UNIVERSITAT ROVIRA I VIRGILI

MODELLING ENVIRONMENT FOR THE DESIGN AND OPTIMISATION OF ENERGY POLYGENERATION SYSTEMS

Jordi Ortiga Guillén

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DOCTORAL THESIS

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Los abajo firmantes, Dr. Alberto Coronas, Catedrático de Universidad del área de Máquinas y Motores Térmicos y Dr. Joan Carles Bruno, Profesor Agregado, del Departament d'Enginyeria Mecànica de la Universitat Rovira i Virgili de Tarragona

HACEN CONSTAR:

Que el trabajo titulado: "MODELLING ENVIRONMENT FOR THE DESIGN AND OPTIMISATION OF ENERGY POLYGENERATION SYSTEMS" presentado por el Sr. Jordi Ortiga Guillén para optar al grado de Doctor de la Universitat Rovira i Virgili, ha sido realizado bajo su dirección inmediata en el CREVER – Grup de recerca d'Enginyeria Tèrmica Aplicada del Departament d'Enginyeria Mecànica de la Universitat Rovira i Virgili, que todos los resultados han sido obtenidos en las experiencias realizadas por dicho doctorando y que cumple los requisitos para poder optar a la Mención Europea.

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ABSTRACT

The optimal design and operation of an energy supply system is very important for the matching of the energy production and consumption so that efficiency is higher than that of conventional systems, especially in the residential-tertiary sector characterized by an energy demand with a high variability. The present thesis is carried out in the framework of the PolyCity project of the CONCERTO initiative, co-funded by the European Commission and the TRIGENED project of the Ministry of Education of Spain. In the PolyCity project three large urban areas are developed in the field of energy optimisation for primary energy saving, building energy sustainability and the use of renewable energies. In the course of the TRIGENED project several microtrigeneration configurations have been analysed from the energy and environmental point of view. The main objective of this thesis is to develop optimisation models for the preliminary design and analysis of polygeneration plants.

The main energy tools and optimisation methodologies have been reviewed and mathematical programming techniques using GAMS are used to solve the optimisation models. The main parameters to be included in the models are the capacity range, investment and operational costs, energy demand and economic costs, efficiencies, pollutant emissions and legal constraints. With the model developed the optimal size and operation of each technology is found by minimizing economic costs. A user friendly interface has been developed to make the model more flexible and easier to apply to other applications. The model is organized in different units represented by blocks that can be connected between each other to create the flowsheet of the polygeneration system. To characterize the energy demand in the residential and tertiary sector a graphic methodology has been developed to select typical energy demand days from a yearly energy demand profile. The energy demand of these days must be representative enough for an optimisation model to reproduce the same results using the data for the whole year or the data just for these days. By using the data from typical days, then, the complexity of the model is reduced.

Some practical examples will be presented. The model is applied in the PolyCity project to evaluate the operation of a polygeneration plant under several scenarios between 2010 and 2014. The results obtained are the operation for each unit, the economic evaluation and the energy saving for each year. Another example is the analysis of a trigeneration plant using a liquid desiccant system for air conditioning installed in a classroom building in the Politecnico di Torino in Italy. The system is modelled using experimental data and an economic and environmental evaluation is performed to calculate its benefits.

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RESUMEN

El diseño y operación óptima de un sistema energético es muy importante para el adecuado ajuste de producción y demanda obteniendo mayores eficiencias que los sistemas convencionales, especialmente en el sector terciario-residencial caracterizado por una demanda energética con alta variabilidad. Esta tesis se desarrolla en el marco del proyecto PolyCity dentro de la iniciativa CONCERTO lanzada por la comisión europea, y el proyecto TRIGENED del Ministerio de Educación de España. En el proyecto PolyCity tres grandes áreas urbanas se desarrollarán en el campo de la optimización energética, ahorro de energía primaria, desarrollo energético sostenible en edificios y uso de energías renovables. En el proyecto TRIGENED diversas tecnologías de microtrigeneración han sido analizadas desde el punto de vista energético y del medio ambiente. El principal objetivo de esta tesis es el desarrollo de modelos de optimización para el diseño preliminar y análisis de plantas de polygeneración.

Se ha realizado una revisión de las principales metodologías de optimización y se ha utilizado programación matemática con GAMS para resolver los modelos. Los principales parámetros que deben ser incluidos en los modelos es el rango de capacidad de los equipos, costes de inversión y operación, demanda y precio de la energía, eficiencias, emisiones de contaminantes y restricciones legales. Con los modelos desarrollados se calculan las capacidades y operación óptimas minimizando los costes. Se ha desarrollado una interfase para realizar modelos más flexibles y fáciles de aplicar a distintos casos. Los modelos estan organizados en distintas unidades representadas por bloques que pueden ser conectados entre ellos para crear el diagrama de flujo del sistema de poligeneración. Para la caracterización de la demanda energética en el sector residencial y terciario, se ha desarrollado un método gráfico para seleccionar días típicos a partir de una demanda energética anual. La demanda energética de estos días típicos debe ser representativa para obtener los mismos resultados en el modelo de optimización respecto al caso en que se utilizara la demanda de todo el año. Con el uso de días típicos se reduce la complejidad del modelo.

En la tesis se presentan algunos casos de aplicación. El modelo se aplica al proyecto PolyCity para evaluar la operación de una planta de polygeneración para distintos escenarios, del 2010 al 2014. Los resultados obtenidos son la operación de cada unidad, la evaluación económica y el ahorro energético para cada año. Otro ejemplo es el análisis de un planta de trigeneración usando un sistema de desecantes líquidos para aire acondicionado instalado en un edificio de aulas en el Politecnico di Torino en Italia. El sistema se ha modelado utilizando datos experimentales y se ha realizado una evaluación económica y ambiental para estimar los beneficios de este sistema.

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RESUM

El disseny i l'operació òptima d'un sistema energètic es molt important per l'adient unió de la producció i demanda amb millors eficiències respecte els sistemes convencionals, especialment en el sector terciari-residencial caracteritzat per una demanda energètica amb una alta variabilitat. En aquesta tesis s'ha desenvolupat en el marc del projecte PolyCity dins la iniciativa CONCERTO llançada per la comissió europea, i el projecte TRIGENED del Ministeri d'Educació d'Espanya. En el projecte PolyCity tres grans zones urbanes es desenvoluparan en el camp de l'optimització energètica, estalvi d'energia primària, desenvolupament energètic sostenible en edificis i l'ús d'energies renovables. En el proyecto TRIGENED diverses tecnologies de microtrigeneración han estat analitzades des de el punt de vista energètic i mediambiental. El principal objectiu d'aquesta tesis és el desenvolupament de models d'optimització per al disseny preliminar i anàlisis de plantes de poligeneració.

S'ha realitzat una revisió de les principals metodologies d'optimització y s'ha utilitzat programació matemàtica amb GAMS per resoldre els models. Els principals paràmetres que s'han d'incloure en los models es el rang de capacitat dels equips, costos d'inversió y operació, demanda i preus de la energia, eficiències, emissions de contaminants i restriccions legals. Amb els models desenvolupats es calculen les capacitats y operació òptimes minimitzant els costos. S'ha desenvolupat una interfase per realitzar models més flexibles y fàcils d'aplicar a diferents casos. Els models estan organitzats en diferents unitats representades por blocs que es poden connectar entre ells per crear el diagrama de flux del sistema de poligeneració. Per a la caracterització de la demanda energètica en el sector residencial i terciari, s'ha desenvolupat un mètode gràfic per a seleccionar dies típics a partir d'una demanda energètica anual. La demanda energètica d'aquests dies típics ha de ser representativa per obtenir els mateixos resultats en el model d'optimització respecto al cas en el que s'utilitza la demanda anual. Amb l'ús de dies típics es redueix la complexitat del model.

En la tesis es presenten alguns casos d'aplicació. El model s'aplica al projecte PolyCity per avaluar l'operació d'una planta de poligeneració per diferents escenaris, del 2010 al 2014. Els resultats obtinguts son la operació de cada unitat, la avaluació econòmica y el estalvi energètic de cada any. Un altre exemple es l'anàlisi d'una planta de trigeneració utilitzant un sistema de descants líquids per aire condicionat instal·lat en un edifici d'aules en el Politecnico di Torino en Italia. El sistema s'ha model·lat utilitzant dades experimentals y s'ha realitzat una avaluació econòmica i ambiental para estimar els beneficis d'aquest sistema.

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LIST OF ABBREVIATIONS

AHU: Air Handling Unit

CC: Combined Cycle

CED: Cumulative Energy Demand

CHP: Combined Heat and Power

COP: Coefficient of Performance

DC: District Cooling

DDP: Dimensional Daily Plot

DES: Distributied Energy Systems

DH: District Heating

DHC: District Heating and Cooling

DHS: DuHandling Series (desiccant units)

EEE: Equivalent Electrical Efficiency (*REE: Rendimiento Eléctrico Equivalente*)

ESCO: Energy Service Company

FR: Feasible Region

GA: Genetic algorithm

GAMS: General Algebraic Modelling System

GUM: GAMS Unit Model

GUME: GAMS Unit Model Editor

GT: Gas Turbine

H: Height

HL: High Level

HW: Hot Water

ICE: Internal Combustion Engine

KKT: Karush Kuhn Tucker

ktoe: kilo ton oil equivalent

L: Length

LiBr: Lithium Bromide

LiCl: Lithium Chloride

LG: Liqued Gateway

LL: Low Level

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LP: Linear Programming

MGEOS: Modular General Energetic Optimisation System

MILP: Mixed Integer Linear Programming

MINLP: Mixed Integer Non-Linear Programming

ML: Medium Level

NLP: Non Linear Programming

NPV: Net Present Value

PEMFC: Polymer Electrolyte Membrane Fuel Cell

PF: Process Fan

PP: Process Pump

Proc Pump: Process Pump

RD: Royal Decree

REE: Red Eléctrica Española (Spanish electrical grid)

RP: Regeneration Pump

Reg Pump: Regeneration Pump

RF: Regeneration Fan

RPF_j: Repetition Factor for Each Time Period

SDF: Scenario Definition File

toe: ton oil equivalent

TP: Time Period

W: Width

WnDm: day of the year corresponding to the m^{th} day, from Monday (1) to Sunday (7) of the n^{th} week (from 1 to 53). The last week has only one day

Subindexes:

i: unit

j: time period

k: outputs from unit

lim: limiting value

n: number of flow

mo: main output (usually power or electrical output in cogeneration units)

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Subindexes meaning units

abs: absorption chiller

boil: boiler

chp: cogeneration unit

comp: compression chiller

cst: cooling storage

hst: heat storage

Subindexes meaning energy flows

c: cooling

fuel: fuel flow

exp: exported electricity

h: heating

imp: imported electricity

Variables and paramters:

ηe: Electrical efficiency of a specific unit

ηt: Thermal efficiency of a specific unit

AE: Coefficient to calculate the power in the evaporator in absorption chillers, kW/ºC

AG: Coefficient to calculate the power in the generator in absorption chillers, kW/ºC

AF: Coefficient of a correlation to calculate the fuel consumption with an equation of the type: FuelConsumption = AF·OutputPower + BF·AirTemperature + BC

AP: coefficient of a correlation of the type: OutputPower =AP·x + BP

AT: Coefficient of a correlation to calculate thermal recovery with an equation of the type: ThermalEnergyRecovered = AT·OutputPower + BT·AirTemperature + BT

B: Benefits for energy flow, €/y

BE: Coefficient to calculate the power in the evaporator in absorption chillers, kW/ºC.

BG: Coefficient to calculate the power in the generator in absorption chillers, kW/ºC.

BF: Coefficient of a correlation (kW/ºC) to calculate the fuel consumption with an equation of the type: FuelConsumption = AF·OutputPower + BF·AirTemperature + BC

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BT: Coefficient of a correlation (kW/ºC) to calculate thermal recovery with an equation of the type: ThermalEnergyRecovered = AT·OutputPower + BT·AirTemperature + BT

BP: coefficient (kW) of a correlation of the type: OutputPower =AP·x + BP

C: Cooling energy in a flow, kWh

CE: Coefficient to calculate the power in the evaporator in absorption chillers, kW/ºC.

CF: Coefficient of a correlation (kW) to calculate the fuel consumption with an equation of the type: FuelConsumption = AF·OutputPower + BF·AirTemperature + BC

CG: Coefficient to calculate the power in the generator in absorption chillers, kW/ºC.

CT: Coefficient of a correlation (kW) to calculate thermal recovery with an equation of the type: ThermalEnergyRecovered = AT·OutputPower + BT·AirTemperature + BT

COP: Coefficient of performance.

Cp: Constant pressure specific heat, kJ/kg·K

DE: Coefficient to calculate the power in the evaporator in absorption chillers, kW

DG: Coefficient to calculate the power in the generator in absorption chillers, kW/ºC

E: Electrical energy in a flow, kWh

EBalance: Energy storaged in the energy storage in each time period.

EEELS: Left side of the equation to impose the minimum EEE constraint, MWh/year

EEELS1: Left side of the equation to impose the minimum EEE constraint for a given minimum EEE value, MWh/year

EEELS2: Left side of the equation to impose the minimum EEE constraint for a given minimum EEE value, MWh/year

ELosses: Parameter between 0 and 1, ratio of energy lost respect to all the energy storaged.

F: Fuel energy in a flow, kWh

FML: Parameter between 0 and 1, usually very close to 1, to force a properly calculation of the nominal capacity.

GE: Emissions, mass of contaminant/year

GEF: Parameter to calculate emissions (g/kWh)

H: Heating energy in a flow, kWh

HCin: Enthalpy of the input cold air to the rotary wheel multiplied by the flow rate, kW

HCout: Enthalpy of the ouput cold air to the rotary wheel multiplied by the flow rate, kW

HHin: Enthalpy of the input hot air to the rotary wheel multiplied by the flow rate, kW

HHout: Enthalpy of the ouput hot air to the rotary wheel multiplied by the flow rate, kW

HxP_j: Hours in each period j, h/period

I: Investment costs, €

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ICF: Parameter to calculate investment costs (€/kW) using and expression of the type: InvestmentCosts = ICF·N+ICB

ICB: Parameter to calculate investment costs (€) using and expression of the type: InvestmentCosts = ICF·N+ICB

In: Input flow (energy or material) to a unit, kWh

InStg: Input energy flow to an energy storage, kWh

L: Energy level of the storage, kWh

N: Nominal capacity of a unit (kW)

O: Operating costs, €/y

Out: Output flow (energy or material) from a unit, kWh

OutStg: Output energy flow from energy storage, kWh

m: mass, kg

MaxCQ: Maximum power exchanged from the cold stream in the rotary wheel, kW

MaxEL: Maximum energy level in the energy storage (kWh)

MaxF: Maximum fuel consumption, MWh/year

MaxHQ: Maximum power exchanged from the hot stream in the rotary wheel, kW

MaxN: Maximum nominal capacity (kW)

MaxNct: Maximum nominal capacity (kW) calculated as a function of the temperature

MaxQ: Maximum power, kW.

MaxTDiff: Parameter that indicates the maximum temperature (ºC) between two temperatures.

MaxNGT: Parameter that indicates the maximum nominal capacity of the gas turbine, kW

MaxOutputS1: Maximum nominal capacity obtained from a correlation as a function of the input air temperature for a gas turbine, if Tair < Tcn, kW

MaxOutputS2: Maximum nominal capacity obtained from a correlation as a function of the input air temperature for a gas turbine, if Tair > Tcn, kW

MC: Maintenance cost, €

MCF: Parameter to calculate the maintenance cost, €/MWh

MinEEE: Minimum Electrical Equivalent Efficiency

MinEEE1: Minimum Electrical Equivalent Efficiency when capacity is lower than 1 MW

MinEEE2: Minimum Electrical Equivalent Efficiency when capacity is higher than 1 MW

MinEL: Minimum energy level in the energy storage indicating the storage is empty, kWh.

MinL: Minimum load, %

P: Price for energy flow, €/MWh

Q: Power exchanged, kW

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QC: Power in the condenser-absorber for absorption chiller, kW

QE: Power in the evaporator for absorption chillers, kW

QEc: Power in the evaporator calculated beforehand the optimisation, kW

QG: Power in the generator for absorption chiller, kW

QGc: Power in the generator calculated beforehand the optimisation, kW

REE_{min}: minimum electrical equivalent efficiency, %

RF: Binary variable indicating the reverse operation of a rotary wheel (the cold input air flow is in the place of the hot input air flow)

RI: Rate of interest

RIF: Rate of interest factor

RPF_j: Repetition factor in period j.

SLK1: Slack variable when there are two minimum EEE values

SLK2: Slack variable when there are two minimum EEE values

SLKE: Slack variable to calculate cooling produced in the evaporator in absorption chillers

SLKG: Slack variable to calculate heating requirements in the generator in absorption chillers

SLKI: Slack variable to calculate power production in internal combustion engines

SLKP: Slack variable to calculate fuel consumption in gas turbines

SLKT: slack variable to calculate thermal recovery in gas turbines

StgByPass: Energy flow by pass between the input and output of an energy storage, kWh

T: Temperature

Tair: Air temperature at the input of a gas turbine, ºC

TAair: Ambient temperature

TC: Total cooling energy, kWh/y

TCin: Tempeature of the input cold air to the rotary wheel, ºC

TCond: Temperature condenser-absorber in absorption chiller.

TCout: Tempeature of the ouput cold air to the rotary wheel, ºC

Tcn: Temperature at which there is a change in the slope of the maximum capacity of a gas turbine as a function of the air temperature, ºC

TEvap: Temperature evaporator in absorption chiller.

TE: Total electrical energy, kWh/y

TF: Total energy fuel, kWh/y

TGen: Generator temeperature in absorption chiller.

TH: Total heating energy, kWh/y

THin: Tempeature of the input hot air to the rotary wheel, ºC

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THout: Tempeature of the ouput hot air to the rotary wheel, ºC

TI: Total investment costs, €

TB: Total benefits (Benefits-Costs), €/y

TO: Total operating costs, €/y

TS: Total number of start-up periods

TTrig: Total heating and cooling production useful from the cogeneration unit, kWh/y

UO: Unitary operating costs for a specific unit, €/kWh

UP: Unitary investment costs for a specific unit, €/kW

y: Binary variable, usually to indicate unit selection

yIntoStg: Binary variable used in the energy storage

yLA: Binary variables

yTh: Binary variables

ytp: Binary variable, usually to indicate ON/OFF state for each time period

yC: Binary variable that determines the ON/OFF state of the cogeneration unit

yN: Binary variable

yS: Binary variable for the cogeneration unit that indicates the start-up periods

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Chapter 1

Introduction and objectives

1.1 Introduction

The uncertainty of the energy prices, the limitation of the existing energy resources and environmental regulations promotes the use of new distributed energy systems, like hybrid integrated systems (using fossil fuels and renewable energy sources) with high-energy efficiency. These integrated systems known as polygeneration systems produce electrical, heating, cooling and/or other energy carriers at higher efficiency than a conventional system, and involve a wide range of technologies with several possible configurations, providing energy to users with a high variable energy demand in the case of residential or tertiary sector applications. These factors make very difficult the optimal design of such systems to assure economical and environmental benefits. Sometimes the design or evaluation of these systems is carried out with the aid of energy tools or mathematical models that are solved or optimised considering economic or environmental factors. The objective of this chapter is to analyse the energetic requirements in Spain, evaluate the Spanish electrical mix to identify and quantify the sectors where polygeneration systems can be applied and the possible energy saving that can be obtained.

Section 1.2 presents the energy context in Spain, analysing the production of electricity and the total primary energy requirements for 2007. The Spanish electrical mix is compared for 2009 and 2006 to state the increase of renewable sources and combined cycles. Section 1.3 presents some of the advantages of distributed energy systems and a comparison with centralized systems. Finally the objectives of the thesis are presented in section 1.4 and the structure of the thesis is detailed in section 1.5.

UNIVERSITAT ROVIRA I VIRGILI
MODELLING ENVIRONMENT FOR THE DESIGN AND OPTIMISATION OF ENERGY POLYGENERATION SYSTEMS
Jordi Ortiga Guillén
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1.2 Energy context in Spain

Optimisation of energy systems is a key issue in the design of more sustainable development models, especially in urban areas, where almost all the electrical energy is produced in far away large scale power plants, and cooling and thermal requirements are produced locally in each dwelling or building. The transportation of energy from the large power plant drives to energy losses, while the production of cooling, usually with compression units located in each dwelling, entails a high electrical energy demand especially in summer. In Spain, electrical demand (figure 1.1) has been growing year by year until the crisis of 2008 (*Red Eléctrica de España S.A.,* Spain Electrical Network). Figure 1.2 shows the annual demand increase from 2005 (red line) and the corresponding corrected values for employment and temperature (black line). The constant energy demand increase of the last years was interrupted in 2008 with an increase of only 0.6 % respect 2007. The energy demand decrease from January to April was 11.8 %, from that point, the rate of decrease moderated. The estimated CO_2 emissions from the electrical sector for 2009 were 74.5 Mton meaning an emission factor of 296.4 ton CO_2/GWh.

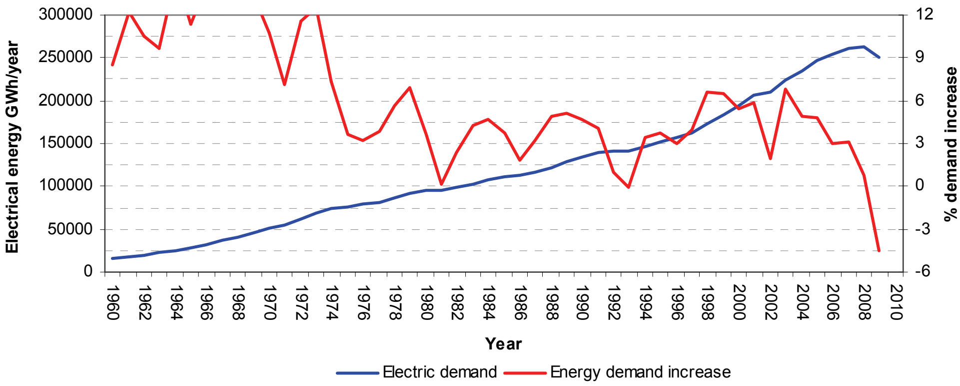

Figure 1.1 Electrical demand trend for the Spanish peninsular system

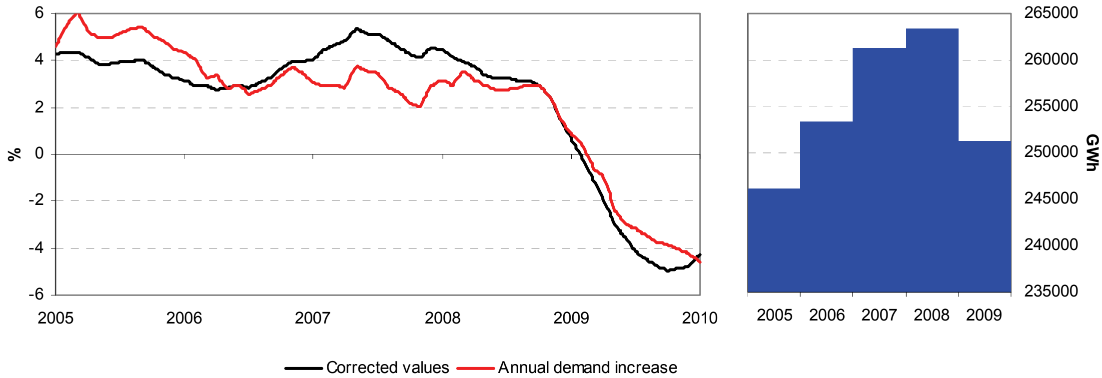

Figure 1.2 Annual energy demand (right) and annual demand increase (left) in Spain (REE)

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Figure 1.3 shows the peak power demand and the energy demand for the peak day for winter and summer from 2005 to 2009. The maximum peak power demand was in 2007 for winter and 2006 for summer. Although the energy demand decreased in 2009, the peak power demand of 2009 is one of the higher of the last years. In 2009 568 MW combined cycle and 2,576 MW wind energy were installed. In the same period two fuel plants with a total capacity of 474 MW were dismantled.

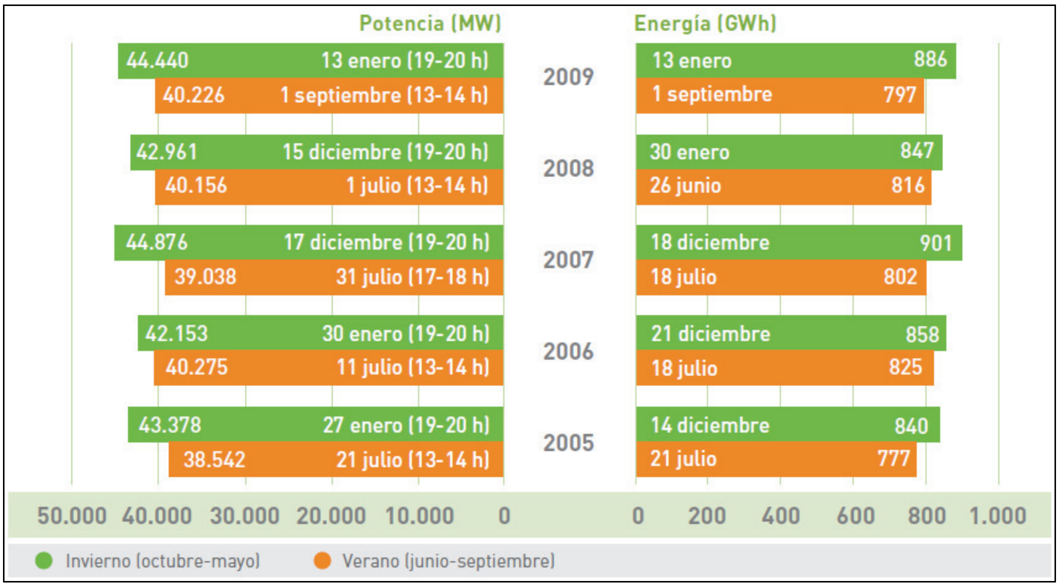

Figure 1.3 Maximum power and daily energy demand for winter and summer peaks (REE)

Figure 1.4 shows the coverage by technology of the annual energy demand for 2009 and figure 1.5 shows the coverage of the peak demand for 2009 (REE). These figures are important to determine the efficiency of the grid, calculate emissions or to deduce which technologies are used to cover peak demand periods.

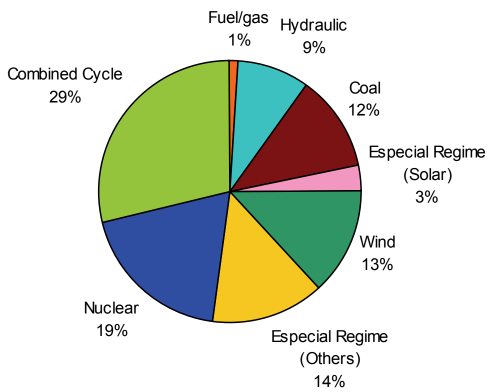

Figure 1.4 Coverage of the annual energy demand for 2009 in Spain

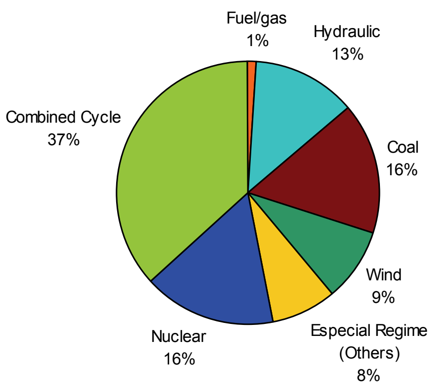

Figure 1.5 Coverage of the peak energy demand for 2009 in Spain

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From the previous figures is important to highlight the role of the renewable source generating almost the 26 % of the annual energy demand, specially the wind energy that for the first time exceeded the production compared with coal plants. The maximum daily production with wind energy was the 8th of November with a production of 251,543 MWh (44.9 % of the energy demand for that day). But the variability of this sources lead to different situations: the 8th of November at 3:59h the wind production was the 53.7 % of the demand, but the 27th of August at 9:49h the wind production was the 1 % of the energy demand.

The evolution of the renewable sources and the use of combined cycle plants can be evaluated comparing the figures for 2009 with the figures 1.6 and 1.7 corresponding to the year 2006. The main difference is the decrease in 2009 of the production using coal plants and the increase of the production with combined cycle plants. It is also important the increase of electrical production with wind and solar energy. The Spanish electrical grid is becoming more efficient and less contaminant (reduction of CO_2 and NO_x emissions) due to the decrease of electrical production with fuel/gas and coal plants.

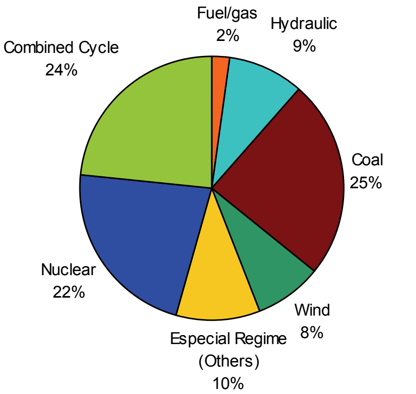

Figure 1.6 Coverage of the annual energy demand for 2006 in Spain

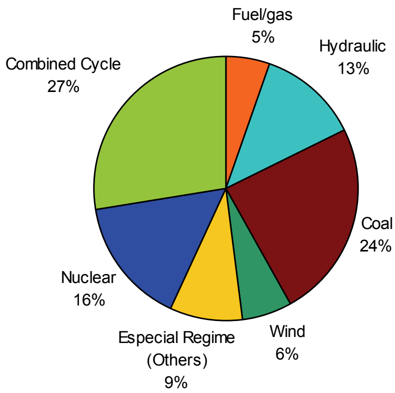

Figure 1.7 Coverage of the summer peak energy demand for 2006 in Spain

Figure 1.8 shows the Sankey diagram of the energy for Spain in 2007. The energetic consumption of each sector (transportation, industry, residential and energy transformation) can be deduced from this figure. The total primary energy input to the system is 146,779 ktep including renewable. All the percentages of the figure are calculated respect this input, except the consumption for the transportation, industry and residential sectors, which are calculated respect the final primary energy 108,197 ktep. This means that 38,582 ktep are lost due to transformation efficiencies and transportation losses. The 38.1 % of the total energy input (146,779 ktep) is used for electricity generation. Renewable sources, nuclear energy and coal are used almost exclusively for electrical generation.

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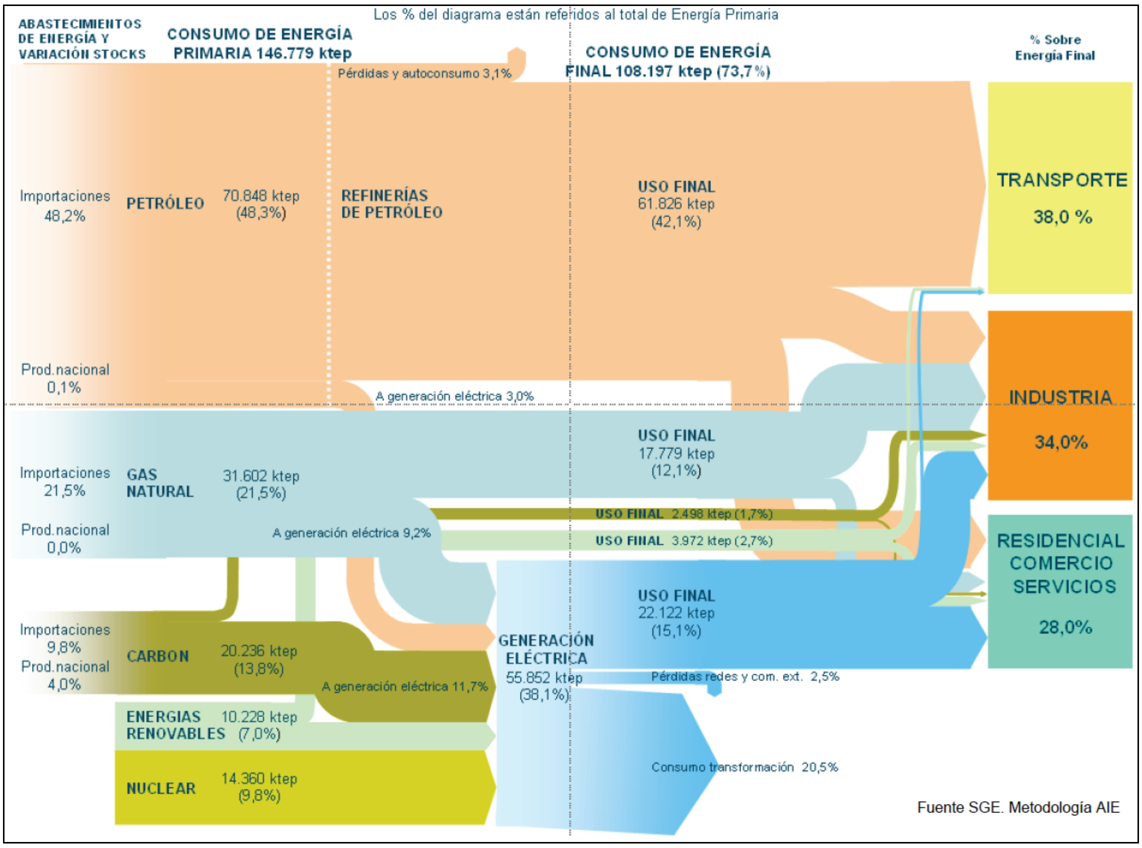

Figure 1.8 Sankey diagram for energy consumption from different sources for Spain in 2007

Figure 1.9 shows the primary energy consumption of each sector respect the total energy input (146,779 ktep) calculated from the figure 1.8. The consumption of all the sectors is quite similar, transportation represent the 28 % of the total primary energy input, all the energy transformation processes and energy losses represent the 26 %. Industry consumes the 25 % of the energy input and finally the residential-tertiary sector consumes the 21 %.

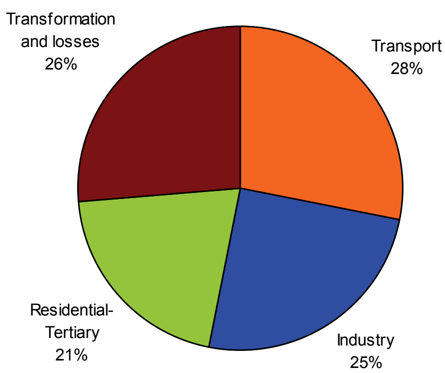

Figure 1.9 Primary energy consumption ratio for each sector in Spain in 2007

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The consumption of the residential sector usually represent between 1/5 and 1/3 of the national energy consumption of a country. Figure 1.10 shows the residential energy consumption as the percentage respect the national energy consumption for several countries (Swan et al 2009). The average value (World) is around 31%.

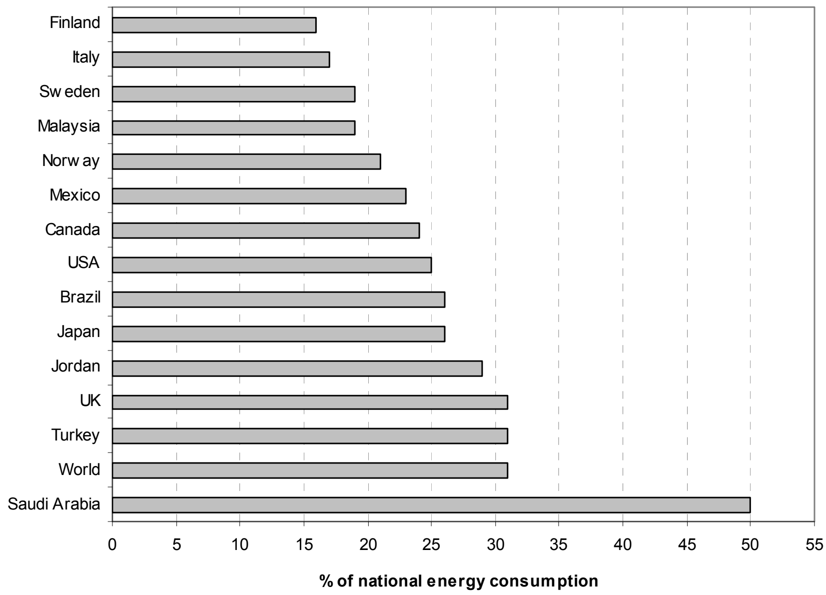

Figure 1.10 Residential energy consumption as a percentage of the total national energy consumption (Swan et al 2009)

1.3 Distributed Energy Systems

Distributed Energy Systems (Alanne et al 2006) concerns to these units for energy conversion that can be placed close the energy consumer, substituting large units by smaller ones. Frequently, the energy produced by Distribute Energy Systems (DES) is supplied to the consumer with district heating and cooling networks (DHC). These networks transport heating and cooling energy to the consumers using hot and cold water as a transportation media. DES and DHC can be applied to reduce the consumption in the residential and energy transformation sectors. DHC and DES avoid energy transportation losses because the supply sites are located near the consumer, and the integration of several technologies with the use of renewable sources, decrease the consumption of primary energy and contaminant emissions respect to large centralized plants. A description and classification of distributed generation technologies can be found in Poullikas 2007. In Spain the use of DES system and DHC is not very extended but the potential of application is significant, the residential and the energy transformation sector consume the 47 % (2007) of the total primary energy consumption (figure 1.9).

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Cogeneration and polygeneration are distributed energy systems producing more than one energy carriers. Cogeneration refers to the simultaneous production of mechanical power (or electricity) and heating. Polygeneration is the simultaneous generation in one process of more than two energy carriers. The therm process should be enlarged in order to refer also to multiple successive processes, where the output or by-product of one process is the input of another process. This succession of thermodynamic processes constitutes an energy supply system (Österreicher et al 2007). The main benefit of polygeneration system is the energy saving of these systems respecto to the conventional system.

Rergarding to the residential and tertiary sector, to supply electricity, heating and cooling the conventional energy system can be defined as the separate production of electricity (imported electricity from the national grid) and the use of individual boilers and compression chillers to produce heating and cooling respectively. The benefits of polygeneration system must be evaluated in comparison with the conventional system and for this reason, and due to the possible integration of local sources; the convenience of polygeneration system will depend for each region. The increasing efficiency during the last years of the Spanish electrical mix due to the use of combined cycle plants and wind energy reduces the energy savings obtained with polygeneration systems. Even when a reference technology is selected to represent the separate production of electricity (Commission decision of 21 December 2006) instead of considering the real electrical mix, not any polygeneration system has energy savings respect to the conventional system selected. An optimal design is very important in order to assure environmental savings and economic viability, two factors that usually are contradictory.

The high number of distribution technologies available to produce electricity, heating and cooling and the different levels of integrations difficults the selection of the optimal configuration. An example of a polygeneration system producing electricity, heating and cooling is shown in figure 1.11. Electricity, heating and cooling must be produced and the figure shows different options of integration using common technologies. In the figure, the main prime movers are internal combustion engines and gas turbines (or microturbines). Boilers can be used as backup for peak periods or when the heating demand is to low to use the prime movers. Two main fuels are included in the figure, natural gas and biomass that can be used directly in a biomass boiler or can be gasified to produce synthesis gas. Additional technologies like solar thermal collectors, photovoltaics or the national grid, used to purchases or export the electrical production. Additionally, the synthesis gas produced can be mixed with the natural gas or with other fuels.

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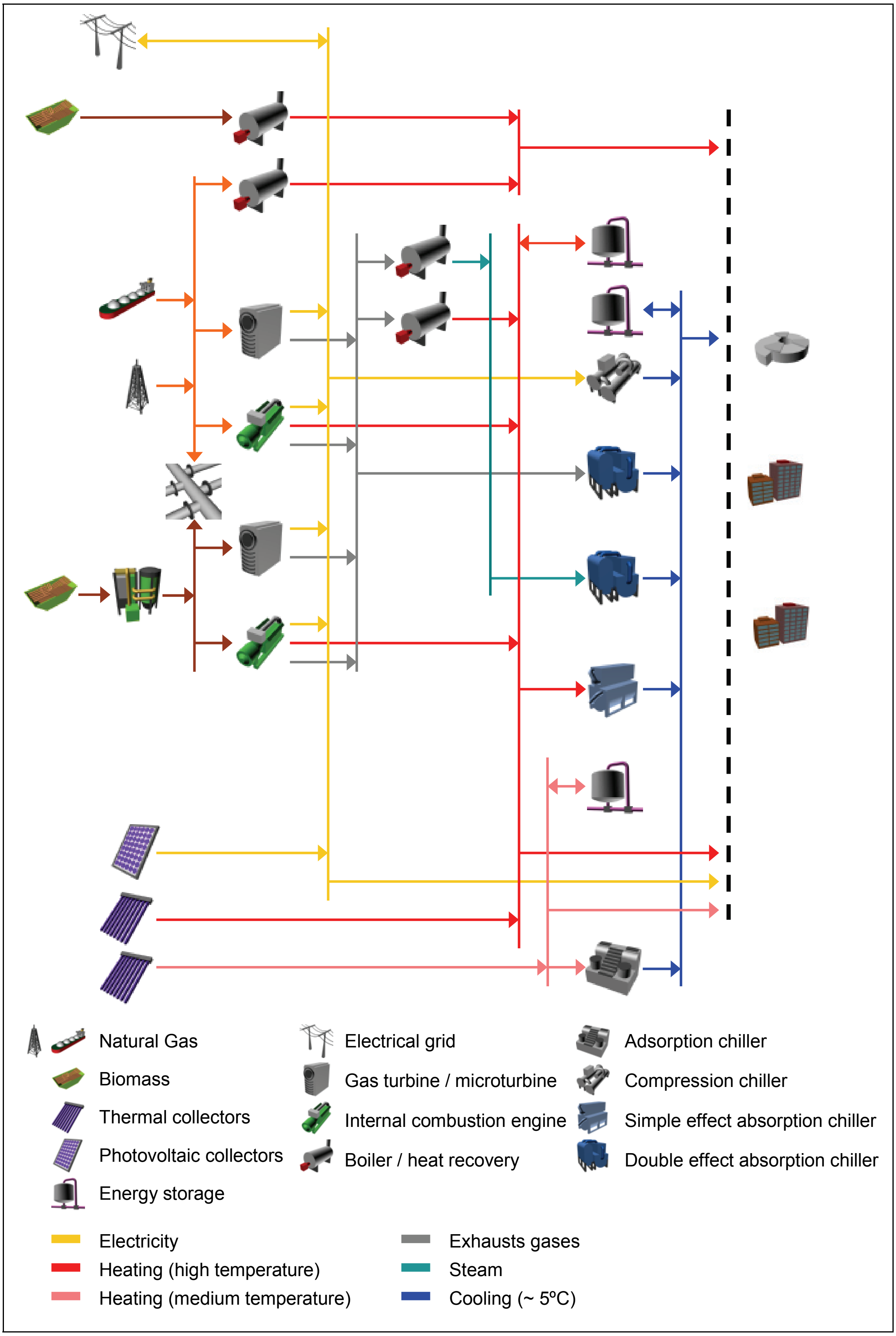

Figure 1.11 Example of several possible configurations to produce electricity, heating and cooling

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Finally, the cooling can be produced with a high variety of thermal driven technologies, including adsorption chillers, simple effect absorption chillers and double effect absorption chillers. The main difference between these technologies is the efficiency and the temperature required to drive the chillers. Compression chillers can be used as backup for peak periods. Usually polygeneration systems are designed to cover a base demand and peak periods are fullfiled together with backup units (boilers, compression chillers or energy storage).

