almacenamiento estacional y la biomasa.

En cuanto a la consecución simultánea de beneficios medioambientales y eficiencia energética, se sugiere un análisis dirigido a facilitar la elaboración de una buena normativa legal (apoyos e imposiciones). Se considera importante especificar: (1) qué se pretende, (2) cómo se consigue técnicamente, y (3) cómo se estimula la aplicación de (2) para conseguir (1). El objetivo es proporcionar apoyo estratégico a los tomadores de decisiones cuando hay objetivos conflictivos a ser considerados.

En cuanto a la combinación del análisis termoeconómico y LCA, esta tesis presenta los primeros pasos hacia lo que puede preverse como una colaboración muy fructífera. El proceso de visualización de la generación y distribución de las cargas ambientales en los sistemas productivos ha dado sus primeros pasos aquí con la aplicación del álgebra y reglas similares a las utilizadas en el análisis termoeconómico para la evaluación de los costes internos en sistemas de trigeneración. Etiquetar los servicios energéticos con el impacto ambiental asociado a su producción daría a los consumidores una indicación de qué servicio energético consumir para garantizar una operación eficiente y respetuosa con el medioambiente.

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APPENDIX I

ECO-INDICATOR 99 SINGLE SCORE CALCULATION

The combustion of 1 kWh of natural gas (*Energy gas I*, from the IDEMAT database) was chosen to illustrate the step by step calculation of the EI-99 Single Score. Resumed EI-99 calculations for the aggregated system inventory of natural gas (*Natural gas, at consumer*, from the Ecoinvent database), Spanish electricity mix (combination of Ecoinvent processes), and for one piece of equipment (FMWR, mechanical chiller), are shown subsequently.

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 k in all processes that form the life cycle of the equipment or utility, yielding the Life Cycle Inventory LCI_k.*

2. *Calculation of the damage IM_{ic} caused in each impact category ic belonging to a specific damage category cm, provoked by each item of LCI_k. This is done by multiplying each item LCI_k obtained in step 1 by the corresponding set of damage factors $df_{ic,k}$:*

$$\mathrm{IM_{ic}} = \sum_{k} \mathrm{df_{ic,k}} \cdot \mathrm{LCI_k} \qquad \forall\ \mathrm{ic}$$

The complete table of damage factors can be found in the CD that accompanies this thesis. The damage factors are used to translate the LCI_k into the associated impacts.

3. *Optional. Aggregation of each impact category into the corresponding damage category:*

$$\mathrm{DAM_{dm}} = \sum_{\mathrm{ic} \in \mathrm{ic(dm)}} \mathrm{IM_{ic}} \qquad \forall\ \mathrm{dm}$$

Where ic(dm) denotes the set of impact categories ic that contribute to damage dm. This step is optional as step 4 can be applied directly to step 2.

4. *Determination of the Eco-indicator 99, through the application of specific normalization σ and weighting ζ factors, and final aggregation:*

$$\mathrm{EI-99} = \sum_{\mathrm{dm}} \zeta \ \cdot \sigma \ \cdot \mathrm{DAM_{dm}}$$

The normalization σ and weighting ζ factors depend on the cultural perspective, and will carry the corresponding subscript.

NATURAL GAS

The consumption of natural gas is a combination of two processes: related emissions of combustion of natural gas and the total aggregated system inventory for a natural gas user in Spain, which includes gas field exploration, natural gas production, long distance transport, distribution and local supply.

i) Combustion of natural gas

The Life Cycle Inventory for the combustion of natural gas is shown in Table A1.1.

Table A1.1 LCI_k for the combustion of natural gas (1 kWh).

Substance k	Compartment	Unit	Quantity
Nitrogen oxides	Air	kg	$6.54 \cdot 10^{-4}$
Sulfur 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

Consultation of the characterization factors $df_{ic,k}$ (contained in the CD) in order to evaluate the contribution of each substance of the inventory towards the different impact categories (Table A1.3).

Values in Table A1.3 were obtained by multiplying each substance of the inventory (LCI_k in Table A1.1) by its corresponding characterization factor $df_{ic,k}$ (Table A1.2). Substances can contribute to more than one impact category. For example, nitrogen oxides contribute to respiratory effects and acidification/eutrophication impact categories.

Table A1.2 Characterization factors $df_{ic,k}$ applicable to the LCI_k of the combustion of natural gas.

LCI_k	Impact category ic			
	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	-
Sulfur 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 A1.3 shows the damage IM_{ic} caused in each impact category. The different impact categories are combined into the three damage categories (Human Health, Ecosystem Quality, and Resources).

Table A1.3 Characterization of inventory for the combustion of natural gas (1 kWh).

	Human Health		**Ecosystem Quality**	**Resources**
	Respiratory Inorganics (DALY) IM_{ic}	Climate Change (DALY) IM_{ic}	Acidification and Eutrophication (PDF·m^2·y) IM_{ic}	Fossil Fuels (MJ surplus) IM_{ic}
Nitrogen oxides	$5.80 \cdot 10^{-8}$		$3.74 \cdot 10^{-3}$	-
Sulfur 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
DAM_{dm}	**$1.09 \cdot 10^{-7}$** DALY		**$3.75 \cdot 10^{-3}$** PDF·m^2·y	**0.431** MJ surplus

Nitrogen oxides contribute with 53% and almost 100% of the final value of Human Health and Ecosystem Quality damage values.

Damage category values (DAM_{dm} in Table A1.3) are multiplied by their corresponding normalization and weighting factors (σ_H and ζ_H in Table A1.4, respectively, for the hierarquist perspective H/H) in order to build the damage model. The multiplication yields the value of Eco-indicator 99 representing the environmental load corresponding to each damage category. Addition of the environmental load in each damage category results in the final EI-99 environmental load, in points.

Table A1.4 Damage model (H/H) for the combustion of natural gas (1 kWh).

	Human Health	**Ecosystem Quality**	**Resources**
Normalization factors (σ_H)	65.1 (1/DALY)	$1.95\cdot10^{-4}$ (1/PDF$\cdot$m$^2\cdot$y)	$1.19\cdot10^{-4}$ (1/MJ surplus)
Weighting factors (ζ_H)	$0.3\cdot10^{-3}$	$0.4\cdot10^{-3}$	$0.3\cdot10^{-3}$
($\sigma_H \cdot \zeta_H \cdot \mathrm{DAM_{dm}}$)	$2.13\cdot10^{-3}$	$2.92\cdot10^{-4}$	$1.54\cdot10^{-2}$
EI-99 (H/H) Single Score	$2.13\cdot10^{-3} + 2.92\cdot10^{-4} + 1.54\cdot10^{-2} =$ **$1.78\cdot10^{-2}$ points**		

i) Aggregated system inventory of natural gas

In order to complete calculations for the utilization of natural gas in the system, the next step is to repeat the procedure for the natural gas aggregated inventory. The CD that accompanies this thesis contains the $\mathrm{LCI_k}$ of the aggregated inventory for 1 kWh of natural gas (*Natural gas, at consumer*).

Characterization factors $\mathrm{df_{ic,k}}$ were consulted to evaluate the contribution of each substance of the inventory $\mathrm{LCI_k}$ towards the different impact categories, yielding Table A1.5, where only the three top contributors to each impact category are shown.

As the tables are significantly extensive, the summarized calculation carried out from now on will apply the sets of normalization and weighting factors (Table A1.6) to the damage $\mathrm{IM_{ic}}$ values (Table A1.5), skipping step 3 of the procedure and yielding the Eco-indicator 99 Single Score per impact category (which will then be added yielding the final EI-99 value). This procedure allows for the verification of the processes that contribute the most towards environmental burden when inventory and characterization tables are extensive. Table A1.7 shows the top contributors to the final value of EI-99.

Table A1.5 Top contributors to damage IM_{ic} for *Natural gas, at consumer* (1 kWh).

	Human Health					
	Carcinogenics (DALY)	Respiratory Organics (DALY)	Respiratory Inorganics (DALY)	Climate change (DALY)	Radiation (DALY)	Ozone Layer (DALY)
Arsenic (water)	$5.38\cdot10^{-10}$	-	-	-	-	-
Cadmium (water)	$1.31\cdot10^{-10}$	-	-	-	-	-
Particulates, < 2.5μm (air)	$2.83\cdot10^{-11}$	-	$2.03\cdot10^{-9}$	-	-	-
NMVOC (air)	-	$1.91\cdot10^{-11}$	-	-	-	-
Ethane (air)	-	$6.43\cdot10^{-12}$	-	-	-	-
Methane, fossil (air)	-	$2.91\cdot10^{-12}$	-	$1.00\cdot10^{-9}$	-	-
Nitrogen oxides (air)	-	-	$6.79\cdot10^{-9}$	-	-	-
Particulates, > 2.5μm and < 10 μm (air)	-	-	$8.29\cdot10^{-10}$	-	-	-
Carbon dioxide (air)	-	-	-	$6.35\cdot10^{-9}$	-	-
Dinitrogen monoxide (air)	-	-	-	$2.37\cdot10^{-9}$	-	-
Radon-222	-	-	-	-	$8.77\cdot10^{-12}$	-
Carbon-14	-	-	-	-	$4.15\cdot10^{-12}$	-
Iodine-129	-	-	-	-	$1.87\cdot10^{-14}$	-
Halon 1211	-	-	-	-	-	$2.83\cdot10^{-11}$
HCFC-22	-	-	-	-	-	$6.88\cdot10^{-13}$
Halon 1301	-	-	-	-	-	$1.80\cdot10^{-13}$