Figure 1.11 ilustrates the high variety of possible combinations to supply with electricity, heating and cooling using just common technologies. Polygeneation systems are characterized by the high integration and interdependency of all the units of the energy systems. An optimal design (number of units, sizes, superstructure or configuration) considering the energy demand and prices is very important in order to assure the economic viability of the system. Optimisation models are widely used for the optimal selection of units and configurations. Moreover, in some occasions several constraints imposed by law must be applied (minimum autoconsumption and/or minimum efficiency) and these contraints can be implemented easily in optimisation models. The main benefits of polygeneration systems are the high efficiency due to the simultaneous production of several energy carriers taking advantage of all the content of the fuel by means of high integrated and interconnected processes. Figure 1.12 exemplifies this energy savings by comparing the production of an arbitrary quantity of electricity, heating and cooling using the conventional or the polygeneration system.

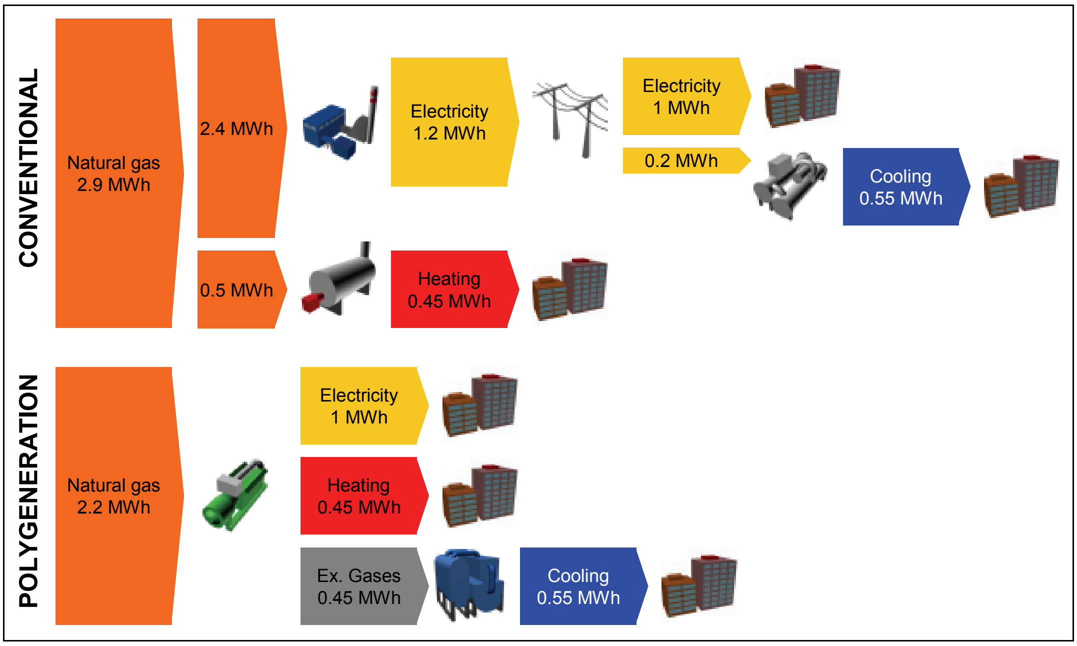

Figure 1.12 Energy savings of a polygeneration system respect to the conventional alternative

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The use of polygeneration energy systems entails other advantages beside energy savings. Polygeneration systems avoid problems on energy distribution and security, which is an important aspect in countries with high peak periods in winter and summer. The high energy demand in some periods of winter and summer usually lead to problems in distribution causing blackouts, moreover high temperatures have caused the failure or the fire of electrical substations, leaving to several zones without energy as happened the summer of 2007 in Barcelona or the damage of several electrical lines due to storms in 2010 in several zones of Catalonia. The use of air conditioning is more extended every year increasing the power demand. Moreover the treaty of Kyoto and environmental policies like *Plan de Acción* try to decrease energy consumption and reduce contaminant emissions. Distributed energy systems are able to produce simultaneously several types of energies with higher efficiency, close to the user increasing the energy savings and the security in distribution. A comparison between centralised and decentralized energy systems can be found in table 1.1.

Table 1.1 Benefits and drawbacks of centralized - decentralized energy systems (Alanne et al 2006)

Centralized	Benefits	Information easy to find. Responsibility, management and expertise easily placed Only a few educated persons needed Uniformity
	Drawbacks	Units must be large Large by-investments “All the eggs in the same basket” Long distances between production and consumption Cannot work independently Lack of individuality and inflexibility
Distributed	Benefits	Scalability Shared load Ability to “live” in networks Can work independently Individuality Flexibility Even distribution of political, technological, economic and social resources Increased control at the local level “Not all the eggs in the same basket”
	Drawbacks	Fragmented information Lack of uniformity and consistency Considerable effort in management and education

1.4 Objectives

The sections above describe the advantages of distributed energy systems in Spain. The residential-tertiary sector and the energy transformation sector (mainly electrical production) consume 47% of the total primary energy in 2007. Distributed energy systems can reduce this consumption by simultaneously producing several energy services close to the user, with higher efficiency and lower emissions than the conventional system, a higher energy distribution security, and the possibility to integrate local renewable sources.

Nevertheless, the efficiency of power supply sites is as important as the energy efficiency of buildings. Energy consumption and contaminant emissions cannot be reduced without evaluating the energy needs of residential sectors, and trying to apply best practices in their design and construction steps. For this reason, prediction of energy demand is one of the first steps in the design and optimisation of distributed energy systems and is usually part of it. Energy demand in buildings is characterized by considerable variability that makes it difficult to couple energy production with energy demand. A preliminary evaluation of all the possible generation technologies must be made so that the best configuration for a given application can be selected and the national regulations and energy saving constraints imposed by law can be taken into account. For all these reasons, a preliminary evaluation of distributed energy systems is very important due to the increasing efficiency of the electrical network in Spain (section 1.2). This means that not all trigeneration or polygeneration systems will be better: the conventional system is becoming more efficient by increasing the ratio of renewable sources. Polygeneration systems must be optimally integrated if they are to be more efficient than the conventional system.

The main objective of this thesis is to develop a methodology for cogeneration, trigeneration or polygeneration systems for residential applications and to evaluate the economic viability, the potential energy savings and possible future pathways to a cleaner energy supply system. The methodology will be based on the characterization of the energy demand and the modeling of each unit of the polygeneration energy system to determine optimal design and operation, using a tool flexible enough to include different technologies and several configurations. Some of the existing energy tools are too detailed for economic and environmental evaluation, while others are specific to a particular sector (electrical sector, heating, transportation), scale (local, regional, national) or time horizon (one year, multiple years) with specific time steps.

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Considering the main objective of this thesis, the specific objectives are listed below:

- To review the main energy tools currently used for the optimisation of energy systems. Other methodologies applied to the optimisation of energy systems such as genetic algorithm and mathematical programming techniques will also be reviewed.

- To review optimisation models for energy systems, focusing on the purpose of the model and the methodology used to perform the optimisation.

- To review the main methodologies for calculating the energy demand in residential or tertiary sector applications. To develop a methodology for selecting typical days to be used in optimisation models. The typical days selected must be representative for the whole year.

- To characterize the main units used in energy systems (e.g. cogeneration engines, gas turbines, chillers and other auxiliary units). The models will be formulated as a function of the optimisation methodology adopted.

- To integrate all the required input data and models for the optimisation of energy systems for the residential and tertiary sector using an environment that facilitates use and can be applied to several cases. The basis of this environment will be the characterization of each unit of the polygeneration system as a block with input and output that can be connected to other blocks, thus creating the flowsheet of the energy system.

- To apply the environment to the PolyCity project and perform several economic, energy and environmental evaluations of the alternatives presented to build a polygeneration plant in Cerdanyola del Vallès to supply a technology park with electricity, heating and cooling.

- To present an example of an energy system characterized with experimental data and using the optimisation environment developed in this thesis.

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1.5 Thesis structure

The thesis is divided into eight chapters. The first chapter reviews the current energy situation in Spain and introduces the contents of the thesis and the main objectives. In Chapter 1, in section 1.2 the primary energy consumption of Spain is analysed for 2007 and the electrical mix for 2009 is compared to 2006. The primary energy consumption of each of the main sectors is also quantified: transportation, industry, residential and energy transformation. The use of such distributed energy systems (section 1.3) as cogeneration, trigeneration or polygeneration systems can reduce energy consumption because these systems are more efficient than conventional systems. The objective of this thesis (section 1.4) is to develop a methodology for optimizing polygeneration systems in residential applications. To optimize polygeneration systems in building applications, various issues must be addressed. An optimisation technique must be selected to solve the model (Chapter 2). The energy demand of the buildings must be characterized properly so that it can be used in the optimisation models (Chapter 3), and the generation or energy conversion technologies that make up the polygeneration system must be modelled (Chapter 4). Finally, all the information provided by the user, the energy demand of the building and the models of the polygeneration units must be integrated into an environment that is sufficiently flexible to be used in several different applications and for different objectives to be chosen. Chapter 5 presents the environment that integrates all these aspects and Chapters 6 and 7 present two case studies.

Chapter 2 analyses several energy tools and the main optimisation methodologies applied for the optimal design and evaluation of polygeneration systems. Several energy tools are compared in section 2.2 and a preliminary selection is made of the most appropriate tools for the objectives of this thesis. These tools are briefly decribed. Energy tools apart, the main strategies applied to optimally configure and design polygeneration systems are evolutionary algorithms and mathematical programming techniques. The main evolutionary algorithm used in literature is the genetic algorithm, presented in section 2.3 Mathematical programming techniques are presented in section 2.4 introducing linear (LP), mixed integer (MIP), non-linear (NLP) and mixed integer non-linear (MINLP) models. Section 2.5 reviews the optimisation models for cogeneration or polygeneration systems using genetic algorithms and mathematical programming techniques, some of which include a district heating and cooling network. Finally section 2.6 introduces multi-objective optimisation and reviews multi-objective optimisation models.

Chapter 3 presents the methodology developed to characterize the energy demand for residential applications. Section 3.2 introduces the energy demand calculation for buildings and such simulation tools as TRNSYS, EnergyPlus or DesignBuilder, which are used to estimate the energy demand of a specific building. The hourly annual energy demand calculated with these tools is too big to be used in optimisation models, but hourly demand data is important when variability is high. Section 3.3 presents a graphical methodology for the selection of typical days using a tool (TipDay) developed for this purpose. Section 3.3.2 presents an optimisation model of a basic trigeneration system used to compare the results of different cases with a different number of typical days. The objective of this optimisation model is to demonstrate that if typical days are selected properly, the results are very similar to those obtained when the energy demand of the whole year is used.

Chapter 4 presents the optimisation model of the main units used to define the polygeneration system (e.g. internal combustion engines, gas turbines, energy storage and absorption chillers). Distributed energy systems are introduced in section 4.2. The proposed models for cogeneration units are listed in section 4.3 (internal combustion engines, gas turbines and fuel cells) considering part load operation and the effect of ambient temperature in the case of the gas turbines. Manufacturer or experimental data can be used to adjust the parameters of the models. The modelling of energy storage based on previous publications is presented in section 4.4. Thermally driven chillers are modelled in section 4.5 considering part load operation based in previous publications using a multi-regression method that considers part load operation as a function of the temperatures of the main components of the chiller.

Chapter 5 presents the optimisation environment developed in this thesis for the application of the optimisations models. Section 5.2 introduces GAMS, the optimisation engine used to solve the models. Around GAMS two new tools have been developed: GUME and MGEOS. GUME (section 5.3) is the text editor that develops the optimisation models of the units that define a polygeneration system as well as its auxiliary units and variables. Sections 5.3.1 to 5.3.4 lay down some guidelines for creating an optimisation model for a specific unit with GUME. MGEOS (section 5.4) is the interface that represents the model of each unit as a block that can be connected with other blocks to create the polygeneration system. MGEOS is the tool that defines the polygeneration system, introduces all the input data and reads the solutions obtained from GAMS. Finally section 5.5 provides a brief summary of the units that are currently available in MGEOS.

The optimisation environment developed (TipDay, GUME, MGEOS) has been applied in two cases studies to evaluate different polygeneration alternatives. The first case is the evaluation of a small-scale polygeneration plant installed in the Politecnico di Torino (Italy). The second case is a scenario analysis of a high capacity polygeneration plant installed in Cerdanyola del Vallès (Spain). In the first case only a few preliminary monitored results are available for some units. In the second case, no monitored data is available yet. These case studies are presented in Chapter 6 and Chapter 7, respectively.

The first case study in Chapter 6 analyses a polygeneration system with desiccant liquids that supplys conditioned air to a classroom building in the Politecnico di Torino (Italy). The objective of this chapter is to show how the optimisation environment can be used to represent a real plant, perform several scenario analyses and evaluate the viability of the plant for different modes of operation. The polygeneration plant is described in section 6.2. Some of the preliminary monitored results for the desiccant liquids and several correlations for predicting the output humidity of the air are compared in section 6.3. The optimisation model and the implementation of the trigeneration system in the optimisation environment are presented in section 6.4. The scenarios analysed are described in section 6.5 and, finally, the results are presented in section 6.6.

Chapter 7 presents the second case study that is based on the economic and environmental evaluation of a polygeneration plant in Cerdanyola del Vallès in the framework of the PolyCity project. The PolyCity project is presented in section 7.2, with an overview of the project and the polygeneration plants. Section 7.3 describes the methodological approach used to evaluate the plants and the system boundaries assumed (section 7.3.1). The energy demand is presented in section 7.3.2 and the emissions calculated for each type of technology in section 7.3.4. The description of the scenarios can be found in section 7.4 and the results in section 7.5.

Chapter 8 presents the conclusion of the thesis and the possibilities of future work. Finally, in the annex, there is an example of the model for a unit using GUME.

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Chapter 2

Energy tools and optimisation techniques

2.1 Introduction

Energy tools and optimisation models are used for design, synthesis and evaluation of energy supply systems. These tools or models represent the energy system until a certain level of detail and solve or optimise the system for a given scenario, with a specified energy demand data and some input information like energy prices, cost of technologies or the superstructure of the energy supply system. The selection of the energy tool or the optimisation technique must be done carefully to fit the requirements of the user. This chapter presents a review of the main energy tools and optimisation techniques available that could be applied for the optimisation of energy supply systems. Some examples found in the literature are presented to investigate which is the most extended methodology for the optimisation of energy supply systems. The objective is to compare and identify which optimisation methodology can be used considering the purpose of this thesis.

Section 2.2 analyses and compares the main energy tools available to simulate and optimise energy systems. Besides energy tools, other optimisation methodologies are presented in the following sections: a brief description of genetic algorithms is presented in section 2.3, and a review of mathematical programming techniques is presented in section 2.4. Several examples found in the literature applied to energy systems are presented in section 2.5. Finally, more cases of application with multiobjective optimisation are presented in section 2.6.

The conclusions in section 2.7 determine the scope and the purpose of the models to be developed and analyse all the energy tools and optimisation techniques reviewed to choose a methodology to be applied in this thesis.

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2.2 Energy tools

Energy tools are commonly used to evaluate energy supply systems. In polygeneration systems the high level of integration and the amount of information is too big to be managed without the aid of computer tools. Despite the type of energy tool, the purpose of all of them is to represent, until a certain level of detail, the configuration of the energy supply system and to calculate their performance or several indicators. Figure 2.1 shows the key aspects of an energy tool that usually are related between them. The time horizon refers to the maximum time span that can be considered in the energy tool (number of years). The scale refers to the geographical application of the tool (global, national, local, etc.). As higher is the level of detail of the simulation/optimisation more information will be required by the user and the time horizon and the scale will be reduced. When an energy tool must be used, the user must be aware of the scope and the level of detail of the analysis to be performed. If the energy tool is not properly selected, the results will not suit the expectative of the user, or in other cases, the tool will be too complicated to use because of the level of information required.

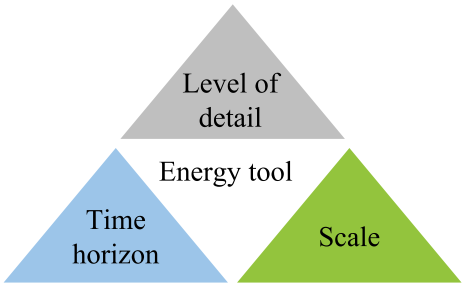

Figure 2.1 Key aspects in an energy tool

A review of energy tools including the use of renewable sources can be found in Connolly et al 2010. According to the author, seven types of energy tools are defined as a function of the purpose of the tool. Figure 2.2 shows the seven types of energy tools and also the relation that may exist between them. Usually an energy tool can be included in more than one group. Regarding the scale of the model, the following classification can be made: Local, Community, Regional, State, National, International or Global. The energy demand, the number of potential users and the size of the technologies trend to be higher as the geographical application of the model grows. In contrast, the level of detail of the modelling trend to be lower. The reason of this effect is not only the higher computational cost that would be required to apply detailed model in large scales, but also the average effect in the behaviour and the efficiencies when several and large plants are considered. Besides the energy tools described in Connolly et al 2010, other tools like ASCEND, INSEL or OSMOSE could be considered.

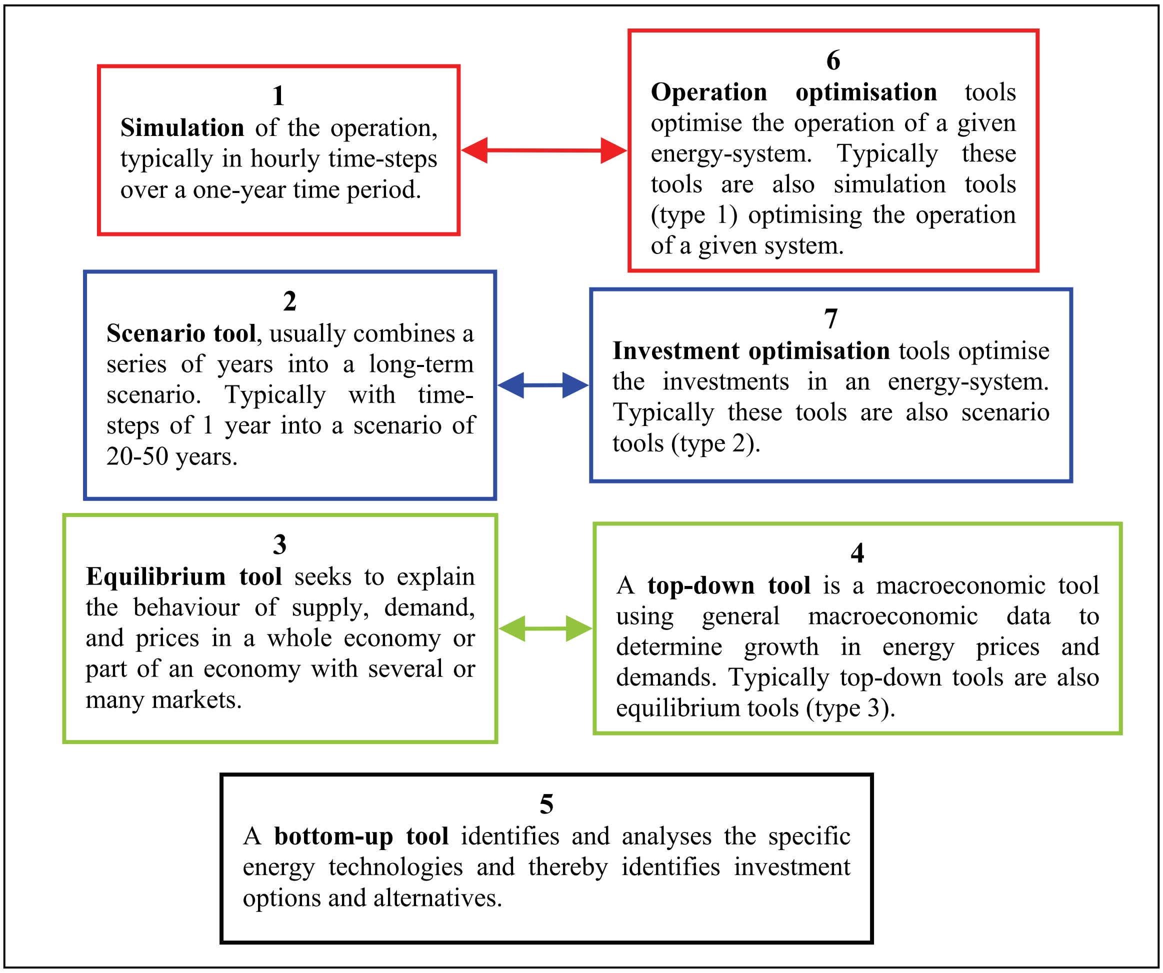

Figure 2.2 Energy tools classification in seven groups as a function of the purpose (Connolly et al 2010)

The optimisation methodology to be used in this thesis must fulfil the following requirements:

- Scenario tool to perform analysis for the typical life time (15-25 years). With this feature will be analysed the economic, environmental and energetic performance of the plant for several time scenario hypothesis, where the energy price, energy demand or technology efficiencies can change with the time.
- Investment optimisation. Economic viability is crucial for the configuration of the energy supply system.
- Operation optimisation. Choosing the best schedule for the operation of the units plays a key role not only in the economic viability, but also in the fulfilment of certain energetic constraints determined by the legislation of each country.
- Enough flexibility to include a wide range of technologies, including production of power, electricity, heating and cooling.

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These characteristics mentioned above will be not required for all the cases, but must be the minimum capacities of the energy tool to be used. Although optimisation tools usually are also simulations tools (figure 2.2), it is not desired a high level of detail of the models that in some cases will be in opposition with the scenario capacities. Furthermore, the optimisation capacities decrease with the complexity (detail) of the models.

Table 2.1 Classification and main properties of several energy tools (Connolly et al 2010)

	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

Table 2.1 shows the energy tools reviewed in Connolly et al 2009, classified by the type of energy tool. The three minimum requirements mentioned above have been used to do an initial selection of energy tools that could be used (green). A short description of these tools is presented below.

- BALMOREL: International scale, emphasis on electricity sector and CHP. Can simulate some of the heat sector (district heating).
- EnergyPLAN: The main purpose of this tool is to assist the design of national or regional energy planning strategies by simulating the entire energy-system: this includes heat and electricity supplies as well as the transport and industrial sectors. Simulate one year at a time, but these can be combined to create a scenario of multiple years.
- EnergyPRO is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation except nuclear, all renewable generation, and all energy storage units to complete the analysis. EnergyPRO only models the heating sector and does not include transport technologies. The analysis is carried out using a one-minute time-step for a maximum duration of 40 years.
- MESSAGE is a systems engineering optimisation tool used for the planning of medium to long-term energy-systems, analysing climate change policies, and developing scenarios for national or global regions. The tool uses a 5 or 10 year time-step to simulate a maximum of 120 years.
- ORCED dispatches power-plants in a region to meet the electricity demands for any given year up to 2030. Only the electricity sector is simulated using ORCED.
- TRNSYS16 has an open modular structure with open source code which simulates electricity, heat and cooling sectors. The tool uses a user-defined time-step, which ranges from 0.01 seconds to 1 hour, and it can analyse a time-horizon of multiple years. System costs are analysed external to TRNSYS16 in a spreadsheet tool.

BALMOREL and EnergyPLAN are focused from a regional to international scale, and the last simulate one year at a time. MESSAGE is also a national to global tool with five year time steps. ORCED simulates only the electricity sector for a US country at a regional to national level. These tools are focused for big scales, from regional to national or international, and could be not suitable to study concrete plants. Moreover, ORCED is specifically developed for the electricity sector, mainly in the US. The time step in MESSAGE is too big (five years) to perform operational optimisation from the units scheduling point of view.

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EnergyPRO and TRNSYS16 are similar tools regarding the scale of the analysis. Both tools are used for a single plant investigation. The former is specifically designed for single CHP or thermal plant investigation. The use of TRNSYS16 is quite extended to simulate thermal systems, including renewable energy sources. Time step is small for both (seconds to minutes). EnergyPRO can simulate a maximum of 40 years but TRNSYS16 simulate one year at a time. These tools are more focused for the simulation of the system with a high level of detail. Usually such level of detail is not required in the cases analysed in this thesis, where the optimisation is more relevant than the simulation. The purpose of the models for this thesis is to perform a preliminary study to determine the economic and environmental viability of several options, as a previous step before to perform detailed and rigorous simulations.

2.3 Genetic algorithms

Genetic algorithms is a strategy for optimisation models; it is a robust method, applicable to all fields, without mattering if the problem is discrete or continuous, linear or nonlinear, differentiable or not, convex or nonconvex. GA uses a codification of the parameters usually in binary form grouped in a vector as if one was a chromosome; each chromosome represents a possible solution of the problem, so the algorithm works with a population of possible solutions and not just a point. Initial population (chromosomes) obtained randomly is evaluated (simulating the model with the data of one chromosome), a solution is obtained and depending of the goodness of the solution, the evaluated chromosomes are classified. Attending to this classification, the chromosomes are combined to obtain a new population through reproduction, crossover or mutation. The solutions are calculated from the combination of other possible solutions, and for these reason, GA is independent of the type of the model and can be applied to all the fields. The foundation of GA lies in the building block hypothesis (Goldberg 2004). All the variables are codified in binary form and distributed along a chromosome, thus a chromosome is formed by a string of 0 and 1. Some sections of these strings (chromosomes), with different length and locations (and depending of the initial values) forms building blocs. Some of these building blocks increase the performance of the string obtaining a higher fitness value. These means, that certain binary values located in certain areas of a chromosome always gives good fitness value. The operators mentioned (reproduction and crossover) explodes these building blocks given to them more trials in the subsequent generations. This is the reason of the importance of a good codification and the manner in which the variables are ordered or distributed along the chromosome. The ordering and the type of codification have to be some meaning considering the type of problem.

GA are non constrained algorithms, the introduction of constraints is done by penalty functions (Yeniay 2005). An optimisation problem of the general form:

Minimize f(x)

Subject to:

$h_j(x) = 0$ j = 1,m (Equality constraints)

$g_d(x) \geq 0$ d = 1,r (Non equality constraints)

$x_i \in R$ independent variables

Can be transformed using penalty function as:

$$\text{Minimize } \phi(x) = f(x) + \left[\sum_{j=1}^{m} c_j \cdot L_j + \sum_{d=1}^{r} k_d \cdot G_d \right]$$

Where:

$\phi(x)$: new objective function.

c_j , k_d: penalty coefficient.

L_j and G_d are functions of $h_j(x)$ and $g_d(x)$ respectively. Usually penalty function takes the form:

$$G_d = \max[0, g_d(x)]^\beta \qquad L_j = |h_j(x)|^\gamma$$

Where β and γ are commonly 1 or 2. Unconstrained solution converges to constrained solution as the penalty coefficient r approaches to infinity. In practical cases, c_j and k_d is sized separately for each type of constraint and model. Figure 3 shows the basic operation of a GA. The algorithm starts creating an initial population of chromosomes (strings) with random values. Each string contains the binary codified values of all the variables to be optimised in the problem (P1). The most common codification is in binary form, but other types of codification or even strings without codification can be used, but codification is recommended, because is in these situation GA can exploit the building blocks and the performance of the algorithm is greater. The length of the string depends of the number of variables and the number of bits required codifying each variable. The number of strings can be selected for the user as a function of the type and difficulty of the problem. Each string is a point in the search space, as much points are processed more easily can be found an optimal, but the information to be processed at each step is higher as well as the necessary memory.

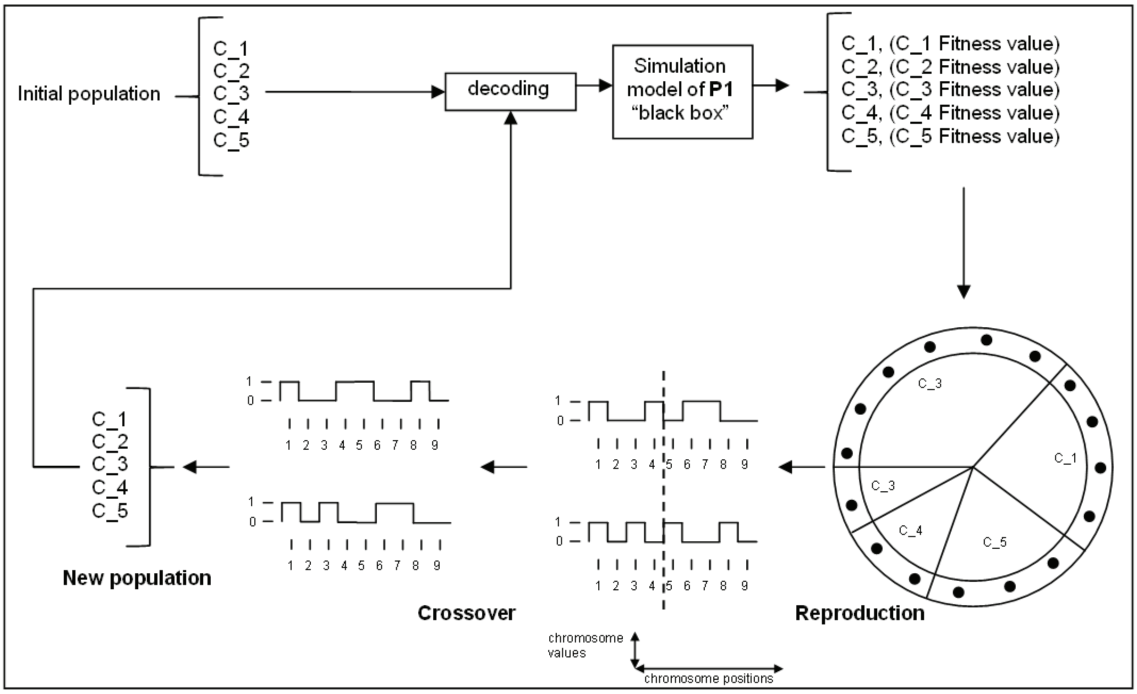

Figure 3 Example of operation of a genetic algorithm to optimise a simulation "black box" model

Each string of the initial population is decoded and with the simulation model (P1) a value of the objective function is obtained (C_1,5 Fitness value). The easiest form to implement the reproduction operator is using a roulette wheel, where the positions of each string in the roulette are proportional to the fitness value. In the figure, C_3 has the major fitness value (if the problem is maximized) and his space in the roulette is proportional to the ratio between its fitness value and the sum of the fitness value of all the strings. An operator is implemented that selects randomly a string to be used in the next step (crossover), strings with higher fitness value has higher probabilities to be selected as exemplifies the roulette. During crossover, a crossing site (position in the string) is randomly selected and two new strings are created swapping all the binary values around the crossing site, until a new population (generation) is created. Mutation operator can be applied during this step, which changes the value of a certain position of a string as a function of the mutation probability. This probability can be implemented as how many binary values are copied until one of these values is mutated. Finally the new population is evaluated and the cycle starts again. The algorithm stops when a certain number of generations are created or when the maximum of the fitness value between the last generations lies between a specified tolerances. These is the description of a basic GA but more sophisticated operators for the reproduction, crossover and mutation can be applied, as well as additional operators like dominance, diploidy or inversion.

2.4 Mathematical programming

Mathematical programming consists in the optimisation of a mathematical model minimizing or maximizing an objective function. Objective function can represent the total cost of the installation (investment and operational costs), environmental parameters or a mixture of both (multi-criteria optimisation). The model has several constraints as a consequence of the physical and operational limitations of the modelled units. The formulation of the model usually is as follows (Biegler and Grossmann 1999):

Minimize $f(x)$

Subject to:

$h_j(x) = 0$	$j = 1,m$ (Equality constraints)
$g_d(x) \geq 0$	$d = 1,r$ (Non equality constraints)
$x_i \in R$	independent variables

Any optimisation problem can be represented in the above form. Maximize a function is equivalent to minimize the negative function, and the inequalities greater or equal to zero, can be reformulated as inequalities that are less or equal than zero multiplying the two terms of the inequality by minus one. In general, the number of variable n will be greater than the number of equations m (equality constraints), the difference (m-n) is commonly denoted as the number of degrees of freedom. The feasible region (FR) of the problem corresponds to all the points of the function's domain delimited by the constraints. FR is given by:

$$FR = \{ x \mid h(x)=0, g(x) \leq 0, x \in R\}$$

FR is convex for any x_1 and $x_2 \in$ FR if:

$$x=\alpha\cdot x_1+(1-\alpha)\cdot x_2 \in FR, \forall \alpha \in [0,1]$$

The feasible region will be convex if all the points of the line that results from joining two points of FR, are also inside FR. Figure 2.4 shows an example of the application of the previous definition to determine if the feasible region is convex. In this figure, the feasible region is the one comprised inside the three lines (constraints) that delimitates the search space where the solutions of the model are located.

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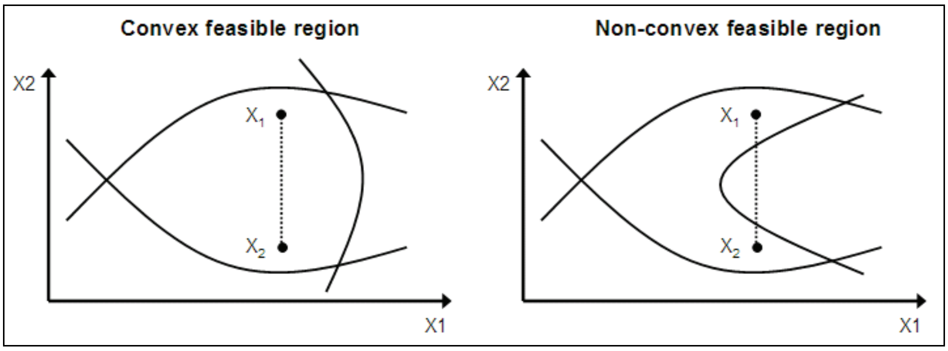

Figure 2.4 Comparison of convex and non-convex feasible regions along two points

A feasible region will be convex if all the equality constraints are linear and the inequalities consist of convex functions. A convex function is those in which the value at the midpoint of every interval in its domain does no exceed the arithmetic mean of its values at the ends of the interval (equation 2.4). In other words, a function if convex if it's epigraph is convex (Sahinidis 2005).

$$f(\alpha \cdot x_1+[1-\alpha] \cdot x_2) \leq \alpha \cdot f(x_1)+[1-\alpha] \cdot f(x_2) \quad \forall \alpha \in [0,1]$$

For any optimisation problem, the goal of the algorithm is to find the global minimum of the objective function (or the global minimum of the negative objective function in the case of maximization). The types of minimum that can be found are:

- Strong local minimum
  $f(x_1)$ is a strong local minimum if $x_1 \in FR$, $\exists \delta>0$, $f(x_1)<f(x) \quad \forall |x-x_1|<\delta$
- Weak local minimum
  $f(x_1)$ is a weak local minimum if $x_1 \in FR$, $\exists \delta>0$, $f(x_1) \leq f(x) \quad \forall |x-x_1|<\delta$
- Global or local minimum
  $f(x_1)$ is a global minimum if $x_1 \in FR$, $f(x_1) \leq f(x) \quad \forall x \in FR$

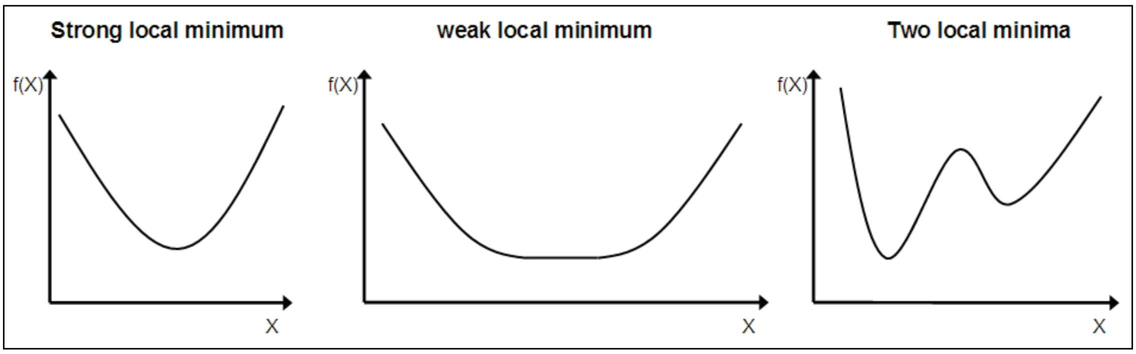

Figure 2.5 Function with several minimum represented: strong, weak local and two local minimum

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2.4.1 Properties of the optimisation models

The properties of the optimisation models can be classified as a function of:

- Independent variables:
    - One or more than one variable (multivariable).
    - Continuous variables, integer, or a mixture of both.
- Objective function:
    - Only one optimum or several optimums.
    - Convex or non convex function.
    - Continuous or discontinuous.
    - Derivable or non derivable.
    - Lineal or non lineal
    - Explicit or non explicit in x
- Constraint functions
    - Problem with or without constraints.
    - Derivable constraints or non derivable.
    - Lineal or non lineal constraints.
    - Equality, non equality constraints or a mixture of both.
    - Domain defined for all the constraints.
    - Explicit or implicit constraints in x.

The selection of the resolution algorithm for the optimisation of the model is a function of the previous parameters, and can be classified as follow:

- Objective function with only one variable.
    - Direct methods.
    - Indirect methods.
    - Interpolation methods.
- Multivariable objective function.
    - Without constraints
        - Direct search.
        - First order methods.
        - Second order methods.
        - Quasi-Newton
    - With constraints
        - Lineal programming (LP)
        - Mixed integer lineal programming (MILP)
        - Non lineal programming (NLP)
        - Mixed integer non lineal programming (MINLP)

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2.4.2 Optimality conditions

Every global minimum is a local minimum, but a local minimum doesn't imply that is a global minimum. To know the type of minimum, the following conditions can be applied as a function of the type of problem.

Unconstrained optimisation

Unconstrained optimisation models can be expressed as:

Minimize f(x)

$x_i \in R$ i=1,n (independent variables)

First order condition, which are necessary for a local minimum at x, are given by the stationary point ∇f(x*)=0. This implies the solution of the following set of equations:

$$\frac{\partial f}{\partial x_i} = 0 \tag{2.1}$$

A strong local minimum can be determined by the Hessian matrix H of second partial derivatives:

$$H = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix} \tag{2.2}$$

If H if definite positive then the local minimum is a strong local minimum. When the Hessian matrix of a function is positive definite, then the function is strictly convex. H is positive when all their eigenvalues are positive. For unconstrained problems, if f(x) is strictly convex and differentiable, if exists a stationary point at x*, then this point correspond to a unique local minimum.

Minimization with equalities

Constrained optimisation problems are those in which the objective function is optimised while some equality constrains must be satisfied. These problems can be expressed as:

Minimize f(x)

Subject to:

$h_j(x) = 0$ j = 1,m (Equality constraints)

$x_i \in R$ i = 1,n (independent variables)

Lagrange function is defined as:

$$L = f(x) + \sum_{j=1}^{m} \lambda_j \cdot h_j(x) \quad (2.3)$$

Where λ_i are the Lagrange multipliers, the conditions to obtain the stationary points are:

$$\frac{\partial L}{\partial x} = \nabla f(x) + \sum_{j=1}^{m} \lambda_j \cdot \nabla h_j(x) = 0 \quad (2.4)$$

$$\frac{\partial L}{\partial \lambda_j} = \nabla h_j(x) = 0 \quad (2.5)$$

Equations 2.4 and 2.5 define a system of n+m equations with m+n unknowns (x and λ). λ are the Lagrange multipliers that compute the stationary points of a constrained function. Equation 2.4 implies that the gradients of the objective function and equalities must be linearly dependents. Thus, the optimisation constrained problem with n unknowns and m constraint is converted to an unconstrained function with m+n variables. A new unknown variable is introduced for each constraint (the Lagrange multiplier) and a new function is defined (Lagrangian). Equation 2.5 implies the feasibility of the equalities. Second order conditions for a strong local minimum are satisfied when the Hessian of the Lagrangian is positive definite. Lagrange multipliers are generalized by the Karush-Kuhn-Tucker conditions.

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Minimization with equalities and inequalities

Constrained optimisation problems are those in which the objective function is optimised while some equality and inequality constrains must be satisfied. These problems can be expressed as:

Minimize f(x)

Subject to:

$h_j(x) = 0$ j = 1,m (Equality constraints)

$g_d(x) \geq 0$ d = 1,r (Non equality constraints)

$x_i \in R$ i=1,n (independent variables)

The necessary conditions for a local minimum are given by the Karush-Kuhn-Tucker conditions:

1. Linear dependence of the gradients:

$$\nabla f(x) + \sum_{j=1}^{m} \lambda_j \cdot \nabla h_j(x) + \sum_{d=1}^{m} \mu_d \cdot \nabla g_d(x) = 0 \qquad (2.6)$$

2. Constraint feasibility:

$$h_j(x) = 0 \qquad (2.7)$$

$$g_d(x) = 0 \qquad (2.8)$$

3. Complementary conditions:

$$\mu_g \cdot g_d(x) = 0 \qquad (2.9)$$

Where $\mu_g \geq 0$

If f(x) and g(x) are convex functions (linear or non linear), and the equalities constraints are linear, a global minimum can be guaranteed and the KKT conditions are necessary and sufficient.

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2.4.3 Linear programming

Linear programming problems involve the optimisation of a linear objective function subject to linear equality and inequality constraints:

Minimize $Z = c^T \cdot x$

Subject to:

$a \cdot x \leq b$

$x \geq 0$

Since linear functions are convex, the objective function is convex and as mentioned previously, the feasible region will be convex if the equality constraints are linear, then by the KKT conditions a local minimum is a global minimum. The linearity of the objective function also implies that an optimal solution can only occur at a boundary point of the feasible region, unless the objective function is constant. The optimum is not necessarily unique; it is possible to have a set of optimal solutions covering an edge or face of the feasible region. There are only two situations in which no optimal solution can be found:

- Constrains contradicts between them (the feasible region is empty).
- The problem is unbounded in the direction of the objective function.

The simplex method exploits the fact that in a LP the optimum lies at a vertex of the feasible region, where the KKT conditions are satisfied. Computational expense dependent mostly on the number of constraints, not so much on the number of variables.

2.4.4 Mixed integer programming

MILP is an extension of LP where a subset of the variables is restricted to integer values (usually 0-1). The general form is:

Minimize $Z = c^T \cdot x + e^T \cdot y$

Subject to:

$a \cdot x + d \cdot y \leq b$

$x \geq 0$

$y \in \{0,1\}$

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The standard method to solve MIP is the branch and bound method (BB). First the relaxed LP problem ($0 \le y \le 1$) is solved. If integer values are obtained for y the problem is solved. If no integer values are obtained, a binary tree is used where in each branch, an integer value for one of the variables is fixed. Nodes with non integer solutions provide the lower bounds (the relaxed optimum solution will be lower than any feasible integer solution). A branch is discarded if its relaxed solution is higher that the best integer solution fount at that moment. For the tree enumeration branching rules are used to decide which binary variable is fixed in the next node. As a guideline, computational expense for BB tends to be proportional to the number of (ordered by importance):

1. Integer variables
2. Constraints
3. Continuous variables

2.4.5 Non linear programming

The problem corresponds to:

Minimize f(x)

Subject to:

$h_j(x) = 0$ j = 1,m (Equality constraints)

$g_d(x) \ge 0$ d = 1,r (Non equality constraints)

$x_i \in R$ i=1,n (independent variables)

Where in general f(x), h(x) and g(x) are non linear functions. The two major methods for solving NLP problems are successive quadratic programming (SQP) and the reduced gradient method. For the SQP algorithm a quadratic programming sub problem of the following form is solved at each iteration:

Minimize $\nabla f\left(x^k\right)^T \cdot d + 0.5 \cdot d^T \cdot B^k \cdot d$

Subject to:

$$h(x^k) + \nabla h(x^k)^T \cdot d = 0$$

$$g(x^k) + \nabla g(x^k)^T \cdot d \le 0$$

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Where x^k is the current point, B^k is the estimation of the Hessian matrix of the Lagrangian, and d is the predicted search direction. Matrix B^k is usually estimated with the BFGS algorithm, and the quadratic problem is solved with standard routines. The point x^k will be in general infeasible, the next point x^{k+1} is set to $x^{k+1} = x^k+\alpha\cdot d$, where α is determined so as to reduce a penalty function that tries to balance the improvement in the objective and the violation of the constraints. SQP algorithm can be shown to be equivalent to applying Newton's methods to the KKT conditions, very fast convergence can be achieved with this algorithm.

In the reduced gradient method the idea is to solve a sequence of sub problems with linearized constraints, where the sub problems are solved by variable elimination. In the implementation of MINOS, the NLP is reformulated through the introduction of slack variables to convert the inequalities into equalities, the NLP reduces to:

Minimize $f(x)$

Subject to:

$r(x) = 0$

Linear approximation of the constraints is considered with an augmented Lagrangian for the objective function:

Minimize $\phi(x) = f(x)+(\lambda^k)^T\cdot[r(x)-r(x^k)]$

Subject to:

$J(x^k)\cdot x = b$

Where:

λ^k : vector of Lagrange multipliers

$J(x^k)$: Jacobian of $r(x)$ evaluated at the point x^k

The Jacobian is the matrix of all first-order partial derivatives of a function. Its importance lies in the fact that represents the best linear approximation to a differentiable function near a given point. The Jacobian can be expressed as:

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$$J = \begin{bmatrix} \frac{\partial r_1}{\partial x_1} & \cdots & \frac{\partial r_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial r_m}{\partial x_1} & \cdots & \frac{\partial r_m}{\partial x_n} \end{bmatrix} \tag{2.10}$$

The sub problem, which is linearity constrained optimisation problem, can be represented by:

Minimize $\phi(x)$

Subject to:

$A \cdot x = b$

Where A is a m×n matrix. This sub problem can be solved with the reduced gradient method. In summary, the sub problem is solved as an inner optimisation problem, while in the outer optimisation the new point is set as $x^{k+1} = x^k + \alpha \cdot \Delta x$. In general, the following guidelines can be applied:

- SQP requires less iteration that the reduced gradient method however is difficult to apply to large scale problems due to the size of the B^k matrix (n×n). SQP method is best suited for "black box" models that involve relatively few variables. SPQ can be applied to large scale problems that involve few decision variables by using decomposition techniques.

- Reduce gradient method, as per the implementation in MINOS, is best suite for problems involving a significant number of linear constraints, and where analytical derivatives can be supplied for the nonlinear functions. With this structure, MINOS can solve problems with several hundred variables and constraints. Compared to SQP, MINOS will require a larger number of function evaluations, but the computational time per iteration will be smaller. Furthermore, in the limiting case when all the functions are linear the method reduces to the simplex algorithm for linear programming.

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2.4.6 Mixed integer non linear programming

MINLP problems are usually the hardest to solve unless a special structure can be exploited. It has been traditionally regarded as a very difficult problem because it is a NP-hard problem that is prone to combinatorial explosion. The most basic form of a MINLP problem can be expressed:

Minimize $Z = f(x,y)$

Subject to:

$g(x,y) \leq 0$

Where x and y are the continuous and discrete variables respectively. The basic algorithms for its resolution are (Grossmann 1996):

- Branch and Bound (BB): a NLP relaxed problem is solved, if all discrete variables take discrete values, the algorithm is stopped, if not, a tree search in the space of the discrete variables is made; solving a sequence of NLP relaxed problems.
- Outer Approximation (OA): the problem is divided in MIP master problems and NLP problems. Both type of problems are solved in a cycle of iterations to generate the points (x^*,y^*). The NLP problem yields an upper bound that corresponds to the best current solution. With the MIP problem a non decreasing sequence of lower bounds are obtained (linearization are accumulated). The algorithm stops when the lower and upper bounds are within an specific tolerance.
- Generalized Benders Decomposition (GBD): This method is similar to the OA, the difference is in the definition of the MIP master problems, where only active inequalities are considered.
- Extended Cutting Plane (ECP): In this method only a sequence of MIP problems is solved, in each iteration, the most violated constraint is added for the predicted point (x^*,y^*). The algorithm is stopped when the maximum constraint violation lies within the specific tolerance.
- LP/NLP Based Branch and Bound: This method avoids the complete solution of the MIP problem. A LP BB method is applied to the MIP problem solving the corresponding NLP sub problems for those nodes in which feasible integer solutions are found.

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2.5 Optimisation models for cogeneration or polygeneration systems

The use of optimisation methodologies for the optimal design and operation of energy systems for the residential or tertiary sector is extended in the literature, some examples for cogeneration, trigeneration or polygeneration systems will be presented in this section with special attention to the superstructure that defines the energy supply system. Models with multi-objective optimisation will be presented in section 2.6.

In Chicco et al 2009 can be found a summary of optimisation models for polygeneration systems classified as a function of the time scale and the type of objective to be optimised. Mathematical programming techniques are the most extended methodology for optimisation of cogeneration and polygeneration systems, and with a minor degree of application, evolutionary algorithms like genetic algorithms. Some models found in the literature will be presented starting with linear models (LP), mixed integer programming models (MIP) and finally mixed integener non linear programming models (MINLP).

2.5.1 Linear programming models

In this section several examples of optimisation models using linear programming techniques will be presented. Optimisation of cogeneration plants are presented in Lahdelma et al 2003 using a special simplex algorithm for an hourly model for the complete year.

Kong et al 2005 minimise the energy costs for a trigeneration plant with gas turbine, using several sets of fixed loads of the form of ratios respect to the turbine size. Figure 2.6 shows the configuration of the energy system considered.

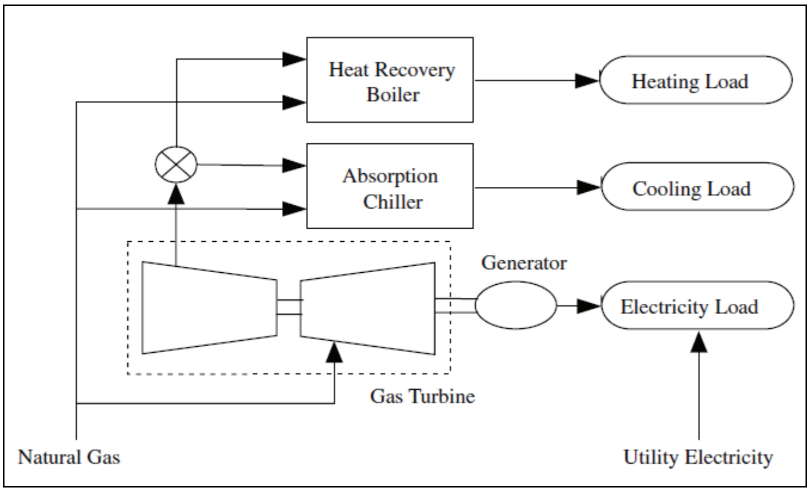

Figure 2.6 Energy supply system with gas turbine in Kong et al 2005

Cardona et al 2006a optimise the primary energy savings and the net cash flow of a polygeneration system in an airport. Typical energy demand profiles of several airports are presented and economic feasibility of a polygeneration system to supply the energy demand is discussed. The superstructure of the polygeneration system is presented in figure 2.7 (the results for one of the cases is compared with the conventional system).

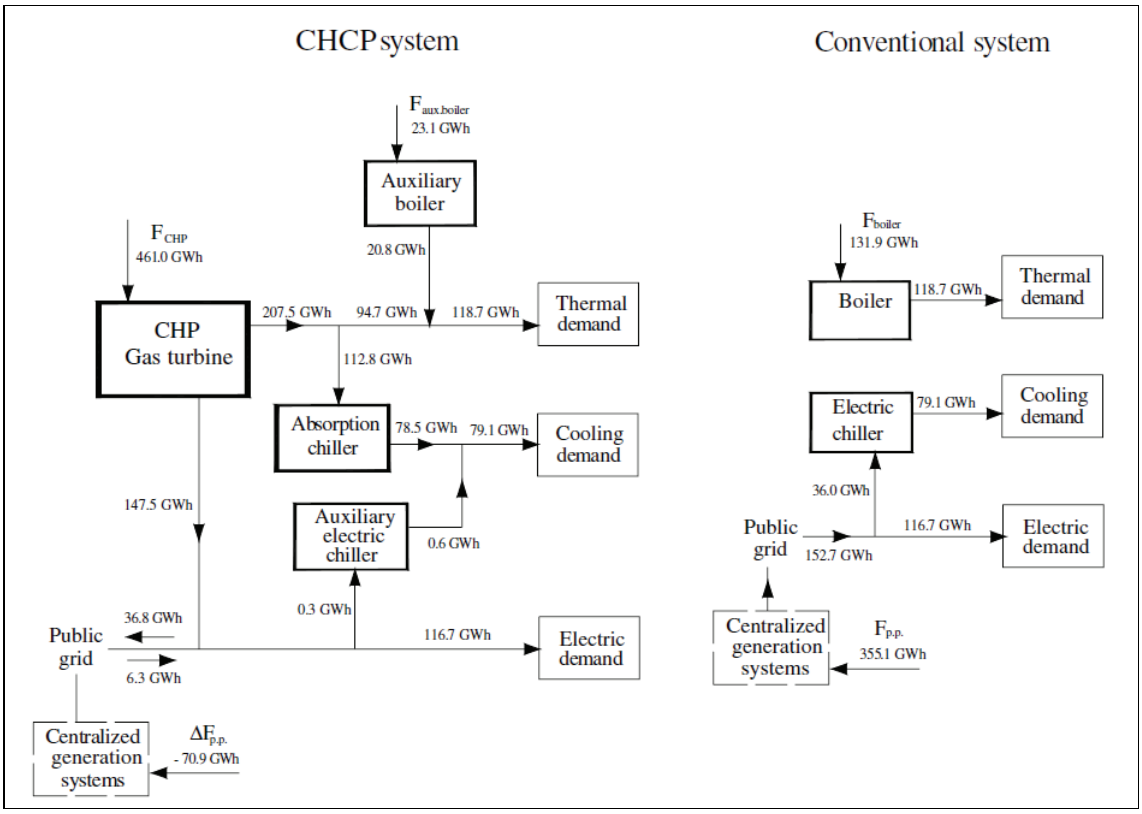

Figure 2.7 Polygeneration system and comparison with conventional system in Cardona et al 2006a

Cardona et al 2006b presents an in-depth analysis for the Malpensa 2000 airport with experimental demand data, optimising the operation and long term planing of a polygeneration plant composed of gas turbines, heat recovery boilers and absorption chillers.

Piacentino et al 2008 presents an hourly optimisation model applied to a hotel and a hospital with electricity, heating and cooling loads. The model was optimised several times considering different numbers of typical days to represent the whole year (from 3 to 60) in order to evaluate the solutions obtained, the resolution time and assest the minimum number of typical days that must be considered in the optimisation model. Figure 2.8 shows the energy supplys sytem considered including the conventional system. Several cases were optimised considering economic or energetic objectives.

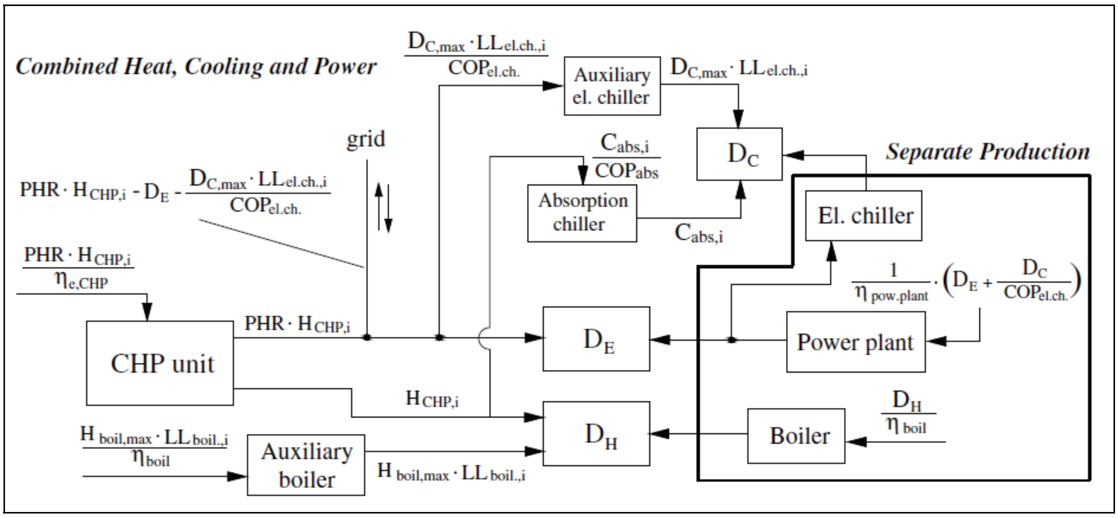

Figure 2.8 Polygeneration and conventional system presented in Piacentino et al 2008

2.5.2 Mixed integer programming models

Sakawa et al 2001 presents an optimisation model for the optimal operation of district heating and cooling plants. The model is solved using the branch and bound method and genetic algorithms. Figure 2.9 shows the configuration of the energy supply system analysed.

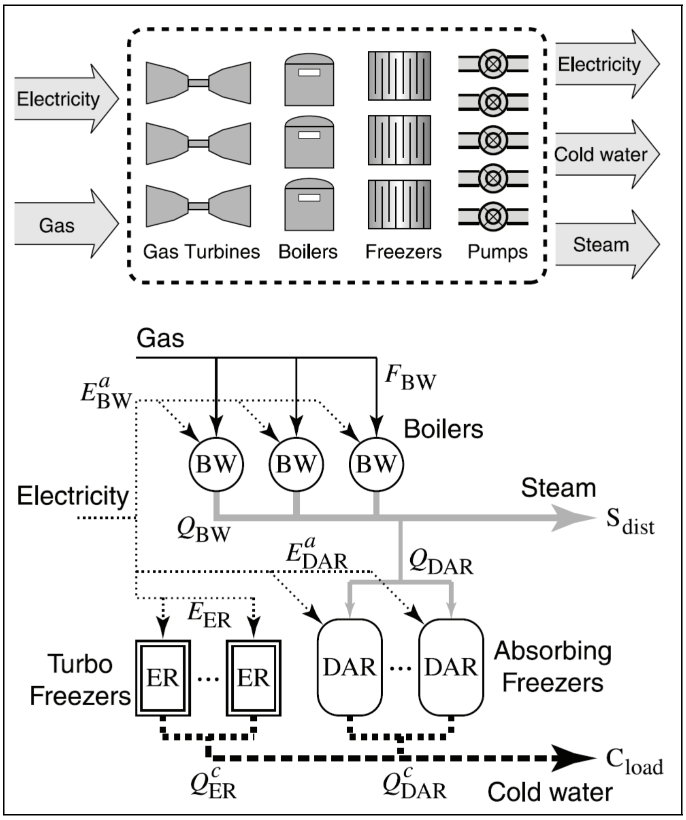

Figure 2.9 DHC plant presented in Sakawa et al 2001

Chinese et al 2005 presents a MILP model, used to study a case of a 1 km^2 expanding industrial area (placed in Italy) using a district heating network with natural gas and biomass fired boilers. The model developed resolves the problem of choosing which existing or new boilers should be integrated into the system and determining their optimal size. Demand is considered as a factor maximizing the profit instead and deciding which consumers will be connected to the district heating. Energy demand is calculated considering an average height and average shape factor (surface-to-volume ratio) for residential buildings, and using the volume specific heat-loss coefficient according to legislation and the difference between the design indoor and outdoor temperature. Energy demand is considered monthly and divided into working and weekend days. Renedo et al 2006 use a MIP model to analyze the best technology (diesel engines or gas turbines) to produce heating and hot tap water to a hostpital center. Two alternatives were considered: to maximize the electrical production and to maximize the time of use at full load.

Models including the production sites and the distribution network are presented in Söderman et al 2006, 2007. The objective is to minimise the overall cost, the solution gives the DES structure (number and location of the production sites, heat transport lines and storages) as well as design parameters. The former is applied to a DH network in the last to a DC network. The solution of the model (figure 2.10) finds which of the possible predefined locations for the supply plants and tank storage are active in the final solution and the optimal connection of the users, through the main DC route defined previously.

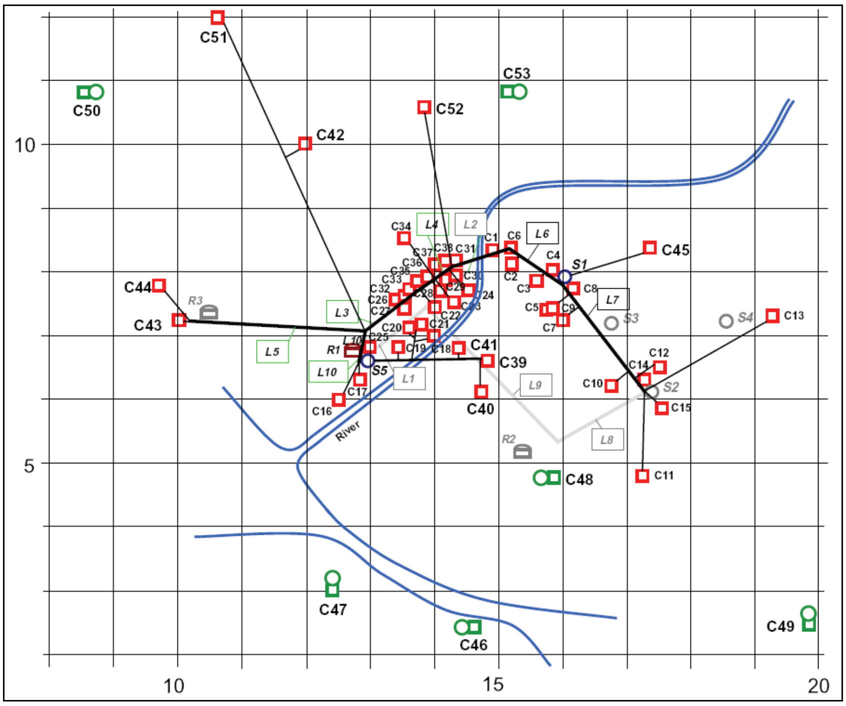

Figure 2.10 Optimal layout of the DC system presented in Söderman 2007

Arcuri et al 2007 optimise the design and operation of a polygeneration plant to supply electricity, heating and cooling to hospital maximizing the net present value. Six typical days were determined using the annual energy demand. Mixed integer programming techniques applied to polygeneration systems has been used in Oh et al 2007 to find the optimal plant configuration of a commercial building using gas engines and heat waste boilers (GE/HWB) and other axuiliary equipments: AUXB (auxiliary boiler), RE (turbo chiller), RS (absopriton chiller) and RF (gas fired absorption chiller).

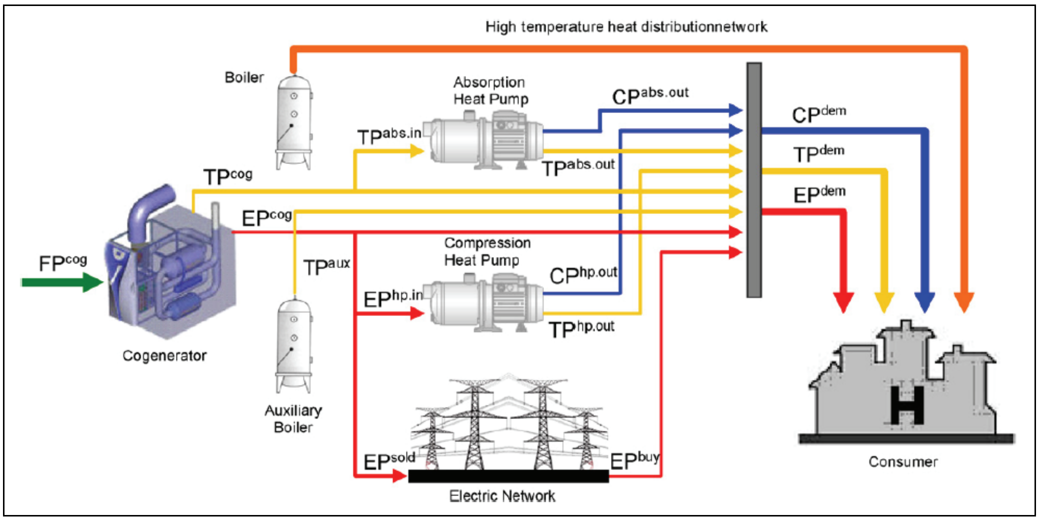

Figure 2.11 Polygeneration plant to supply a hospital energy demand in Arcuri et al 2007

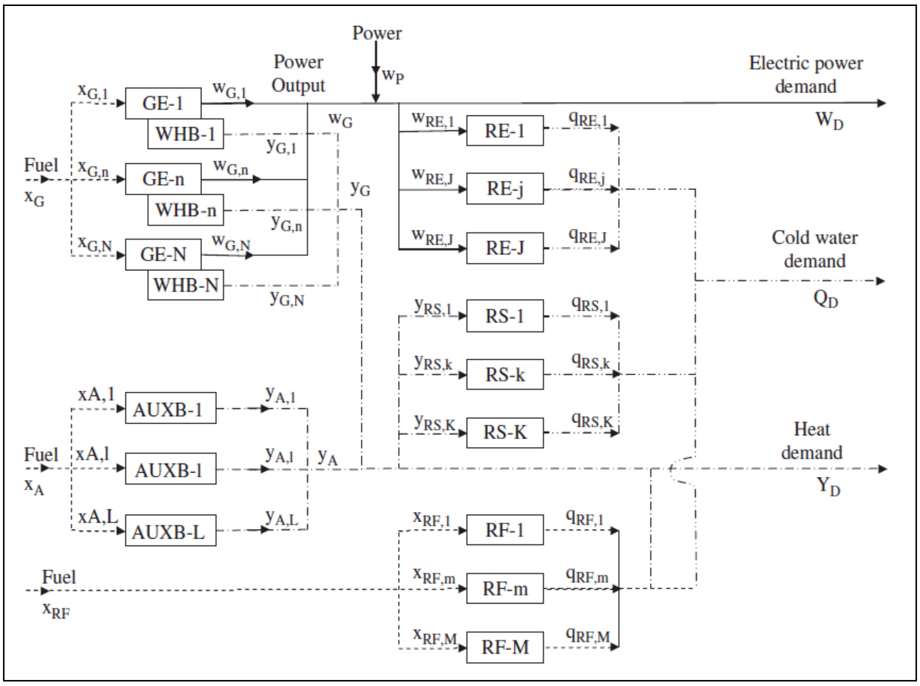

Figure 2.12 Scheme of the polygeneration system presnted in Oh et al 2007

Yoshida et al 2007 presents a MIP model to determine the optimal structure and operational strategies from a defined superstructure (figure 2.13) where all the conventional equipments are included. The model minimizes the annual costs ans is applied to a hospital using an estimated energy demand for fourteen typical days.

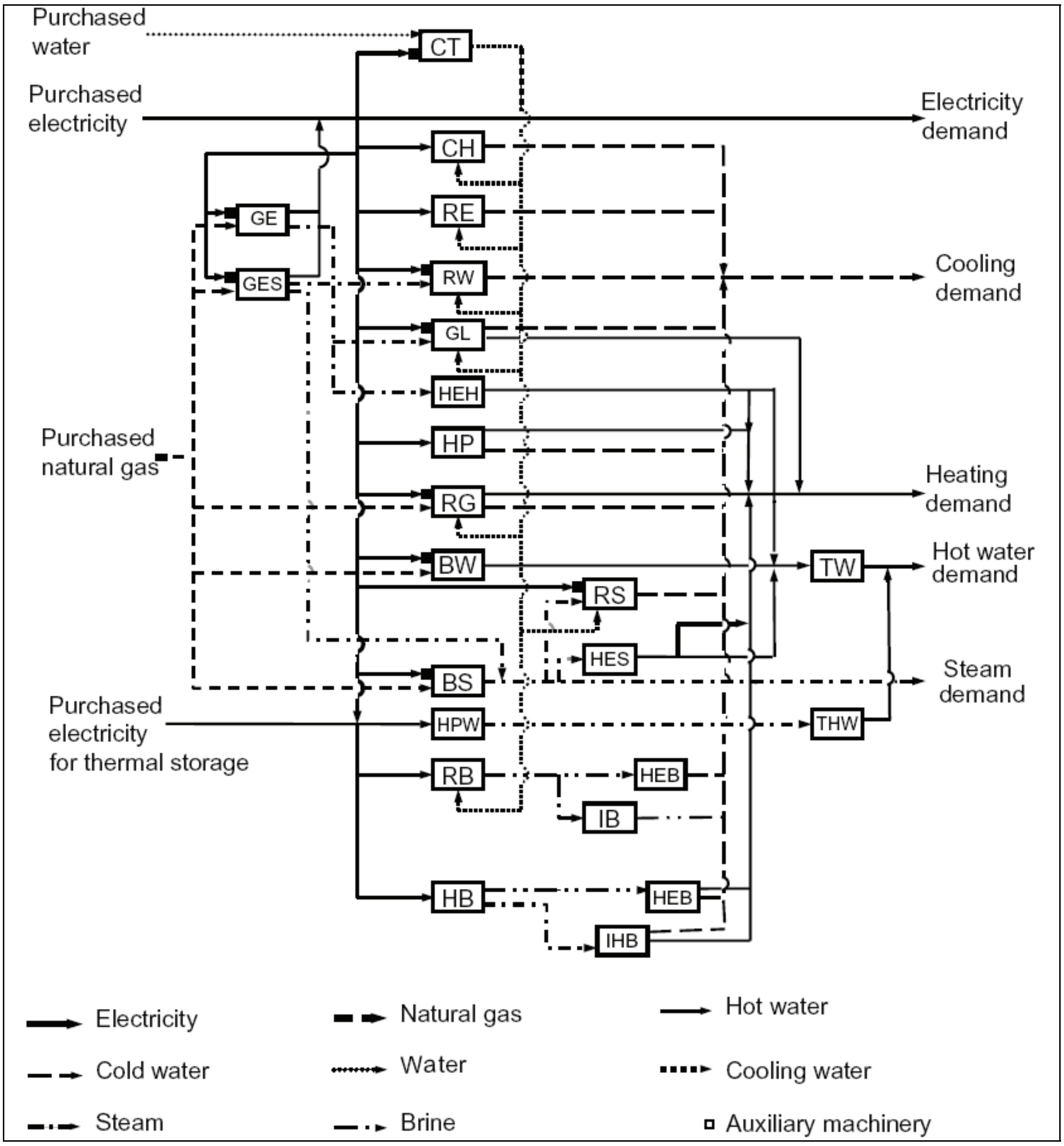

Figure 2.13 Superestructure of the energy supply system for a hospital in Yoshida et al 2007

The units included are: CT cooling tower, CH chilling unit, RE electric refrigerator, GE gas engine (hot water), RW hot water absorption refrigerator, GES gas engine (hot water and steam), GL steam absorption refrigerator, HP electric heat pump, RG-L large scale gas-fired absorption refrigerator, RG-M meddle-scale gas-fired absorption refrigerator, BW boiler, RS

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steam absorption refrigerator, BS steam boiler, HPW electric heat pump for hot water, RB electric compression refrigerator for ice storage, IB ice storage tank, HB brine electric heat pump, IHB ice and hot water storage tank, TW hot water tank, THW hot water tank for HPW, HEH heat exchanger from water to water, HES heat exchanger from steam to water, HEB heat exchanger from brine to water.

Seo et al 2008 presents a MIP model for the optimisation of cogneration sytems in eight apartments minimising the annual cost. The yearly operation of the system was optimised considering typical days for each month calculated using monitored data during two years from one of the buildings. Figure 2.14 shows the superstructure considered.

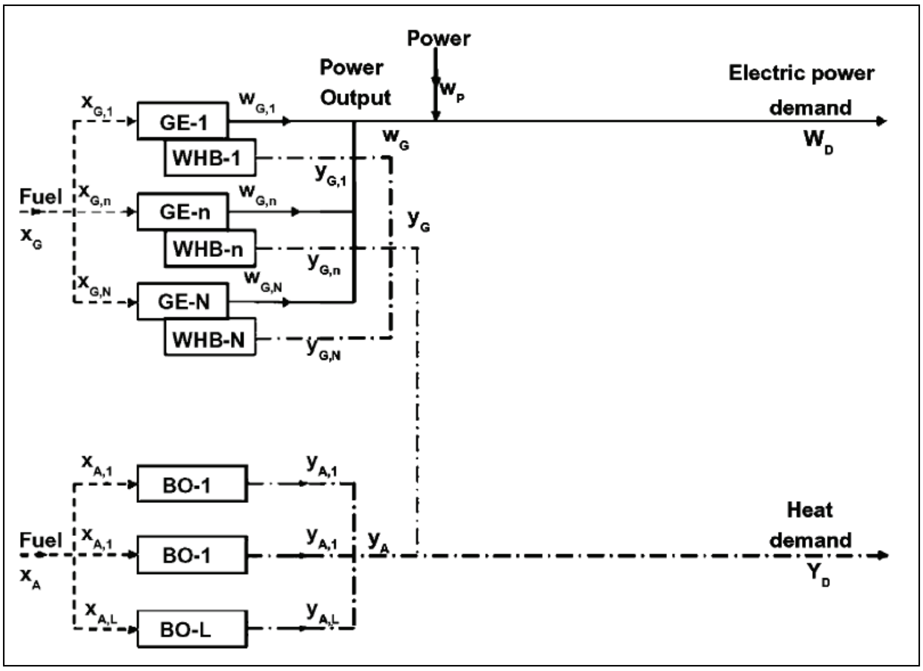

Figure 2.14 Cogeneration system for apartments presented in Seo et al 2008

Chao-zhen et al 2008 study the influence of different energy demand (with different heat-electricity and cooling-electricity ratios) on the optimal capacity of a polygeneration system minimizing the annual costs. Figure 2.15 shows the superestructure considered, where: GT gas turbine, HE heat exchanger, AR absorption refrigerator, DH exhaust heat-excharger, GB gas boiler, ER electrical refrigerator, PG purchased electricity.

Ren et al 2010 presents MIP models for the integration and evaluation of distributed energy resources, consisting of interconnected power generations, storage and several energy carriers. Some of the layouts that could be obtained are presented in figure 2.16.

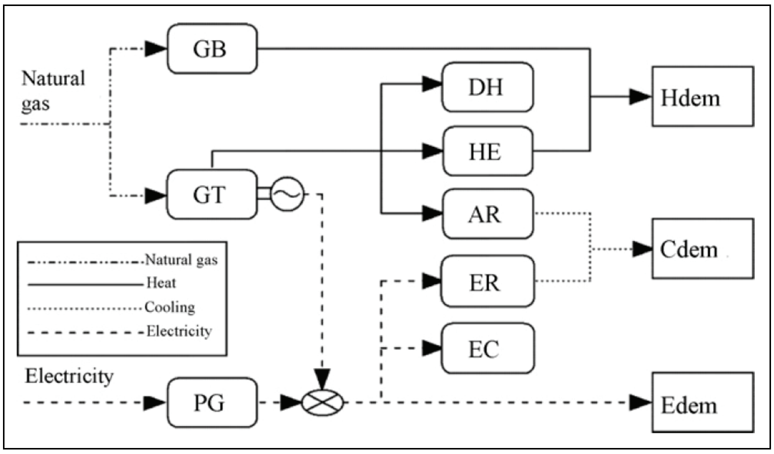

Figure 2.15 Superestructure presented in Chao-zhen et al 2008

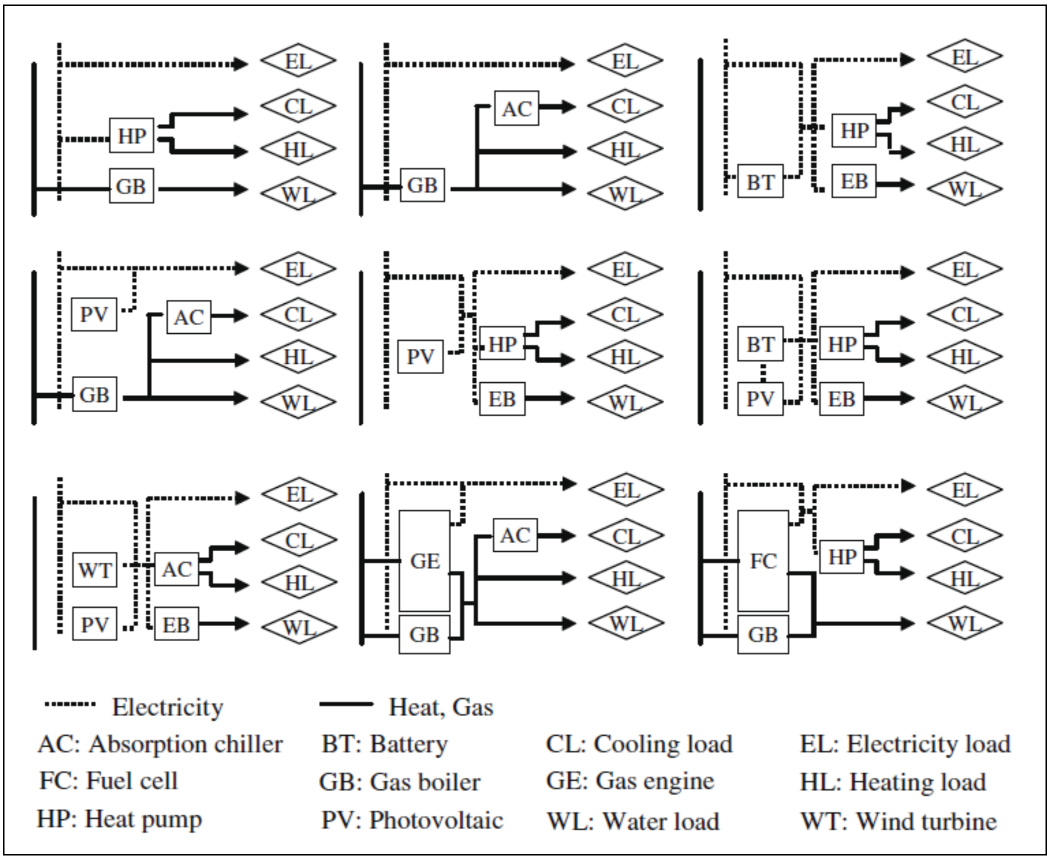

Figure 2.16 Several layouts including different technologies presented in Ren et al 2010

Lozano et al 2010 uses a MIP model of a trigeneration system (figure 2.17) providing energy services for a set of buildings to evaluate the impact of legal constrainga on the solutions obtained. The objective is the minimization of tha annual costs and the legal constrains considered are minimum equivalent electrical efficiency and the minimum electrical self consumption.

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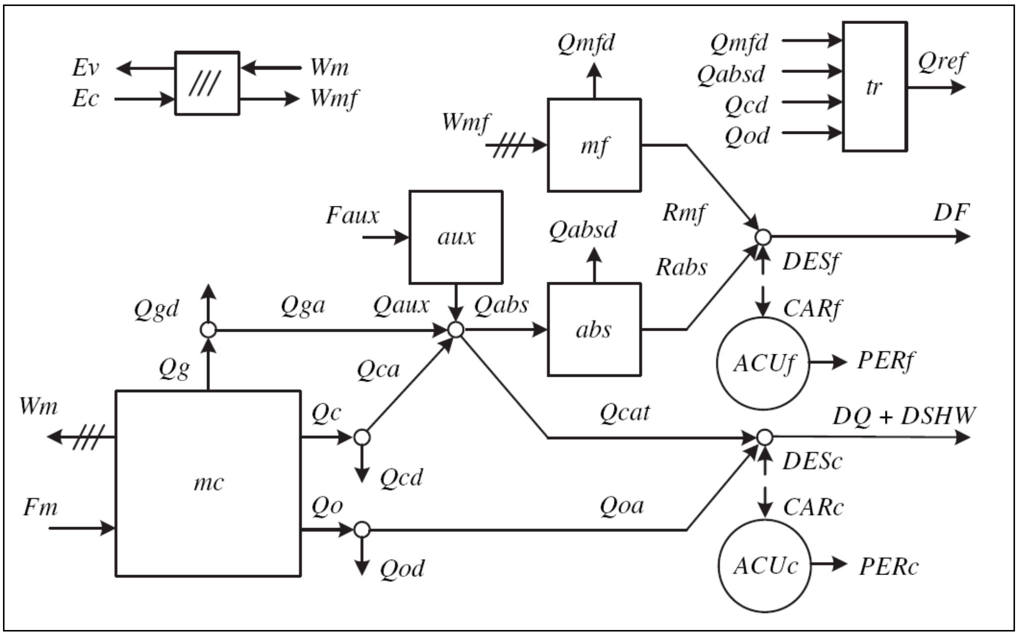

Figure 2.17 Superestructure of the trigeneration system optimised in Lozano et al 2010

2.5.3 Mixed integer non linear programming models

Regarding to MINLP problems, Bruno et al 1998 proposes a model for the design and operation of utility plants, for a given electrical, mechanical and heating demands of industrial processes, based in a superstructure where all major conventional utility plant equipment are included.

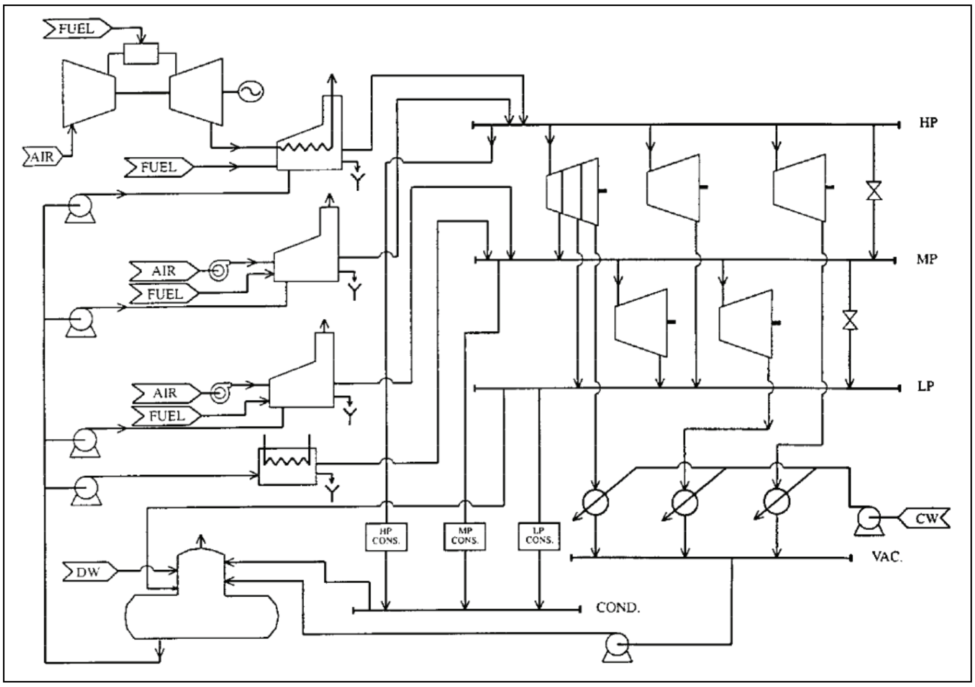

Figure 2.18 Superestructure of the utility plant presented in Bruno et al 1998

Savola et al 2007a, 2007b uses a MINLP model for CHP plants (1-20 MW) synthesis and operation composed of steam turbines. Ren et al 2008 present a MINLP for the optimal design of cogeneration systems for residential applications, minimizing the annual cost of the system for a given customer.

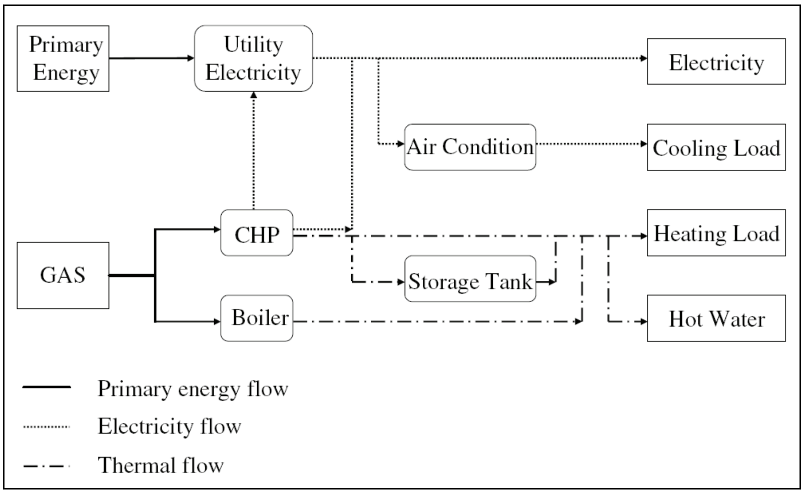

Figure 2.19 Cogeneration system implemented in Ren et al 2008

Beihong et al 2006 presents a MINLP for the optimal sizing of cogeneration plants minimizing the annual costs and considering the energy demand and operational strategies, reporting an example of application in a hospital.