	Ecosystem Quality				Resources	
	Ecotoxicity ($PDF\cdot m^2\cdot y$)	Acidification/ Eutrophication ($PDF\cdot m^2\cdot y$)	Land use ($PDF\cdot m^2\cdot y$)		Minerals (MJ surplus)	Fossil fuels (MJ surplus)
Zinc (air)	$2.84\cdot10^{-5}$	-	-		-	-
Zinc (soil)	$2.70\cdot10^{-5}$	-	-		-	-
Nickel	$2.48\cdot10^{-5}$	-	-		-	-
Nitrogen oxides (air)	-	$4.37\cdot10^{-4}$	-		-	-
Sulfur dioxide (air)	-	$9.35\cdot10^{-6}$	-		-	-
Ammonia (air)	-	$1.42\cdot10^{-6}$	-		-	-
Transf., to mineral extraction site (raw)	-	-	$5.68\cdot10^{-4}$		-	-
Transf., to dump site, benthos (raw)	-	-	$4.57\cdot10^{-4}$		-	-
Transformation, to arable (raw)	-	-	$8.86\cdot10^{-5}$		-	-
Nickel, in crude ore (raw)	-	-	-		$1.70\cdot10^{-4}$	-
Iron, in crude ore (raw)	-	-	-		$3.45\cdot10^{-5}$	-
Copper, in crude ore (raw)	-	-	-		$1.10\cdot10^{-5}$	-
Gas, natural, in ground (raw)	-	-	-			$5.44\cdot10^{-1}$
Oil, crude, in ground (raw)	-	-	-		-	$2.62\cdot10^{-3}$
Coal, hard, in ground (raw)	-	-	-		-	$1,12\cdot10^{-4}$

[1] Non-methane volatile organic compound.

[2] "Benthos" is used to indicate the offshore drilling wastes spread on the seafloor, affecting the benthic organisms.

Table A1.6 Normalization and weighting factors for the Hierarchist perspective (H/H).

	Human Health	**Ecosystem Quality**	**Resources**
Normalization factors (σ_H)	65.1 (1/DALY)	$1.95\cdot10^{-4}$ ($1/PDF\cdot m^2\cdot y$)	$1.19\cdot10^{-4}$ (1/MJ surplus)
Weighting factors (ζ_H)	$0.3\cdot10^{-3}$	$0.4\cdot10^{-3}$	$0.3\cdot10^{-3}$

Table A1.7 Eco-indicator 99 Single Score for *Natural gas, at consumer* (1 kWh).

	Human Health (points)	**Ecosystem Quality (points)**	**Resources (points)**
Gas, natural, in ground (raw)			$1.94\cdot10^{-2}$ (Fossil fuels)
Nitrogen oxides (air)	$1.32\cdot10^{-4}$ (Respiratory inorganics)	$3.41\cdot10^{-5}$ (Acidification and eutrophication)	
Carbon dioxide (air)	$1.24\cdot10^{-4}$ (Climate change)		
Oil, crude, in ground (raw)			$9.37\cdot10^{-5}$ (Fossil fuels)
Transf., to mineral extraction site (raw)		$4.43\cdot10^{-5}$ (Land use)	
Particulates, < 2.5 μm (air)	$5.53\cdot10^{-7}$ (Carcinogens) $3.96\cdot10^{-5}$ (Respiratory inorganics)		
Total (partial)	$\mathbf{2.96\cdot10^{-4}}$	$\mathbf{7.84\cdot10^{-5}}$	$\mathbf{1.95\cdot10^{-2}}$
Total EI-99 Single Score		**$2.00\cdot10^{-2}$ points**	

There is a difference between the total EI-99 Single Score and the partial total (2.00 – (0.03 + 0.01 + 1.95)) = $0.01\cdot10^{-2}$ which is due to the smaller constributions to the environmental burden that due to spatial imitations, are not shown. The smaller contributions represent only ≈ 0.5% of the final EI-99 Single Score.

The final EI-99 Single Score associated with the consumption of 1 kWh of natural gas is obtained by adding the contributions of the combustion (Table A1.4) and aggregated system inventory (Table A1.7): $1.78\cdot10^{-2} + 2.00\cdot10^{-2} =$ **$3.78\cdot10^{-2}$ points.**

ELECTRICITY MIX

The Spanish electricity mix was a combination of Ecoinvent processes, considering the following contributors to the mix: 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 (REE, 2007a).

The CD that accompanies this thesis contains the LCI_k of the Spanish electricity mix (1 kWh).

Characterization factors $df_{ic,k}$ were consulted to evaluate the contribution of each substance of the inventory LCI_k towards the different impact categories, yielding Table A1.8, where only the top contributors to each damage category are shown. The final value for the Spanish electricity mix was obtained by multiplying each contributor by its corresponding proportion.

The next step is the application of the sets of normalization and weighting factors (Table A1.6) to the damage IM_{ic} values (Table A1.8), yielding the Eco-indicator 99 Single Score per impact category (which will then be added yielding the final EI-99 value). Table A1.9 shows the top contributors to the final value of EI-99 for the Spanish electricity mix.

Table A1.8 Damage IM$_{ic}$ for *Spanish Electricity mix* contributors.

Contributors to Human Health categories (DALY)	Spanish Electricity mix contributors						
	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Nitrogen oxides (air) / Respiratory inorganics	$3.79\cdot10^{-7}$	$2.73\cdot10^{-8}$	$2.71\cdot10^{-9}$	$1.27\cdot10^{-9}$	$3.36\cdot10^{-9}$	$2.15\cdot10^{-7}$	$2.03\cdot10^{-8}$
Sulfur dioxide (air) / Respiratory inorganics	$4.23\cdot10^{-7}$	$7.99\cdot10^{-9}$	$1.77\cdot10^{-9}$	$3.30\cdot10^{-10}$	$2.82\cdot10^{-9}$	$1.04\cdot10^{-7}$	$8.19\cdot10^{-9}$
Carbon dioxide, fossil (air) / Climate change	$2.13\cdot10^{-7}$	$8.35\cdot10^{-8}$	$1.44\cdot10^{-9}$	$8.58\cdot10^{-10}$	$3.31\cdot10^{-9}$	$1.51\cdot10^{-7}$	$2.55\cdot10^{-8}$
Arsenic, ion (water) / Carcinogens	$2.22\cdot10^{-7}$	$1.52\cdot10^{-9}$	$6.53\cdot10^{-8}$	$4.97\cdot10^{-19}$	$9.60\cdot10^{-9}$	$5.87\cdot10^{-9}$	$4.84\cdot10^{-9}$
Particulates, < 2.5 µm (air) / Carcinogens,	$4.98\cdot10^{-9}$	$7.91\cdot10^{-11}$	$1.90\cdot10^{-10}$	$3.92\cdot10^{-11}$	$1.65\cdot10^{-10}$	$5.47\cdot10^{-10}$	$6.22\cdot10^{-11}$
Respiratory inorganics	$2.88\cdot10^{-8}$	$1.44\cdot10^{-9}$	$9.32\cdot10^{-9}$	$4.05\cdot10^{-9}$	$6.52\cdot10^{-9}$	$1.13\cdot10^{-8}$	$2.97\cdot10^{-9}$

Contributors to Ecosystem Quality categories (PDF·m^2·y)	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Nitrogen oxides (air) / Acidification and eutrophication	$2.44\cdot10^{-2}$	$1.76\cdot10^{-3}$	$1.74\cdot10^{-4}$	$8.16\cdot10^{-5}$	$2.16\cdot10^{-4}$	$1.38\cdot10^{-2}$	$1.31\cdot10^{-3}$
Sulfur dioxide (air) / Acidification and eutrophication	$8.08\cdot10^{-3}$	$1.52\cdot10^{-4}$	$3.38\cdot10^{-5}$	$6.30\cdot10^{-6}$	$5.37\cdot10^{-5}$	$1.98\cdot10^{-3}$	$1.56\cdot10^{-4}$
Nickel (air) / Ecotoxicity	$2.08\cdot10^{-3}$	$4.91\cdot10^{-5}$	$3.26\cdot10^{-4}$	$1.55\cdot10^{-5}$	$3.71\cdot10^{-4}$	$7.03\cdot10^{-3}$	$1.06\cdot10^{-4}$
Nickel, ion (water) / Ecotoxicity	$6.13\cdot10^{-3}$	$6.04\cdot10^{-5}$	$1.30\cdot10^{-4}$	$4.86\cdot10^{-5}$	$6.75\cdot10^{-4}$	$2.23\cdot10^{-4}$	$1.23\cdot10^{-4}$
Transf., to mineral extraction site (raw) / Land use	$6.65\cdot10^{-4}$	$8.76\cdot10^{-4}$	$8.12\cdot10^{-5}$	$3.03\cdot10^{-5}$	$4.00\cdot10^{-5}$	$4.94\cdot10^{-3}$	$2.90\cdot10^{-4}$