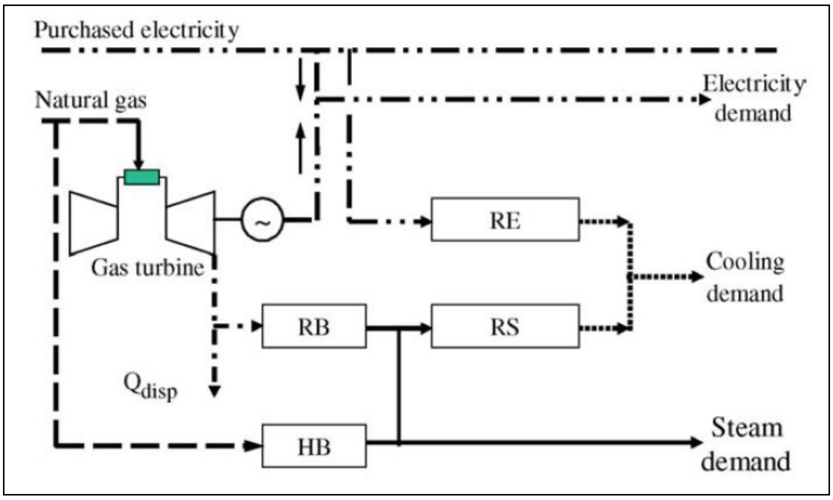

Figure 2.20 Energy supply system with gas turbine in Beihong et al 2006

Li et al 2006 present a MINLP model solved using genetic algorithms of a polygeneration system in an urban residential area maximizing the net present value. The model optimises a superstructure where several predefined cogeneration and cooling technologies are included.

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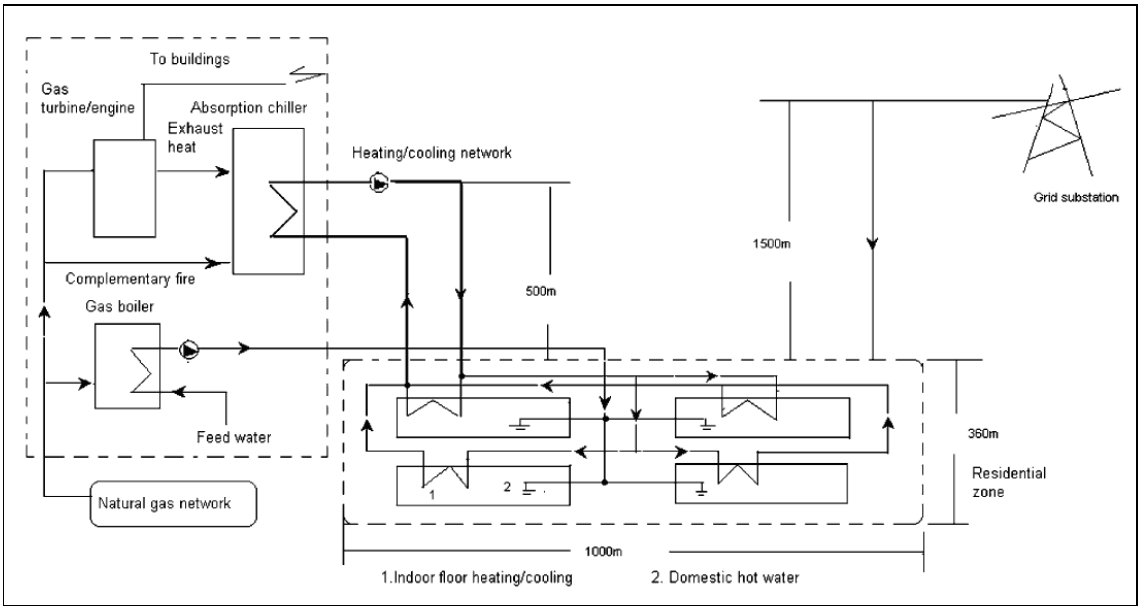

Figure 2.21 Superestructure of the energy supply system and building cluster in Li et al 2006

Verda et al 2005 present three models for the optimisation of a DH network applied to an area in the west part of Turin. The model accounts for the investment and operational costs of the network which is represented in the form of a tree. Figure 2.22 shows the network when all the possible users are connected. Each point of the network corresponds to a group of users that have been joined to simplify the model. The first model proposed is a deterministic approach while the two others are probabilistic approach derived from the simulated annealing technique. This model finds the best configuration for the network disconnecting those users that have a higher unit cost for the heat delivered for that user.

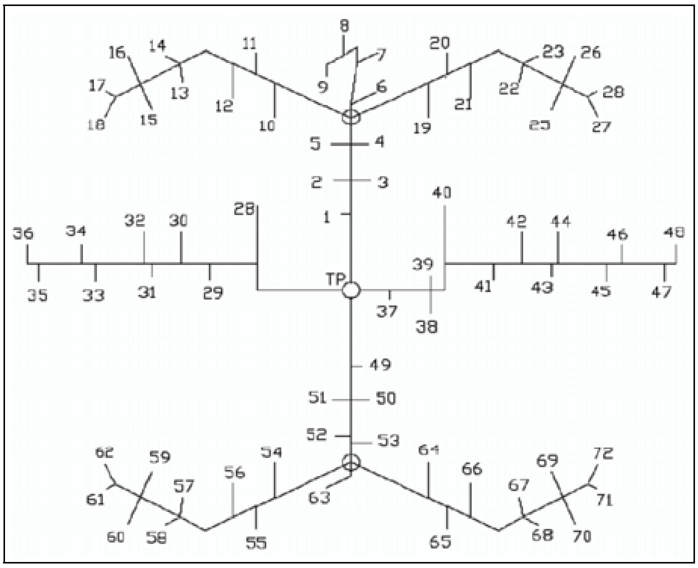

Figure 2.22 Network sketch presented in Verda et al 2005

2.6 Multi-objective optimisation

Optimisation deals with the problem to find the best system configuration and operation through the evaluation of an objective function to test the fitness of the solution with constraints of different nature (design limitations, minimum and maximum operational conditions, etc.). Instead of one scalar objective function, usually several conflicting and non-comparable criteria appear in optimisation problems. The most common is economical criteria, but others like emissions of contaminants (environmental criteria), product quality, safety or flexibility have been considered. Sometimes sensitivity analysis can be used to test the effect of different factors over the final solution, but only local information around the optimal solution is obtained, multi-criteria optimisation can be viewed as systematic overall sensitivity analysis. The single criteria optimisation is necessary, thus multi-criteria solutions are usually generated by solving a parameterized single criteria problem several times. As a result, not only an optimal solution is found, but a set of optimal solutions, in the sense that no one is better than any other in the domain when compared on all criteria, is found. These solutions are non-dominating points called Pareto optimal set or Pareto domain. The comparison and classification of the alternative solutions is made through the experience and knowledge of decision maker's. If the objectives are not conflicting, the problem converges to one solution, not to a Pareto domain.

The more extended techniques to treat multi-criteria problems are the combination of all the criteria factors into a scalar objective function (weighting method) or choose one of the criteria as the objective function and transform the other into constraints. In the first case, a normalization of all the parameters (usually with different units) and the inclusion of weighting factors (one for each parameter) are used to compensate the relative importance between them. The problem gives raise in the selection of the weighting factors. By selecting the weighting factors, the optimal solution of the problem is fixed, even if this solution is not yet known. The key issue is to find good values for weighting factors and no systematic way is available when a scalar objective function is used. Something similar happens with the second approach, where some criteria are converted into restrictions. The selection of the limits of the constraints determines the solution of the problem, and their chose can be one of the most important decisions in the design process. Adaptations of these methods can be applied to try to obtain the entire Pareto domain, for instance, in the weighting method, the values of the weighting factors can be varied and each scalar problem can be solved for each fixed parameters, the problem arise when the model is non-convex, in this situation the entire Pareto domain can not be generated (Messac et al 2001). Similarly, for the constrained method, the problem can be solved varying the constraint values, Pareto domain can be generated even for non-convex problems but at high time computational cost. Other drawbacks of these techniques are described in Whitney, where three algorithms for generating the Pareto domain, are compared in their application to a chemical process and the design of a controller. Other multi objective optimisation techniques have been proposed like the Normalized Normal Contraint method (Messac et al 2003, Martínez et al 2007). A review of more techniques applied in multi-criteria problems can be found in Pohekar et al 2004.

In Pilavatchi et al 2006 a multi-criteria analysis of 16 CHP systems (ICE, Gas turbines, Steam turbines and Combined cycles) is performed using weighting factors and applied to seven cases to determine the best option. A similar procedure is used in Afgan et al 2002 to compare several types of power plants. Multi-objective optimisation applied to trigeneration or polygeneration systems, minimizing energy costs and CO_2 emissions can be found in Rong et al 2005 using linear programming models

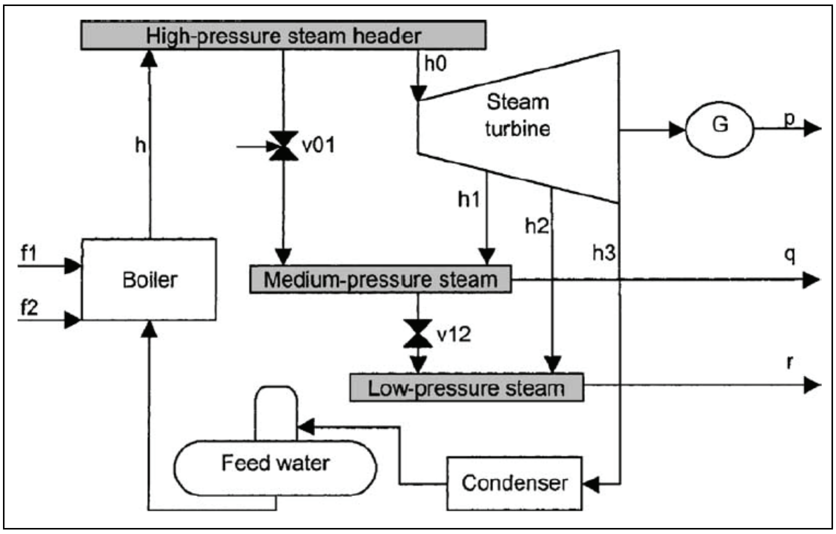

Figure 2.23 Generic steam turbine plant considered in Rong et al 2005

Burer et al 2003 presents a multi-objective evolutionary algorithm for the simultaneous optimisation of the design and operation of a distict heating and cooling plant composed of solid oxide fuel cell, gas turbine, compression heat pump, compression chiller, absorption chiller and a gas boiler. Economic and enviornmental criteria are considered in the model (figure 2.24). Weber et al 2006, uses a bi-level optimisation method using evolutionary algorithms in the first level to optimise the design parameters of the polygeneration system, and linear programming models in the second level to optimise the daily operation of the system (figure 2.25, AC1 single-stage absorption chiller, AC2 double-stage absorption chiller, RC Reciprocating chiller, SOFC solid oxide fuel cell).

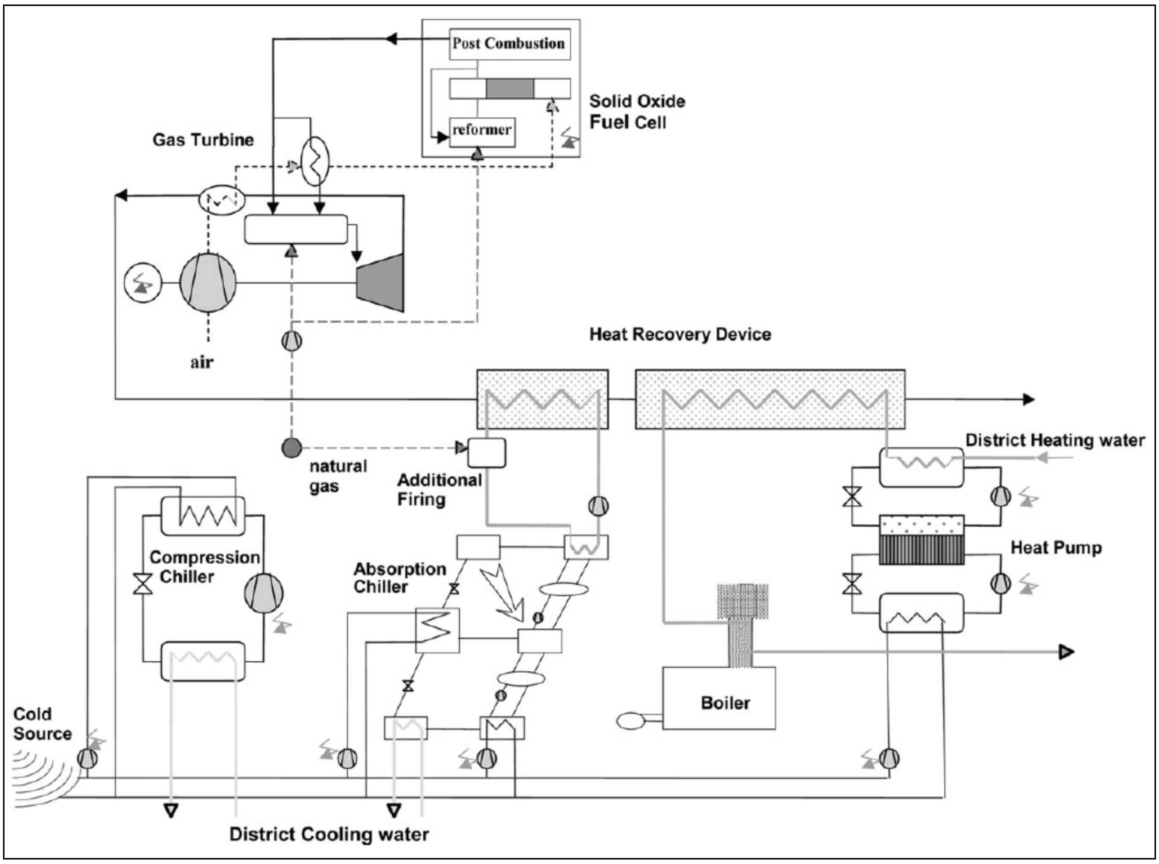

Figure 2.24 Polygeneration system optimised using an evolutionary algorithm in Bürer et al 2003

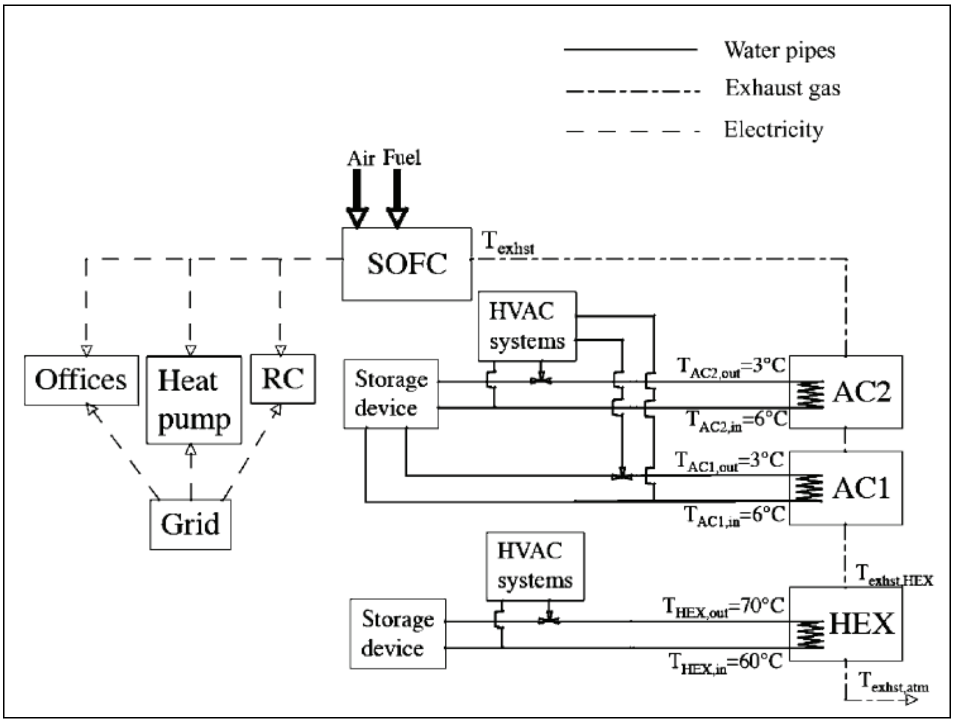

Figure 2.25 Polygeneration system optimised in Weber et al 2006

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Weber et al 2007 presents a decomposition method to optimise MINLP problems related to the design of district energy systems. The multi-objective optimisation problems are decomposed into two sub-problems: a master optimisation problem and a slave optimisation problem. The master optimisation problem is responsible of the selection of the technologies to be used, their design size and the heating and cooling temperatures of the district network. The slave optimisation problem defines the optimal network design and operation from the solutions obtained from the master optimisation problem. The first is a multi-objective optimisation minimizing CO_2 production and total costs, the second is a mono-objective optimisation minimizing the costs.

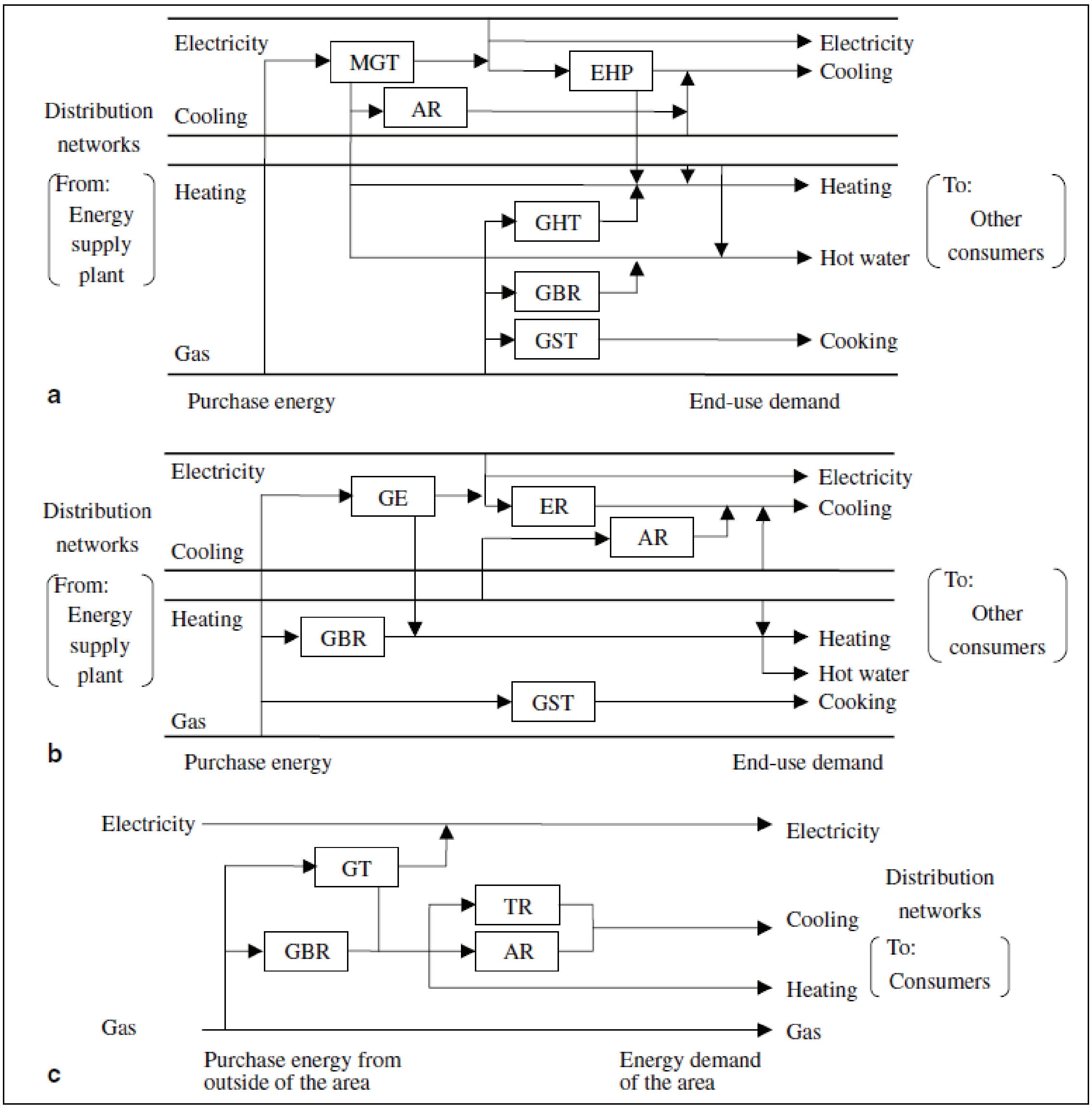

Figure 2.26 System configurations presented in Aki et al 2006, (a) Residential dwellings, (b) Busisness facilities, (c) Energy-supply plant

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Aki et al 2006 (figure 2.26) search for the optimal price of three kinds of energy services for urban areas, taking into account the emissions constraints and the minimization of the annual costs. The equipments considered are the following: AR Absorption refrigerator, EHP Electric heat pump, ER Electric turbo-refrigerator, GBR Gas boiler, GE Gas engine, GHT Gas heater, GST Gas stove, GT Gas turbine, MGT Micro gas turbine and TR Turbo refrigerator.

Kavvadias et al 2010 use a multiobjective model for trigeneration plants considering three objectives indicators: economic, energetic and environmental. The model is solved with genetic algorithms and an example of the model applied to a hospital is presented. Figure 2.27 shows the superestructure considered in this multiobjective model. The models are non linear due to the efficiency curves considered and the inclusion of economy of scales on the capital cost calculation.

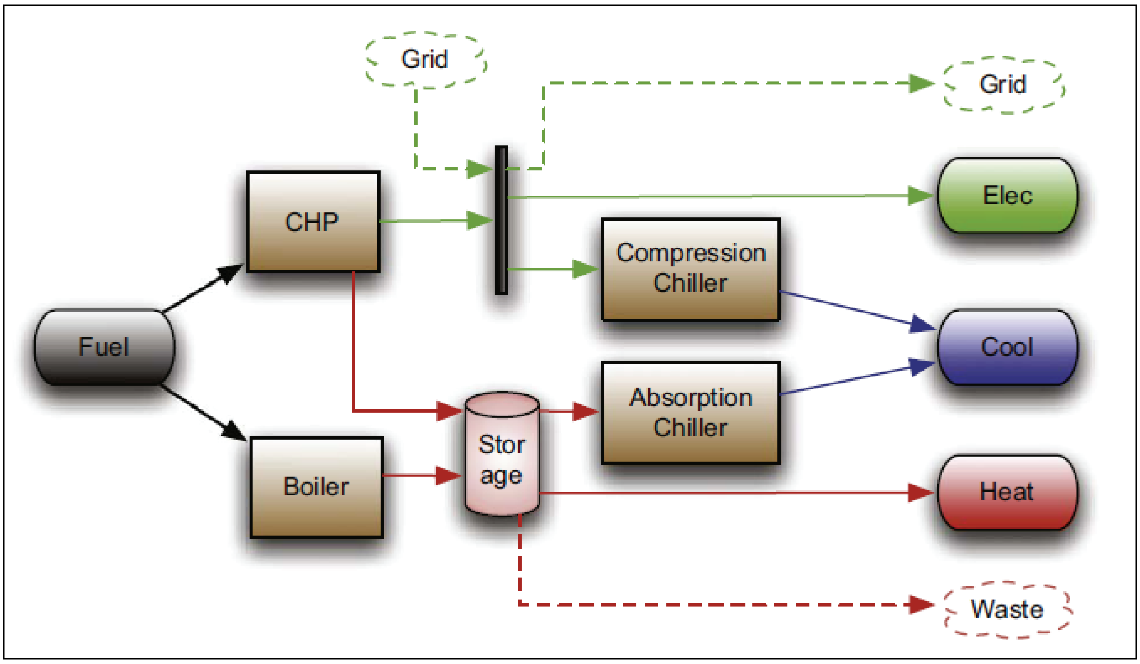

Figure 2.27 Energy flow diagram of the polgyeneration system presented in Kavvadias et al 2010

Examples of adaptations of multi-criteria models are presented in Mavrotas et al 2005, where an enhanced version of a Multi Criteria Branch and Bound (MCBB) algorithm developed by the author (Mavrotas 1998) is described. Genetic Algorithms is another technique that has been widely adapted for multi-criteria problems.

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2.7 Conclusions

The objective of this thesis is the use and development of optimisation models for polygeneration systems. The models will be used to evaluate the viability, to optimally configure and design or to compare polygeneration systems with other alternatives. A model with a high level of detail is not desired because in some cases several years will be analysed (scenario tool). For simulation/optimisation of energy supply system with a high level of detail tools like EnergyPRO, TRNSYS or INSEL can be used. Other tools are focused from regional to international scale, the time step is too big (years) or not all the technologies are represented. In contrast genetic algorithms or mathematical programming offers a high flexibility to develop the models as a function of the case of application or the user. The use of genetic algorithms or mathematical programming is extended in the literature for the optimisation of energy supply systems. The advantage of mathematical programming is that the developer of the models must not care about the algorithm to be used to solve the problem. The use of genetic algorithm usually implies the development also of the genetic algorithm itself, use to solve the model. Recently, genetics algorithms are an extended tool used for the optimal operation schedule of the units. Although GA can deal with any type of problem, without mattering of their nature (convex, non convex, derivable, etc.), special operators or different types of codification and ordering can be required to obtain the desired performance (G.R. Raidl 1998).

Typically, mathematical programming of processes is a nonlinear problem with integer variables, that can be solved to a global optimum with actual solvers; despite that, detailed models or modelling of complex systems (rigorous models, considering a high number of decision variables, with several time periods) can derive to problems that can not be solved, due to the size of the problem, the high number of decision variables or the number of time periods considered. Several alternatives (usually related with reducing the complexity of the problem or reducing the search space) can be applied to deal with these problems:

- Reduce the size and complexity of the problem (reducing the size of the superstructure).
- Dividing the problem into sub-problems.
- Performing a linearization of the model.
- Setting tighter bounds on the variables.
- Combining mathematical programming with experimental design.

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In almost all cases mentioned previously, a simplification of the problem is made. The level of detail of the model and the simplifications depend on the application. As mentioned previously, another difficulty in the modelling of energy system raise when a large number of time periods are considered. Usually, description of the energy demand is divided into time series depending on the available data or for simplification reasons. Several schemes can be considered:

- Multi-period operation as a function of different stages or steps of the production process.
- Models with a representative day or average day for each week, month or season.

Usually, the first case correspond to industrial applications, where energy demand depends on the production and planning process, and tends to be constant for each period considered. The last case corresponds to residential applications, where the key factors are human behaviour and meteorological conditions. For these reasons, in residential applications energy demand, although is not constant, is similar for some periods (day and night, and as a function of the season). The use of typical or average days, even though is a simplification of the model, gives raise to practical models that can be solved and optimised. The optimisation of an annual hourly non-linear model is practically always impossible.

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Chapter 3

Characterisation of the energy demand

3.1 Introduction

The energy demand data are inputs in all the cases analysed in this thesis and are a decisive factor in the economic and environment evaluation of energy supply systems. The main characteristic of the energy demand in the residential and tertiary sector is the high variability mainly due to the external ambient conditions and the behaviour of the users. In simulation and optimisation models for tertiary-residential sector hourly models are preferable to include energy storage technologies and consider properly peak production or demand periods, but include all the hours of the year in the model is not a good practice due to the computational expenses. The usual strategy to use hourly demand data in optimisation models is to work just with representative days for the whole year, but there are no guidelines for the selection of these typical days. In this chapter is presented a methodology for selecting typical energy demand days that represent properly the energy demand of the whole year obtained from simulation tools.

Section 3.2 presents a general classification of modelling energy techniques for the residential sector. Using these techniques the energy demand for the whole year can be calculated, the selection of typical days that will be used in the optimisation model can be done following the methodology presented in section 3.3. An example is presented in section 3.3.3: The method for selecting typical days is applied three times to obtain a five-, seven- and ten-days scenario. These three scenarios and the scenario with the original hourly energy demand for the whole year are introduced in an optimisation model that is solved several times to show the influence of the selected days on the solutions. The objective of this example is to show if similar results are obtained using different number of typical days.

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3.2 Estimation of the energy demand for buildings

Energy demand is one of the more important input data of the optimisation models and must be estimated before to use the optimisation model of the energy supply system. The main difference of the residential energy demand respect to other sector is the high variability. The energy demand of other sectors like industry or transportation is more constant due to the nature of the process. A review of modelling energy demand techniques for the residential sector is presented in Swan et al 2009. Two main approaches are identified, top-down and bottom-up models. Top-down models treats the residential sector as and energy sink without distinguish energy consumption due to individual end-uses. Typical input variables for top-down models are macroeconomic indicators (gross domestic product, employment rates, prices), climatic conditions, housing construction-demolition rates, estimates of appliance ownership and number of units in the residential sector. Bottom-up models calculate the energy consumption of individual or group of houses and then extrapolate these results to represent a region or nation, typical input data of these models are the dwelling properties (geometry, envelope fabric) climate properties, indoor temperatures, occupancy schedules and equipment use. For the purpose of this thesis the energy demand for each type of user is required, so top-down models are not suitable and only bottom-up models will be considered.

Bottom-up models are divided in statistical and engineering models. The former rely on historical information and types of regression analysis which are used to attribute dwelling energy consumption to particular end-uses. The last is based on power ratings, use of equipment and systems and/or heat transfer and thermodynamic relationships. Engineering models is the only method that can fully develop the energy consumption of the users without any historical energy consumption information. Simulation tools of this type are TRNSYS, DOE-2, DesignBuilder or EnergyPlus. To use these tools is necessary concise data of the building structure, construction materials, number and behaviour of the inhabitants, climate data, internal loads, schedules of occupation and use of equipments, etc. These tools can be applied to simulate a concrete building to size its energy supply system, or to simulate representative buildings or dwellings for the zone, where the DHC is going to be implemented. The results are the thermal and cooling demand for each time considered (for example, hourly basis, daily, monthly, etc.) or in other cases just the peaks demand to be used as the design demand. A brief description of simulation for the calculation of the energy demand in buildings will be presented as follows.

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TRNSYS is a transient simulation tool with an open modular structure which simulates the electricity, heat and cooling sectors of an energy system. Each component of the energy system is represented by a TYPE (or block) that can be connected to other TYPE to create the energy system. TYPE56 is a standard multi-zone building model which is surrounded by other components that impose boundary conditions to it. These conditions refers to the walls temperatures in contact to the ground, meteorological conditions, radiation calculation for the different orientations of the buildings façades, modifiers for the radiation terms due to the presence of windows overhangs or remote obstacles, etc. Figure 3.1 shows a screenshot of a simulation model using the TYPE 56 (Bruno et al 2006).

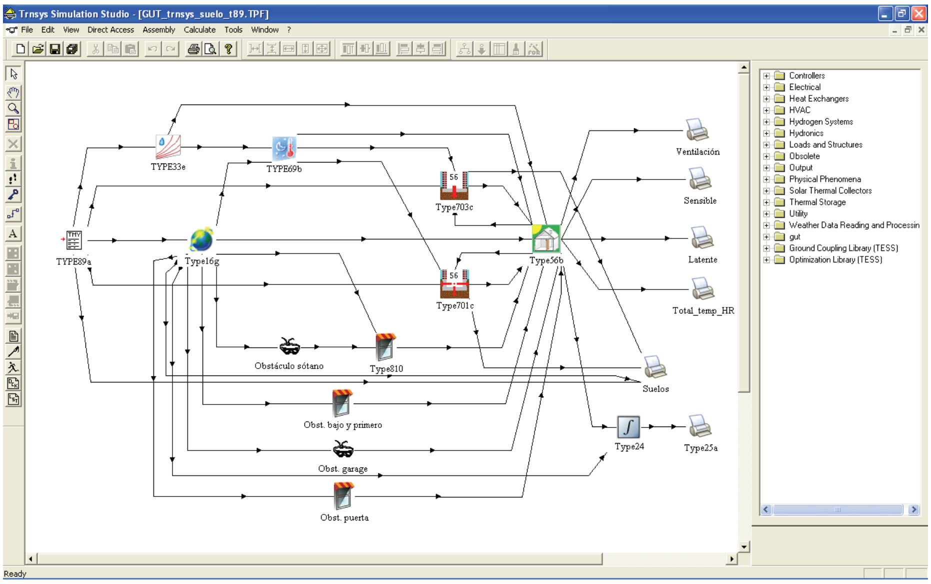

Figure 3.1 TRNSYS simulation for a building using TYPE 56 (Bruno et al 2006)

EnergyPlus (U.S. Department of Energy) is a stand-alone simulation program without an “user friendly” graphical interface specific for the energy demand calculation in buildings. The interaction with the user is through text files, the program reads input and writes output as text files. EnergyPlus models heating, cooling, lighting, ventilating, and other energy flows as well as water in buildings. While originally based on the most popular features and capabilities of BLAST and DOE-2, EnergyPlus includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems. A number of graphical interfaces that use EnergyPlus as the calculation engine are available or under development. One of the most extended interfaces for EnergyPlus is DesignBuilder.

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DesignBuilder is an interface for EnergyPlus, developed to simplify the process of building simulation, allowing a rapid comparison of the function and performance of building designs. DesignBuilder allow to simulate complex buildings rapidly even by non-expert users, building models are assembled by positioning, stretching and cutting blocks in a 3D space, providing visual feedback of actual element thickness and room areas and volumes. DesignBuilder contains several Data templates to load common building constructions, activities, HVAC and lighting systems into the design. Custom templates can be created. A screenshot of DesignBuider is presented in figure 3.2.

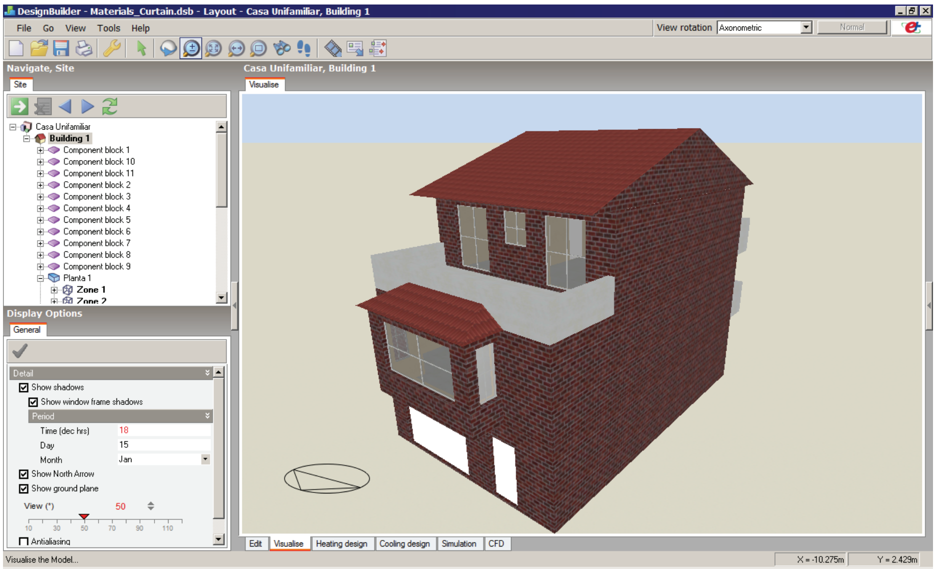

Figure 3.2 Screenshot of DesignBuilder rendering the 3D model of a family house

Another example of bottom-up engineering models can be found in Henning et al 2009. A tool to calculate hourly energy demand is used for the pre-design of solar thermal systems in combination with thermally driven chillers. The energy demand calculation tool is a 2C-3R-model (figure 3.3). The model is defined by two thermal capacitances (one for the air and another for the building thermal mass) linked to each other by a resistance and each of them is linked to the outside air by a resistance. The input data required by the model is the size of the zone, the building thermal mass, desired indoor comfort (minimum and maximum room temperature, maximum relative humidity), schedules, internal loads, ventilation rate and energy standard of the building (expressed as annual heating and cooling load kWh/m^{2}year). The required heating and cooling power is determined for each time step to guarantee the indoor comfort.

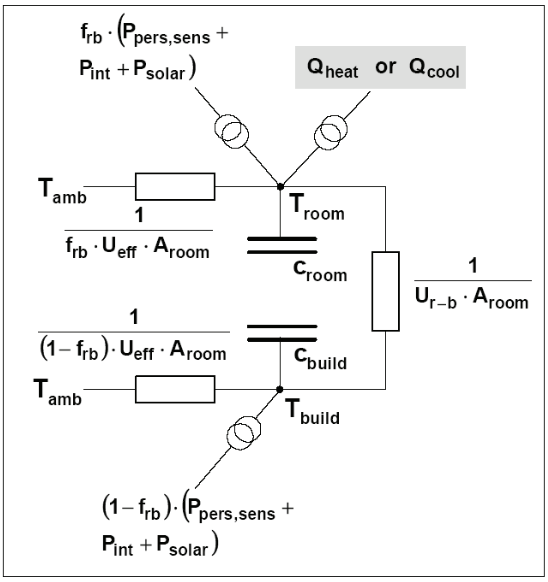

Figure 3.3 Load Generator, Henning et al 2009

3.3 Selection of typical days for optimisation models

Optimisation models are quite commonly used to optimally configure and design cogeneration and trigeneration systems in both the industrial and the tertiary-residential sector. The typical structure of trigeneration systems is presented in figure 3.4. The cogeneration unit (CHP) produces electricity and waste heat simultaneously. The electricity can be sold to the grid or can be used for self-consumption, while the waste heat can be used for heating requirements or to produce chilled water using sorption chillers. Auxiliary units such as a boilers or compression chillers are needed to cover peak demand periods. Optimisation models can be used to optimise the operation of a specific configuration with fixed nominal capacities for each unit, or in other cases, to simultaneously optimise both configuration (type and number of units and nominal capacities) and operation (energy produced and costs). Table 3.1 summarises the main factors that can be considered in optimisation models.

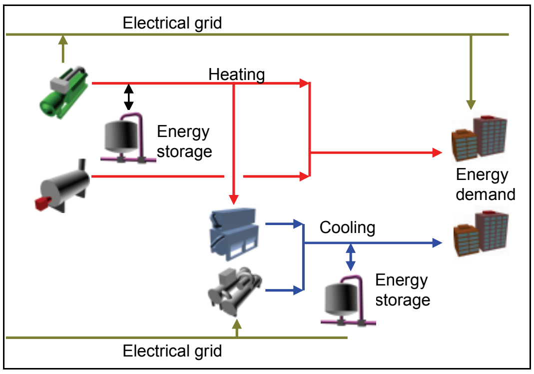

Figure 3.4 Schema of a trigeneration system

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Table 3.1 Main parameters to be considered in the optimisation of a trigeneration system

Investment cost	Unitary price of all the units, depending on installed capacity
Variable costs	Maintenance costs, depending on energy produced Price of the primary energy resources (natural gas, fuel) Price of imported and exported electricity to the grid Price of heating and cooling
Constraints	Annual average efficiency of the system imposed by legislation Minimum partial load of the units Number of start-up periods
Technology	Several types of technologies available, with different investment and maintenance costs; different efficiencies and several possible combinations to create the trigeneration system

Due to the large number of parameters and the possible feasible combinations of units that can be used, optimisation models are very useful in selecting the optimal configuration of a trigeneration system. The more detailed the model, the more complex and difficult it is to solve. One of the main factors that make an optimisation model difficult to solve is the number of periods. These periods are defined by the number of different energy demands that have to be covered, and the periodicity considered in the model (hourly, weekly, monthly). When a high number of time periods must be analysed, the model must be simplified or the number of time periods reduced. For the input of energy demand data into optimisation models, long time periods such as weeks or months can be considered for industrial applications, characterised by quite constant energy demands that are fairly independent of ambient conditions. Hourly energy demand data is very important when residential trigeneration systems are analysed, where the influence of ambient conditions is quite important, and where each type of energy service can be produced with competing technologies, as can be seen for heating and cooling production in figure 3.4. In this last case with hourly data, one alternative is to use only the energy demand of typical days. When the nominal capacity of the units is given, the optimisation models can be used to optimise the operation of the supply system for one typical day (Ashok et al 2003, Chicco et al 2009b). But usually typical days are used to represent certain time periods. For example, three typical days can be used, one for winter, one for midseason and another for summer (Yokoyama et al 2002, Renedo et al 2006). In Chicco et al 2007 load profile patterns for electricity, heating and cooling demand are defined: a one-day profile for winter representing 150 days, a one-day profile for midseason representing 125 days, and one for summer representing 90 days. These patterns reflect the typical seasonal variability for outdoor-temperature-related loads. Twelve typical days can also be used, one representing each month of the year (Beihong et al 2006, Seo et al 2008, Lozano et al 2010). In addition to these twelve days, two more days can be used, one to represent the heating peak-demand day, and the other to represent the cooling peak-demand day (Yoshida et al 2007).

All these hourly data for typical days used in the optimisation models of cogeneration systems are sometimes calculated from measured data, or using building energy demand simulation tools. Although the use of typical days for simulation and optimisation is quite extensively covered in the literature, there are no guidelines to selecting these days, and it is important to verify whether these days correctly represent the energy demand of the whole year, since energy demand has a great influence on the optimal design of the system (Chao-Zhen et al 2008). The influence of the number of typical days selected for the optimisation model has been discussed in Piacentino et al 2007, 2008, where a MILP model has been applied for two specific cases (a hotel and a hospital). Considering the computational resource consumption and the stabilisation of the solutions, the authors propose using between 24 and 30 days to represent the whole year in these two specific cases.

In the following section, a method is proposed for selecting a minimum number of typical days from hourly energy demand data, and several runs for an optimisation model are carried out to show the influence of the selected days on the solutions. As the optimisation model must be simple enough to be able to optimise the whole year, the results obtained and the comparison of the solutions using different numbers of typical days are more important than the level of detail of the model, or the applicability of the solutions.

3.3.1 Method for selecting typical days

The method proposed for selecting typical energy demand days is a graphic method using a tool developed for this purpose. The basic idea of the methodology proposed is to select some days of the year and calculate how many times these days must be repeated (RPF_j) to reproduce the energy demand of the whole year. The RPF_j for each day is calculated creating a Cumulative Energy Demand curve (CED) with the selected days repeated RPF_j times. This reproduced CED curve must be as close as possible to the original CED curve created with the hourly energy demand data for the whole year. One CED curve must be reproduced for each type of energy demand. In this section the methodology is applied to an example that considers heating and cooling demands so one CED curve must be reproduced for heating and another for cooling. As

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all the energy demands are simultaneous (the time basis is the same for all demands) the reproduction of the CED curves is also simultaneous. This means that when a day is selected with simultaneous demand for heating and cooling, this day affects the CED curve reproduced for heating and cooling. Figure shows 3.5 shows a screenshot of the developed tool which allows the creation of different types of plots from an annual hourly energy demand. The tool (TIPDAY) has been developed with Borland Delphi 2006 and has almost 4,000 lines of code. For the energy demand introduced, TIPDAY creates different types of plots, like average energy deman days, maximum energy demand days, CED curves, etc. In the left panel the user can select the typical days and the RPF_j values, the plots are updated as a function of the selected typical days and the repetitions assigned to each of them.