Contributors to Resource categories (MJ surplus)	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Gas, natural, in ground (raw) / Fossil fuels	$1.37\cdot10^{-2}$	$9.88\cdot10^{-1}$	$3.88\cdot10^{-3}$	$8.36\cdot10^{-4}$	$9.87\cdot10^{-3}$	$6.22\cdot10^{-1}$	$2.82\cdot10^{-1}$
Oil, crude, in ground (raw) / Fossil fuels	$6.44\cdot10^{-2}$	$5.56\cdot10^{-3}$	$4.38\cdot10^{-3}$	$2.60\cdot10^{-3}$	$6.90\cdot10^{-4}$	$6.73\cdot10^{-4}$	$2.75\cdot10^{-4}$
Coal, hard, in ground (raw) / Fossil fuels	$9.73\cdot10^{-2}$	$1.94\cdot10^{-4}$	$2.59\cdot10^{-4}$	$1.07\cdot10^{-4}$	$6.94\cdot10^{-4}$	$6.73\cdot10^{-4}$	$2.75\cdot10^{-4}$
Nickel, in crude ore, in ground (raw) / Minerals	$7.48\cdot10^{-4}$	$6.08\cdot10^{-4}$	$1.74\cdot10^{-3}$	$1.08\cdot10^{-3}$	$1.78\cdot10^{-2}$	$6.96\cdot10^{-4}$	$7.33\cdot10^{-4}$
Copper, in ground (raw) / Minerals	$2.05\cdot10^{-4}$	$9.96\cdot10^{-5}$	$1.19\cdot10^{-4}$	$7.62\cdot10^{-6}$	$1.10\cdot10^{-3}$	$1.57\cdot10^{-4}$	$3.49\cdot10^{-4}$

Table A1.9 EI-99 Single Score for the *Spanish Electricity mix* contributors.

Contributors to Human Health categories (points)	Spanish Electricity mix contributors						
	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Nitrogen oxides (air) / Respiratory inorganics	$7.40\cdot10^{-3}$	$5.32\cdot10^{-4}$	$5.29\cdot10^{-5}$	$2.48\cdot10^{-5}$	$6.56\cdot10^{-5}$	$4.20\cdot10^{-3}$	$3.97\cdot10^{-4}$
Sulfur dioxide (air) / Respiratory inorganics	$8.28\cdot10^{-3}$	$1.56\cdot10^{-4}$	$3.46\cdot10^{-5}$	$6.45\cdot10^{-6}$	$5.50\cdot10^{-5}$	$2.03\cdot10^{-3}$	$1.60\cdot10^{-4}$
Particulates, < 2.5 µm (air) / Carcinogens,	$9.73\cdot10^{-5}$	$1.55\cdot10^{-6}$	$3.71\cdot10^{-6}$	$7.65\cdot10^{-7}$	$3.22\cdot10^{-6}$	$1.07\cdot10^{-5}$	$1.21\cdot10^{-6}$
Respiratory inorganics	$6.96\cdot10^{-3}$	$1.11\cdot10^{-4}$	$2.66\cdot10^{-4}$	$5.48\cdot10^{-5}$	$2.31\cdot10^{-4}$	$7.64\cdot10^{-4}$	$8.70\cdot10^{-5}$
Carbon dioxide, fossil (air) / Climate change	$4.17\cdot10^{-3}$	$1.63\cdot10^{-3}$	$2.82\cdot10^{-5}$	$1.67\cdot10^{-5}$	$6.47\cdot10^{-5}$	$2.96\cdot10^{-3}$	$4.99\cdot10^{-4}$
Contributors to Ecosystem Quality categories (points)	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Nitrogen oxides (air) / Acidification and eutrophication	$1.90\cdot10^{-3}$	$1.37\cdot10^{-4}$	$1.36\cdot10^{-5}$	$6.37\cdot10^{-6}$	$1.69\cdot10^{-5}$	$1.08\cdot10^{-3}$	$1.02\cdot10^{-4}$
Sulfur dioxide (air) / Acidification and eutrophication	$6.30\cdot10^{-4}$	$1.19\cdot10^{-5}$	$2.64\cdot10^{-6}$	$4.91\cdot10^{-7}$	$4.19\cdot10^{-6}$	$1.54\cdot10^{-4}$	$1.22\cdot10^{-5}$
Contributors to Resource categories (points)	Coal	Natural gas, combined cycle	Nuclear	Hydraulic	Eolic	Fuel-gas	Others
Gas, natural, in ground (raw) / Fossil fuels	$4.90\cdot10^{-4}$	$3.53\cdot10^{-2}$	$1.38\cdot10^{-4}$	$2.96\cdot10^{-5}$	$3.52\cdot10^{-4}$	$2.22\cdot10^{-2}$	$1.00\cdot10^{-2}$
Oil, crude, in ground (raw) / Fossil fuels	$2.30\cdot10^{-4}$	$1.99\cdot10^{-4}$	$1.56\cdot10^{-4}$	$9.28\cdot10^{-5}$	$2.47\cdot10^{-4}$	$3.11\cdot10^{-2}$	$4.23\cdot10^{-4}$
Total (partial)	$3.10\cdot10^{-2}$	$3.78\cdot10^{-2}$	$5.73\cdot10^{-4}$	$2.90\cdot10^{-4}$	$1.04\cdot10^{-3}$	$6.45\cdot10^{-2}$	$1.17\cdot10^{-2}$
EI-99 Single Score per contributor	$4.09\cdot10^{-2}$	$3.84\cdot10^{-2}$	$1.24\cdot10^{-3}$	$3.70\cdot10^{-4}$	$2.71\cdot10^{-3}$	$8.55\cdot10^{-2}$	$1.31\cdot10^{-2}$
Proportion of contribution	25.8%	24.4%	19.7%	9.4%	9.4%	0.9%	10.4%
EI-99 for the Spanish Electricity mix	**$2.26\cdot10^{-2}$ points**						

MECHANICAL CHILLER, FMWR

The CD that accompanies this thesis contains the LCI_k of the mechanical chiller, FMWR (one piece of equipment).

Characterization factors $df_{ic,k}$ were consulted to evaluate the contribution of each substance of the inventory LCI_k towards the different impact categories, yielding Table A1.10, where only the top contributors to each impact category are shown. The life cycle of equipment considered the processes necessary to obtain the equipment (materials, transformation processes, and transportation) and final waste scenario (landfill).

Table A1.10 Top contributors to damage IM_{ic} for *mechanical chiller* (one piece of equipment).

Contributors to Human Health categories (DALY)	Equipment	Landfill scenario
Arsenic, ion (water) / Carcinogens	$1.03\cdot10^{-2}$	$1.56\cdot10^{-9}$
Cadmium, ion (water) / Carcinogens	$6.49\cdot10^{-3}$	$6.40\cdot10^{-10}$
Carbon dioxide, fossil (air) / Climate change	$1.76\cdot10^{-2}$	$5.59\cdot10^{-8}$
Ethane (air) / Respiratory organics	$7.25\cdot10^{-7}$	-
Climate change	$1.62\cdot10^{-3}$	-
Ozone layer	$1.37\cdot10^{-3}$	-

Contributors to Ecosystem Quality categories ($PDF\cdot m^2\cdot y$)	Equipment	Landfill scenario
Sulfur dioxide (air) / Acidification and eutrophication	407.95	-
Nickel (air) / Ecotoxicity	364.64	$8.16\cdot10^{-4}$
Transformation, to urban (raw) / Land use	314.99	-
Nitrogen oxides (air) / Acidification and eutrophication	260.9	$1.82\cdot10^{-2}$
Lead (air) / Ecotoxicity	200.1	$2.21\cdot10^{-4}$

Contributors to Resource categories (MJ surplus)	Equipment	Landfill scenario
Copper, in ground (raw) / Minerals	18,761	$2.23\cdot10^{-4}$
Oil, crude, in ground (raw)/ Fossil fuels	20,207	$4.84\cdot10^{-1}$
Gas, natural, in ground (raw) / Fossil fuels	6780	$7.43\cdot10^{-3}$
Nickel, in ground (raw) / Minerals	657.12	-
Lead, in ground (raw) / Minerals	625.88	$2.65\cdot10^{-5}$

The next step is the application of the sets of normalization and weighting factors (Table A1.7) to the damage IM_{ic} values (Table A1.11), yielding the Eco-indicator 99 Single Score per impact category (which will then be added yielding the final EI-99 value). Table A1.11 shows the top contributors to the final value of EI-99.

Table A1.11 Eco-indicator 99 Single Score for *mechanical chiller* (one piece of equipment).

	Human Health (points)		**Ecosystem Quality (points)**		**Resources (points)**	
	Equipment	Landfill scenario	Equipment	Landfill scenario	Equipment	Landfill scenario
Copper, in ground (raw)					669.78 (Minerals)	$7.99\cdot10^{-6}$ (Minerals)
Sulfur dioxide (air)	417.88 (Respiratory inorganics)	-	31.82 (Acidification and eutrophication)	-		
Carbon dioxide (air)	344.11 (Climate change)	$1.09\cdot10^{-3}$ (Climate change)				
Oil, crude, in ground (raw)					710.8 (Fossil fuels)	$1.72\cdot10^{-2}$ (Fossil fuels)
Arsenic, ion (water)	201.3 (Carcinogens)	$3.09\cdot10^{-5}$ (Carcinogens)				
Gas natural, in ground (raw)					213.47 (Fossil fuels)	-
Total (partial)	**963.30**		**31.82**		**1594.06**	
EI-99 Single Score	**3130 points**					

APPENDIX II

ENERGY DEMANDS FOR A MEDIUM-SIZE HOSPITAL LOCATED IN ZARAGOZA

Table A2.1 Domestic hot water and heating demands (MW) – Working days.