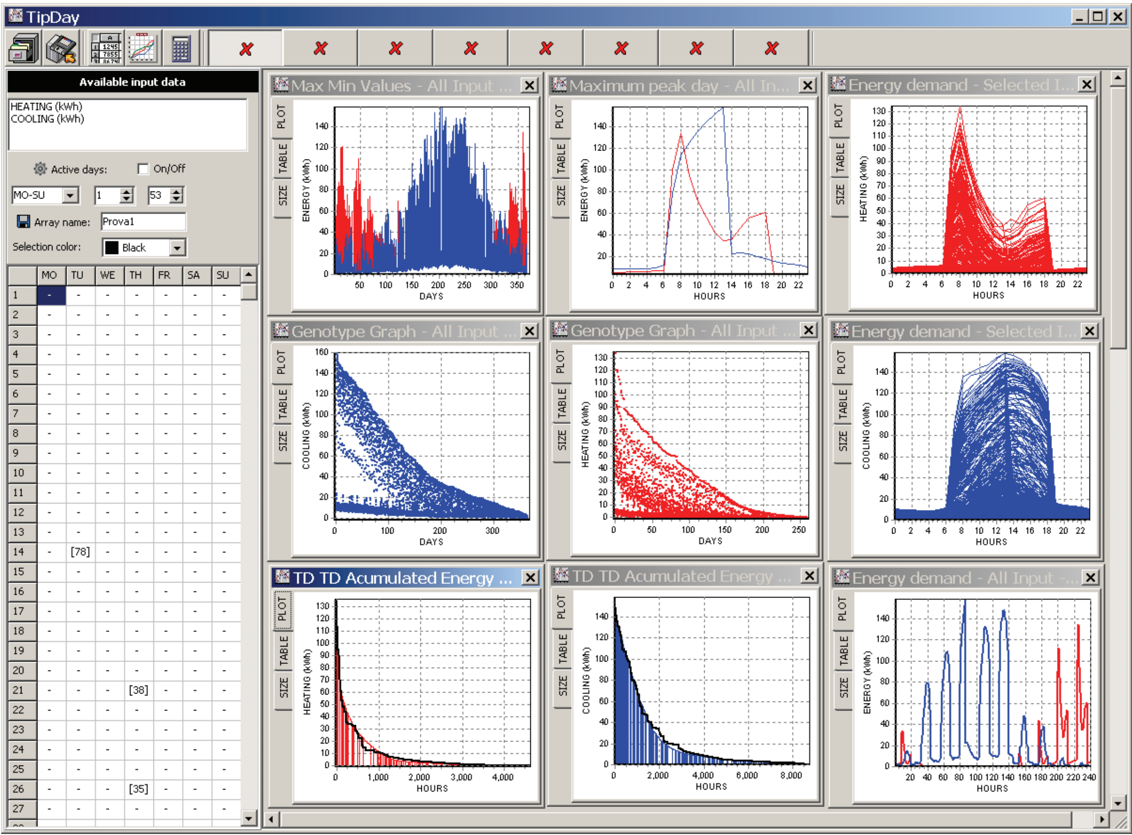

Figure 3.5 Screenshoot of TIPDAY, a tool for guiding the selection of typical energy demand days

The example of hourly energy demand data that will be used in this section to explain the methodology is shown in figure 3.6 for heating and in figure 3.7 for cooling. These energy demand data calculated with TRNSYS have been used in previous works to evaluate the economic viability of a trigeneration system for a building comparing several technological alternatives (Bruno et al 2006).

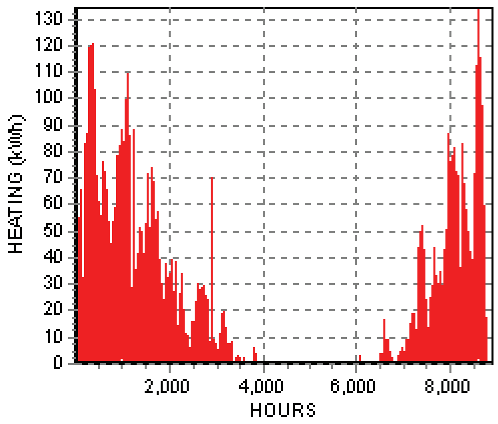

Figure 3.6 Heating data for the whole year

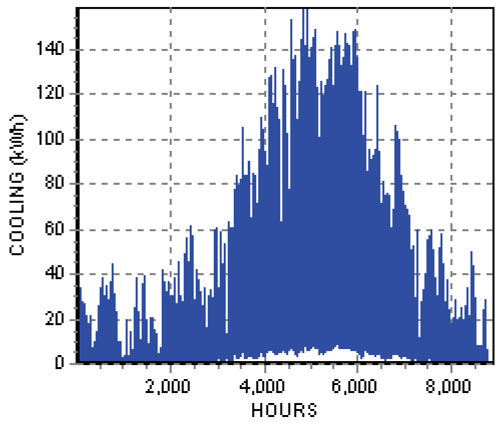

Figure 3.7 Cooling data for the whole year

As the peak demand days are very important because they determine the overall capacity of the trigeneration system (total heating and cooling capacity), it is good practice to include those days as typical days. It must be kept in mind that to determine the optimal capacity of each unit (CHP, boiler, absorption and compression chillers from figure 3.4) an economic or environmental evaluation of the operation for the whole year is also required. Therefore, the first days selected as typical days will be the peak heating day and the peak cooling day. The RPF_j values assigned to these two days will be small compared to the RPF_j values assigned to the other days selected. Two types of days will be selected as typical days:

- Peak demand days, one for each type of energy. The purpose is to assure that the overall capacity of the trigeneration system is correct. The corresponding RPF_j values for these days will be small.

- All the other typical days selected, with higher RPF_j values, will ensure the proper reproduction of the whole energy demand for the correct sizing of each unit of the energy supply system and the calculation of energy balances.

Once the peak demand days are selected, the remaining typical days can be chosen using the Density Demand Plots (DDP) and CED curves. The DDP is a new plot proposed to represent how the energy demand data is distributed and accounts for how the energy demand is discretised. In the DDP (figures 3.8 and 3.9) all the days of the year are represented. For each day, all the energy demand data is plotted only in one dimension, regardless of the hours at which the energy demand takes place. The days are sorted according to the maximum energy demand value for each day. Figure 3.10 shows how a single day is represented in the DDP. Figures 3.11 and 3.12 show the DDP for the first twenty days.

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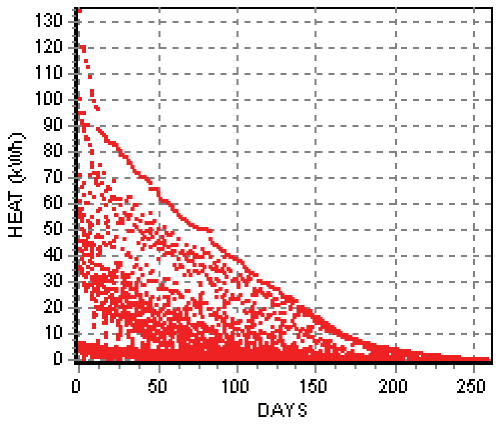

Figure 3.8 DDP for the heating demand

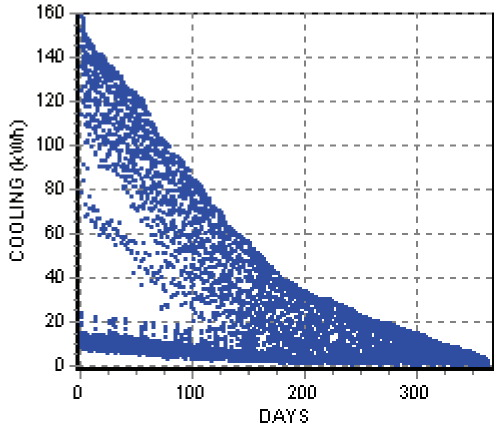

Figure 3.9 DDP for the cooling demand

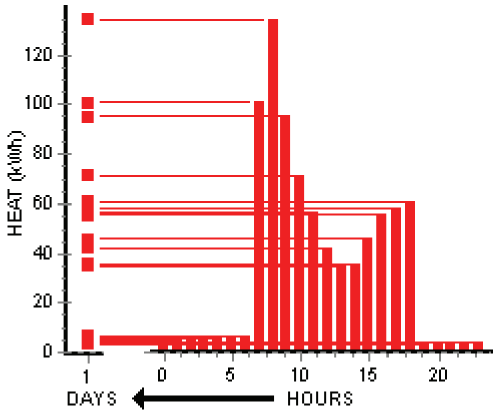

Figure 3.10 Creating the DDP for one day

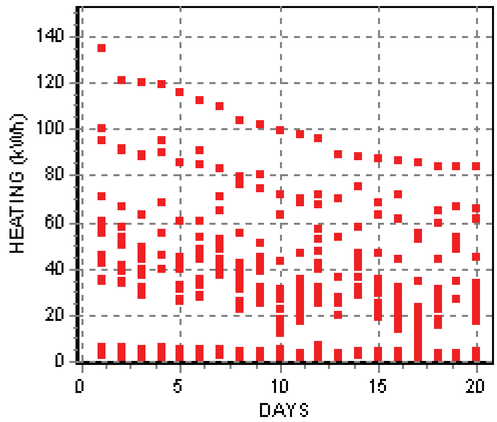

Figure 3.11 DDP for the first twenty days considering the heating demand

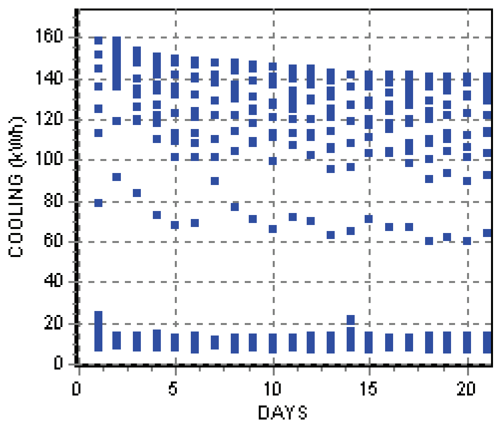

Figure 3.12 DDP for the first twenty days considering the cooling demand

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The empty zones of the DDP, for example, the empty space in figure 3.12 (cooling) between 100 kW and 20 kW, depends of the level of discretisation of the energy demand data. As figure 3.10 (heating) for hourly energy demand data shows, there are great differences between the energy demand of two consecutive hours at some times of day (from hour 6 to 7, and from hour 18 to 19). These differences create the empty zones of the DDP where there is no energy demand data. Each bar of the DDP accounts for how the data is distributed for each day with respect to the energy demand. The steps for selecting the minimum number of typical days are as follows: first, the peak demand days for heating and cooling are selected. In the examples presented here, for the cooling demand, the peak demand day is W29D6 (day 6 in week 29). The vertical lines in figure 3.13 show how the energy demand data of day W29D6 are distributed along the original CED curve (grey line). When an RPF_j value is assigned to W29D6, a reproduced CED curve is obtained by repeating day W29D6 RPF_j times. Figure 3.14 shows the reproduced CED curve (thick line) with respect to the original CED curve (thin line) when 5, 10 and 15 RPF_j are assigned to W29D6.

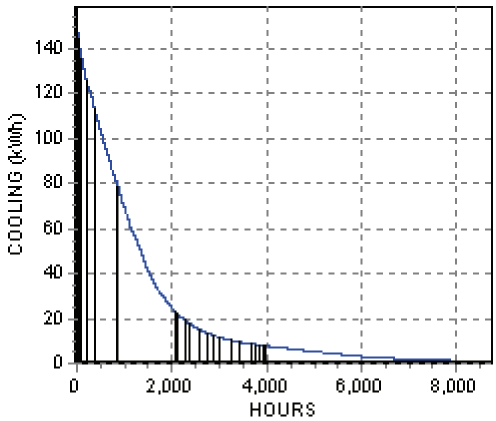

Figure 3.13 W29D6 hours in CED curve

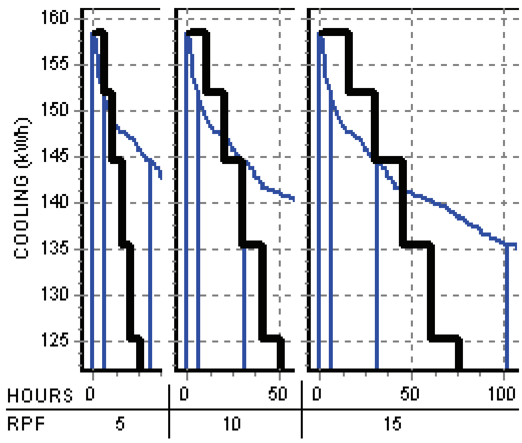

Figure 3.14 RPF of cooling peak day W29D6

The empty zone for the peak cooling day starts at around 120 kW (first day of figure 3.12). The beginning of the empty zone implies that the day's capacity to reproduce the CED curve from this point is very bad because the reproduced CED curve drops suddenly at this point. As shown in figure 3.15, the reproduced CED curve begins to drop suddenly around 120 kW (change in the slope of the thick black lines). But for W29D6 the capacity to reproduce the CED curve is lost earlier, at around 145 kW. From this point, the slope of the original CED flattens out, and the reproduced CED crosses the original CED and cannot follow the original CED curve. The reproduction of the original CED is usually difficult for the first hours because the slope of the original CED changes very quickly. The RPF_j value assigned to the peak days will be low.

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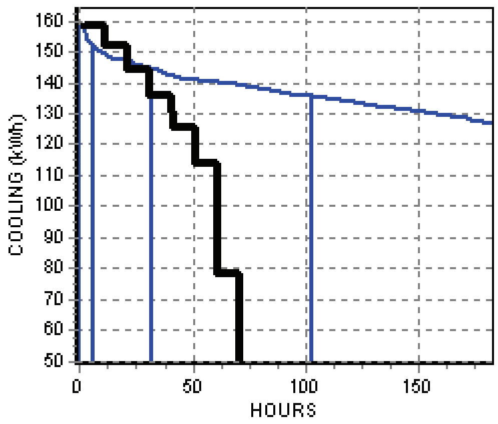

Figure 3.15 Reproduced CED curve for the day W29D6 and value for RPF = 10

As the peak demand day is able to reproduce the CED curve up to approximately 145 kW, the following typical day will be selected from figure 3.16. This figure shows a zoom of the DDP for cooling at around 140 kW (with peak daily values between 145 and 135 kW). Several days selected from this figure will be tested to check their capacity to reproduce the CED curve together with the previous days already selected as typical days. Day W36D4 (figure 3.17) is one of the days from figure 3.16 that best reproduces the CED curve.

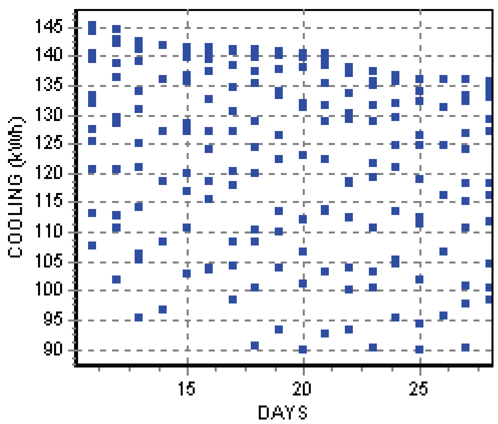

Figure 3.16 Searching for the second typical day for cooling using the DDP

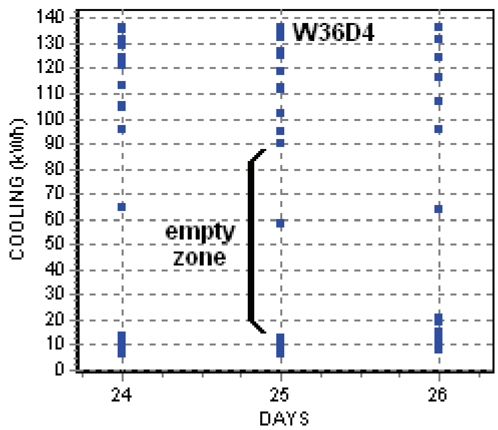

Figure 3.17 Second typical day selected using the DDP, marked the empty zone

Figure 3.18 shows the reproduced CED curve including the peak demand day (W29D6) and the best day (W36D4) taken from figure 3.16 for the second typical day. The empty zone for W36D4 starts at around 90 kW, and the RPF value assigned to W36D4 is the value that adjusts the “useful” section of that day (from the peak value to 90 kW) to the original CED curve.

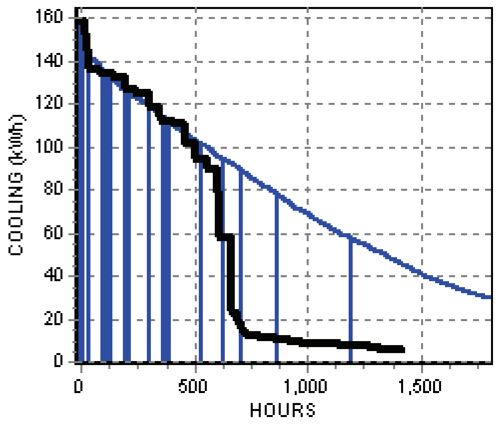

Figure 3.18 Reproducing the CED curve [W29D6, RPF=10] + [W36D4, RPF=49]

The beginning of the empty zone for day W36D4 indicates approximately up to which value W36D4 can reproduce the CED curve. Another typical day must be selected starting from this point. This procedure is repeated until the original CED curve is reproduced using the selected typical days and their corresponding RPF values for each day. Figures 3.19 and 3.20 summarize this procedure. First the peak demand days are selected for heating and cooling, and by assigning an RPF value, the level up to which energy demand value can reproduce the CED curve (horizontal lines) is checked. A zoom (boxes in figures 3.19 and 3.20) is made in the DDP curves around the value previously found, in order to look for the next typical day.

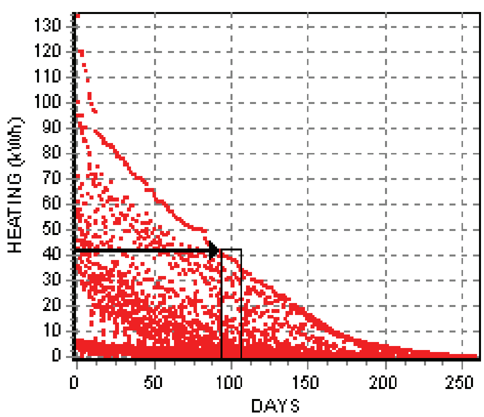

Figure 3.19 Minimum number of days selected. Heating = peak day + one day

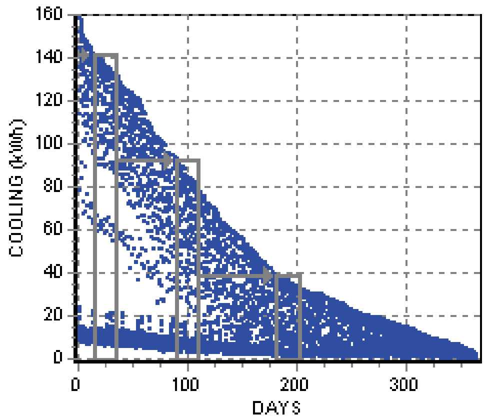

Figure 3.20 Minimum number of days selected. Cooling = peak day + three days

Figures 3.21 and 3.22 show the DDP of the typical days selected using the method proposed in this chapter. Day 1 for heating is the same day as day 5 for cooling, and day 2 for heating is the same day as day 4 for cooling. A total of five days for cooling have been selected (the scenario

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with the minimum number of typical days). The profiles of the typical days selected are presented in figure 3.23, with the days plotted in the same order as they are presented in table 3.2. The dark line is heating demand and the lighter line cooling demand. The vertical black lines separate each day. Although in figure 3.23 the typical days are plotted side by side, in the optimisation model there is no temporal relationship between each typical day.

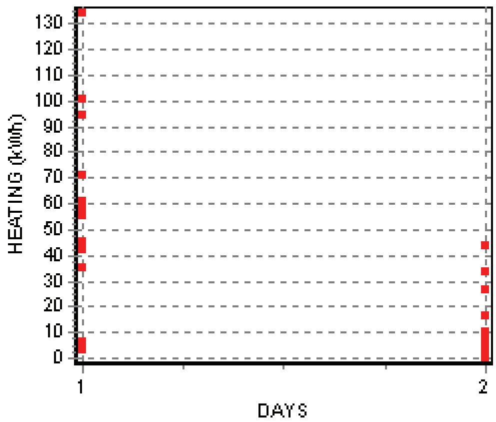

Figure 3.21 Selected typical heating days

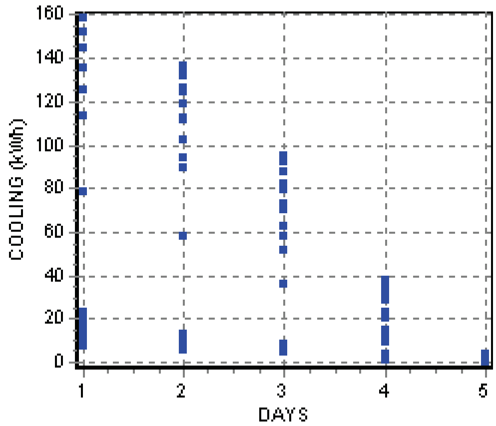

Figure 3.22 Selected typical cooling days

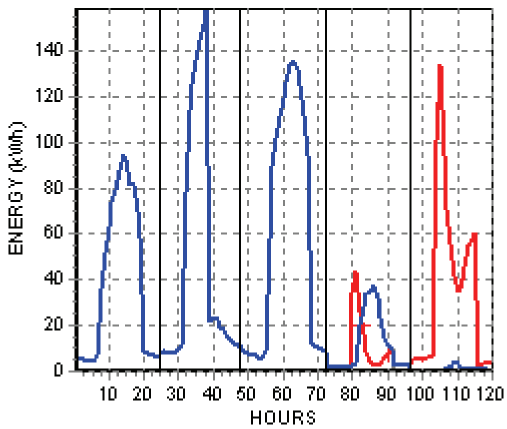

Figure 3.23 Profiles for heating and cooling of the selected typical days

Table 3.2 Selection of typical days and RPF values

Scenario	Day	RPF
	W24D2	58
	W29D6	10
5 days	W36D4	49
	W46D4	156
	W52D2	16

Figures 3.24 and 3.25 present the reproduced CED curve (thick line) compared to the original CED curve (thin line). The vertical lines represent how the energy demand values of all the typical days are distributed along the CED curve.

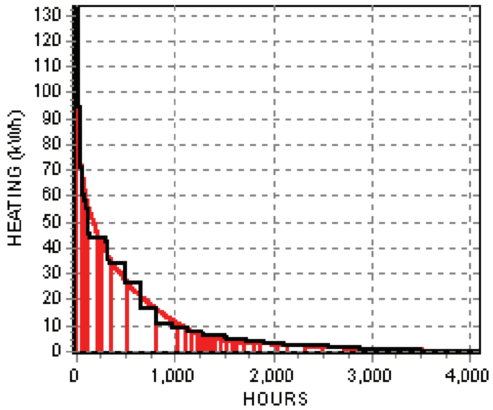

Figure 3.24 Heating reproduced CED

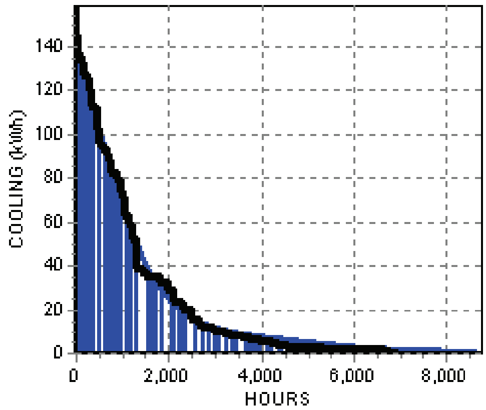

Figure 3.25 Cooling reproduced CED

Figures 3.19 and 3.20 can also be used to find a priori the approximate minimum number of typical days that must be selected, creating the stairs from the peak values of a group of days to the beginning of the empty zone of that group. The meaning of figures 3.19 and 3.20 is that the empty zones of a typical day, where there is no energy demand, must be "filled" with the following typical day selected. The empty zones and peak values determine the minimum number of typical days. The greater the peak value and empty zone, the more typical days are required. Figures 3.19 and 3.20 show that two hourly daily profiles (peak day + 1 day) for heating demand and four hourly daily profiles (peak day + 3 days) for cooling demand are required to represent approximately the whole year.

This graphic method can be applied to the demand for a whole year or in general to any energy demand during a certain period. It can also be used to characterise hourly data from other energy sources, such as solar irradiation (if solar collectors are included in the model). An example of application will be presented in the case study in Chapter 6 to characterize the heating, sensible and latent cooling, ambient dry and wet temperature and ambient humidity.

In the selection of typical days it is not necessary to make any distinction between different types of days, like working or non-working days, but these types of distinction could be necessary for other reasons, like differences in the tariff prices. In that case, other criteria in the selection of typical day could be more convenient, for example one representative day for each month.

3.3.2 Trigeneration system using typical days

A basic trigeneration system is presented in this section to apply the methodology discussed in section 3.3 for the selection of typical days for energy demand. The goal of this section is to check the differences obtained in the results of the optimisation model when only some typical days are considered instead of the energy demand of the whole year. Three scenarios with different numbers of typical days have been created to calculate the effect of using more typical days on the optimal solution. Table 3.3 shows the days selected for each scenario and the RPF values. These typical days and the RPF values will be used in the optimisation model to compare the results with respect to the scenario in which demand data from the entire year is used.

Table 3.3 Selection of typical days and RPF values

Scenario	Day	RPF
5 days	W24D2	58
	W29D6	10
	W36D4	49
	W46D4	156
	W52D2	16
7 days	W11D6	179
	W26D1	46
	W29D6	4
	W34D1	13
	W37D4	65
	W50D2	47
	W52D2	4
10 days	W14D2	78
	W21D4	38
	W26D4	35
	W29D6	4
	W33D3	29
	W34D1	13
	W43D4	113
	W46D4	28
	W52D1	16
	W52D2	7

Figures 3.26, 3.28 and 3.30 show the reproduced CED curve for the heating demand for the scenarios with five, seven and ten typical days, respectively. In all the cases, the vertical lines represent how the energy demand of the selected typical days is distributed in the CED curve. The thickest lines are the reproduced CED curve, and the thinnest are the original CED curve. Figures 3.27, 3.29 and 3.31 show the reproduced CED curve for the cooling demand using five, seven and ten typical days. The energy demand scenarios that will be compared are listed below:

- Entire year demand, 8,760 hour values for heating and 8,760 hour values for cooling.
- Five-day demand, with 120 hour values for heating and 120 hour values for cooling.
- Seven-day demand, with 168 hour values for heating and 168 hour values for cooling.
- Ten-day demand, with 240 hour values for heating and 240 hour values for cooling.

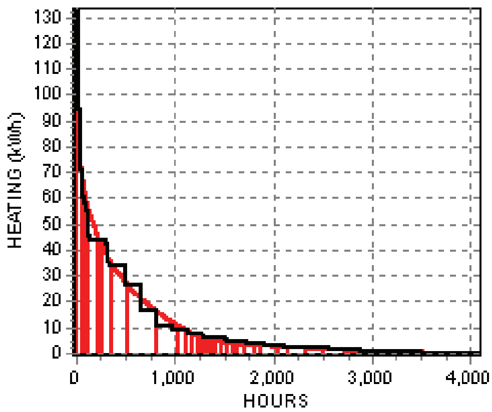

Figure 3.26 Reproduced CED curve for heating using five typical days

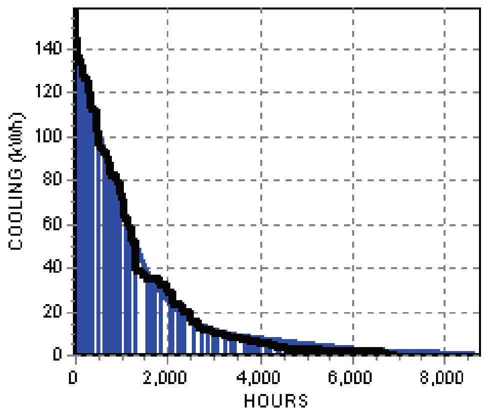

Figure 3.27 Reproduced CED curve for cooling using five typical days

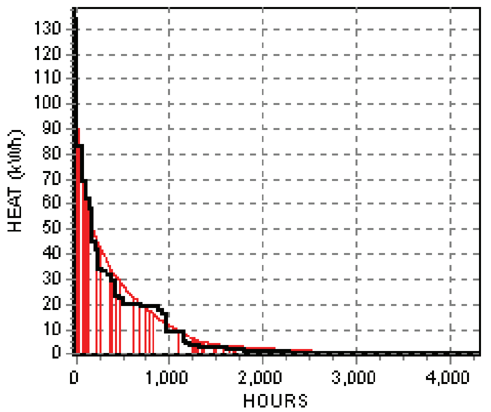

Figure 3.28 Reproduced CED curve for heating using seven typical days

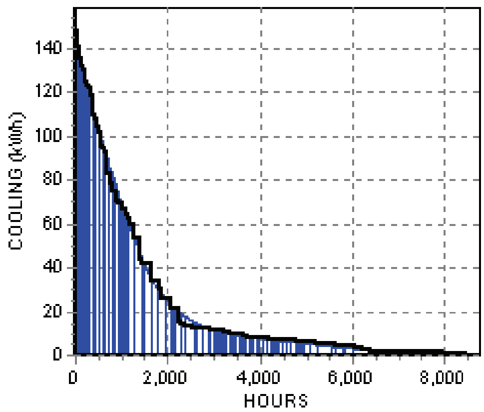

Figure 3.29 Reproduced CED curve for cooling using seven typical days

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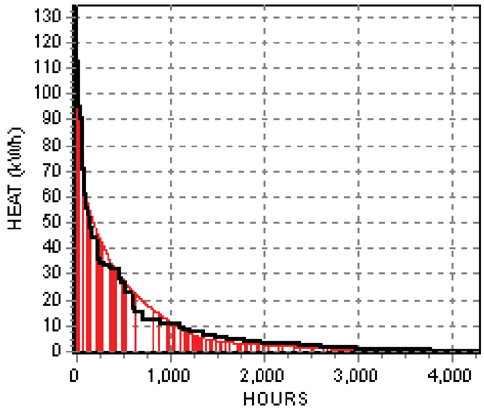

Figure 3.30 Reproduced CED curve for heating using ten typical days

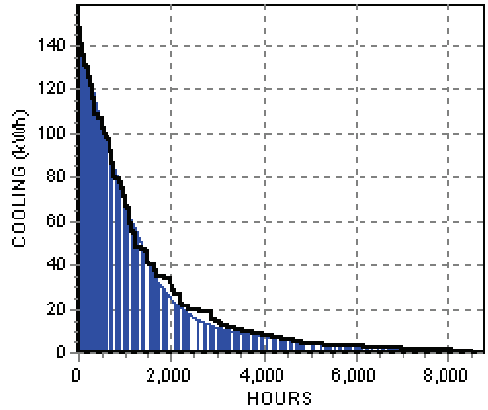

Figure 3.31 Reproduced CED curve for cooling using ten typical days

Figures 3.32, 3.33 and 3.34 show the hourly energy profiles of the selected days for the five-, seven- and ten-day scenarios, respectively. The vertical lines are shown to separate each day.

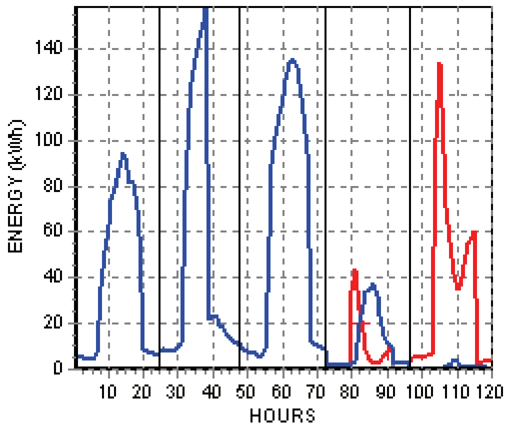

Figure 3.32 Energy demand profiles of the typical days for the 7-day scenario

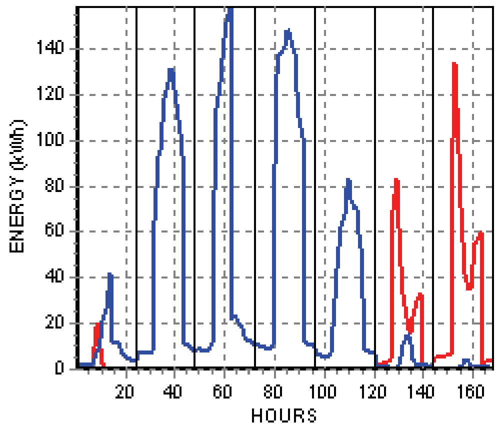

Figure 3.33 Energy demand profiles of the typical days for the 7-day scenario

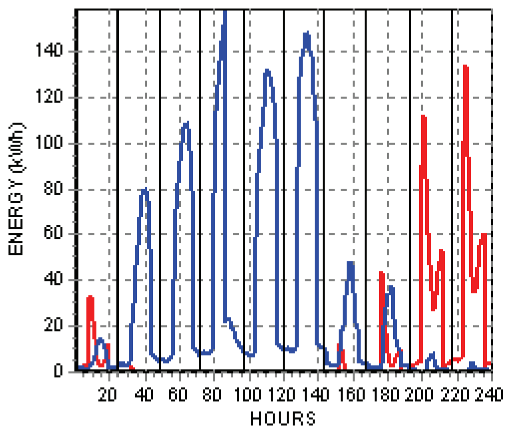

Figure 3.34 Energy demand profiles of the typical days for the 10-day scenario

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3.3.3 Optimisation model for the trigeneration plant

A model for a trigeneration plant has been developed that is simple enough to be able to optimise a whole year using hourly energy demand data. The model has been implemented using the optimisation environment developed in this thesis (Chapter 5) and solved with GAMS. The structure of the trigeneration system is shown in figure 3.35. The main units of the trigeneration system shown in this figure are the following:

- "CHP unit": produces electrical energy and heating
- "Boiler1": an auxiliary boiler to produce heating
- "Abs1": an absorption chiller to produce cooling
- "Comp1": a compression chiller to produce cooling
- "H storage": an energy storage unit for heating
- "C storage": an energy storage unit for cooling
- "H Cons.": consumption for heating
- "C Cons.": consumption for cooling
- "Natural Gas": consumption of natural gas for the cogeneration unit and the boiler
- "GridIn": purchase of electricity for the compression chiller
- "Gridout": exported electricity produced by the cogeneration unit

At the top left of the diagram in figure 3.35 there are some blocks inside two shaded boxes, S1 and S2. S1 are used to control the ON/OFF status of the cogeneration unit and to prevent the CHP unit from being ON or OFF for less than two hours. This means that if the CHP unit is ON, it will run for a minimum of three hours, and if it is OFF, it will be OFF for a minimum of three hours. The units inside S2 are used to control the number of start-up periods of the cogeneration unit. A range or a maximum number of start-up periods can be fixed. S2 can also be used to calculate the total number of start-up periods without adding any other constraint. The energy flows between units are represented by arrows with a small box with a number inside. These numbers identify the energy flows. The electrical demand of the building is not considered and all the electricity produced is sold to the grid. The heat produced by the cogeneration unit can be used for heating or to produce cooling using an absorption chiller. The electricity required by the compression chiller is purchased from the grid. The main energy flows identified in figure 3.35 are listed in table 3.4.

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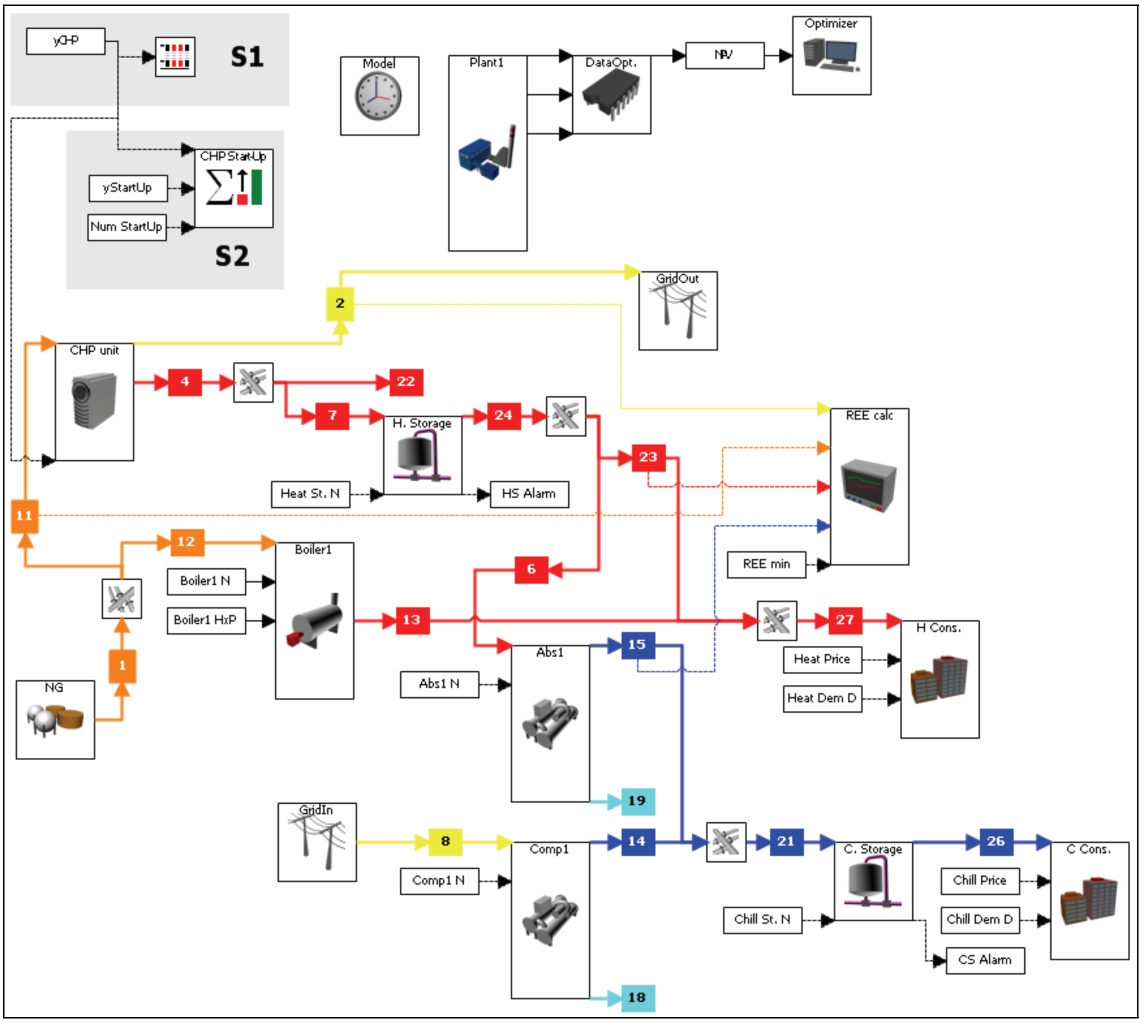

Figure 3.35 Block diagram of the trigeneration supply system considered with several typical days

Table 3.4 Identification of the main energy flows in figure 3.35

Electricity	2, 8
Heating	4, 6, 7, 13, 22, 23, 24, 27
Cooling	14, 15, 21, 26
Fuel	1, 11, 12

Several cases have been analysed to compare the influence of the selection of typical days on whole-year optimisation, where all the hours of the entire year are considered. In this case, the level of detail of the model is limited by the fact that the model must be simple enough to be solved with hourly energy demand data for a whole year. The cases analysed with the main assumptions considered are listed in table 3.5. For all the runs, the objective function is the maximization of the Net Present Value (NPV).

Table 3.5 Optimisation cases considered in the example

Case	Description	Type of model
A.1	S1 not used S2 not used Max $N_{hst} = 30$ $N_{cst} = 0$ $H_{22,j}=0$	LP
A.2	S1 not used S2 not used Max $N_{hst} = 30$ Max $N_{cst} = 30$ $H_{22,j}=0$	LP
B.1	S1 not used S2 not used Max $N_{hst} = 30$ $N_{cst} = 0$ $H_{22,j}>0$	LP
B.2	S1 not used S2 not used Max $N_{hst} = 30$ Max $N_{cst} = 30$ $H_{22,j}>0$	LP
C.1	S1 used S2 not used Max $N_{hst} = 30$ $N_{cst} = 0$ $H_{22,j}>0$ CHP min load = 30%	MILP
D.1	S1 used S2 used Max $N_{hst} = 30$ $N_{cst} = 0$ $H_{22,j}>0$ CHP min load = 30% Max StartUp = 450	MILP

Cases A.# and B.# are linear models, cases C.# and D.# are mixed integer linear models. Due to the computational time required to solve a whole-year optimisation model, the model cannot be too rigorous. In the #.1 models the capacity (kW) of cooling storage is fixed at zero and only heating storage is used. In the #.2 models, both heating and cooling energy storage are used. For

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all the runs the nominal capacity of the energy storage systems are restricted to a maximum value of 30 kW. This maximum value has been set to ensure that the energy storage in the whole-year model will not be used to accumulate energy for more than one day (daily charge-discharge). To compare a whole-year optimisation with an optimisation using typical days, daily charge-discharge periods must be used, because when typical days are used there is no temporal relationship between each day and the next.

"$H_{22,j} = 0$" means that the value of heating flow 22 is defined as a parameter with a fixed value (zero), and all the heat from the cogeneration unit must be used. In "$H_{22,j} > 0$" flow 22 is defined as a positive variable and heat from the CHP can be dissipated while the minimum "Equivalent Electrical Efficiency" (REE) required by law is fulfilled. The minimum REE value for cogeneration systems in Spain is imposed by law (Royal Decree 661/2007). This is a legal minimum efficiency required for all CHP systems connected to, exporting and buying electricity from the public grid. The minimum EEE used in this study is 55%, although a lower value can be used when the capacity is less than 1 MW. The equations of the models are presented below.

Electrical and heating production

$$F_{1,j} = F_{11,j} + F_{12,j} \tag{3.1}$$

$$E_{2,j} = F_{11,j} \cdot \eta e_{CHP} \tag{3.2}$$

$$H_{4,j} = F_{11,j} \cdot \eta t_{CHP} \tag{3.3}$$

$$H_{13,j} = F_{12,j} \cdot \eta t_{boil} \tag{3.4}$$

Heating energy balances

$$H_{4,j} = H_{22,j} + H_{7,j} \tag{3.5}$$

$$H_{23,j} + H_{6,j} = H_{24,j} \tag{3.6}$$

Cooling energy balances

$$C_{15,j} = H_{6,j} \cdot COP_{abs} \tag{3.7}$$

$$C_{14,j} = E_{8,j} \cdot COP_{comp} \tag{3.8}$$

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$$C_{15,j} + C_{14,j} = C_{21,j} \tag{3.9}$$

$$C_{26,j} = C_{17,j} + C_{20,j} \tag{3.10}$$

Energy storage

$$H_{7,j} = H_{InHS,j} + H_{BypassHS,j} \tag{3.11}$$

$$H_{24,j} = H_{OutHS,j} + H_{BypassHS,j} \tag{3.12}$$

$$L_{hst,j} = L_{hst,j-1} + H_{InHS,j} - H_{OutHS,j} \tag{3.13}$$

$$C_{21,j} = H_{InCS,j} + H_{BypassCS,j} \tag{3.14}$$

$$C_{26,j} = H_{OutCS,j} + H_{BypassCS,j} \tag{3.15}$$

$$L_{cst,j} = L_{cst,j-1} + H_{InCS,j} - H_{OutCS,j} \tag{3.16}$$

Nominal capacities

$$N_{CHP} \cdot HxP_j \geq E_{2,j} \tag{3.17}$$

$$N_{boil} \cdot HxP_j \geq H_{13,j} \tag{3.18}$$

$$N_{abs} \cdot HxP_j \geq C_{15,j} \tag{3.19}$$

$$N_{comp} \cdot HxP_j \geq C_{14,j} \tag{3.20}$$

$$N_{hst} \cdot HxP_j \geq L_{hst,j} \tag{3.21}$$

$$N_{hst} \cdot HxP_j \geq H_{25,j} \tag{3.22}$$

$$N_{cst} \cdot HxP_j \geq L_{cst,j} \tag{3.23}$$

$$N_{cst} \cdot HxP_j \geq C_{21,j} \tag{3.24}$$

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Yearly balances

$$TF_1 = \sum_j F_{1,j} \cdot RPF_j \qquad (3.25)$$

$$TE_2 = \sum_j E_{2,j} \cdot RPF_j \qquad (3.26)$$

$$TE_8 = \sum_j E_{8,j} \cdot RPF_j \qquad (3.27)$$

$$TH_{22} = \sum_j H_{22,j} \cdot RPF_j \qquad (3.28)$$

$$TH_{27} = \sum_j H_{27,j} \cdot RPF_j \qquad (3.29)$$

$$TC_{14} = \sum_j C_{14,j} \cdot RPF_j \qquad (3.30)$$

$$TC_{15} = \sum_j C_{15,j} \cdot RPF_j \qquad (3.31)$$

$$TC_{26} = \sum_j C_{26,j} \cdot RPF_j \qquad (3.32)$$

$$TTrig = \sum_j (H_{23,j} \cdot RPF_j + C_{15,j} \cdot RPF_j) \qquad (3.33)$$

$$\left(TF_{11} - \frac{TTrig}{0.9} \right) \cdot EEE_{min} \leq TE_2 \qquad (3.34)$$

Economics

$$B_c = TC_{26} \cdot P_c \qquad (3.35)$$

$$B_h = TH_{27} \cdot P_h \qquad (3.36)$$

$$B_{exp} = TE_2 \cdot P_{exp} \qquad (3.37)$$

$$B_{imp} = TE_8 \cdot P_{imp} \qquad (3.38)$$

$$B_{fuel} = TF_1 \cdot P_{fuel} \qquad (3.39)$$

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$$O_{CHP} = TE_2 \cdot UO_{CHP} \tag{3.40}$$

$$O_{boil} = TH_{13} \cdot UO_{boil} \tag{3.41}$$

$$O_{abs} = TC_{15} \cdot UO_{abs} \tag{3.42}$$

$$O_{comp} = TC_{14} \cdot UO_{comp} \tag{3.43}$$

$$I_{CHP} = N_{CHP} \cdot UP_{chp} \tag{3.44}$$

$$I_{boil} = N_{boil} \cdot UP_{boil} \tag{3.45}$$

$$I_{abs} = N_{abs} \cdot UP_{abs} \tag{3.46}$$

$$I_{comp} = N_{comp} \cdot UP_{comp} \tag{3.47}$$

$$I_{cst} = N_{cst} \cdot UP_{cst} \tag{3.48}$$

$$I_{hst} = N_{hst} \cdot UP_{hst} \tag{3.49}$$

$$TI = I_{CHP} + I_{boil} + I_{abs} + I_{comp} + I_{hst} + I_{cst} \tag{3.50}$$

$$TO = O_{CHP} + O_{boil} + O_{abs} + O_{comp} \tag{3.51}$$

$$TB = B_{exp} + B_h + B_c - B_{imp} - B_{fuel} \tag{3.52}$$

$$NPV = TI - (TB - TO) \cdot RIF \tag{3.53}$$

Avoid two isolated ON states in S1

$$yC_{j+1} + yC_{j-1} > yC_j \tag{3.54}$$

$$yC_{j+2} > yC_j + yC_{j+1} - yC_{j-1} - 1 \tag{3.55}$$

Avoid two isolated OFF states in S1

$$yC_{j+1} + yC_{j-1} < 1 + yC_j \tag{3.56}$$

$$yC_{j+2} > yC_j + yC_{j+1} - yC_{j-1} + 1 \tag{3.57}$$

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Start-up in S2

$$yS_j > yC_j - yC_{j-1} \tag{3.58}$$

$$yS_j < \frac{1 + yC_j - yC_{j-1}}{2} \tag{3.59}$$

$$TS > \sum_j (yS_j \cdot RPF_j) \tag{3.60}$$

Calculations performed with the results:

$$EEE = \frac{TE_2}{TF_{11} - \frac{TTrig}{0.9}} \tag{3.61}$$

In equations 3.13 and 3.16, for the scenarios with typical days, the (j-1) index is fixed so each typical day has no temporal relationship with another, following a daily charge-discharge operation. To calculate the NPV using equation 3.53, as all the prices are constant over time, the RIF factor is calculated beforehand to perform the optimisation using the following expression.

$$RIF = \sum_{i=1}^{n} \frac{1}{(1 + RI)^i} \tag{3.62}$$

Where RI is the rate of interest with a value of 6%, and the total years considered (n) are 15.

3.3.3.1 Optimisation results

For each case presented in table 3.5, four runs of the optimisation model were conducted, one for each scenario presented in table 3.3 and another one using the hourly data of the whole year. Tables 3.6 to 3.11 show the results of the optimisation models. In these tables, for each row, the top number is the absolute result obtained, and the bottom number is the percentage of error with respect to the "whole year" scenario.

TH_{27} and TC_{26} are the final energy delivered to users for heating and cooling, respectively. These values do not change in each scenario (five, seven or ten days) because they are the typical days selected multiplied by the corresponding RPF_j values

Table 3.6 and 3.7 show the results for cases A.1 and A.2 in which flow $H_{22,j}$ is fixed at zero. For both cases, the main results, such as NPV, investment and operating costs, profits and nominal capacities for each scenario with different numbers of typical days are very similar to the "whole year" scenario. The main differences can be found in the nominal capacity of the electrical compression chiller (N_{comp}), and the cooling production of this unit (TC_{14}). For all the other variables the error is below 10%. It is important to highlight, that in Spain to connect a cogeneration system to the grid the minimum REE (eqn 3.61) must be met. In the scenarios with typical days, the NPV and REE obtained is very similar to the whole year scenario. In general, the results of case A.1 (only heating storage) are better than case A.2 (heating and cooling storage). The greater error in the A.2 case may be the result of three causes:

- The use of the cooling energy storage adds [3×(Time periods)+1] degree of freedom to the optimisation model.
- The cooling energy storage could be a redundant unit. As the model is linear (efficiencies are constant) and no operational restrictions (ON/OFF periods) are applied for the chillers, the cooling storage does not add any special functionality in coparison to the case with only heat storage. When the cooling storage of 30 kW is not used in the "whole year" scenario (case A.1), the total cooling capacity is increased by only 11 kW.
- Although the operation of the energy storage has a daily charge-discharge, it is possible that the operation of the energy storage is more sensitive to the profile of the selected days rather than the number of typical days or the RPF values. The smallest error for TC_{14} in the #.1 cases is obtained for the seven-day scenario.

It is most likely a combination of the three hypothesis mentioned above that gave rise to greater errors when two energy storage systems were used in this study. Similar results are obtained in tables 3.8 and 3.9. In cases B.1 and B.2, heat from the cogeneration unit can be dissipated whenever the minimum EEE of 55 % is met. None of the results exceed an error of 10 % except for the nominal capacity of the compression chiller in case B.2 and its cooling production (TC_{14}). The NPV increases because more electricity can be produced and sold to the grid. TH_{22} represents dissipated heat.

In cases C.1 (table 3.10) and D.1 (table 3.11) only heating storage is considered and binary variables are introduced to control the operation of the cogeneration unit. A minimum load of 30% is fixed for the cogeneration unit. Additional restrictions are added to prevent switching on or shutting off the cogeneration unit for only one or two hours. In case C.1, the S2 subsystem of figure 3.35 is not used, and the total number of start-up periods (TS) is calculated from the

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binary variable that controls the operation of the cogeneration unit (yC). TS is calculated after the model is solved and has no influence on the optimisation model. Cases C.1 and D.1 have been introduced because it is usually important to control the operation of the cogeneration unit, preventing operation at very low load or too many start-up periods. As in the previous cases, all the variables in the typical days are very similar to the "whole year" case, including the number of start-up periods. The main difference for TS can be found for the seven-day scenario. As was the case for energy storage, it is possible that TS is more influenced by the profiles of the selected days than for the number of selected days.

For case D.1, the resulting "whole year" model was limited to a maximum computational resolution time of 50,000 seconds (almost 14 hours). After that time, several solutions were found and the best solution was used. As the optimisation model did not finish after 50,000 seconds and better solutions could be found, for the scenario using typical days the TS variable was limited to a value between 438 and 440 (around the value found for the "whole year" scenario). The D.1 case is the only one with a nominal capacity greater than zero for the boiler in the "whole year" scenario, due to the restriction of the number of start-up periods of the cogeneration unit. Only the scenario with ten typical days has a boiler capacity greater than zero but very far from the "whole year" scenario. Nevertheless, the nominal capacity found in the "whole year" scenario is very low, only 8 kW with a production of 673 kWh/year (140 kWh/year for the ten-day scenario). For this reason the difference in boiler operation has no influence on the overall results.

Table 3.6 Summary of the results for case A.1

	Whole year	5 days	7 days	10 days
NPV [€]	112,289	105,296	109,667	118,158
		-6.2%	-2.3%	5.2%
TI [€]	69,488	66,641	71,599	71,196
		-4.1%	3.0%	2.5%
TB [€/y]	20,519	19,405	20,470	21,379
		-5.4%	-0.2%	4.2%
TO [€/y]	1,836	1,734	1,840	1,918
		-5.6%	0.2%	4.5%
N_{CHP} [kW]	92.0	87	96.2	95.5
		-5.4%	4.6%	3.8%
N_{boil} [kW]	0	0	0	0
N_{abs} [kW]	94.9	95	96.5	95.8
		0.1%	1.7%	0.9%
N_{comp} [kW]	63.6	63.5	62	62.7
		-0.2%	-2.5%	-1.4%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	0	0	0	0
TF_1 [kWh/y]	601,906	568,321	601,716	628,679
		-5.6%	0.0%	4.4%
TE_2 [kWh/y]	210,667	198,912	210,600	220,038
		-5.6%	0.0%	4.4%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	16,106	19,424	15,023	15,306
		20.6%	-6.7%	-5.0%
TC_{15} [kWh/y]	173,438	161,043	175,608	181,507
		-7.1%	1.3%	4.7%
TH_{22} [kWh/y]	0	0	0	0
EEE [%]	57.7	57.9	57.6	57.5
		0.3%	-0.2%	-0.3%
N. Iter.	16,480	352	504	759
Time[s]	31.3	0.34	0.41	0.56

Table 3.7 Summary of the results for case A.2

	Whole year	5 days	7 days	10 days
NPV [€]	115,389	109,024	112,987	122,325
		-5.5%	-2.1%	6.0%
TI [€]	66,982	61,326	69,946	69,542
		-8.4%	4.4%	3.8%
TB [€/y]	20,586	19,227	20,657	21,666
		-6.6%	0.3%	5.2%
TO [€/y]	1,843	1,719	1,856	1,946
		-6.7%	0.7%	5.6%
N_{CHP} [kW]	89.9	81	96.2	95.5
		-9.9%	7.0%	6.2%
N_{boil} [kW]	0	0	0	0
N_{abs} [kW]	91.0	81.9	96.5	95.8
		-10.0%	6.0%	5.3%
N_{comp} [kW]	56.3	59.7	45.1	45.8
		6.0%	-19.9%	-18.7%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	30	30	30	30
TF_1 [kWh/y]	603,903	562,985	607,316	638,368
		-6.8%	0.6%	5.7%
TE_2 [kWh/y]	211,366	197,044	212,561	223,429
		-6.8%	0.6%	5.7%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	16,106	21,225	13,133	12,876
	-	31.8%	-18.5%	-20.1%
TC_{15} [kWh/y]	173,438	159,242	177,498	184,777
	-	-8.2%	2.3%	6.5%
TH_{22} [kWh/y]	0	0	0	0
EEE [%]	57.7	57.9	57.5	57.5
		0.3%	-0.3%	-0.3%
N. Iter.	39,118	766	906	1040
Time[s]	42.5	0.39	0.49	0.63

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Table 3.8 Summary of the results for case B.1

	Whole year	5 days	7 days	10 days
NPV [€]	120,062	112,963	116,974	125,722
		-5.9%	-2.6%	4.7%
TI [€]	69,850	66,641	71,599	73,423
		-4.6%	2.5%	5.1%
TB [€/y]	21,481	20,314	21,336	22,525
		-5.4%	-0.7%	4.9%
TO [€/y]	1,962	1,854	1,955	2,058
		-5.5%	-0.4%	4.9%
N_{CHP} [kW]	93.1	87.2	96.2	99.4
		-6.3%	3.3%	6.8%
N_{boil} [kW]	0	0	0	0
N_{abs} [kW]	95.4	95	96.5	100
		-0.4%	1.2%	4.8%
N_{comp} [kW]	63.2	63.5	62	58.5
		0.5%	-1.9%	-7.4%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	0	0	0	0
TF_1 [kWh/y]	652,905	617,416	648,500	684,662
		-5.4%	-0.7%	4.9%
TE_2 [kWh/y]	228,517	216,096	226,975	239,632
		-5.4%	-0.7%	4.9%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	16,372	19,424	15,023	12,799
		18.6%	-8.2%	-21.8%
TC_{15} [kWh/y]	173,173	161,043	175,608	184,014
		-7.0%	1.4%	6.3%
TH_{22} [kWh/y]	22,405	22,093	21,053	22,951
		-1.4%	-6.0%	2.4%
EEE [%]	55	55	55	55
N. Iter.	16,427	314	586	617
Time[s]	21.6	0.36	0.41	0.52

Table 3.9 Summary of the results for case B.2

	Whole year	5 days	7 days	10 days
NPV [€]	123,169	116,664	120,320	129,936
		-5.3%	-2.3%	5.5%
TI [€]	67,018	61,326	69,946	71,769
		-8.5%	4.4%	7.1%
TB [€/y]	21,511	20,312	21,526	22,817
		-5.6%	0.1%	6.1%
TO [€/y]	1,965	1,839	1,971	2,087
		-6.4%	0.3%	6.2%
N_{CHP} [kW]	90.0	81.1	96.2	99.4
		-9.9%	6.9%	10.4%
N_{boil} [kW]	0	0	0	0
N_{abs} [kW]	91.0	81.9	96.5	100
		-10.0%	6.0%	9.9%
N_{comp} [kW]	56.3	59.7	45.1	41.6
		6.0%	-19.9%	-26.1%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	30	30	30	30
TF_1 [kWh/y]	653,840	611,913	654,275	694,653
		-6.4%	0.1%	6.2%
TE_2 [kWh/y]	228,844	214,169	228,996	243,129
		-6.4%	0.1%	6.2%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	16,066	21,225	13,133	10,369
		32.1%	-18.3%	-35.5%
TC_{15} [kWh/y]	173,479	159,242	177,498	187,284
		-8.2%	2.3%	8.0%
TH_{22} [kWh/y]	22,418	22,018	21,232	22,963
		-1.8%	-5.3%	2.4%
EEE [%]	55	55	55	55
N. Iter.	31,940	772	910	1126
Time[s]	34.2	0.44	0.50	0.66

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Table 3.10 Summary of the results for case C.1

	Whole year	5 days	7 days	10 days
NPV [€]	109,020	108,449	107,875	117,886
		-0.5%	-1.1%	8.1%
TI [€]	74,464	73,768	73,768	73,804
		-0.9%	-0.9%	-0.9%
TB [€/y]	20,759	20,606	20,558	21,689
		-0.7%	-1.0%	4.5%
TO [€/y]	1,902	1,879	1,889	1,988
		-1.2%	-0.7%	4.5%
N_{CHP} [kW]	100	100	100	100
N_{boil} [kW]	0	0	0	0.5
N_{abs} [kW]	102.6	100.2	100.2	100.9
		-2.3%	-2.3%	-1.7%
N_{comp} [kW]	55.9	58.3	58.3	57.6
		4.3%	4.3%	3.0%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	0	0	0	0
TF_1 [kWh/y]	631,349	626,329	624,855	659,274
		-0.8%	-1.0%	4.4%
TE_2 [kWh/y]	220,649	219,215	218,699	230,705
		-0.6%	-0.9%	4.6%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	22,898	16,507	22,762	21,040
		-27.9%	-0.6%	-8.1%
TC_{15} [kWh/y]	166,647	163960	167869	175773
		-1.6%	0.7%	5.5%
TH_{22} [kWh/y]	21822.0	22214.0	20730.0	23106.0
		1.8%	-5.0%	5.9%
EEE [%]	55	55	55	55
TS	529	513	622	546
		-3.0%	17.6%	3.2%
N. Iter.	181,515	682	1591	2210
Time[s]	3,859.8	0.50	0.77	1.2

Table 3.11 Summary of the results for case D.1

	Whole year	5 days	7 days	10 days
NPV [€]	108,771	110,502	107,260	117,135
		1.6%	-1.4%	7.7%
TI [€]	74,258	73,753	73,767	73,822
		-0.7%	-0.7%	-0.6%
TB [€/y]	20,708	20,835	20,489	21,606
		0.6%	-1.1%	4.3%
TO [€/y]	1,897	1,898	1,884	1,981
		0.1%	-0.7%	4.4%
N_{CHP} [kW]	100	100	100	100
N_{boil} [kW]	8.8	0	0	0.8
				-90.9%
N_{abs} [kW]	102.6	99.5	100.2	100.9
		-3.0%	-2.3%	-1.7%
N_{comp} [kW]	55.9	59.1	58.3	57.6
		5.7%	4.3%	3.0%
N_{hst} [kW]	30	30	30	30
N_{cst} [kW]	0	0	0	0
TF_1 [kWh/y]	629,727	633,286	622,757	656,789
		0.6%	-1.1%	4.3%
TE_2 [kWh/y]	228,517	221,650	217,965	229,821
		-3.0%	-4.6%	0.6%
TH_{27} [kWh/y]	40,505	41,020	36,629	40,057
		1.3%	-9.6%	-1.1%
TC_{26} [kWh/y]	189,544	180,467	190,631	196,813
		-4.8%	0.6%	3.8%
TC_{14} [kWh/y]	23,529	14,230	23,448	21,831
		-39.5%	-0.3%	-7.2%
TC_{15} [kWh/y]	166,015	166237	167183	174982
		0.1%	0.7%	5.4%
TH_{22} [kWh/y]	21854.0	22309.0	20701.0	22951.0
		2.1%	-5.3%	5.0%
EEE [%]	55	55	55	55
TS	439	438	438	439
N. Iter.	Limited 50,000	23,644	38,341	3,888
Time[s]		6.9	28.0	1.484

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From the results obtained, it is important to emphasise that choosing more typical days does not necessarily imply better results. In general, the best results are obtained working with seven typical days. As a general rule, the accuracy of the optimisation results not only depends on the number of typical days, but also on the ability of those days to reproduce the whole year. It is more important which days are selected and which RPF is assigned to each day than the number of days. Obviously, as more days are selected, the likelihood of better producing the CED curve increases. However, as can be seen in figures 3.23, 3.33 and 3.34, the more days that are selected, the more days with simultaneous heating and cooling demand there are. On those days it is more difficult to manually adjust the cooling and heating CED curve because the RPF values assigned affect both curves. An algorithm could be used to improve the selection of typical days and the assignment of RPF values.

To add some meaning to the differences found between the "whole year" scenario and the other scenarios using typical days, the errors obtained could be compared with the typical errors associated with the input parameters of the optimisation models. Table 3.12 shows some confidence intervals (Alanne et al 2007a, Alanne et al 2007b) for techno-economic parameters.

Table 3.12 Confidence intervals for techno-economic parameters (Alanne et al 2007a,b)

Parameter	Min	Max
Electricity demand [% error]	-10	+10
Primary energy demand [% error]	-10	+10
Discount rate [%]	2	6
Price of district heat [% error]	-5	+5
Price of natural gas [% error]	-10	+10
Price of electricity [% error]	-10	+10
Price of oil [% error]	-10	+10
Micro-CHP total efficiency [%]	75	85

For the main parameters, the confidence error is ±10%, tables 3.6 to 3.11 show that for almost all the results the error compared to the "whole year" scenario is less than ±10%, with the already mentioned exception of the compression chiller in some cases and scenarios. As a conclusion it might be said that the use of typical days to optimise the main parameters of a trigeneration system, does not add an additional or greater error than the intrinsic error of the input data of the model.

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There are some situations in which the selection of more typical days could be advantageous. For example, to calculate variables that could be highly influenced by the profile of the selected typical days. The energy production and the economic results are expected to have a small influence with respect to the number of typical days if the original CED curve is reproduced properly. But the number of ON/OFF and start-up periods could be more influenced by the profiles of the selected typical days. As can be seen in table 3.10, the seven-day case has the worst TS value, but the five- and ten-day scenarios have a very similar TS value. On the other hand, only the ten-day scenario has heating production using the boiler in case D.1. These results could indicate that when binary variables are used to control the ON/OFF status of the units, the use of more typical days may lead to better results in some situations. Another case when more typical days could be selected is when the energy tariff change with the time or the season and then the energy demand must be distributed equally to consider properly the effect of the variable tariff.

3.4 Conclusions

Using an optimisation model for a trigeneration system, several runs were conducted to compare the results using the whole-year demand data or only some selected typical days. A graphic method has been proposed to select typical days that represent the energy demand of the entire year (or any period). The method is easy to apply but several days must be tested to ensure that they correctly represent the whole year. Considering the results obtained from the optimisation cases, the method of selecting typical days is efficient, because in general, the results obtained using typical days are very similar to the scenario with the whole-year hourly demand. Furthermore, the method is robust, because the number of typical days selected has little influence on the results.

With the method proposed is not necessary to make any distinction between different types of days, like working or non-working days. The number of typical days can be adjusted to the requirements of the optimisation model, such as the number of time periods to be considered depending on the complexity of the model. The use of binary variables to control the ON/OFF status of the units could be also one important factor to be considered in choosing the number of selected days. Depending on the energy demand, a minimum number of typical days can be calculated. Some types of variables could be more influenced by the profiles of the selected days than for the number of selected days. In other cases, the selection of typical days could be determined by other factors like variable tariffs.

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Chapter 4

Modelling of distributed energy technologies

4.1 Introduction

Distributed Energy Systems (DES) means to produce locally the energy services required by the users, in contrast with the conventional alternative, with centralised power plants to produce electricity and individual systems to produce locally heating and cooling. Distributed energy systems, like cogeneration, trigeneration or polygenerations systems allow the integration of several systems producing several energy services, with the possibility to use local renewable resources obtaining a system with a higher efficiency than the conventional alternative. A key aspect for the success of DES is the optimal design and operation of the system to assure the economic viability, even for the first stages of a project when not very detailed data is available. Several examples of optimisation models for polygeneration multi-period systems have been presented in Chapter 2. The objective of this chapter is to propose optimisation models for several technologies. These models will be used in the optimisation environment presented in Chapter 5 to develop the optimisation models of each type of unit that could be used to build the configuration of the polygeneration system. Currently the optimisation environment has 79 units, so only few type of units will be presented in this chapter, some of the models presented are used in the case studies.

Section 4.1 introduces distributed energy systems and mathematical programming optimisation techniques. Cogeneration units including internal combustion engines, gas turbines and fuel cells are presented in section 4.3. Energy storage is presented in section 4.4. Thermally driven chillers, especially absorption chillers, are presented in section 4.5. The model for a rotary wheel working with air flows is discussed in section 4.6. Finally the inclusion of a legal constraint for cogeneration systems in Spain is detailed in section 4.7.

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4.2 Distributed energy systems

Distributed energy or distributed generation systems (Chapter 1) means the simultaneous production of several types of energy close to the user, so the waste heat can be used for heating or cooling purposes in contrast with large centralized plants. The most extended configuration is the use of a cogeneration unit that produces electricity and heating simultaneously. Cooling can be produced combining the cogeneration unit with a thermally driven chiller (trigeneration). The term polygeneration is a generalisation of the term trigenartion applied to the simultaneous production of more than two energy carriers. Distributed energy technologies are applied to a local scale and is very important an optimal selection and design of the system to match the energy production with the energy demand to obtain significant primary energy savings (Martens 1998). Electrical production can be sold to the grid, but the heating and cooling production must be consumed locally. Excessive heat dissipation can lead to low efficiency systems losing its advantages respect to the traditional energy production system.

Optimisation techniques are usually applied to the design and synthesis of cogeneration or polygeneration systems, several models can be applied to perform different tasks, like the selection between different alternatives, decide the optimal size of the units or estimate the optimal schedule as a function of energy prices or tariffs. Two main groups of models could be distinguished from the examples presented in section 2.5 and 2.6: linear and non-linear models. Usually linear models consider the efficiency of the units constant. Non-linear models are more detailed and accurate respect to linear models, but the use of binary variables led to complex MINLP models. Binary variables are important to implement decision variables and almost all the multi-period models contain binary variables. MIP problems are more complicated to solve respect linear models but a good solution can be obtained in a reasonable time.

Mixed integer linear models will be presented in the following sections for the main units of a polygeneration system. These types of models offer a good equilibrium between the level of detail and complexity of the model. The models presented are suitable for units that can be found for civil application like in urban districts, hotels or commercial areas. These units such as internal combustion engines, gas turbines, microturbines or fuel cells are characterized by complex mechanisms that can not be modelled in optimisation models considering several time periods. Although the presented models are linear, in almost all the cases part load behaviour for hourly models can be considered using linear regression models from several factors. For non-hourly models, considering large time steps (weeks or months) it is not necessary to consider part load operation.

The models presented in this chapter for a specific technology could be different as a function of several situations. For the same technology, different equations are presented as a function of several factors (input data or use of certain variables). In the optimisation environment presented in Chapter 5, all the equations are implemented but only some specific equations will be used to built the optimisation model. The models presented here are used in the optimisation environment to build the units. Currenlty there are 79 units so only few units will be presented.

4.3 Cogeneration units

Cogeneration units (CHP) are able to produce simultaneously heat and power (or electricity) using the same fuel. The most extended cogeneration units are internal combustion engines, turbines, microturbines and fuel cells. The heat is recovered from the exhausts gas or/and from the cooling circuits. In optimisation models these units are modelled using constant efficiencies or using linear relations for each type of energy produced as a function of the fuel consumption. This relation (fuel consumption-output power) trend to be linear and avoids the use of non linear efficiencies that depends of the unit's load. The main characteristics of each technology are outlined in the following sections and some examples are presented.

4.3.1 Internal combustion engines

Internal combustion engines (ICE) are one of the most mature cogeneration technologies, available for a wide range of capacities (3 kW – 20 MW) and high electrical efficiency (35 - 45 %). The useful heat is recovered from two different circuits, the exhausts gases with typical temperatures between 300 - 400 ºC and the refrigeration circuit of the engine producing hot water up to 90 ºC. ICE are able to use liquid or gaseous fuels like diesel, natural gas or biogas and the overall efficiency range from 65 to 92 %.

The power and thermal production of the engines can be approximated using linear relations respect to the fuel consumption (Cho et al 2009), a linear correlation can be made for each output using experimental data or manufacturer data of the engine at several partial loads. Figure 4.1 shows the fuel consumption with respect to the output power of the engine at 50, 75 and 100% load (Gas Natural). Figure 4.2 shows the fuel consumption respect to the thermal energy recovery. In both cases the energy consumption respect to the energy production can be approximated with linear correlation, using a correlation for the data of a specific engine, or using a correlation for the data of several engines. In the case of figures 4.1 and 4.2, both engines can be approximated quite well with the same correlation.

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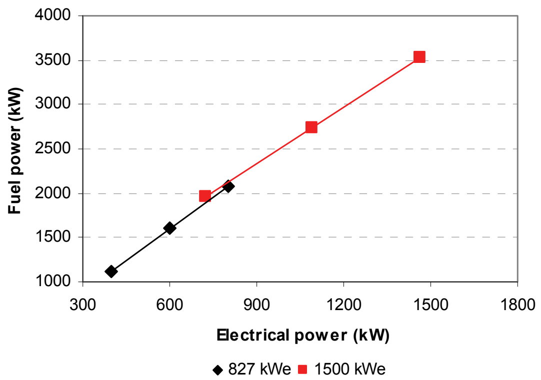

Figure 4.1 Electrical production for two ICE from 50 to 100% load.

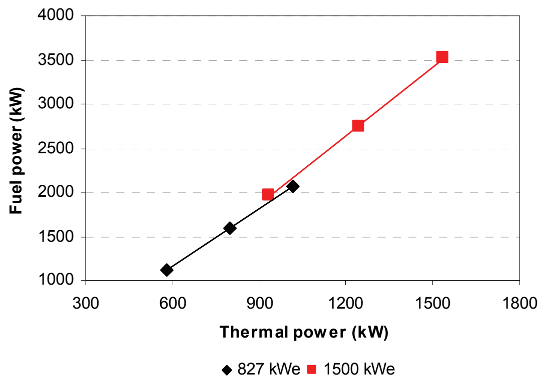

Figure 4.2 Thermal production for two ICE from 50 to 100% load.

Figure 4.3 shows the input and output variables that will be used to model the internal combustion engine. The red arrow represents energy flows corresponding to the energy content of the fuel, electricity or thermal production. The black inputs are data and do not represent energy flows. y_i is a binary variable that determines if the unit is selected in the final solution and $ytp_{i,j}$ is also a binary variable that indicates if the unit is ON or OFF for each time considered. y_i is optional and is only necessary when other calculations concerning to other units depends on the presence of this unit, or when a concrete number of units must be selected.

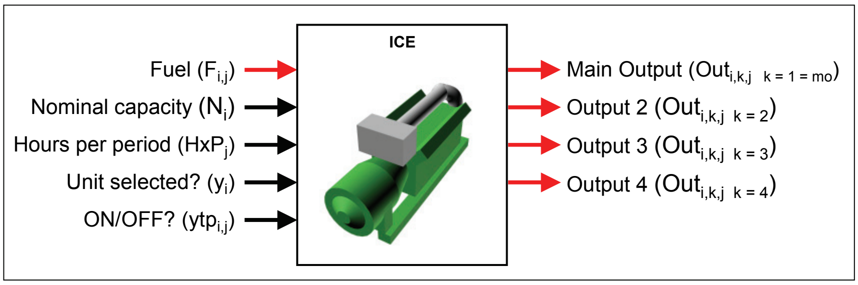

Figure 4.3 Input and outputs for internal combustion engine model

The equations to model the internal combustion engines are listed below. Equation 4.1 relates each output of the engine (electricity, heating, energy content in the exhausts gases and the low temperature circuit) by means of a linear relation as a function of the fuel consumption. If the nominal capacity of the unit is unknown, equation 4.2 can be used to determine the capacity of the cogeneration unit.

$$Out_{i,k,j} = AP_{i,k} \cdot F_{i,j} + BP_{i,k} \cdot HxP_j \cdot ytp_{i,j} \quad (4.1)$$

$$Out_{i,mo,j} \leq N_i \cdot HxP_j \quad (4.2)$$

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Where k is each of the energy outputs of the engine (figure 4.3), $A_{i,k}$ and $B_{i,k}$ are the correlation parameters obtained from manufacturer or experimental data for each unit and output. Two types of binary variables can be used to determine the state of the unit. y_i indicates if the unit is selected in the final solution using the equation 4.3. $ytp_{i,j}$ indicates the ON/OFF state of the unit in equation 4.1, equation 4.4 is used to set all the $ytp_{i,j}$ values to zero when the unit is not selected in the final solution.

$$Out_{i,mo,j} \leq MaxN_i \cdot HxP_j \cdot ytp_i \qquad (4.3)$$

$$ytp_{i,j} \leq y_i \qquad (4.4)$$

Economic and environmental indicators are calculated with the following equations. In all the cases there is a cost factor or an emission factor as a function of the energy production. As a function of the environmental factors $GEF_{i,j}$, the emissions can be calculated using the input fuel to the unit (equation 4.7) or the output production (equation 4.8).

$$I_{i,j} = N_i \cdot ICF_i + ICB_i \cdot y_i \qquad (4.5)$$

$$MC_{i,j} = Out_{i,mo,j} \cdot HxP_j \cdot MCF_{i,j} \qquad (4.6)$$

$$GE_{i,j} = Fuel_{i,j} \cdot HxP_j \cdot GEF_{i,j} \qquad (4.7)$$

$$GE_{i,j} = Out_{i,mo,j} \cdot HxP_j \cdot GEF_{i,j} \qquad (4.8)$$

Additional constraint can be added to consider several factors. Equations 4.9 and 4.10 can be used to specify a minimum load for the cogeneration engine. If the engine is ON, the load must be equal or higher than $N_i \cdot MinL_{i,j}$, where $MinL_{i,j}$ is fixed by the user and ranges from 0 to 100%. N_i is the nominal capacity (variable) and SLK is a slack variable. If N_i is a parameter (a constant value), equations 4.9 and 4.10 can be replaced by equation 4.11

$$Out_{i,mo,j} \geq N_i \cdot HxP_j \cdot \frac{MinL_{i,j}}{100} - SLKI_{i,j} \qquad (4.9)$$

$$SLK_{i,j} \leq MaxN_i \cdot HxP_j \cdot (1 - ytp_{i,j}) \qquad (4.10)$$

$$Out_{i,mo,j} \geq N_i \cdot HxP_j \cdot \frac{MinL_{i,j}}{100} \cdot ytp_{i,j} \qquad (4.11)$$

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Equations 4.12 and 4.13 can be used to calculate the nominal capacity properly. When the nominal capacity is a positive variable and must be optimised, if it is included in the objective function by means of the investment costs, the value of the nominal capacity will be just the output production in the peak period with the maximum demand (equation 4.2). This means $N_i \cdot HXP_j$ will be just the maximum value of $Out_{i,mo,j}$. But equation 4.2 is fulfilled for any value of N_i higher than the real nominal capacity, to prevent this situation equations 4.12 and 4.13 can be used. In these equations $yN_{i,j} = 1$ when the output of the unit ($Out_{i,mo,j}$) is higher or equal than $N_i \cdot FML_i$ (FML_i could be 0.99 or higher); so equation 4.14 determines that at least, there is a time period in which the load of the engine must be greater or equal to FML_i. Table 4.1 resumes the value of $yN_{i,j}$ as a function of the values for N_i and $Out_{i,mo,j}$.

$$N_i \cdot FML_i \cdot HxP_j - Out_{i,mo,j} \leq MaxN_i \cdot HxP_j \cdot \left(1 - yN_{i,j}\right) \tag{4.12}$$

$$N_i \cdot FML_i \cdot HxP_j - Out_{i,mo,j} \geq -MaxN_i \cdot HxP_j \cdot yN_{i,j} \tag{4.13}$$

$$\sum_j yN_{i,j} \geq 1 \tag{4.14}$$

Table 4.1 Main sections of the GUM file.

$Out_{i,mo,j} = N_i \cdot FML_i \cdot HxP_j$	$yN_{i,j} = 0$ or 1
$Out_{i,mo,j} > N_i \cdot FML_i \cdot HxP_j$	$yN_{i,j} = 1$
$Out_{i,mo,j} < N_i \cdot FML_i \cdot HxP_j$	$yN_{i,j} = 0$

4.3.2 Gas Turbines and Microturbines

Gas turbines are the most extended technologies for big scale cogeneration. Typically the capacity for distributed generation range from 500 kW to 50 MW and for centralised cogeneration plants for electrical production up to 250 MW. The efficiency of gas turbines is more sensible to the ambient conditions respect to internal combustion engines. When the temperature raises the density of the air decrease reducing the air mass flow through the gas turbine and the net power obtained. Figure 4.4 shows the nominal rated performance for a Mars T-14000 gas turbine (Petchers, 2003). In the figure the output power, fuel consumption, exhausts temperature and exhausts flow are related to the input air temperature. The data of the figure 4.4 can be used to model the turbine. Like the internal combustion engines, the fuel consumption can be approximated with a linear relation of the output power. For gas turbines the ambient temperature can be included also in this linear relation (equations 4.15 and 4.16).

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$$\text{Fuel} = \text{AF} \cdot \text{OutputPower} + \text{BF} \cdot \text{AirTemp} + \text{CF} \tag{4.15}$$

$$\text{ThermalRecovery} = \text{AT} \cdot \text{OutputPower} + \text{BT} \cdot \text{AirTemp} + \text{CT} \tag{4.16}$$

Where AF, BF, CF and AT, BT, CT are the coefficients of the correlations calculated using manufacturer or experimental data to calculate the output power and the thermal recovery respectively.

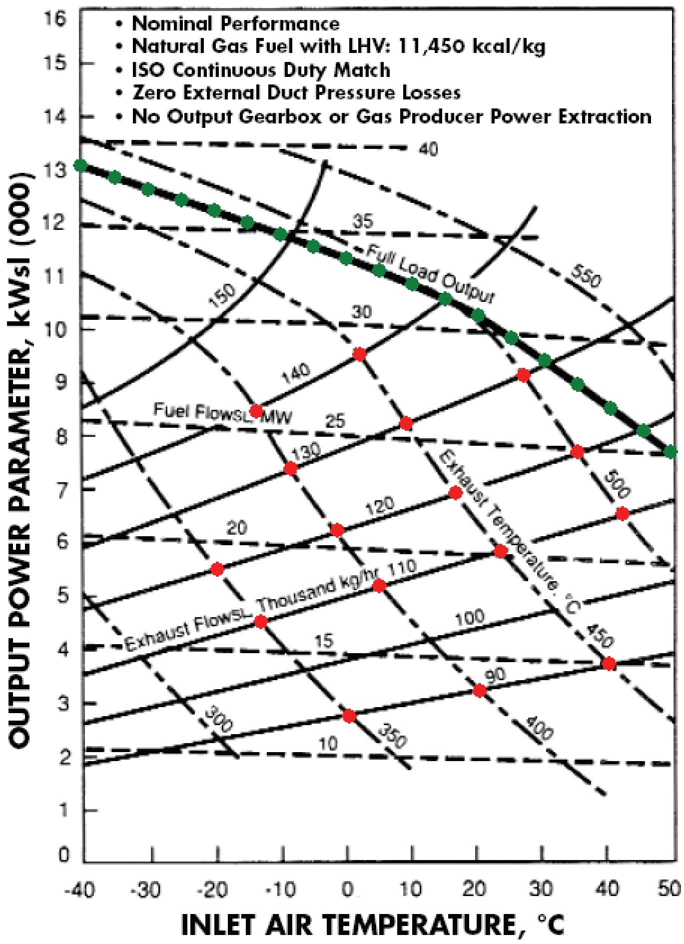

Figure 4.4 Nominal rated performance for Mars T-14000 gas turbine at several temperatures (Petchers 2003)

The values of the red points plotted in figure 4.15 have been used to obtain two linear correlations, one for fuel consumption and another for the thermal energy recovered, in both cases as a function of the output power and the ambient temperature. The thermal recovery has been calculated assuming a final temperature of the exhausts gas of 120 ºC. The comparison between the manufacturer data and the linear correlation results are presented in figure 4.5 for the output power and figure 4.6 for the thermal recovery.

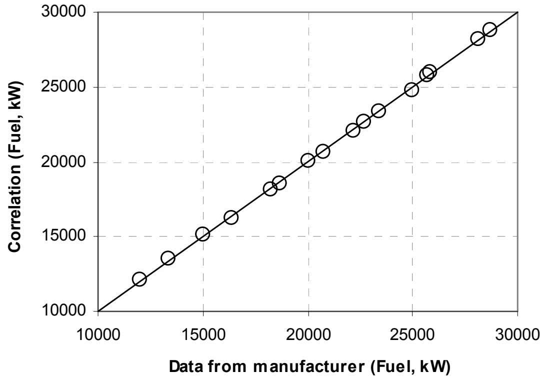

Figure 4.5 Comparison with the correlation results for output power, Mars T-14000

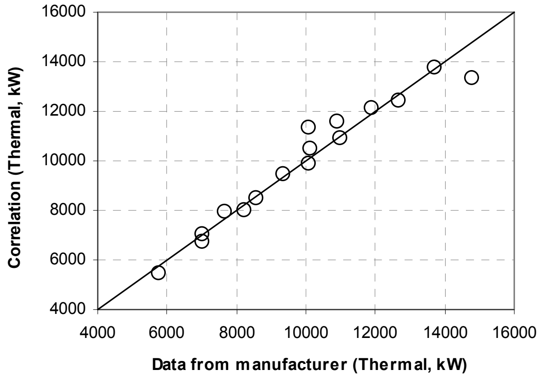

Figure 4.6 Comparison with the correlation results for thermal recovery, Mars T-14000

The ambient temperature also determines the maximum output power obtained with the gas turbine ("Full Load Output" curve in figure 4.4). Usually the effect of the temperature is lower or has no influence below the nominal operating conditions of the gas turbine. The "Full Load Output" curve in figure 4.4 can be divided in two linear sections (S1 and S2), and a linear correlation can be made for each section (equations 4.17 and 4.18).

$$\mathrm{MaxOutput}_{S1} = a_{S1} \cdot \mathrm{AirTemp} + b_{S1} \tag{4.17}$$

$$\mathrm{MaxOutput}_{S2} = a_{S2} \cdot \mathrm{AirTemp} + b_{S2} \tag{4.18}$$

Using the data from figure 4.4 (green points) the linear correlations as a function of the air temperature are presented in figure 4.7. As a function of the air temperature, on of the two correlations must be used. Since all the correlations are adjusted from manufacturer data, the model presented here is for specific (or commercial) gas turbines and can not be used to find the optimal nominal capacity (but can be used to choose between different units).