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
00h-01h	1.4861	1.2527	0.9609	0.7268	0.3932	0.1375	0.0798	0.0798	0.1479	0.4937	1.0660	1.4044
01h-02h	1.3170	1.1086	0.8480	0.6390	0.3410	0.1168	0.0652	0.0652	0.1260	0.4307	0.9418	1.2440
02h-03h	1.3239	1.1134	0.8503	0.6392	0.3382	0.1142	0.0621	0.0621	0.1235	0.4568	0.9450	1.2503
03h-04h	1.3280	1.1158	0.8506	0.6378	0.3345	0.1112	0.0587	0.0587	0.1206	0.4258	0.9461	1.2537
04h-05h	1.4645	1.2365	0.9515	0.7229	0.3970	0.1421	0.0857	0.0857	0.1522	0.4951	1.0541	1.3847
05h-06h	1.5980	1.3546	1.0504	0.8063	0.4584	0.1726	0.1124	0.1124	0.1834	0.5631	1.1599	1.5128
06h-07h	1.8109	1.5421	1.2062	0.9366	0.5524	0.2185	0.1520	0.1520	0.2304	0.6681	1.3271	1.7168
07h-08h	2.0209	1.7272	1.3601	1.0655	0.6456	0.2640	0.1914	0.1914	0.2771	0.7720	1.4923	1.9181
08h-09h	2.4502	2.0954	1.6518	1.2959	0.7885	0.3242	0.2364	0.2364	0.3399	0.9413	1.8115	2.3260
09h-10h	2.8790	2.4630	1.9430	1.5257	0.9310	0.3839	0.2810	0.2810	0.4024	1.1100	2.1302	2.7334
10h-11h	2.7835	2.3742	1.8625	1.4519	0.8666	0.3481	0.2468	0.2468	0.3662	1.0428	2.0467	2.6403
11h-12h	2.6856	2.2833	1.7805	1.3769	0.8018	0.3120	0.2125	0.2125	0.3299	0.9750	1.9615	2.5448
12h-13h	2.5758	2.1847	1.6959	1.3036	0.7446	0.2822	0.1855	0.1855	0.2996	0.9129	1.8719	2.4389
13h-14h	2.4630	2.0836	1.6093	1.2288	0.6864	0.2520	0.1582	0.1582	0.2689	0.8497	1.7801	2.3302
14h-15h	2.4321	2.0556	1.5850	1.2074	0.6691	0.2429	0.1498	0.1498	0.2596	0.8312	1.7544	2.3003
15h-16h	2.3984	2.0252	1.5588	1.1840	0.6510	0.2334	0.1411	0.1411	0.2500	0.8116	1.7260	2.2678
16h-17h	2.3359	1.9768	1.5281	1.1679	0.6547	0.2417	0.1529	0.1529	0.2576	0.8092	1.6896	2.2102
17h-18h	2.2705	1.9260	1.4955	1.1500	0.6575	0.2496	0.1644	0.1644	0.2649	0.8058	1.6505	2.1500
18h-19h	2.2864	1.9373	1.5010	1.1509	0.6519	0.2442	0.1579	0.1579	0.2597	0.8022	1.6581	2.1642
19h-20h	2.3017	1.9481	1.5061	1.1514	0.6458	0.2387	0.1512	0.1512	0.2544	0.7981	1.6652	2.1779
20h-21h	2.1922	1.8477	1.4172	1.0717	0.5792	0.2024	0.1172	0.1172	0.2177	0.7275	1.5722	2.0717
21h-22h	2.0804	1.7455	1.3269	0.9910	0.5122	0.1660	0.0832	0.0832	0.1809	0.6564	1.4776	1.9632
22h-23h	1.8677	1.5711	1.2003	0.9028	0.4788	0.1622	0.0888	0.0888	0.1753	0.6064	1.3338	1.7639
23h-24h	1.6550	1.3967	1.0737	0.8146	0.4453	0.1583	0.0944	0.0944	0.1698	0.5565	1.1900	1.5646

Table A2.2 Domestic hot water and heating demands (MW) – Holiday/weekend days.

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
00h-01h	1.3956	1.1778	0.9056	0.6871	0.3758	0.1337	0.0798	0.0798	0.1433	0.4695	1.0036	1.3194
01h-02h	1.3490	1.1351	0.8676	0.6530	0.3472	0.1181	0.0652	0.0652	0.1276	0.4393	0.9639	1.2741
02h-03h	1.3365	1.1238	0.8580	0.6447	0.3406	0.1147	0.0621	0.0621	0.1241	0.4322	0.9537	1.2621
03h-04h	1.3235	1.1121	0.8479	0.6358	0.3336	0.111	0.0587	0.0587	0.1204	0.4246	0.943	1.2495
04h-05h	1.3701	1.1584	0.8938	0.6814	0.3788	0.1381	0.0857	0.0857	0.1475	0.4699	0.9891	1.2960
05h-06h	1.4162	1.2042	0.9391	0.7265	0.4233	0.1648	0.1124	0.1124	0.1743	0.5146	1.0345	1.3420
06h-07h	1.5598	1.3343	1.0525	0.8264	0.5040	0.2078	0.1520	0.1520	0.2178	0.6011	1.1540	1.4809
07h-08h	1.7012	1.4626	1.1644	0.9251	0.5840	0.2504	0.1914	0.1914	0.2610	0.6867	1.2717	1.6177
08h-09h	2.0113	1.7321	1.3831	1.1031	0.7040	0.3055	0.2364	0.2364	0.3178	0.8242	1.5088	1.9136
09h-10h	2.3210	2.0012	1.6014	1.2807	0.8235	0.3601	0.2810	0.2810	0.3743	0.9611	1.7453	2.2091
10h-11h	2.1825	1.8767	1.4946	1.1879	0.7508	0.3224	0.2468	0.2468	0.3360	0.8824	1.6322	2.0755
11h-12h	2.0440	1.7523	1.3877	1.0952	0.6782	0.2846	0.2125	0.2125	0.2976	0.8038	1.5190	1.9419
12h-13h	1.9622	1.6769	1.3203	1.0342	0.6264	0.2561	0.1855	0.1855	0.2687	0.7492	1.4487	1.8623
13h-14h	1.8780	1.5995	1.2513	0.9719	0.5737	0.2271	0.1582	0.1582	0.2395	0.6936	1.3766	1.7805
14h-15h	1.7490	1.4903	1.1669	0.9074	0.5375	0.2138	0.1498	0.1498	0.2253	0.6489	1.2833	1.6585
15h-16h	1.6178	1.3792	1.0810	0.8417	0.5006	0.2001	0.1411	0.1411	0.2107	0.6033	1.1883	1.5343
16h-17h	1.6317	1.3941	1.0970	0.8587	0.5190	0.2117	0.1529	0.1529	0.2222	0.6213	1.2040	1.5485
17h-18h	1.6452	1.4086	1.1127	0.8754	0.5370	0.2229	0.1644	0.1644	0.2334	0.6389	1.2192	1.5624
18h-19h	1.6067	1.3748	1.0850	0.8525	0.5210	0.2153	0.1579	0.1579	0.2255	0.6208	1.1894	1.5256
19h-20h	1.5658	1.3391	1.0556	0.8282	0.5041	0.2073	0.1512	0.1512	0.2173	0.6017	1.1577	1.4865
20h-21h	1.5168	1.2888	1.0038	0.7751	0.4491	0.1736	0.1172	0.1172	0.1837	0.5472	1.1064	1.4370
21h-22h	1.4680	1.2387	0.9520	0.7220	0.3942	0.1399	0.0832	0.0832	0.1501	0.4929	1.0552	1.3877
22h-23h	1.4550	1.2295	0.9477	0.7216	0.3992	0.1446	0.0888	0.0888	0.1546	0.4963	1.0492	1.3761
23h-24h	1.4402	1.2189	0.9422	0.7203	0.4039	0.1491	0.0944	0.0944	0.1590	0.4992	1.0418	1.3627

Table A2.3 Refrigeration and electricity demands (MW).