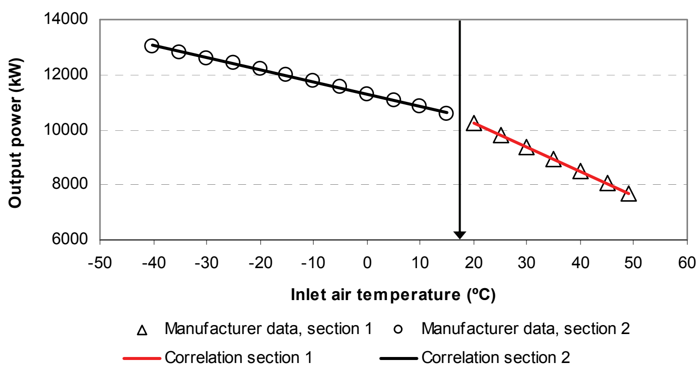

Figure 4.7 Mars T-14000 maximum capacity

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The nominal rated performance for a Solar Saturn gas turbine (Petchers 2003) is presented in figure 4.8. Some values (red points) have been used to perform the linear correlations, which results are compared in figures 4.9 and 4.10.

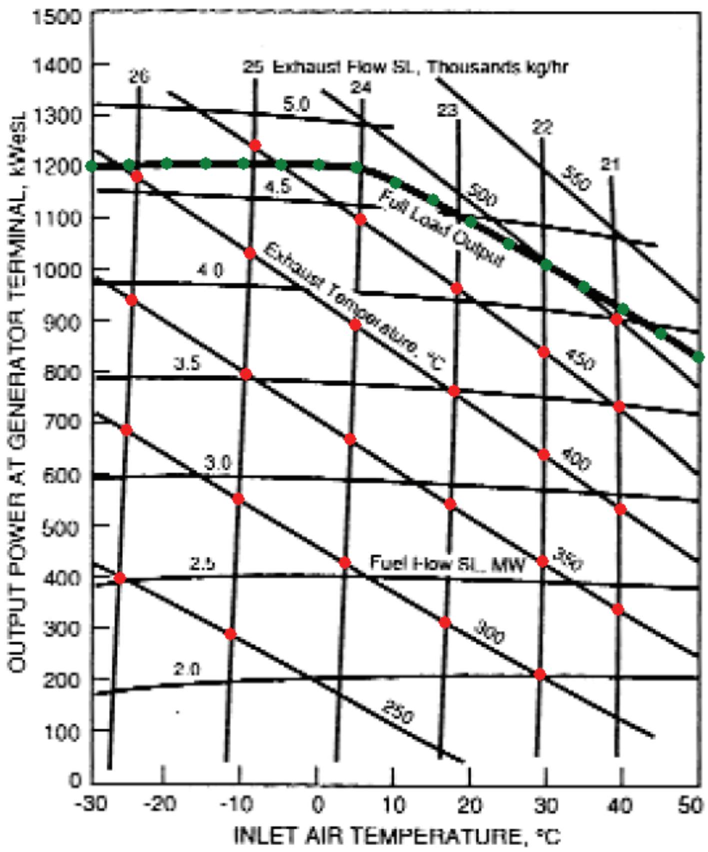

Figure 4.8 Nominal rated performance for Solar Saturn gas turbine at several temperatures (Petchers 2003)

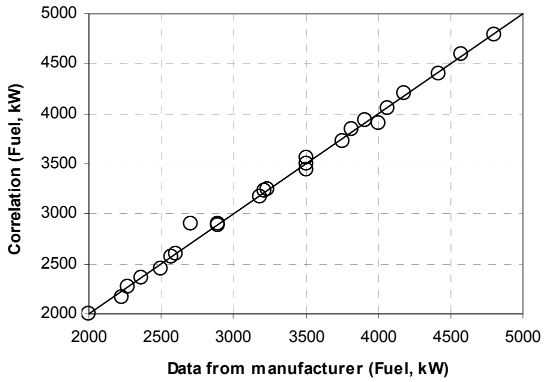

Figure 4.9 Comparison with the correlation results for output power, Solar Saturn

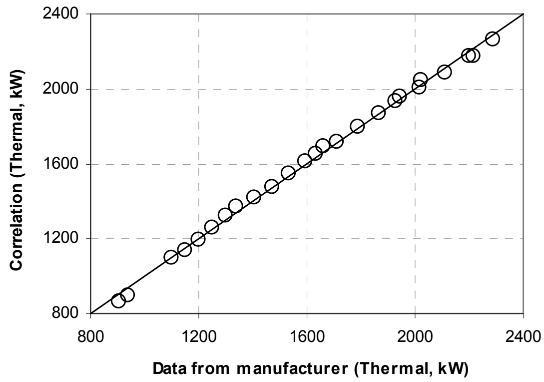

Figure 4.10 Comparison with the correlation results for thermal recovery, Solar Saturn

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MODELLING ENVIRONMENT FOR THE DESIGN AND OPTIMISATION OF ENERGY POLYGENERATION SYSTEMS
Jordi Ortiga Guillén
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The maximum output power approximated with two linear correlations is presented in figure 4.11. In this case the temperature that decides which correlation must be used is lower compared with the Mars T-14000 gas turbine.

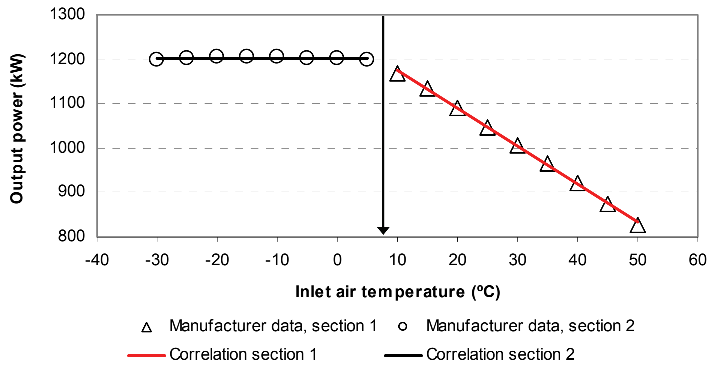

Figure 4.11 Solar Saturn maximum capacity

The input and output variables and parameters to model a gas turbine are presented in figure 4.12. Only two energy outputs are required, one for the electrical (or power) production and another for the thermal energy recovered. The nominal capacity is not required because is calculated from the correlations. The input air temperature can be obtained from meteorological data or can be introduced if the turbine is not taking ambient air. y_i and $ytp_{i,j}$ has the same meaning than for the internal combustion engine.

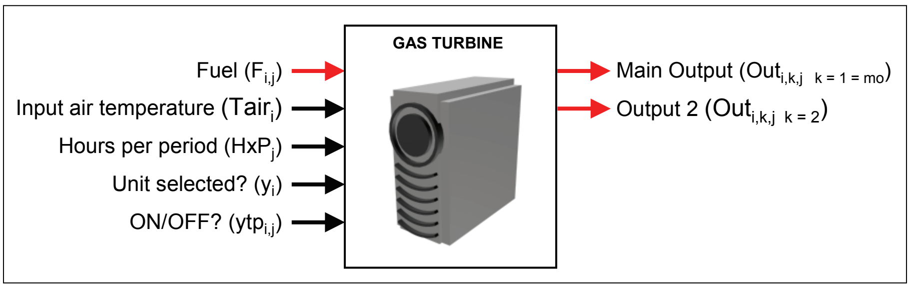

Figure 4.12 Input and outputs for gas turbine model

With the input and output variables of figure 4.12 and the correlations described in the equations 4.15, 4.16, 4.17 and 4.18 the optimisation model for the gas turbine is formulated with the following equations. The fuel consumption and the thermal output can be calculated as a function of the output power of the unit (equation 4.19 and 4.20). $SLKP_{i,j}$ and $SLKP_{i,j}$ are slack variables used to obtain zero fuel consumption and zero thermal production when the unit is not working.

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$$F_{i,j} = AF_i \cdot OutP_{i,j} + BF_i \cdot Tair_{i,j} \cdot HxP_j + CF_i \cdot HxP_j - SLKP_{i,j} \tag{4.19}$$

$$OutT_{i,j} = AT_i \cdot OutP_{i,j} + BT_i \cdot Tair_{i,j} \cdot HxP_j + CT_i \cdot HxP_j - SLKT_{i,j} \tag{4.20}$$

$$SLKP_{i,j} \leq MaxFuel_i \cdot (1 - ytp_{i,j}) \tag{4.21}$$

$$SLKT_{i,j} \leq MaxThermal_i \cdot (1 - ytp_{i,j}) \tag{4.22}$$

$$Fuel_{i,j} \leq MaxFuel_i \cdot ytp_{i,j} \tag{4.23}$$

$$OutT_{i,j} \leq MaxThermal_i \cdot ytp_{i,j} \tag{4.24}$$

Usually the input temperature of the gas turbine is not a variable and is a parameter of the model (for example $TAair_j$ = to the ambient temperature from a meteorological file). In this case equations 4.19 to 4.24 can be replaced by the equations 4.25 and 4.26, where the binary variable multiply the temperature, and the slack variables are not necessary.

$$Fuel_{i,j} = AF_i \cdot OutP_{i,j} + (BF_i \cdot TAair_j \cdot HxP_j + CF_i \cdot HxP_j) \cdot ytp_{i,j} \tag{4.25}$$

$$OutT_{i,j} = AT_i \cdot OutP_{i,j} + (BT_i \cdot TAair_j \cdot HxP_j + CT_i \cdot HxP_j) \cdot ytp_{i,j} \tag{4.26}$$

The relation between the binary variables is the same respect to the internal combustion engine, when the main binary variable (y_i) is zero, all the values for $ytp_{i,j}$ will be zero.

$$ytp_{i,j} \leq y_i \tag{4.27}$$

Since the equations presented are for specific gas turbines, the investment cost is know and fixed (parameter, equation 4.28). As a function of the environmental factors $GEF_{i,j}$ the emissions can be calculated using the input fuel to the unit (equation 4.30) or the output production (equation 4.31).

$$IC_{i,j} = ICB_i \cdot y_i \tag{4.28}$$

$$MC_{i,j} = Out_{i,mo,j} \cdot HxP_j \cdot MCF_{i,j} \tag{4.29}$$

$$GE_{i,j} = Fuel_{i,j} \cdot HxP_j \cdot GEF_{i,j} \tag{4.30}$$

$$GE_{i,j} = Out_{i,mo,j} \cdot HxP_j \cdot GEF_{i,j} \tag{4.31}$$

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Additional constraints can be used to fix a minimal load using in the equation 4.32 $MinP_{i,j}$ that determines the minimum capacity ranging from 0 to 100%. The maximum production is calculated with equations 4.17 and 4.18 as a function of the input temperature to the turbine. Usually this temperature is constant and the maximum production of the unit can be calculated before the optimisation ($MaxNct_{i,j}$) and an upper bound for $Out_{i,j}$ can be fixed using $MaxNct_{i,j}$:

$$OutP_{i,j} \geq N_i \cdot HxP_j \cdot \frac{MinL_{i,j}}{100} \cdot ytp_{i,j} \tag{4.32}$$

$$OutP_{i,j}.up = MaxNct_{i,j} \tag{4.33}$$

If the temperature to the input of the turbine is unknown and is a variable of the model, the following equations must be used. Equations 4.34 and 4.35 decide to which section (figure 4.7 and 4.11) corresponds the input temperature to the turbine. As a function of the binary variable $yTh_{i,j}$, the corresponding equation for the section is activated. Table 4.2 shows the values of $yTh_{i,j}$ as a function of the value for the ambient temperature.

$$Tcn_i - Tair_{i,j} \leq MaxTDiff_i \cdot (1 - yTh_{i,j}) \tag{4.34}$$

$$Tcn_i - Tair_{i,j} \geq -MaxTDiff_i \cdot yTh_{i,j} \tag{4.35}$$

$$MaxOutputS1_{i,j} = aS1_{i,j} \cdot Tair_{i,j} + bS1_{i,j} - SLKS1_{i,j} \tag{4.36}$$

$$MaxOutputS2_{i,j} = aS2_{i,j} \cdot Tair_{i,j} + bS2_{i,j} - SLKS2_{i,j} \tag{4.37}$$

$$SLKS1_{i,j} \leq MaxNGT_i \cdot (1 - yTh_{i,j}) \tag{4.38}$$

$$SLKS2_{i,j} \leq MaxNGT_i \cdot yTh_{i,j} \tag{4.39}$$

$$MaxOutputS1_{i,j} \leq MaxNGT_i \cdot yTh_{i,j} \tag{4.40}$$

$$MaxOutputS2_{i,j} \leq MaxNGT_i \cdot (1 - yTh_{i,j}) \tag{4.41}$$

$$MaxN_{i,j} = MaxOutputS1_{i,j} + MaxOutputS2_{i,j} \tag{4.42}$$

$$Out_{i,mo,j} \leq MaxN_{i,j} \cdot HxP_j \cdot y_i \tag{4.43}$$

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Table 4.2 Main sections of the GUM file.

$Tair_{i,j} = Tcn_i$	$yTh_{i,j} = 0$ or 1
$Tair_{i,j} > Tcn_i$	$yTh_{i,j} = 1$ (section 1, figure 4.7 and 4.11)
$Tair_{i,j} < Tcn_i$	$yTh_{i,j} = 0$ (section 2, figure 4.7 and 4.11)

4.3.3 Fuel cells

Fuel cells are small scale generation technologies with typical capacities ranging from 1 kW to 10 MW. Fuel cells can be classified as a function of the electrolyte as follows:

- Alkaline Fuel Cell (AFC).
- Molten Carbonate Fuel Cell (MCFC).
- Phosphoric Acid Fuel Cell (PAFC)
- Polymer Electrolyte Membrane Fuel Cell (PEMFC).
- Solid Oxide Fuel Cell (SOFC).

In the framework of the TRIGENED project a PEMFC has been tested in the laboratories of INTA (Huelva). The tested PEMFC is a 5 kW nominal power Teledyne Perry 72-cell, supplied by Teledyne Energy Systems and able to operate with pure hydrogen or reformate gas, with a minimum hydrogen content of 38%. The main characteristics of this stack are described below:

- Number of Cells: 72
- Open Circuit Voltage: 67-70 V
- Peak Power: 7.5 kW
- Max. Current: 165 A
- Nominal Current: 100 A
- Nominal Voltage: 50 V
- Nominal Power: 5.0 kW
- Nominal Inlet Pressure: 5 psig
- Max. Pressure: 30 psig
- Max. required Air Flow (at 7.5 kW): 531 standard litres per minute
- Max required H2 Flow (at 7.5 kW): 134 standard litres per minute
- Max. required Reformate Gas Flow (at 7.5 kW): 352 slpm (for 38% H2)
- Min./Max. Temperature: 10 - 70 ºC
- Nominal Temperature: 60 ºC

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The stack has been operated in a PEMFC test bench, which is placed in a building destined to hydrogen technologies and fuel cells in the facilities of INTA (El Arenosillo, Huelva, Spain). The combustible used for the tests has been hydrogen. The Fuel Cell System boundaries have been set up according to figure 4.13.

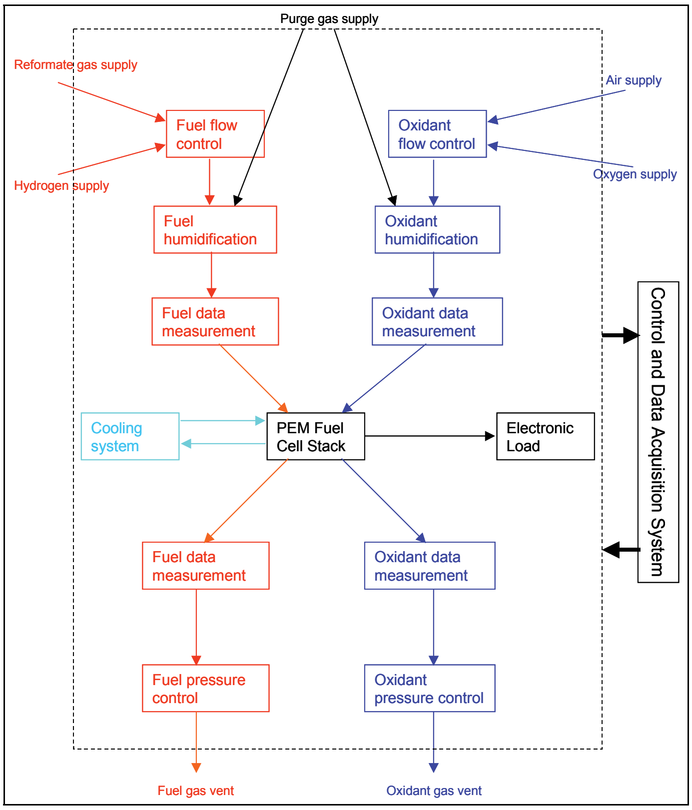

Figure 4.13 Control and flow diagram of the PEM fuel cell

Maximum limit for operation temperature is 70 ºC due to the intrinsic nature of the state-of-the-art materials used in the PEMFC, especially to the MEA (Membrane Electrode Assembly). The type of membrane more often used is a membrane manufactured by DuPont and sold under the label Nafion® No. 117. Nafion can dehydrate rapidly at temperatures higher than 70 –80 ºC, unless high pressures are applied, loosing its favourable proton exchange conductivity. New membranes are under development to achieve a higher temperature operation (higher than 120 ºC). Figure 4.14 shows the fuel consumption as a function of the electrical production for several loads, and figure 4.15 shows the fuel consumption as a function of the thermal energy recovered from the cooling circuit of the fuel cell (Ortiga et al 2008). The behaviour of the unit is very similar respect to the internal combustion engines, a linear correlation can be made between the fuel consumption and the electricity and thermal production respectively, using the same equations than the internal combustion engine.

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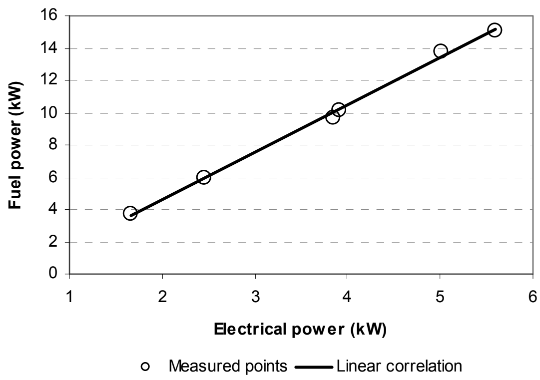

Figure 4.14 Experimental electrical production of a 5.5 kWe fuel cell.

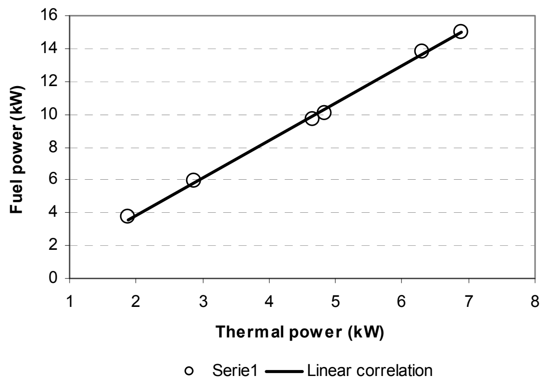

Figure 4.15 Experimental thermal production of a 5.5 kWe fuel cell.

4.4 Energy storage

Energy demand in buildings has a high variability during the day and each season. Energy storages systems allow coupling the production with the demand, obtaining several benefits like the reduction of the size of the installed units and the increase of the working hours of these units. The most common energy storage are thermal storage system using water, ice or phase change materials (Sharma et al 2009, Bal et al 2010). A review of electrical energy storage (EES) can be found in Chen et al 2009 and Kaldellis et al 2009. The use of electrical storage is not so extended compared with thermal storage but in all cases the purpose of the storage system is the same. Figure 4.16 shows the main operating strategies for energy storage, load levelling to left to maintain the generation units working at constant load, and peak saving where the purpose of the energy storage is to cover just the peak demand.

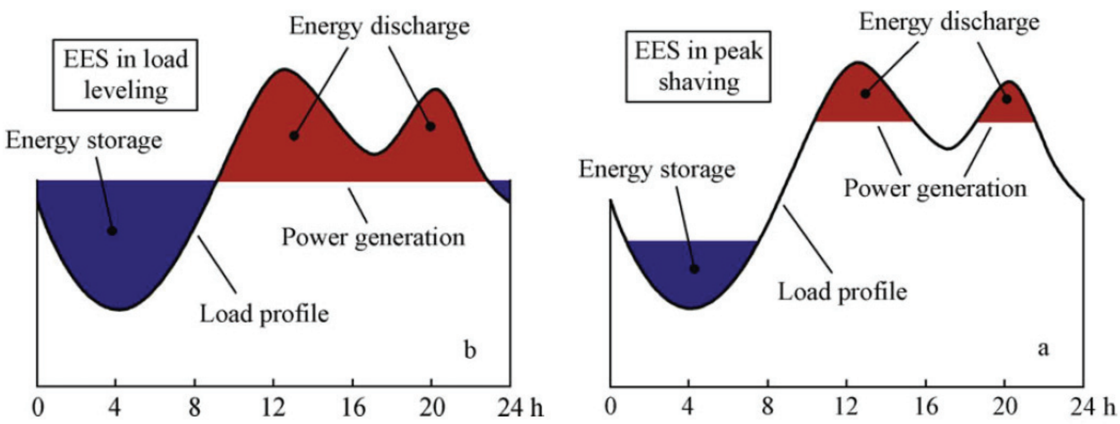

Figure 4.16 Energy storage strategies operation: load levelling and peak saving (Chen et al 2009)

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Examples of energy storage in mathematical programming models can be found in Weber et al 2006 and Lozano et al 2010. Energy storage is modelled considering the input energy to the storage, the output energy from the storage and the total energy content of the storage for each time period considered in the model. Additionally some losses or an average temperature can be calculated. Figure 4.17 shows the inputs and output for the energy storage model proposed. Two types of model can be implemented, one considering a bypass (figure 4.18) and other without by-pass where the input is used to charge the storage and the output is used to discharge the unit. In this section the model with the by-pass will be presented.

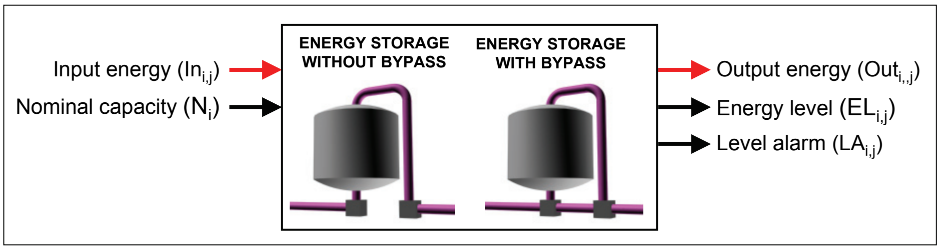

Figure 4.17 Input and output for the omptimisation model of the energy storage

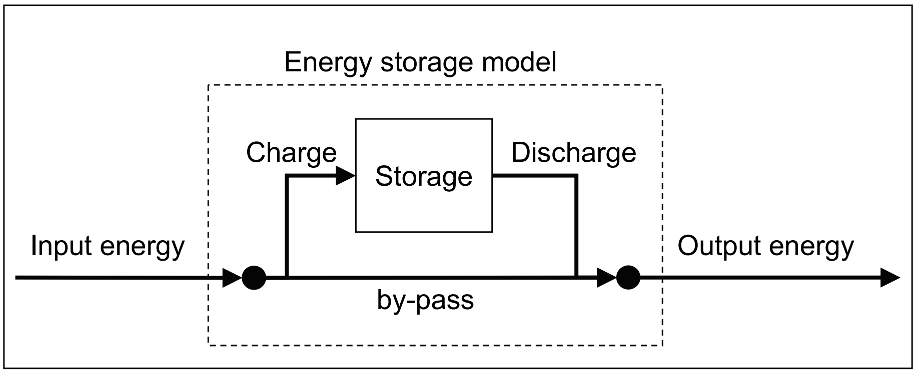

Figure 4.18 Input and output variables of the optimisation energy storage model

The storage is simulated considering only the energy input-outputs and the energy content of the storage. A by-pass is included to decide if the energy input to the storage is accumulated or goes directly to the output. Equations 4.44 and 4.45 relate the input and the output of the energy storage with the quantity of energy that is by-passed and is not accumulated. Equation 4.46 is the quantity of energy accumulated or extracted from the storage and equation 4.47 evaluates the total amount of energy in the storage for each time period.

$$In_{i,j} = InStg_{i,j} + StgByPass_{i,j} \tag{4.44}$$

$$Out_{i,j} = OutStg_{i,j} + StgByPass_{i,j} \tag{4.45}$$

$$EBalance_{i,j} = InStg_{i,j} - OutStg_{i,j} \quad (4.46)$$

$$EL_{i,j} = EL_{i,j-1} \cdot \left(1 - ELosses_{i,j}\right) + EBalance_{i,j} \quad (4.47)$$

The following constraints can be added to avoid the charge and discharge of the storage at the same time period.

$$InStg_{i,j} \leq MaxInOut_i \cdot yInToStg_{i,j} \quad (4.48)$$

$$OutStg_{i,j} \leq MaxInOut_i \cdot \left(1 - yInToStg_{i,j}\right) \quad (4.49)$$

In the case of daily charge-discharge of the energy storage the following equations can be used to force the completely discharge of the storage. $yLA_{i,j}$ is a binary variable with value equal to one when the energy content of the storage ($EL_{i,j}$) is lower respect a fixed value ($MinEL_i$). The value $MinEL_i$ indicates at which energy level the storage is considered empty (for example 0.1 kW).

$$EL_{i,j} \leq MaxEL_i \cdot \left(1 - yLA_{i,j}\right) + MinEL_i \cdot yLA_{i,j} \quad (4.50)$$

$$EL_{i,j} \geq MinEL_i \cdot \left(1 - yLA_{i,j}\right) \quad (4.51)$$

$$\sum_{d=1}^{nd} \sum_{j=d1}^{d2} yLA_{i,j} \geq 1 \quad (4.52)$$

Equation 4.52 force for each day that at least there is one hour when the storage is empty. In this equation nd is the number of days included in the energy demand introduced in the model. d1 and d2 are calculated as a function of the day that is evaluated as follows:

- d1 = (d-1)·24+1
- d2 = (d-1)·24+24

To force the completely discharge of the storage at least one time per day (or week, etc.) is very important to avoid excessive volumes of the storage. The energy storage (especially using water) is quite cheap compared with the cogeneration units. As a function of the model, the optimal solution would be to install very large storage to produce more heating than the required by the final user but allowing the cogeneration unit to produce more electricity.

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4.5 Thermal driven chillers

Thermally driven chillers and heat pumps are systems that use thermal energy to deliver cooling or heating at several temperature levels. This technology also called sorption technology covers the same working segment as mechanical compression systems: chillers, refrigerating machines and heat pumps. There are various types of sorption cycles with different level of commercial development and availability:

- Absorption chillers
- Absorption heat pumps
- Solid sorption systems
- Desiccant systems

In the following section a model for absorption chillers will be presented using a multiregression correlation as a function of the working temperatures of the cycle.

4.5.1 Absorption Chillers

Absorption chiller can be activated with wasted heat in several forms (hot water, vapour, thermal oil, exhausts gases, etc.). The available capacities range from few kW up to 6 MW. The working principle of an absorption system is similar to that of a mechanical compression system with respect to the refrigerant path through the evaporator and condenser. The compression of the vapour is carried out by means of a “heat driven” compression cycle consisting of two main components, absorber and generator.

Absorption cooling systems always work with a mixture, i.e. a working pair, consisting of a volatile component (refrigerant) and an absorbent. The most common working pairs are Water (refrigerant) / Lithium Bromide (absorbent) and Ammonia (refrigerant) / Water (absorbent). These two main types of mixtures are applied dependent mainly of the required cooling temperature, and other factors like COP or the cooling media for the absorber-condenser (using a cooling tower or an air cooler).

- Cooling temperature > 5 °C: Water / Lithium Bromide (LiBr) absorption chiller.
- Cooling temperature < 5 °C: Ammonia / Water absorption refrigerator.

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The simplest design of an absorption chiller (simple effect, figure 4.19) consists of an evaporator, a condenser, an absorber, a generator, a solution heat exchanger and a solution pump. Compressing the refrigerant vapour is effected by the absorber, the solution pump and the generator in combination, instead of a mechanical vapour compressor. Vapour generated in the evaporator is absorbed into a liquid absorbent in the absorber. The absorbent that has taken up refrigerant, the rich solution, is pumped to the generator with a previous preheating with the solution coming out of it. In the generator the refrigerant is released as a vapour, which vapour is to be condensed in the condenser. The regenerated or strong absorbent is then led back to the absorber to pick up refrigerant vapour. Heat is supplied to the generator at a comparatively high temperature and rejected from the absorber/condenser at a comparatively low level. Cold is produced in the evaporator.

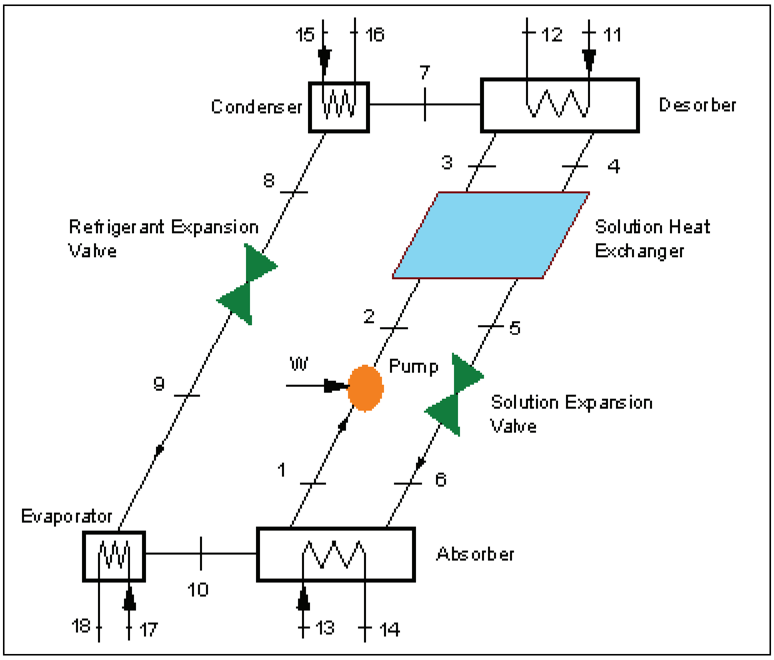

Figure 4.19 Schematic diagram of a simple effect absorption chiller

A more efficient configuration is the double-effect absorption chillers (figure 4.20). The easiest way to describe this cycle is to consider two single-effect cycles staged on top of each other. The cycle on top is driven either directly by a natural gas or oil burner, or indirectly by steam. Heat is added to the generator of the topping cycle (primary generator), which generates refrigerant vapour at a relatively higher temperature and pressure. The vapour is then condensed at this higher temperature and pressure and the heat of condensation is used to drive the generator of the bottoming cycle (secondary generator), which is at a lower temperature.

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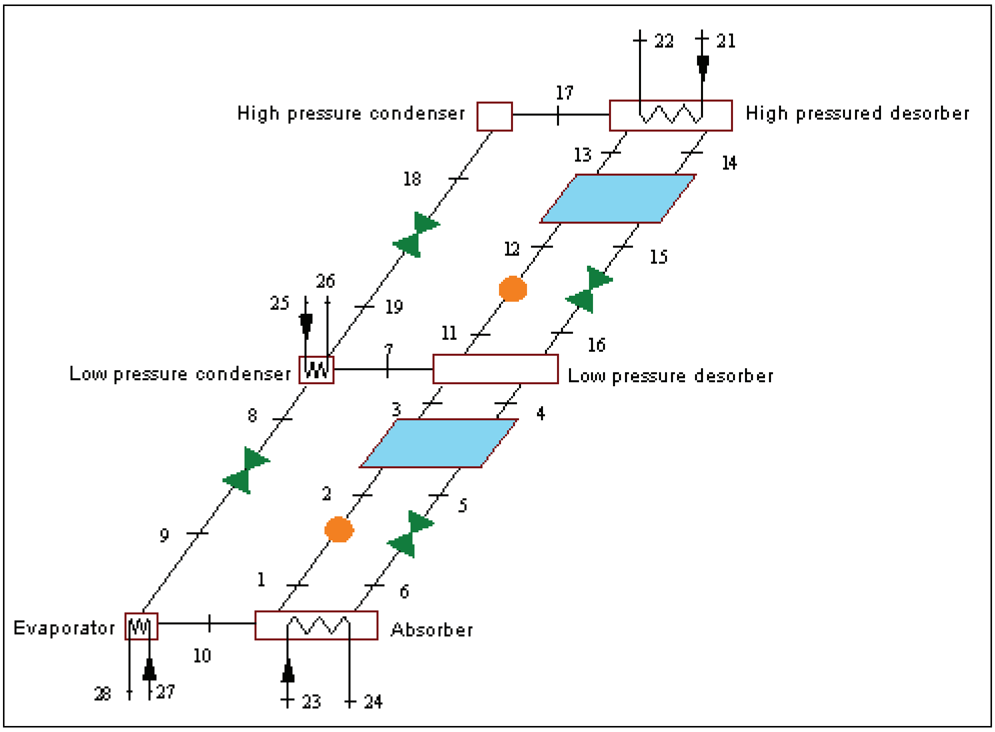

Figure 4.20 Schematic diagram of a double effect absorption chiller

Absorption chillers can be modelled using the characteristic equation method (Kühn et al 2005, Puig et al 2010). The energy required in the generator and the cooling produced in the evaporator can be calculated as a linear correlation of the average temperature in the main components of the absorption cycle (generator, evaporator and condenser-absorber) using equations of the type 4.53 and 4.54.

$$QE = AE \cdot TGen + BE \cdot TCond + CE \cdot TEvap + DE \qquad (4.53)$$

$$QG = AG \cdot TGen + BG \cdot TCond + CG \cdot TEvap + DG \qquad (4.54)$$

Where AE, BE, CE, DE and AG, BG, CG, DG are the coefficients of the correlations calculated from manufacturer or experimental data to calculate the cooling production and the energy requirements in the generator respectively. The variables required to model the absorption chiller using this methodology are presented in figure 4.21. Beside the binary variable to determine the operation of the chiller (y_i and $ytp_{i,j}$), the temperature for each component is also required. The nominal capacity is not necessary because is implied in equations 4.53 and 4.54, thus the model presented here using these equations is specific for concrete absorption chillers and can not be used to find the optimal nominal capacity of the chiller.

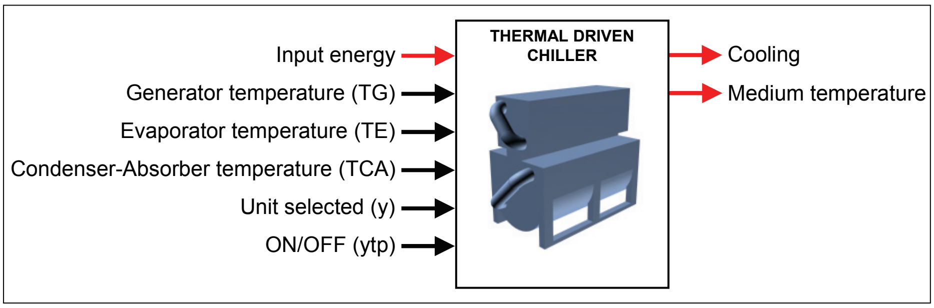

Figure 4.21 Input and outputs for the absorption chiller optimisation model

The equations for the optimisation model of the absorption chiller will be presented below. Equations 4.55, 4.56 and 4.57 calculate the cooling produced in the evaporator, the energy requirements in the generator and the cooling to be dissipated in the condenser-absorber respectively.

$$QE_{i,j} = AE_i \cdot TGen_{i,j} + BE_i \cdot TCond_{i,j} + DE_i \cdot TE_{i,j} + DEvap_i - SLKE_{i,j} \qquad (4.55)$$

$$QG_{i,j} = AG_i \cdot TGen_{i,j} + BG_i \cdot TCond_{i,j} + DG_i \cdot TEvap_{i,j} + DG_i - SLKG_{i,j} \qquad (4.56)$$

$$QC_{i,j} = QE_{i,j} + QG_{i,j} \qquad (4.57)$$

$$QE_{i,j} \le MaxQ_i \cdot ytp_{i,j} \qquad (4.58)$$

$$QG_{i,j} \le MaxQ_i \cdot ytp_{i,j} \qquad (4.59)$$

$MaxQ_i$ is a constant value that represents the maximum energy for any of the inputs or outputs of the chiller (input to generator, cooling or medium temperature). If the temperatures are variables of the model, slack variables ($SLKE_{i,j}$ and $SLKG_{i,j}$) are required to obtain zero values for $QE_{i,j}$ and $QG_{i,j}$ if the absorption unit is not working when some of the temperatures are not zero. The values of the slack variables can be calculated with the following equations:

$$SLKE_{i,j} \le MaxQ_i \cdot \left(1 - ytp_{i,j}\right) \qquad (4.60)$$

$$SLKG_{i,j} \le MaxQ_i \cdot \left(1 - ytp_{i,j}\right) \qquad (4.61)$$

$$SLKE_{i,j} \ge -MaxQ_i \cdot \left(1 - ytp_{i,j}\right) \qquad (4.62)$$

$$SLKG_{i,j} \ge -MaxQ_i \cdot \left(1 - ytp_{i,j}\right) \qquad (4.63)$$

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If the temperatures of the absorption chiller are constants $QE_{i,j}$ and $QG_{i,j}$ can be calculated beforehand to perform the optimisation for each time step, for example for fixed temperatures in the generator and the evaporator for each time step, and temperatures in the condenser-absorber calculated from the meteorological data. If $QEc_{i,j}$ and $QGc_{i,j}$ are the calculated values for each time step using the equations 4.53 and 4.54, the model can be written as follows:

$$QE_{i,j} = QEc_{i,j} \cdot ytp_{i,j} \tag{4.64}$$

$$QG_{i,j} = QGc_{i,j} \cdot ytp_{i,j} \tag{4.65}$$

$$QC_{i,j} = QE_{i,j} + QG_{i,j} \tag{4.66}$$

Other required equations and the economic balances can be calculated as follows:

$$ytp_{i,j} \leq y_i \tag{4.67}$$

$$MC_{i,j} = QE_{i,j} \cdot HxP_j \cdot MCF_{i,j} \tag{4.68}$$

4.5.2 Inertia for the absorption chillers

As a function of the size of the absorption chiller, once the heat source start delivering heating to the generator, the production of cooling in the evaporator can take some time. This delay depends on the size of the chiller and the quantity of solution that must be heated. This effect is never considered in mathematical programming optimisation models for several reasons. For example in scenario models with long time steps (weeks or months) is not necessary to consider this effect. In other cases it is possible to assume that the heat supplied to the generator until the evaporator start producing cooling, can be recovered because the cooling production will last some time once the heating supply to the generator stopped. From the economic and energetic point of view could be not necessary to consider this inertia, but in terms of operational and schedule optimisation this effect could be important, because affect the operation of the cogeneration units.

When the chiller is start-up some time is required to achieve the required temperature in the generator and start producing the refrigerant. Once the heating source of the generator is stopped, the hot solution in the generator is able to continue producing vapour during some time. The behaviour is very similar to the energy storage and the configuration presented in the figure 4.22 is proposed to consider the inertia in the generator.

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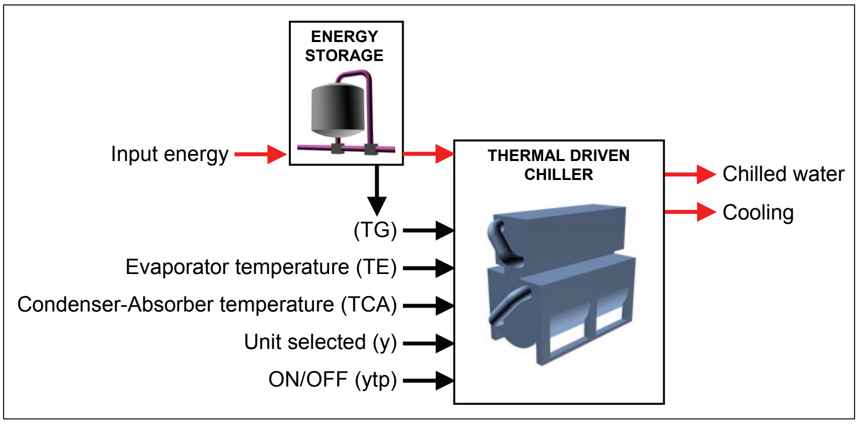

Figure 4.22 Absorption chiller and energy storage simulating inertia

The temperature of the generator to be used in the equation 4.55 and 4.56 is calculated using the energy level of the storage ($EL_{i,j}$ in equation 4.47).

If a prediction of the temperature is needed considering the energy accumulated in the storage,

$$m \cdot Cp \cdot \frac{dT}{dt} = Q \tag{4.69}$$

$$T_{t+1} = \frac{\Delta t \cdot Q_{\Delta t}}{m \cdot Cp} + T_t \tag{4.70}$$

$$T_{j+1} = \frac{HxP_j \cdot EBalance_{i,j}}{m \cdot Cp} + T_j \tag{4.71}$$

$$T_{t+1} \leq TAair \cdot yLA_{i,j} + MaxTDiff \cdot (1 - yLA_{i,j}) \tag{4.72}$$

$$T_{t+1} \geq TAair \cdot yLA_{i,j} - MaxTDiff \cdot (1 - yLA_{i,j}) \tag{4.73}$$

4.6 Rotary wheel for air flows

Rotary wheel are heat recovery systems usually applied for air conditioning. In winter, the supply air is preheated with the exhausts air of the building. Figure 4.23 shows a simplified scheme of a rotary wheel that consists of a wheel made with flat and corrugated aluminium foil. Half wheel is heated with the exhausts air and half wheel is cooled with the supply air. After some time, the wheel rotates so the part of the wheel that was in contact with the exhausts air preheats the supply air. The efficiency of the rotary wheel depends of the velocity of rotation. Typically the maximum efficiency that can be achieved is around 75%. In summer, the rotary

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wheel can be used the pre-cool the supply air if the exhaust air from the building is humidified to decrease its temperature, in that case the exhausts temperature of the building can be reduced around 19 ºC.