	Refrigeration								Electricity	
	Working day				Holiday/Weekend day				Working day	Holiday/ Weekend day
Time	Jun	Jul	Ago	Sept	Jun	Jul	Aug	Sept	All year	
00h-01h	0.0864	0.4044	0.3656	0.0283	0.0660	0.3089	0.2793	0.0216	0.3117	0.2956
01h-02h	0.0834	0.3901	0.3527	0.0273	0.0637	0.2981	0.2694	0.0209	0.2990	0.2821
02h-03h	0.0834	0.3901	0.3527	0.0273	0.0637	0.2981	0.2694	0.0209	0.2906	0.2767
03h-04h	0.0834	0.3901	0.3527	0.0273	0.0637	0.2981	0.2694	0.0209	0.2816	0.2709
04h-05h	0.0834	0.3901	0.3527	0.0273	0.0637	0.2981	0.2694	0.0209	0.2821	0.2747
05h-06h	0.0834	0.3901	0.3527	0.0273	0.0637	0.2981	0.2694	0.0209	0.2821	0.2786
06h-07h	0.1040	0.4863	0.4396	0.0341	0.0794	0.3716	0.3359	0.0260	0.2890	0.2809
07h-08h	0.1241	0.5807	0.5250	0.0407	0.0948	0.4437	0.4011	0.0311	0.2959	0.2832
08h-09h	0.1694	0.7927	0.7166	0.0555	0.1295	0.6056	0.5475	0.0424	0.4028	0.3319
09h-10h	0.2148	1.0047	0.9083	0.0704	0.1641	0.7676	0.6939	0.0538	0.5091	0.3806
10h-11h	0.2490	1.1650	1.0532	0.0816	0.1903	0.8901	0.8047	0.0623	0.5192	0.3837
11h-12h	0.2833	1.3254	1.1982	0.0928	0.2164	1.0126	0.9154	0.0709	0.5293	0.3864
12h-13h	0.3320	1.5534	1.4043	0.1088	0.2537	1.1868	1.0729	0.0831	0.5144	0.3791
13h-14h	0.3808	1.7814	1.6104	0.1247	0.2909	1.3610	1.2304	0.0953	0.4996	0.3714
14h-15h	0.3690	1.7262	1.5605	0.1209	0.2819	1.3188	1.1922	0.0923	0.4657	0.3486
15h-16h	0.3572	1.6710	1.5106	0.1170	0.2729	1.2766	1.1541	0.0894	0.4319	0.3254
16h-17h	0.2947	1.3788	1.2465	0.0965	0.2252	1.0534	0.9523	0.0738	0.4202	0.3196
17h-18h	0.2323	1.0867	0.9824	0.0761	0.1775	0.8302	0.7505	0.0581	0.4086	0.3134
18h-19h	0.1774	0.8301	0.7505	0.0581	0.1356	0.6342	0.5733	0.0444	0.4165	0.3265
19h-20h	0.1226	0.5736	0.5186	0.0402	0.0937	0.4382	0.3962	0.0307	0.4245	0.3393
20h-21h	0.1119	0.5237	0.4735	0.0367	0.0855	0.4001	0.3617	0.0280	0.4218	0.3497
21h-22h	0.1009	0.4721	0.4268	0.0331	0.0771	0.3607	0.3260	0.0253	0.4192	0.3598
22h-23h	0.0952	0.4454	0.4026	0.0312	0.0727	0.3402	0.3076	0.0238	0.3721	0.3346
23h-24h	0.0895	0.4186	0.3784	0.0293	0.0684	0.3198	0.2891	0.0224	0.3244	0.3091

APPENDIX III

FLOW AND OPERATION DETAILS

V.I Economic optimal

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Equipment installed:

   Gas turbine             :  0 , (kW)  = 0 ,       (€/unit) = 1530000
   Gas engine              :  3 , (kW)  = 1740 ,    (€/unit) = 435000
   Steam boiler            :  0 , (kW)  = 0 ,       (€/unit) = 182000
   Hot water boiler        :  3 , (kW)  = 1709 ,    (€/unit) = 30000
   VA -> WC heat exchanger :  0 , (kW)  = 0 ,       (€/unit) = 2500
   WC -> WR heat exchanger :  4 , (kW)  = 1600 ,    (€/unit) = 6500
   DE absorption chiller   :  0 , (kW)  = 0 ,       (€/unit) = 370000
   SE absorption chiller   :  1 , (kW)  = 490 ,     (€/unit) = 200000
   Mechanical chiller      :  3 , (kW)  = 1470 ,    (€/unit) = 175000
   Cooling tower           :  3 , (kW)  = 3000 ,    (€/unit) = 25000

 Initial investment in equipment (€) =      2554150

 TOTAL Cost  (€/year) =       570169

   Fixed Cost     (€/year) =       510830
   Variable Cost  (€/year) =        59339


 Energy flows (MWh/year) :

   Steam demand              =            0
   Hot water demand          =         8059
   Cold water demand         =         1265
   Electricity demand        =         3250

   Natural gas consumption   =       37324   Cost   (€/year) =      933092
   Purchase of electricity   =          29   Cost   (€/year) =        3207
   Sale of electricity       =       11389   Profit  (€/año) =      876960



 ANNUAL FLOWS (MWh)

 Fuel for cogeneration =  36638
 Cogenerated work =  14954
 Cogenerated heat  =  14356
 Consumed cogenerated heat =   8602
 Fuel attributable to cogenerated work =  27080
 Waste heat =   5754

 WR  of engine =   2991

 Fuel for boiler =    686
 WC  of boiler =    635

 WC  of heat exchanger =   5754

 EE  of absorption chiller =      8
 WC  of absorption chiller =   1179
 WR  of absorption chiller =   1965
 WF  of absorption chiller =    786

 EE  of mechanical chiller =    110
 WR  of mechanical chiller =    589
 WF  of mechanical chiller =    479

 WR  of cooling tower =  11299
 EE  of cooling tower =    226
 AA  of cooling tower =      0

 Minimum Equivalent Electrical Efficiency (%) = 55.223
 Minimum Self-consumption of electricity  (%) =  0.000
 Total consumption of electricity =   3565
 Real self-consumption (%) = 23.840
 PES (%) =       10.009
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```
Natural gas consumption(kW) =
            JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
   1AM          4263         4263         4263         4263         4263         4263         4263         4263
   2AM          4263         4263         4263         4263         4263         4263         4263         4263
   3AM          4263         4263         4263         4263         4263         4263         4263         4263
   4AM          4263         4263         4263         4263         4263         4263         4263         4263
   5AM          4263         4263         4263         4263         4263         4263         4263         4263
   6AM          4263         4263         4263         4263         4263         4263         4263         4263
   7AM          4414         4263         4263         4263         4263         4263         4263         4263
   8AM          4641         4296         4324         4263         4263         4263         4263         4263
   9AM          5105         4631         4722         4329         4263         4263         4263         4263
   10AM         5568         4965         5119         4620         4557         4263         4263         4263
   11AM         5465         4816         5023         4485         4470         4263         4263         4263
   12AM         5359         4666         4924         4351         4381         4263         4263         4263
   1PM          5240         4578         4818         4270         4290         4263         4263         4263
   2PM          5119         4487         4709         4263         4263         4263         4263         4263
   3PM          5085         4347         4679         4263         4263         4263         4263         4263
   4PM          5049         4263         4646         4263         4263         4263         4263         4263
   5PM          4981         4263         4593         4263         4263         4263         4263         4263
   6PM          4911         4263         4539         4263         4263         4263         4263         4263
   7PM          4928         4263         4551         4263         4263         4263         4263         4263
   8PM          4944         4263         4562         4263         4263         4263         4263         4263
   9PM          4826         4263         4454         4263         4263         4263         4263         4263
   10PM         4705         4263         4344         4263         4263         4263         4263         4263
   11PM         4476         4263         4263         4263         4263         4263         4263         4263
   12PM         4263         4263         4263         4263         4263         4263         4263         4263

              MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
   1AM          4263         4263         4263         4263         4263         4263         4263         4263
   2AM          4263         4263         4263         4263         4263         4263         4263         4263
   3AM          4263         4263         4263         4263         4263         4263         4263         4263
   4AM          4263         4263         4263         4263         4263         4263         4263         4263
   5AM          4263         4263         4263         4263         4263         4263         4263         4263
   6AM          4263         4263         4263         4263         4263         4263         4263         4263
   7AM          4263         4263         4263         4263         4263         4263         4263         4263
   8AM          4263         4263         4263         4263         4263         4263         4263         4263
   9AM          4263         4263         4263         4263         4263         4263         4263         4263
   10AM         4263         4263         4263         4263         4263         4263         4263         4263
   11AM         4263         4263         4263         4263         2842         4263         4263         4263
   12AM         4263         4263         4263         4263         2842         4263         2842         4263
   1PM          4263         4263         4263         4263         2842         2842         2842         2842
   2PM          4263         4263         4263         4263         1494         2842         1421         2842
   3PM          4263         4263         4263         4263         1421         2842         1421         2842
   4PM          4263         4263         4263         4263         1421         2842         2842         2842
   5PM          4263         4263         4263         4263         2842         2842         2842         4263
   6PM          4263         4263         4263         4263         2842         4263         4263         4263
   7PM          4263         4263         4263         4263         4263         4263         4263         4263
   8PM          4263         4263         4263         4263         4263         4263         4263         4263
   9PM          4263         4263         4263         4263         4263         4263         4263         4263
   10PM         4263         4263         4263         4263         4263         4263         4263         4263
   11PM         4263         4263         4263         4263         4263         4263         4263         4263
   12PM         4263         4263         4263         4263         4263         4263         4263         4263

          SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
   1AM          4263         4263         4263         4263         4263         4263         4263         4263
   2AM          4263         4263         4263         4263         4263         4263         4263         4263
   3AM          4263         4263         4263         4263         4263         4263         4263         4263
   4AM          4263         4263         4263         4263         4263         4263         4263         4263
   5AM          4263         4263         4263         4263         4263         4263         4263         4263
   6AM          4263         4263         4263         4263         4263         4263         4263         4263
   7AM          4263         4263         4263         4263         4263         4263         4313         4263
   8AM          4263         4263         4263         4263         4263         4263         4530         4263
   9AM          4263         4263         4263         4263         4415         4263         4971         4525
   10AM         4263         4263         4263         4263         4759         4343         5411         4844
   11AM         4263         4263         4263         4263         4669         4263         5310         4700
   12AM         4263         4263         4263         4263         4577         4263         5207         4556
   1PM          4263         4263         4263         4263         4480         4263         5092         4470
   2PM          4263         4263         4263         4263         4381         4263         4975         4381
   3PM          4263         4263         4263         4263         4353         4263         4943         4263
   4PM          4263         4263         4263         4263         4323         4263         4908         4263
   5PM          4263         4263         4263         4263         4284         4263         4845         4263
   6PM          4263         4263         4263         4263         4263         4263         4780         4263
   7PM          4263         4263         4263         4263         4263         4263         4796         4263
   8PM          4263         4263         4263         4263         4263         4263         4811         4263
   9PM          4263         4263         4263         4263         4263         4263         4696         4263
   10PM         4263         4263         4263         4263         4263         4263         4579         4263
   11PM         4263         4263         4263         4263         4263         4263         4363         4263
   12PM         4263         4262         4263         4263         4263         4263         4263         4263
```

```
Purchase of electricity (kW) =
            JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0            0            0            0            0
   3PM             0            0            0            0            0            0            0            0
   4PM             0            0            0            0            0            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0

              MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF       AUGUSTL      AUGUSTF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0          314            0          280            0
   3PM             0            0            0            0          274            0          232            0
   4PM             0            0            0            0          225            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0

          SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0            0            0            0            0
   3PM             0            0            0            0            0            0            0            0
   4PM             0            0            0            0            0            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0
```

```
Sale of electricity (kW) =
           JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
  1AM          1417         1431         1412         1427         1407         1422         1402         1417
  2AM          1426         1444         1422         1440         1417         1434         1413         1430
  3AM          1435         1449         1431         1445         1426         1440         1421         1435
  4AM          1444         1455         1440         1450         1435         1445         1430         1441
  5AM          1446         1452         1442         1448         1436         1442         1431         1438
  6AM          1449         1449         1444         1445         1438         1439         1433         1435
  7AM          1444         1449         1441         1445         1434         1439         1429         1435
  8AM          1437         1449         1437         1445         1430         1439         1425         1434
  9AM          1330         1401         1330         1401         1329         1395         1322         1389
  10AM         1223         1352         1223         1352         1223         1351         1221         1344
  11AM         1213         1349         1213         1349         1213         1345         1209         1339
  12AM         1203         1346         1203         1346         1203         1340         1197         1335
  1PM          1218         1353         1218         1353         1218         1346         1211         1341
  2PM          1233         1361         1233         1360         1232         1353         1224         1347
  3PM          1267         1384         1267         1380         1265         1374         1258         1369
  4PM          1301         1406         1301         1401         1298         1395         1291         1391
  5PM          1312         1412         1312         1407         1309         1401         1302         1397
  6PM          1324         1419         1324         1414         1320         1408         1314         1403
  7PM          1316         1405         1316         1400         1313         1394         1306         1390
  8PM          1308         1391         1308         1387         1305         1381         1298         1376
  9PM          1311         1380         1311         1375         1306         1370         1299         1365
  10PM         1313         1369         1313         1364         1306         1358         1300         1354
  11PM         1360         1394         1358         1389         1351         1383         1345         1379
  12PM         1408         1419         1403         1414         1396         1409         1391         1404

             MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
  1AM          1395         1411         1388         1404         1377         1396         1378         1397
  2AM          1407         1424         1400         1417         1390         1409         1391         1410
  3AM          1415         1429         1408         1423         1398         1415         1399         1416
  4AM          1424         1435         1417         1429         1407         1420         1408         1421
  5AM          1425         1432         1417         1425         1407         1417         1408         1418
  6AM          1426         1429         1418         1422         1408         1414         1409         1415
  7AM          1421         1428         1411         1420         1399         1410         1400         1411
  8AM          1416         1428         1405         1418         1369         1406         1383         1408
  9AM          1312         1381         1298         1369         1209         1328         1229         1343
  10AM         1209         1335         1191         1321         1050         1239         1074         1258
  11AM         1197         1330         1179         1316          432         1204         1027         1226
  12AM         1186         1326         1168         1312          380         1169          413         1194
  1PM          1200         1333         1180         1318          336          565          374          594
  2PM          1213         1339         1193         1324            0          528            0          561
  3PM          1247         1361         1227         1346            0          561            0          594
  4PM          1280         1384         1261         1370            0          595          429          626
  5PM          1292         1390         1275         1377          474          658          508         1250
  6PM          1304         1396         1289         1385          561         1288         1154         1308
  7PM          1296         1383         1282         1373         1185         1324         1205         1340
  8PM          1288         1370         1276         1361         1242         1350         1256         1351
  9PM          1289         1358         1278         1350         1256         1340         1265         1341
  10PM         1290         1347         1280         1340         1267         1330         1269         1331
  11PM         1337         1373         1327         1365         1315         1356         1317         1357
  12PM         1384         1398         1375         1391         1364         1382         1365         1383

         SEPTEMBERL    SEPTEMBERF    OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
  1AM          1390         1406         1397         1413         1409         1424         1416         1430
  2AM          1402         1419         1409         1426         1419         1436         1425         1443
  3AM          1410         1424         1418         1431         1427         1442         1434         1448
  4AM          1419         1430         1426         1437         1436         1447         1443         1453
  5AM          1419         1427         1427         1434         1438         1444         1445         1450
  6AM          1420         1423         1428         1431         1440         1441         1447         1447
  7AM          1414         1422         1423         1430         1437         1441         1444         1448
  8AM          1408         1420         1419         1430         1433         1441         1437         1448
  9AM          1301         1372         1315         1384         1330         1397         1330         1401
  10AM         1196         1324         1212         1338         1223         1352         1223         1352
  11AM         1185         1320         1201         1333         1213         1348         1213         1349
  12AM         1174         1317         1189         1329         1203         1343         1203         1346
  1PM          1187         1323         1203         1335         1218         1349         1218         1353
  2PM          1201         1330         1217         1342         1233         1355         1233         1361
  3PM          1235         1352         1250         1364         1267         1376         1267         1384
  4PM          1269         1375         1283         1386         1301         1397         1301         1404
  5PM          1281         1382         1295         1392         1312         1404         1312         1411
  6PM          1294         1389         1307         1399         1324         1410         1324         1417
  7PM          1286         1376         1299         1385         1316         1396         1316         1403
  8PM          1279         1363         1291         1372         1308         1383         1308         1390
  9PM          1281         1352         1292         1360         1309         1372         1311         1378
  10PM         1283         1342         1293         1349         1309         1360         1313         1367
  11PM         1330         1367         1339         1374         1354         1386         1360         1392
  12PM         1377         1393         1386         1400         1399         1411         1406         1417
```

```
Number of engines in operation =
          JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
 1AM             3            3            3            3            3            3            3            3
 2AM             3            3            3            3            3            3            3            3
 3AM             3            3            3            3            3            3            3            3
 4AM             3            3            3            3            3            3            3            3
 5AM             3            3            3            3            3            3            3            3
 6AM             3            3            3            3            3            3            3            3
 7AM             3            3            3            3            3            3            3            3
 8AM             3            3            3            3            3            3            3            3
 9AM             3            3            3            3            3            3            3            3
 10AM            3            3            3            3            3            3            3            3
 11AM            3            3            3            3            3            3            3            3
 12AM            3            3            3            3            3            3            3            3
 1PM             3            3            3            3            3            3            3            3
 2PM             3            3            3            3            3            3            3            3
 3PM             3            3            3            3            3            3            3            3
 4PM             3            3            3            3            3            3            3            3
 5PM             3            3            3            3            3            3            3            3
 6PM             3            3            3            3            3            3            3            3
 7PM             3            3            3            3            3            3            3            3
 8PM             3            3            3            3            3            3            3            3
 9PM             3            3            3            3            3            3            3            3
 10PM            3            3            3            3            3            3            3            3
 11PM            3            3            3            3            3            3            3            3
 12PM            3            3            3            3            3            3            3            3

            MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
 1AM             3            3            3            3            3            3            3            3
 2AM             3            3            3            3            3            3            3            3
 3AM             3            3            3            3            3            3            3            3
 4AM             3            3            3            3            3            3            3            3
 5AM             3            3            3            3            3            3            3            3
 6AM             3            3            3            3            3            3            3            3
 7AM             3            3            3            3            3            3            3            3
 8AM             3            3            3            3            3            3            3            3
 9AM             3            3            3            3            3            3            3            3
 10AM            3            3            3            3            3            3            3            3
 11AM            3            3            3            3            2            3            3            3
 12AM            3            3            3            3            2            3            2            3
 1PM             3            3            3            3            2            2            2            2
 2PM             3            3            3            3            1            2            1            2
 3PM             3            3            3            3            1            2            1            2
 4PM             3            3            3            3            1            2            2            2
 5PM             3            3            3            3            2            2            2            3
 6PM             3            3            3            3            2            3            3            3
 7PM             3            3            3            3            3            3            3            3
 8PM             3            3            3            3            3            3            3            3
 9PM             3            3            3            3            3            3            3            3
 10PM            3            3            3            3            3            3            3            3
 11PM            3            3            3            3            3            3            3            3
 12PM            3            3            3            3            3            3            3            3

        SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
 1AM             3            3            3            3            3            3            3            3
 2AM             3            3            3            3            3            3            3            3
 3AM             3            3            3            3            3            3            3            3
 4AM             3            3            3            3            3            3            3            3
 5AM             3            3            3            3            3            3            3            3
 6AM             3            3            3            3            3            3            3            3
 7AM             3            3            3            3            3            3            3            3
 8AM             3            3            3            3            3            3            3            3
 9AM             3            3            3            3            3            3            3            3
 10AM            3            3            3            3            3            3            3            3
 11AM            3            3            3            3            3            3            3            3
 12AM            3            3            3            3            3            3            3            3
 1PM             3            3            3            3            3            3            3            3
 2PM             3            3            3            3            3            3            3            3
 3PM             3            3            3            3            3            3            3            3
 4PM             3            3            3            3            3            3            3            3
 5PM             3            3            3            3            3            3            3            3
 6PM             3            3            3            3            3            3            3            3
 7PM             3            3            3            3            3            3            3            3
 8PM             3            3            3            3            3            3            3            3
 9PM             3            3            3            3            3            3            3            3
 10PM            3            3            3            3            3            3            3            3
 11PM            3            3            3            3            3            3            3            3
 12PM            3            3            3            3            3            3            3            3
```

V.II CO$_2$ and EI-99 Optimals

```
Equipment installed:

   Gas turbine             :  0 , (kW)  = 0 ,       (emission)  = 80500 kg CO2 / 8700 points
   Gas engine              :  0 , (kW)  = 0 ,       (emission)  = 37350 kg CO2 / 4030 points
   Steam boiler            :  0 , (kW)  = 0 ,       (emission)  = 15810 kg CO2 / 1420 points
   Hot water boiler        :  6 , (kW)  = 3420 ,    (emission)  = 3050 kg CO2 / 205 points
   VA -> WC heat exchanger :  0 , (kW)  = 0 ,       (emission)  = 2350 kg CO2 / 251 points
   WC -> WR heat exchanger :  0 , (kW)  = 0 ,       (emission)  = 5010 kg CO2 / 532 points
   DE absorption chiller   :  0 , (kW)  = 0 ,       (emission)  = 98600 kg CO2 / 11100 points
   SE absorption chiller   :  0 , (kW)  = 0 ,       (emission)  = 58900 kg CO2 / 5890 points
   Mechanical chiller      :  4 , (kW)  = 1960 ,    (emission)  = 85420 kg CO2 / 3130 points
   Cooling tower           :  3 , (kW)  = 3000 ,    (emission)  = 23530 kg CO2 / 2990 points

 Initial investment in equipment (€) =      1098250

 TOTAL Cost  (€/year) =       804184

   Fixed Cost     (€/year) =       219650
   Variable Cost  (€/year) =       584534


 Energy flows (MWh/year) :

   Steam demand             =           0
   Hot water demand         =        8059
   Cold water demand        =        1265
   Electricity demand       =        3250

Natural gas consumption   =  8703   Emission (__/year) =  2367296 kg CO2 / 328984 points
Purchase of electricity   =  3572   Emission (__/year) =  1375264 kg CO2 / 80730 points
Sale of electricity       =    0    Emission (__/year) =               0 / 0

 TOTAL emission           (__/year)  =      3785616 kg CO2 / 411986 points

   Fixed emission         (__/year)  =        43057 kg CO2 / 2272 points
   Variable emission      (__/year)  =      3742559 kg CO2 / 409714 points


 ANNUAL FLOWS (MWh)

 Fuel for cogeneration =      0
 Cogenerated work =      0
 Cogenerated heat  =      0
 Consumed cogenerated heat =      0
 Fuel attributable to cogenerated work =      0
 Waste heat =      0

 WR  of engine =      0

 Fuel for boiler =   8703
 WC  of boiler =   8059

 WC  of heat exchanger =      0

 EE  of absorption chiller =      0
 WC  of absorption chiller =      0
 WR  of absorption chiller =      0
 WF  of absorption chiller =      0

 EE  of mechanical chiller =    291
 WR  of mechanical chiller =   1556
 WF  of mechanical chiller =   1265

 WR  of cooling tower =   1556
 EE  of cooling tower =     31
 AA  of cooling tower =      0
```

```
Natural gas consumption(kW) =
            JANUARYL     JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
   1AM          1604         1507         1352         1272         1037          978          784          742
   2AM          1422         1456         1197         1225          915          937          690          705
   3AM          1429         1443         1202         1213          918          926          690          696
   4AM          1434         1429         1205         1201          918          915          688          686
   5AM          1581         1479         1335         1251         1027          965          780          735
   6AM          1725         1529         1462         1300         1134         1014          870          784
   7AM          1955         1684         1665         1441         1302         1136         1011          892
   8AM          2182         1837         1865         1579         1468         1257         1150          999
   9AM          2646         2172         2263         1870         1783         1493         1399         1191
   10AM         3109         2506         2660         2161         2098         1729         1647         1383
   11AM         3006         2357         2564         2026         2011         1614         1568         1282
   12AM         2900         2207         2465         1892         1922         1498         1487         1182
   1PM          2781         2119         2359         1811         1831         1425         1407         1116
   2PM          2660         2028         2250         1727         1738         1351         1327         1049
   3PM          2626         1888         2220         1609         1711         1260         1303          979
   4PM          2590         1747         2187         1489         1683         1167         1278          909
   5PM          2522         1762         2134         1505         1650         1184         1261          927
   6PM          2452         1776         2080         1521         1615         1201         1242          945
   7PM          2469         1735         2092         1484         1621         1171         1242          920
   8PM          2485         1691         2103         1446         1626         1140         1243          894
   9PM          2367         1638         1995         1391         1530         1084         1157          837
   10PM         2246         1585         1885         1337         1433         1028         1070          779
   11PM         2017         1571         1696         1327         1296         1023          975          779
   12PM         1787         1555         1508         1316         1159         1017          879          777

              MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
   1AM           424          405          148          144           86           86           86           86
   2AM           368          374          126          127           70           70           70           70
   3AM           365          367          123          123           67           67           67           67
   4AM           361          360          120          119           63           63           63           63
   5AM           428          409          153          149           92           92           92           92
   6AM           495          457          186          177          121          121          121          121
   7AM           596          544          235          224          164          164          164          164
   8AM           697          630          285          270          206          206          206          206
   9AM           851          760          350          329          255          255          255          255
   10AM         1005          889          414          388          303          303          303          303
   11AM          935          810          375          348          266          266          266          266
   12AM          865          732          336          307          229          229          229          229
   1PM           804          676          304          276          200          200          200          200
   2PM           741          619          272          245          170          170          170          170
   3PM           722          580          262          230          161          161          161          161
   4PM           703          540          252          216          152          152          152          152
   5PM           707          560          261          228          165          165          165          165
   6PM           710          579          269          240          177          177          177          177
   7PM           704          562          263          232          170          170          170          170
   8PM           697          544          257          223          163          163          163          163
   9PM           625          485          218          187          126          126          126          126
   10PM          553          425          179          151           89           89           89           89
   11PM          517          431          175          156           95           95           95           95
   12PM          480          436          170          161          101          101          101          101

          SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
   1AM           159          154          533          507         1151         1083         1516         1424
   2AM           136          137          465          474         1017         1041         1343         1376
   3AM           133          134          493          466         1020         1029         1350         1363
   4AM           130          130          459          458         1021         1018         1353         1349
   5AM           164          159          534          507         1138         1068         1495         1399
   6AM           198          188          608          555         1252         1117         1633         1449
   7AM           248          235          721          649         1433         1246         1854         1599
   8AM           299          281          833          741         1611         1373         2071         1747
   9AM           367          343         1016          890         1956         1629         2512         2066
   10AM          434          404         1198         1037         2300         1884         2952         2385
   11AM          395          362         1126          952         2210         1762         2851         2241
   12AM          356          321         1053          868         2118         1640         2748         2097
   1PM           323          290          985          809         2021         1564         2634         2011
   2PM           290          258          917          749         1922         1486         2516         1922
   3PM           280          243          897          700         1894         1385         2484         1791
   4PM           270          227          876          651         1864         1283         2449         1657
   5PM           278          239          873          671         1825         1300         2387         1672
   6PM           286          252          870          690         1783         1316         2322         1687
   7PM           280          243          866          670         1790         1284         2337         1647
   8PM           274          234          861          649         1798         1250         2352         1605
   9PM           235          198          785          590         1697         1194         2237         1551
   10PM          195          162          708          532         1596         1139         2120         1498
   11PM          189          166          654          536         1440         1133         1905         1486
   12PM          183          171          601          539         1285         1125         1689         1471
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Purchase of electricity (kW) =
            JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
   1AM           311          295          311          295          311          295          311          295
   2AM           299          282          299          282          299          282          299          282
   3AM           290          276          290          276          290          276          290          276
   4AM           281          270          281          270          281          270          281          270
   5AM           282          274          282          274          282          274          282          274
   6AM           282          278          282          278          282          278          282          278
   7AM           289          280          289          280          289          280          289          280
   8AM           295          283          295          283          295          283          295          283
   9AM           402          331          402          331          402          331          402          331
   10AM          509          380          509          380          509          380          509          380
   11AM          519          383          519          383          519          383          519          383
   12AM          529          386          529          386          529          386          529          386
   1PM           514          379          514          379          514          379          514          379
   2PM           499          371          499          371          499          371          499          371
   3PM           465          348          465          348          465          348          465          348
   4PM           431          325          431          325          431          325          431          325
   5PM           420          319          420          319          420          319          420          319
   6PM           408          313          408          313          408          313          408          313
   7PM           416          326          416          326          416          326          416          326
   8PM           424          339          424          339          424          339          424          339
   9PM           421          349          421          349          421          349          421          349
   10PM          419          359          419          359          419          359          419          359
   11PM          372          334          372          334          372          334          372          334
   12PM          324          309          324          309          324          309          324          309

              MAYL         MAYF         JUNEL        JUNEF      JULYL        JULYF        AUGUSTL      AUGUSTF
   1AM           311          295          333          312          414          374          404          366
   2AM           299          282          320          298          398          357          388          350
   3AM           290          276          311          292          389          352          380          345
   4AM           281          270          302          287          380          346          371          339
   5AM           282          274          303          290          381          350          371          343
   6AM           282          278          303          294          381          354          371          347
   7AM           289          280          315          301          412          375          400          366
   8AM           295          283          327          307          443          396          429          385
   9AM           402          331          445          364          604          486          585          471
   10AM          509          380          563          422          764          576          740          557
   11AM          519          383          582          432          815          610          787          588
   12AM          529          386          601          441          866          644          834          619
   1PM           514          379          598          443          909          681          871          652
   2PM           499          371          596          445          953          717          909          684
   3PM           465          348          559          420          905          684          863          652
   4PM           431          325          522          394          857          650          816          619
   5PM           420          319          495          376          771          587          737          562
   6PM           408          313          467          358          685          524          658          504
   7PM           416          326          461          361          627          487          607          472
   8PM           424          339          455          363          570          450          556          440
   9PM           421          349          450          371          555          451          542          441
   10PM          419          359          444          379          539          451          527          442
   11PM          372          334          396          353          485          421          474          412
   12PM          324          309          347          326          430          390          420          382

          SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL    NOVEMBERF    DECEMBERL    DECEMBERF
   1AM           318          301          311          295          311          295          311          295
   2AM           305          287          299          282          299          282          299          282
   3AM           297          282          290          276          290          276          290          276
   4AM           288          276          281          270          281          270          281          270
   5AM           289          280          282          274          282          274          282          274
   6AM           289          283          282          278          282          278          282          278
   7AM           297          287          289          280          289          280          289          280
   8AM           306          291          295          283          295          283          295          283
   9AM           416          342          402          331          402          331          402          331
   10AM          527          394          509          380          509          380          509          380
   11AM          539          399          519          383          519          383          519          383
   12AM          552          404          529          386          529          386          529          386
   1PM           542          400          514          379          514          379          514          379
   2PM           531          395          499          371          499          371          499          371
   3PM           496          372          465          348          465          348          465          348
   4PM           461          348          431          325          431          325          431          325
   5PM           444          338          420          319          420          319          420          319
   6PM           427          328          408          313          408          313          408          313
   7PM           431          337          416          326          416          326          416          326
   8PM           434          347          424          339          424          339          424          339
   9PM           431          356          421          349          421          349          421          349
   10PM          427          366          419          359          419          359          419          359
   11PM          380          340          372          334          372          334          372          334
   12PM          331          314          324          309          324          309          324          309
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Sale of electricity (kW) =
             JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0            0            0            0            0
   3PM             0            0            0            0            0            0            0            0
   4PM             0            0            0            0            0            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0

              MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0            0            0            0            0
   3PM             0            0            0            0            0            0            0            0
   4PM             0            0            0            0            0            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0


          SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
   1AM             0            0            0            0            0            0            0            0
   2AM             0            0            0            0            0            0            0            0
   3AM             0            0            0            0            0            0            0            0
   4AM             0            0            0            0            0            0            0            0
   5AM             0            0            0            0            0            0            0            0
   6AM             0            0            0            0            0            0            0            0
   7AM             0            0            0            0            0            0            0            0
   8AM             0            0            0            0            0            0            0            0
   9AM             0            0            0            0            0            0            0            0
   10AM            0            0            0            0            0            0            0            0
   11AM            0            0            0            0            0            0            0            0
   12AM            0            0            0            0            0            0            0            0
   1PM             0            0            0            0            0            0            0            0
   2PM             0            0            0            0            0            0            0            0
   3PM             0            0            0            0            0            0            0            0
   4PM             0            0            0            0            0            0            0            0
   5PM             0            0            0            0            0            0            0            0
   6PM             0            0            0            0            0            0            0            0
   7PM             0            0            0            0            0            0            0            0
   8PM             0            0            0            0            0            0            0            0
   9PM             0            0            0            0            0            0            0            0
   10PM            0            0            0            0            0            0            0            0
   11PM            0            0            0            0            0            0            0            0
   12PM            0            0            0            0            0            0            0            0
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Number of engines in operation =
           JANUARYL       JANUARYF     FEBRUARYL     FEBRUARYF    MARCHL      MARCHF       APRILL       APRILF
  1AM             0            0            0            0            0            0            0            0
  2AM             0            0            0            0            0            0            0            0
  3AM             0            0            0            0            0            0            0            0
  4AM             0            0            0            0            0            0            0            0
  5AM             0            0            0            0            0            0            0            0
  6AM             0            0            0            0            0            0            0            0
  7AM             0            0            0            0            0            0            0            0
  8AM             0            0            0            0            0            0            0            0
  9AM             0            0            0            0            0            0            0            0
  10AM            0            0            0            0            0            0            0            0
  11AM            0            0            0            0            0            0            0            0
  12AM            0            0            0            0            0            0            0            0
  1PM             0            0            0            0            0            0            0            0
  2PM             0            0            0            0            0            0            0            0
  3PM             0            0            0            0            0            0            0            0
  4PM             0            0            0            0            0            0            0            0
  5PM             0            0            0            0            0            0            0            0
  6PM             0            0            0            0            0            0            0            0
  7PM             0            0            0            0            0            0            0            0
  8PM             0            0            0            0            0            0            0            0
  9PM             0            0            0            0            0            0            0            0
  10PM            0            0            0            0            0            0            0            0
  11PM            0            0            0            0            0            0            0            0
  12PM            0            0            0            0            0            0            0            0

              MAYL         MAYF         JUNEL        JUNEF       JULYL        JULYF        AUGUSTL      AUGUSTF
  1AM             0            0            0            0            0            0            0            0
  2AM             0            0            0            0            0            0            0            0
  3AM             0            0            0            0            0            0            0            0
  4AM             0            0            0            0            0            0            0            0
  5AM             0            0            0            0            0            0            0            0
  6AM             0            0            0            0            0            0            0            0
  7AM             0            0            0            0            0            0            0            0
  8AM             0            0            0            0            0            0            0            0
  9AM             0            0            0            0            0            0            0            0
  10AM            0            0            0            0            0            0            0            0
  11AM            0            0            0            0            0            0            0            0
  12AM            0            0            0            0            0            0            0            0
  1PM             0            0            0            0            0            0            0            0
  2PM             0            0            0            0            0            0            0            0
  3PM             0            0            0            0            0            0            0            0
  4PM             0            0            0            0            0            0            0            0
  5PM             0            0            0            0            0            0            0            0
  6PM             0            0            0            0            0            0            0            0
  7PM             0            0            0            0            0            0            0            0
  8PM             0            0            0            0            0            0            0            0
  9PM             0            0            0            0            0            0            0            0
  10PM            0            0            0            0            0            0            0            0
  11PM            0            0            0            0            0            0            0            0
  12PM            0            0            0            0            0            0            0            0

         SEPTEMBERL    SEPTEMBERF     OCTOBERL     OCTOBERF   NOVEMBERL   NOVEMBERF     DECEMBERL    DECEMBERF
  1AM             0            0            0            0            0            0            0            0
  2AM             0            0            0            0            0            0            0            0
  3AM             0            0            0            0            0            0            0            0
  4AM             0            0            0            0            0            0            0            0
  5AM             0            0            0            0            0            0            0            0
  6AM             0            0            0            0            0            0            0            0
  7AM             0            0            0            0            0            0            0            0
  8AM             0            0            0            0            0            0            0            0
  9AM             0            0            0            0            0            0            0            0
  10AM            0            0            0            0            0            0            0            0
  11AM            0            0            0            0            0            0            0            0
  12AM            0            0            0            0            0            0            0            0
  1PM             0            0            0            0            0            0            0            0
  2PM             0            0            0            0            0            0            0            0
  3PM             0            0            0            0            0            0            0            0
  4PM             0            0            0            0            0            0            0            0
  5PM             0            0            0            0            0            0            0            0
  6PM             0            0            0            0            0            0            0            0
  7PM             0            0            0            0            0            0            0            0
  8PM             0            0            0            0            0            0            0            0
  9PM             0            0            0            0            0            0            0            0
  10PM            0            0            0            0            0            0            0            0
  11PM            0            0            0            0            0            0            0            0
  12PM            0            0            0            0            0            0            0            0
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