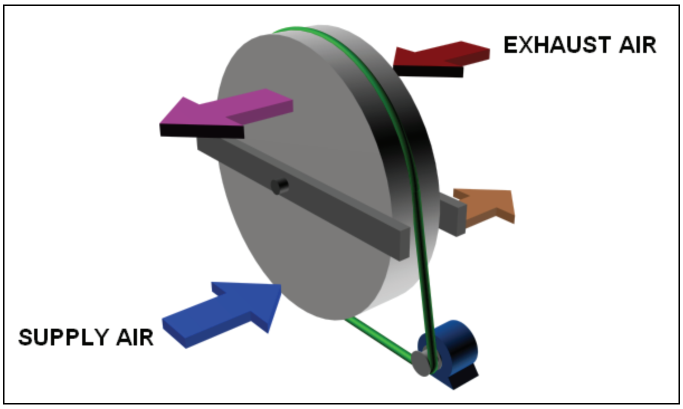

Figure 4.23 Rotary wheel pre heating the supply air

The rotary wheel can be modelled considering that a maximum efficiency can not be exceeded. As the efficiency depend of the velocity of rotation, from the optimisation point of view any efficiency between zero and the maximum efficiency is possible. The model proposed calculates the optimum heat exchange without exceeding the maximum determined by the maximum efficiency. Figure 4.24 shows the inputs and output for the rotary wheel models. In this figure green arrows means air flows, each air flow contains the following variables: mass flow rate (kg/s), temperature (ºC), humidity ratio (g/kg) and enthalpy (kJ/kg).

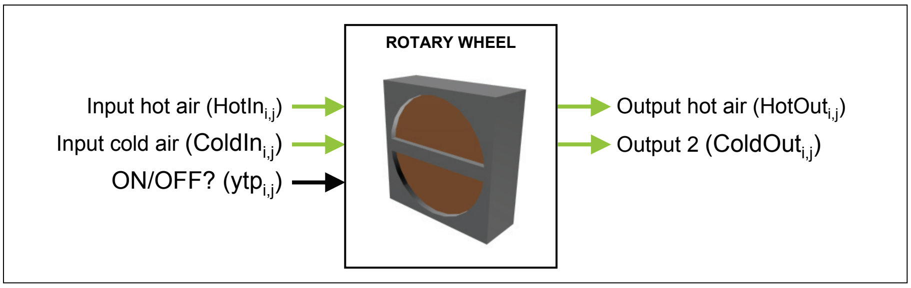

Figure 4.24 Inputs and output for the rotary wheel optimisation model

If the rotary wheel is used in summer and winter, the input hot air in summer (the ambient air) will be different from the input hot air in winter (the exhausts air from the building). For this reason, the energy balances must take into account the season. A parameter (RE) is defined with value zero when the real hot air corresponds with the "Input hot air" input in figure 4.24, and value one when the air flow in the "Input hot air" is the cold air. So the parameter RE indicates

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the season (winter or summer). The variable $ytp_{i,j}$ is a binary variable that indicates the state (ON/OFF) of the rotary wheel. Additionally to $ytp_{i,j}$, another binary variable ($yT_{i,j}$) must be defined to determine if with the current conditions, the temperature of the hot air is higher than the temperature of the cold air. For example, in summer, when the hot air is the ambient air, it is possible that in the first hours in the morning, the ambient air is colder than the exhaust air, in that case, the $yT_{i,j}$ will prevent the operation of the rotary wheel. The value $yT_{i,j}$ is calculated with equations 4.74 and 4.75.

$$\left(TCin_{i,j} - THin_{i,j}\right) \cdot \left(1 - 2 \cdot RF_{i,j}\right) \leq MaxTDiff_i \cdot \left(1 - yT_{i,j}\right) \tag{4.74}$$

$$\left(TCin_{i,j} - THin_{i,j}\right) \cdot \left(1 - 2 \cdot RF_{i,j}\right) \geq -MaxTDiff_i \cdot yT_{i,j} \tag{4.75}$$

Variables $ytp_{i,j}$ and $yT_{i,j}$ determines the operational status of the rotary wheel with the following equations:

$$Q_{i,j} \leq MaxQ_i \cdot ytp_{i,j} \tag{4.76}$$

$$Q_{i,j} \leq MaxQ_i \cdot yT_{i,j} \tag{4.77}$$

Additionally another variable can be introduced for the selection of the unit in the optimal solution using the binary variable y_i and the equation 4.78 if $ytp_{i,j}$ is used in the model or equation 4.79 if $ytp_{i,j}$ is not used in the model. As the solution determines the optimal quantity of heat exchanged between the air flows (Q), and this quantity can be zero, the presence of $ytp_{i,j}$ in the model is only necessary when there is other factors that determines the availability of the rotary wheel (for example, it can only work during certain hours or it can work only if another units are ON or OFF).

$$ytp_{i,j} \leq y_i \tag{4.78}$$

$$Q_{i,j} \leq MaxQ_i \cdot ytp_{i,j} \tag{4.79}$$

The heat recovered with the rotary wheel can be calculated with the following equations:

$$Q_{i,j} \geq 0 \text{ (Q defined as a positive variable)} \tag{4.80}$$

$$MaxHQ_{i,j} \cdot \left(1 - 2 \cdot RF_{i,j}\right) = \eta_{t,max} \cdot mH_{i,j} \cdot \left(THin_{i,j} - TCin_{i,j}\right) \cdot Cp \tag{4.81}$$

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$$MaxCQ_{i,j} \cdot (1 - 2 \cdot RF_{i,j}) = \eta_{t,max} \cdot mC_{i,j} \cdot (THin_{i,j} - TCin_{i,j}) \cdot Cp \tag{4.82}$$

$$Q_{i,j} \leq MaxHQ_{i,j} + 2 \cdot MaxQ_i \cdot (1 - yT_{i,j}) \tag{4.83}$$

$$Q_{i,j} \leq MaxCQ_{i,j} + 2 \cdot MaxQ_i \cdot (1 - yT_{i,j}) \tag{4.84}$$

$$Q_{i,j} \cdot (1 - 2 \cdot RF_{i,j}) = HCout_{i,j} - HCin_{i,j} \tag{4.85}$$

$$Q_{i,j} \cdot (1 - 2 \cdot RF_{i,j}) = HHin_{i,j} - HHout_{i,j} \tag{4.86}$$

Equations 4.81 and 4.82 determines the maximum heat that can be exchanged as a function of the maximum efficiency, and the heat exchanged if each input reach the same temperature that the opposite input air to the wheel (THin-TCin). These equations calculate maximum values of heat that can be exchanged. The heat exchanged (Q) must be lower (equations 4.83 and 4.84) that any of the maximum values calculated ($MaxHQ_{i,j}$ and $MaxCQ_{i,j}$) and the upper bound delimited with the binary variables (equations 4.76, 4.77 and 4.79).

The "direction" of the heat exchanged is determined using the RF factor. The term $2 \cdot MaxQ_i \cdot (1 - yT_{i,j})$ is introduced in equations 4.83 and 4.84 because when the input temperatures are crossed and the rotary wheel can not be used ($yT_{i,j} = 0$ and equation 4.77) the values $MaxHQ_{i,j}$ and $MaxCQ_{i,j}$ can be negative. Since $Q_{i,j}$ must be equal or greater than zero, the term $2 \cdot MaxQ_i \cdot (1 - yT_{i,j})$ prevents the violation of the equations 4.83 and 4.84.

4.7 Legal constraints: minimum EEE

Cogeneration plants that export electricity to the Spanish national grid must fulfil a minimum annual equivalent electrical efficiency (EEE) specified in the Royal Decree 661/2007. EEE is calculated using the equation 4.87.

$$EEE = \frac{E}{F - \frac{H + C}{\eta_{t\,ref}}} \tag{4.87}$$

Where E is the electrical production with the cogeneration units, F is the fuel consumption and H_{used} is the heating energy used by the user from all the usefull heating production (figure 4.25). The minimum EEE value that must be fulfilled depends of the type of fuel and the size of the cogeneration system.

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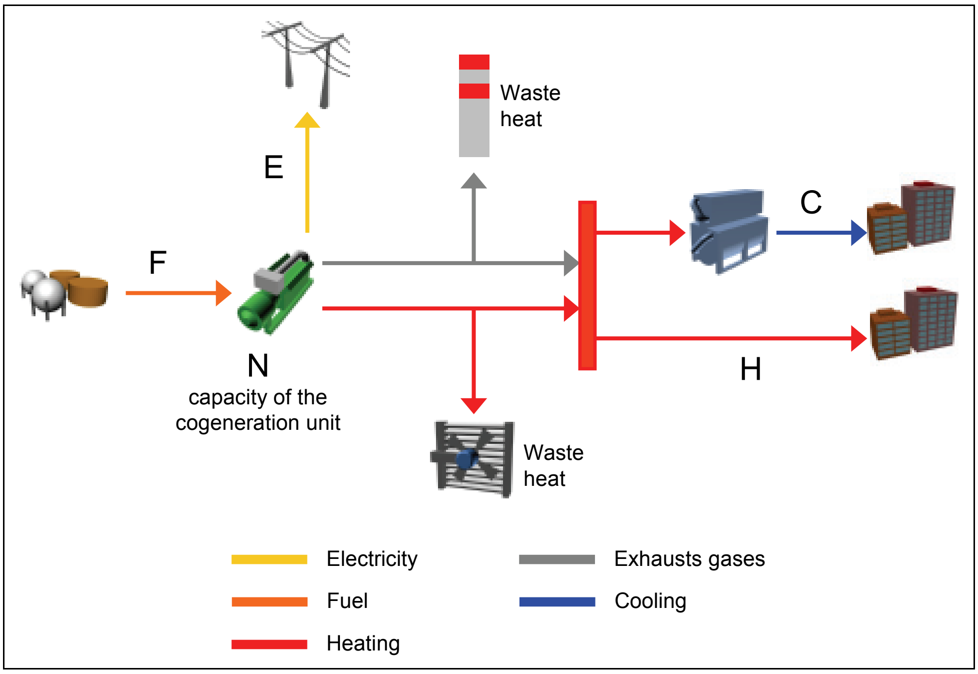

Figure 4.25 Energy flows required to calculate the EEE for a polygeneration system

For cogeneration engines with natural gas EEE must be greater than 55 % if the installed capacity is higher than 1 MW, otherwise EEE must be greater than 49.5 %. Figure 4.26 shows the inputs required to consider the minimum EEE constraint. The optimal size (N) of the cogeneration system is necessary only if two minimum EEE must be considered.

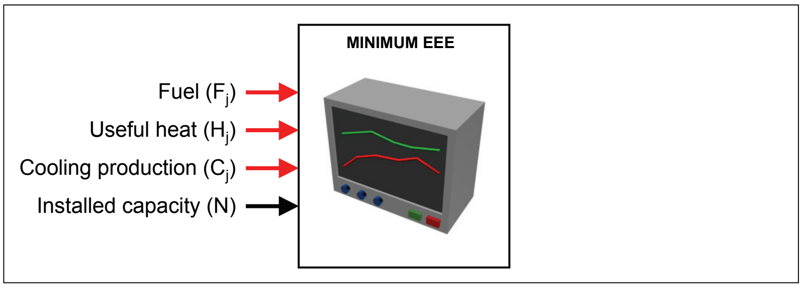

Figure 4.26 Inputs for the constraint EEE imposed in RD 661/2007

In the optimisation model this constraint can be implemented using the equation:

$$\mathrm{MinEEE}_i \cdot \left(F_{i,j} - \frac{H_{i,j} + C_{i,j}}{\eta_{t\,ref}} \right) \leq E_{i,j} \tag{4.88}$$

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If the nominal capacity of the cogeneration system is unknown and two different minimum EEE values must be included in the model, equation 4.87 must be replaced by the following equations:

$$MinLS_{i,j} = MinLS1_{i,j} + MinLS2_{i,j} \tag{4.89}$$

$$MinLS1_{i,j} = MinEEE1_i \cdot \left(F_{i,j} - \frac{H_{i,j} + C_{i,j}}{\eta_{t\,ref}} \right) - SLK1_{i,j} \tag{4.90}$$

$$MinLS2_{i,j} = MinEEE2_i \cdot \left(F_{i,j} - \frac{H_{i,j} + C_{i,j}}{\eta_{t\,ref}} \right) - SLK2_{i,j} \tag{4.91}$$

$$N_i - N_{i,lim} \leq 100 \cdot (1 - yEEE_i) \tag{4.92}$$

$$N_i - N_{i,lim} \geq -100 \cdot yEEE_i \tag{4.93}$$

$$SLK1_{i,j} \leq MaxF_i \cdot (1 - yEEE_i) \tag{4.94}$$

$$SLK2_{i,j} \leq MaxF_i \cdot yEEE_i \tag{4.95}$$

$$MinLS1_{i,j} \leq MaxF_i \cdot yEEE_i \tag{4.96}$$

$$MinLS2_{i,j} \leq MaxF_i \cdot (1 - yEEE_i) \tag{4.97}$$

Where $MinEEE_2$ is the minimum EEE when the installed capacity is higher than 1 MW, and $MinEEE_1$ is the minimum EEE when the capacity is lower than 1 MW. MaxF is an upper bound for SLK and MinLS variables, and is an approximated value of the maximum yearly consumption for the cogeneration units. Table 4.3 shows the values that can take the binary variable yEEE as a function of the optimal installed capacity (N) and the limiting capacity to determine the minimum EEE (1 MW).

Table 4.3 Values of the binary variable as a function of the capacity N

$N_{lim} = N$	$yEEE = 0$ or 1
$N_{lim} > N$	$yEEE = 1$
$N_{lim} < N$	$yEEE = 0$

4.8 Conclusions

Optimisation models have been presented in this chapter for several technologies. These models will be used to develop units (or blokcs used to create a flowsheet when are connected between them) using the optimisation environment (Chapter 5). Currently the optimisation environment has 79 units, so only few units have been presented in this chapter. The general guideline is to develop the units irrespective of other already developed units, so each unit is an independent module respect to the others. This means that some unit are modeled using just energy flows and other units may require the use of material flows (including mass flow rate, temperatures, enthalpy, etc.). The models and the environment are very flexible so the level of detail of the flowsheet for a specific case study can be adapted to the requirements of the analysis to be performed. Two examples of case studies are presented in Chapter 6 and Chapter 7. The former is an hourly model with a combination of units working with energy flows and other with material flows. The last is a model with fifteen days time steps and all the units works with energy flows.

Each unit can be modelled as a function of several factors, considering the input data from the user and the use of certain variables to determine ON/OFF states or selection of units. For this reason, the model that finally is solved with GAMS could be different for each unit.

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Chapter 5

Optimisation environment

5.1 Introduction

Mathematical programming in GAMS will be used for the development of the optimisation models. Mathematical programming is commonly used for the synthesis design, evaluation and operational optimisation of energy supply systems. The advantages of using GAMS are the flexibility to model the energy system and the availability of a high number of state of the art solvers, but sometimes it is difficulty for other users to expand or modify an existing model and reuse the models for other applications. Polygeneration systems are characterized for a high variety of possible combinations of technologies and different operational conditions that makes difficult to obtain a general model for all the cases. A user friendly interface (MGEOS) for Windows has been developed in this thesis to facilitate the use and the maintenance of the models and facilitate the use of the models to other users. Each unit of the polygeneration system is modelled using GUME, a self made editor that creates a GUM file for each unit. MGEOS represents each GUM file as a block that can be connected to other blocks to represent the entire flowsheet of the polygeneration system.

Section 5.2 presents a general overview of GAMS and the optimisation environment developed in this thesis. The main components of the optimisation environment are presented in the following sections. In section 5.3 is presented the GUME editor, with an outline of the structure and the syntax of the GUM files. Section 5.4 presents the MGEOS interface used to build the flowsheets of the polygeneration systems, explaining how to place and connect the units, how the input data is introduced, and how the model is solved and the solutions are stored. In section 5.5 there are a brief description of the current units developed for MGEOS.

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5.2 GAMS and the optimisation environment

All the optimisation models presented in this thesis are solved with GAMS (General Algebraic Modelling System). GAMS is an optimisation environment with several algorithms (solvers), those algorithms are applied as a function of the type of model (LP, NLP, MIP, MINLP). The users can write the optimisation model using the GAMS language without caring for the algorithm that will be used to solve the problem. Once the model is written and the algorithm is chosen, GAMS uses that algorithm to optimise the model. Figure 5.1 shows the GAMS interface where the users write the variables and equations for the model. This interface is called GAMS IDE (Integrated Development Environment). When the model is optimised, GAMS retrieves the solutions obtained (figure 5.2).

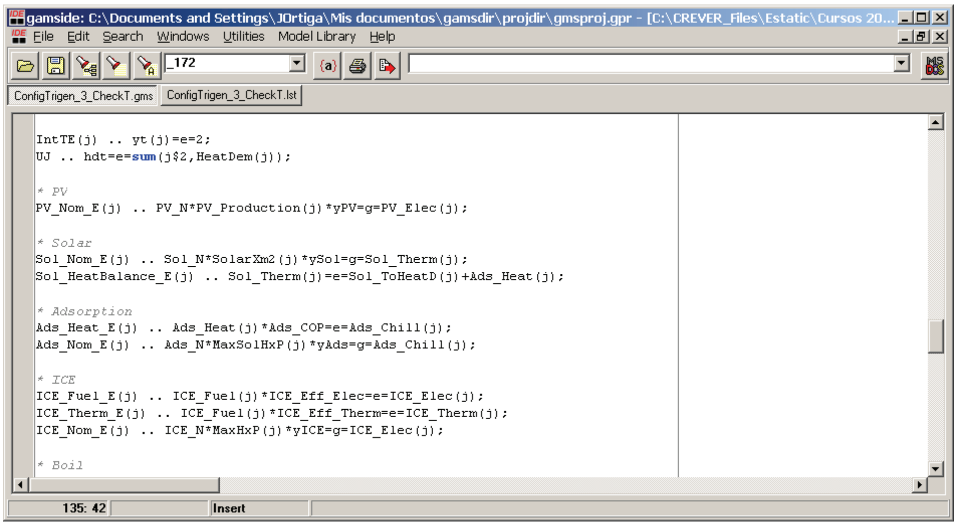

Figure 5.1 GAMS IDE screenshot, main window with an example of some equations

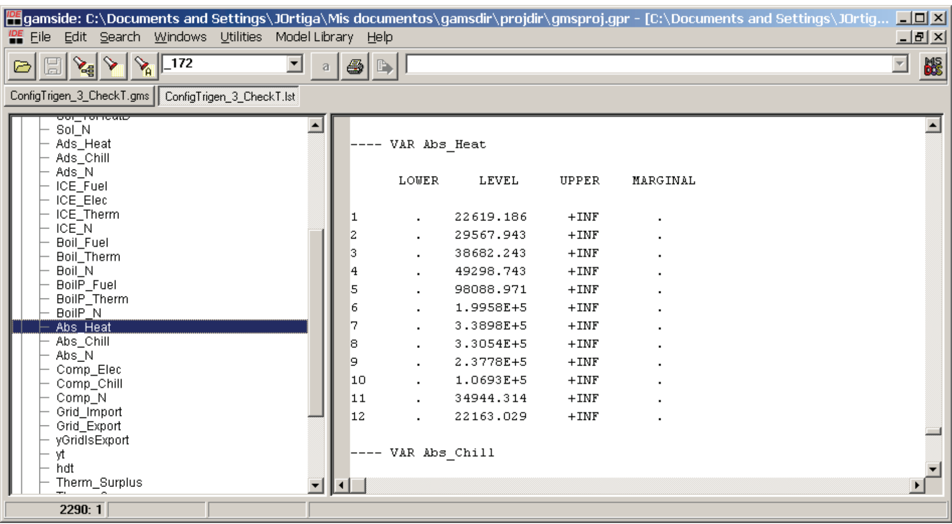

Figure 5.2 GAMS IDE screenshot with the solutions (variables list in the left panel)

The use of GAMS requires the knowledge of the GAMS language and the way in which optimisation models are formulated. Moreover, to write a general model for polygeneration plants is complicated due to the different possible technologies and configurations that must be considered. Usually the optimisation models are written for a specific application by skilled users of GAMS and the use of these models by other users could be difficult. The optimisation models developed in this thesis must be enough flexible and understandable to be applied to different applications and to be used by different users. A windows oriented interface has been developed to facilitate the application of the models and to facilitate the potentials users to build the polygeneration configuration. Users without knowledge of GAMS language will be able to use the configurations or models that already exist. All the input data and all the results are displayed through the interface called MGEOS (Modular General Energetic Optimisation System). In the interface, each unit of the polygeneration system (a cogeneration engine, an absorption chiller, etc.) is represented as a block that can be connected with others blocks, creating the flowsheet of the polygeneration system. Two types of users can be distinguished:

- "Standard" uses the interface with the units available to create the flowsheet of the polygeneration system, introduce the required information and optimise the model. The created flowsheet and the solutions can be saved and used by other "standard" users.
- "Developer" writes new units to be used in the interface or modifies existing units. This user must know the GAMS language and also the language used to create the units.

Figure 5.3 shows the whole optimisation environment developed in this thesis (Ortiga et al 2009). The GUM files contain the description of each unit and are created with GUME (GUM Editor). GUME is a text editor with special functions to facilitate the development of the unit's models. MGEOS reads the GUM files when is started and represents each file as a unit (or block) that can be connected to others blocks to create the flowsheets. The user introduces all the required information of the model (energy demand, efficiencies, etc.) using MGEOS. When the flowsheet is completed and all the information is introduced, MGEOS writes the optimisation model, executes GAMS and all the results are displayed in MGEOS. The flowsheets created, as well as all the information introduced and the results obtained, can be saved in a *.SDF file (Scenario Definition File) so other users can use the flowsheet with the information introduced and the results obtained, or just to change some values to obtain new solutions. In the next sections there is a brief description of all the components that appears in figure 5.3.

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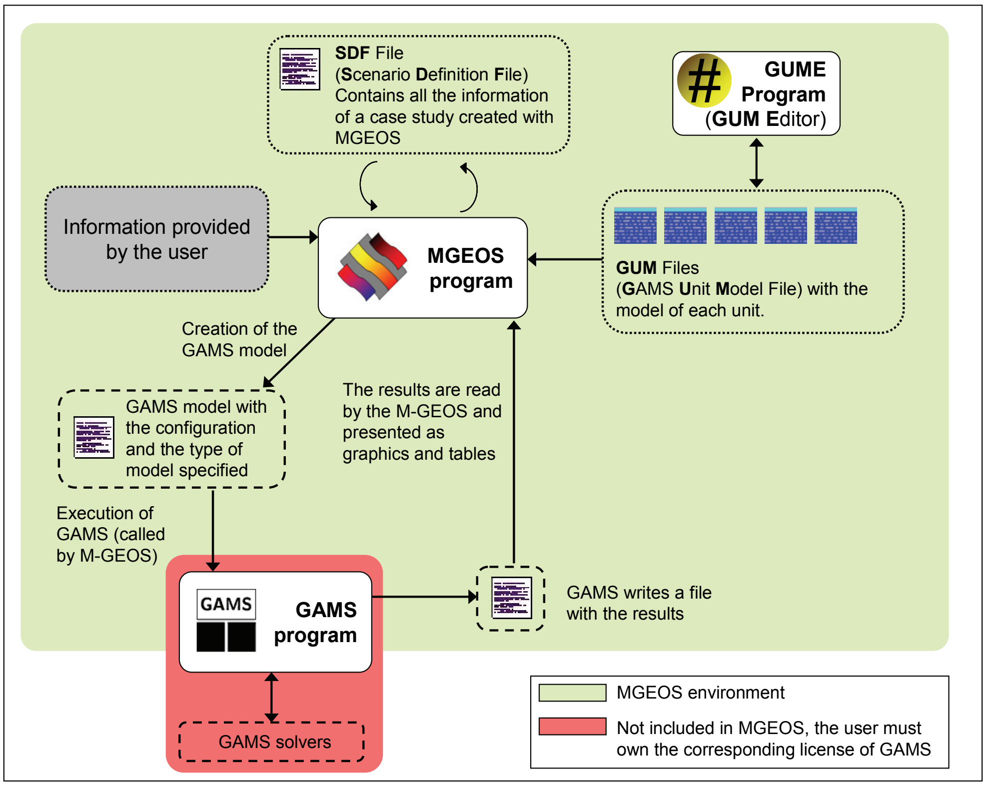

Figure 5.3 Optimisation environment, with the developed tools MGEOS and GUME

5.3 GUM Editor (GUME)

GUME editor is used to create the GUM files, which contains the description of the units for MGEOS their input parameters and the equations that will be used to create the GAMS models. Each GUM file represents a type of unit (a cogenerator, an absorption chiller, etc.) that can be placed in the flowsheet as times as necessary. Although several units of the flowsheet could belong to the same GUM file, the values for the input parameters of each unit and the connections performed are different.

The GUM files and its modularity to create the flowsheets are the basis of the optimisation environment presented in the previous section. The environment is open and more GUM files can be added or the existing GUM files can be modified. When a new file is created or an existing one is modified, MGEOS must be restarted or the “Reload” button in the MGEOS library must be pressed to update the changes in the MGEOS library. GUME has been made to facilitate the development and the maintenance of the optimisation models and to unify the way in which models are developed.

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A special language for GUME has been created to describe the properties of the units, define the parameters and variables and write the equations. GUME files are not written using the GAMS language, but knowledge of GAMS is necessary. In the GUM files is decided which variables or equations are defined and added to the GAMS model as a function the input parameters from the user, the flowsheet and the performed connections.

Figure 5.4 shows a screenshot of GUME, which has been created with Borland Delphi 2006 and has almost 26,000 lines of code. For the development of GUME is required the component TMS AdvMemo from TMS Software. With GUME it is possible to work with up to ten files simultaneously and has several shortcuts and features to facilitate the development of the GUM files:

- Syntax highlight: all the items like key words, indexes, comments, sections of the file are highlighted with a special format and colour following a criteria for the new language developed.
- Files comparator allows the comparison of two files line per line to find the differences in the text.
- Repetition of text changing an index. This function is used to repeat block of instructions or equations where the only different is a numeric index.
- Enumeration of all the key items described inside the GUM file (input parameters, connectors, variables and indexes)
- Hint for instructions, GUME shows the required parameters for the current instruction (small yellow squared, in figure 5.4)
- Several types of comments can be used in GUME:
    - General comments for GUME: Orange text (using !) or red text (using \)
    - Section comments: text with grey background (using |)
    - Comments in GUME that are copied to the GAMS models: grey text using &

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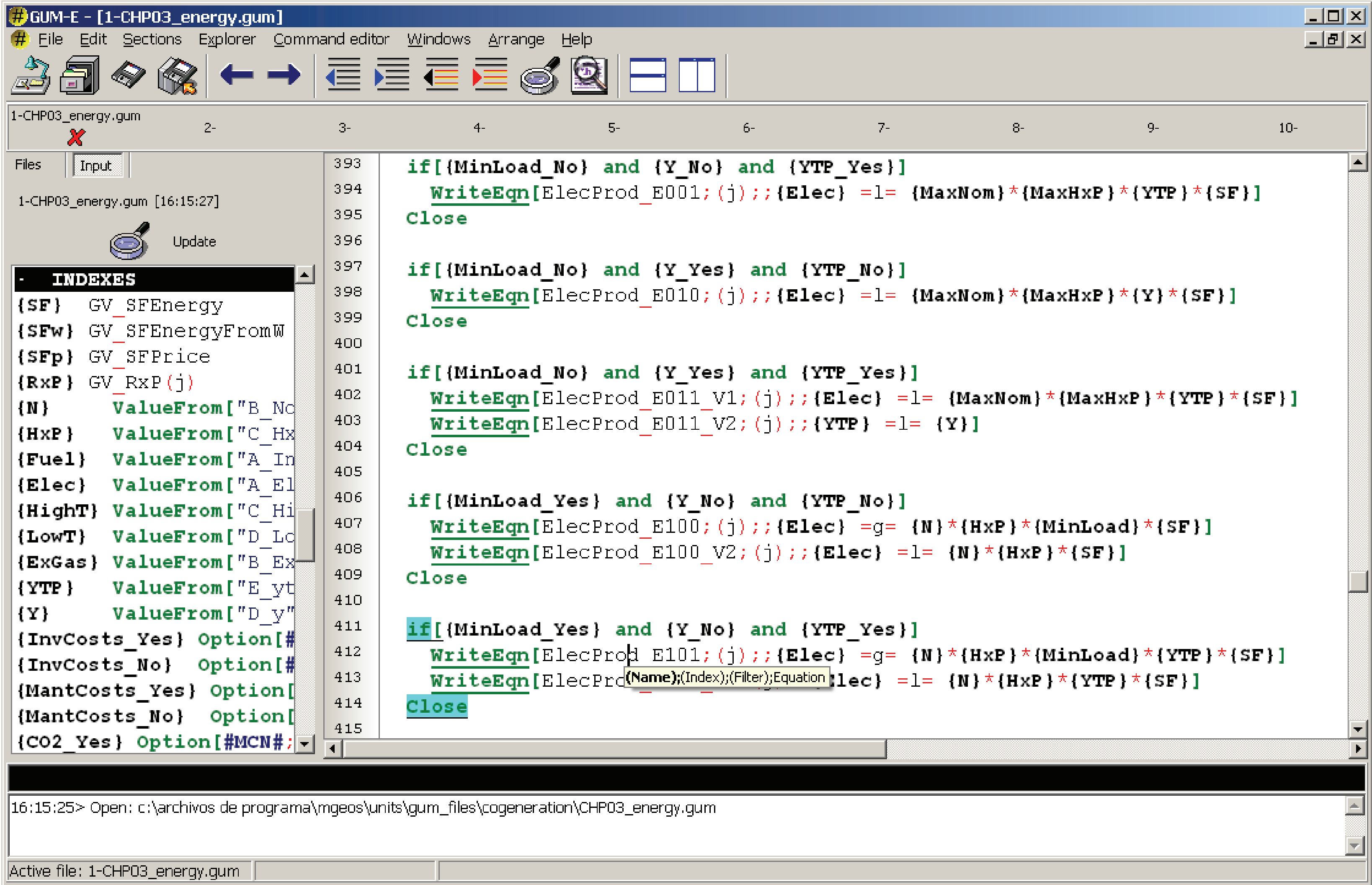

Figure 5.4 GUME editor screenshot with an example of a GUM file, showing the equations section

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Table 5.1 summarizes the main sections of a GUM file and figure 5.5 shows a screenshot of an empty GUM file created with GUME. All the sections are highlighted and can be distinguished easily. Each section of the GUM file has a different purpose. Only section 2 must be fulfilled completely because contains the information required by MGEOS to represent the GUM file as a block. Each section of the GUM file will be described from section 5.3.1 to 5.3.4.

Table 5.1 Brief description of a GUM file with a brief description of the purpose of each section

Section		Syntax	Purpose
1	General description	**#TEXT** *…Description…* **#F**	Describe the purpose of the unit, what is modelled and how. This information is displayed to the user in the unit library in MGEOS.
2	Unit description	**#DESCRIPTION** CommonName:"" CodeName:"" Hierarchy: Classification:"" TypeDrawing: BigIcon:"" SmallIcon:"" InsideUnit:"" MaxUnits: **#F**	Describe the main properties that identifies each unit in MGEOS
3	Unit parameters	**#INPUT** Name,String,Unit name,"Name" **#F**	Define the input parameters required for each unit.
4	Connectors	**#CONNECTORS** **#F**	Define the input and output connections.
5	Options	**#DOP-** **#F**	Define options those are applied for all the units of the same type.
6	Process	**#PROCESS** **#F**	Declare parameters and variables and to write the input values of the unit. Indexes are declared in this section.
7	Equations	**#EQN_** **#F**	Write the equations that characterizes each unit.

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```
· 1.GENERAL DESCRIPTION                                              [NO RELOAD]·

#TEXT

#F

· 2.UNIT DESCRIPTION                                                    [RELOAD]·

#DESCRIPTION
CommonName:""
CodeName:""
Hierarchy:
Classification:""
TypeDrawing:
BigIcon:""
SmallIcon:""
InsideUnit:""
MaxUnits:
#F

· 3.UNIT PARAMETERS                                                     [RELOAD]·

!Parameter name,Type,Default Value,Text description (all in one single line)
!For array: Parameter name,Type,Text description (all in one single line)
#INPUT
Name,String,Unit name,"Name"

#F

· 4.INPUT AND OUTPUT CONNECTORS                                         [RELOAD]·

! Code name,Connector type,IsMultiple?,Common name
#CONNECTORS

#F

· 5.OPTIONS                                                             [RELOAD]·

! Common name
! Type of option (integer, usually 0)
! Default value (integer)
! Total number of values for this option (integer)
#DOP-

#F

· 6.PROCESS                                  [RELOAD only if Link[] is changed]·

#PROCESS

#F

· 7.EQUATIONS                             [RELOAD only if model name is changed]·

#EQN_

#F
```

Figure 5.5 Screenshot of an empty GUM file created with GUME showing all the sections of the file

5.3.1 "General description" and "Unit description" sections.

The first section is a brief description of the GUM file that will be displayed when the user is looking for a unit in the MGEOS library. The second section contains the main information that MGEOS uses to identify and represent each unit as a block for the flowsheet. The meaning of each property of this section is described below:

- **CommonName** is the name displayed to the user in the MGEOS library.
- **CodeName** is an internal name used to write the GAMS model.
- **Hierarchy** is used to organise the units inside the GAMS model. Several groups (or sets) are defined, for example a group of units with investment costs, a group of unit with CO_2 emissions, etc. In this property are defined to which groups correspond each unit. The groups defined currently are listed below (more groups can be added):
  - All_S: all the units are included in this group.
  - *UnitCodeName_S*: the Code Name of each type of unit is used to create a group where those units are included.
  - Master_S: in this group are included the units that contain other units. The units included in the group Master_S are responsible to calculate several indicators for each unit, time period and year. These indicators correspond to the groups indicated below. If a unit is included in one of the following groups, the corresponding indicator will be calculated for that unit; and the results will be available in the unit and in the corresponding master unit.
    - Dim_IC: Investment cost.
    - Dim_BSC: Operational benefits and costs.
    - Dim_MC: Maintenance costs.
    - Dim_CO2: CO_2 production.
    - Dim_SO2: SO_2 production.
    - Dim_EPC: Primary energy consumption.
- **Classification** is the tree structure (order) in which the units are displayed in the MGEOS library.
- **TypeDrawing** indicates how is represented the block in MGEOS for each unit (from the graphical point of view). There are four possible values listed in table 5.2.

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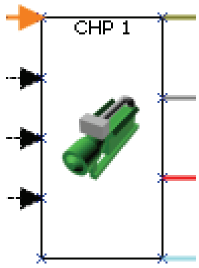
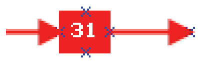
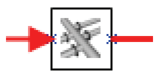
Table 5.2 Representation of each block in MGEOS as a function of "TypeDrawing"

Value for "TypeDrawing"	Example	Purpose
0		Default representation for the main units, inputs placed to the left, output to the right. The height of the block depends on the number of connections
2		Representation for variables, only the name is displayed, without any picture. Height and width is fixed.
3		Typical representations for energy or material flows, the maximum number of connectors that can be used are four. Input connector placed to the left, output connector placed to the right. Input data connector to the bottom and output data connector placed up. Height and with fixed, the name must be a number.
4		Representation for small or auxiliary units, the name of the unit is not displayed in the flowsheet, only the small image that represent the unit. Height and width fixed.

- **BigIcon** is a big image (44x44 pixels) that represents the unit or block in the MGEOS flowsheet as a function of the parameter **TypeDrawing**

- **SmallIcon** is a small image (22x22 pixels) that represents the unit or block in the MGEOS flowsheet as a function of the parameter **TypeDrawing**

- **InsideUnit** indicates inside which type of unit (**CodeName**) can be placed the current unit when is inserted to the MGEOS project. The type of unit specified in this field is the "Master" for the current unit.

- **MaxUnits** is the maximum number of units that can be placed in the flowsheet, if -1 there is no limit.

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5.3.2 Units parameters and Connectors sections

The third section, **Unit parameters** contains all the input parameters of the unit, like investment costs, efficiencies, emissions, etc. The type of parameters that can be specified and some examples are listed in table 5.3.

Table 5.3 Type of parameters that can be defined in the GUM file as input parameters

Parameter type — **Example (input parameter form in MGEOS)**

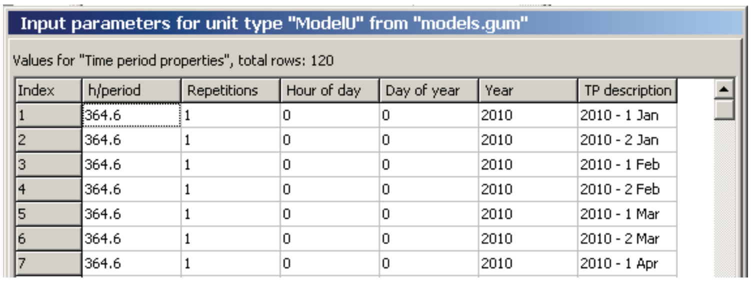
Integer

Real

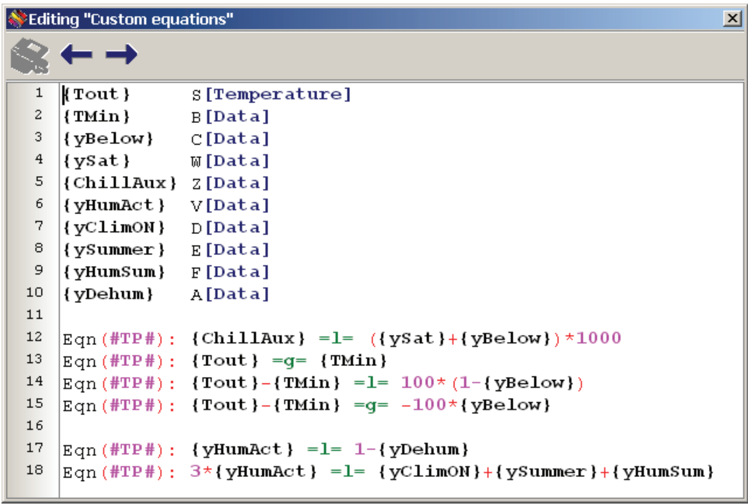
String

Boolean

Array



Memo



TypeVar

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In the fourth section **Connectors,** there is the description of all the input and output connectors. The connectors are declared as follows:

ConnectorCodeName,ConnectorType,MultipleOption,ConnectorName

The meaning of each term is described below:

- **ConnectorCodeName** is the internal name of the connector used inside the GUM file.
- **ConnectorType** indicates the type of connector (input/output) and to which type of connector can be attached.
- **MultipleOption**, if true, more than one connection can be made for to the same connector.
- **ConnectorName** is the name that appears in MGEOS, when the user is performing the connections.

5.3.3 Options section

An option is a value specified for all the units (or blocks) of the same GUM file. In contrast to the input parameters (each unit has different values), the value specified in Options are the same for all the units belonging to the same GUM file. Options are used in few occasions, one example can be found in the master unit that represents a power plant (figure 5.6). This unit has several option parameters to decide if results like investment costs, maintenance costs, emissions, etc. must be calculated. The value specified affects to all the plants of the flowsheet. Figure 5.6 summarizes how the options are defined (orange text) and shows and example.

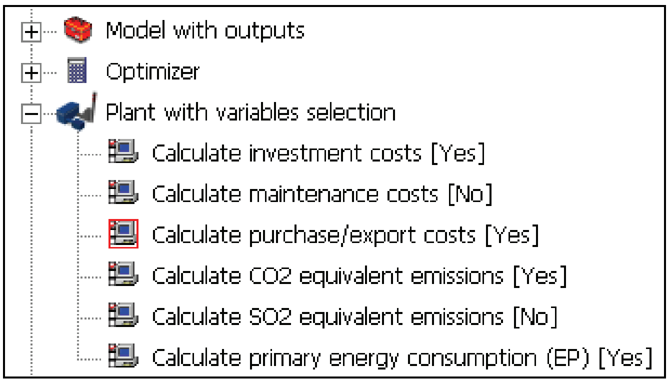

Figure 5.6 Units library in MGEOS, options of Plant unit

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```
! Common name
! Total number of values for this option (integer)
! List of options
! Description of the option
#DOP-InvCosts
"Calculate investment costs"
2
"Yes"
"No"
"This option allows the calculation of the investment costs for all the units"
"placed inside the Plant unit. The investment cost for each unit and the total"
"investment cost will be available as an output in the Plant unit."
#F
```

Figure 5.7 Option example in a GUM file to choose if investment costs must be calculated

5.3.4 Process and equations section

The users can declare and write in the **Process** section the values of the parameters or variables that will be used in the GAMS model. The equations of the units are written in the **Equations** section. These equations are the energy balances or constraints of the units. The instructions that declare the variables and writes values or equations can be placed inside loop and conditionals expressions. This means the parameters, variables or equations written in the GAMS model created by MGOES for several units corresponding to the same GUM file, can be different as a function of the input parameters or connections performed for each unit. If there are no loop or conditionals expressions, the equations for several units of the same GUM file will be equal. For this reason, due to the nature of the model, with several units with different characteristics, all the instructions must be placed inside **For[]** loops. Loops and conditionals expressions are described in table 5.4.

Indexes are a special feature of the GUM files and are defined in the **Process** section, but can be used in the **Process** and **Equations** sections. Indexes are the only instruction that is placed outside a loop because indexes only indicate the string that is replacing. Indexes are used to facilitate the development of the models and make the GUM files more readable. Indexes are declared as follows:

{Index Name} String to replace

Indexes can replace parameters, variables or conditional expressions so in the rest of the GUM file it is only necessary just to write the index instead of the string that the index replaces. Moreover, if an input variable or parameter is modified in the GUM file, it is only necessary to update the index, and it is not necessary to update all the instructions and equations where appears the modified variable or parameter. Figure 5.8 shows and example for several indexes.

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Table 5.4 Description of loop and conditional instructions that can be used in the GUM files

For[;#CN#] *Instructions* Close	The instructions inside this FOR are repeated for each unit of the flowsheet corresponding to the current GUM file. #CN# means CodeName. The meaning of this instruction is "for all the units with the CodeName = to the CodeName of this GUM file"
For[all_tp;#CN#] *Instructions* Close	The instructions inside this FOR are repeated for each unit of the flowsheet corresponding to the current GUM file and for each time period. The meaning of this instruction is "for all the units with the CodeName = to the CodeName of this GUM file and from time period = *Initial TP* to time period = *Final TP*"
If[*Conditions* AND/OR *Conditions*] *Instructions* Close	The *Instructions* are evaluated if the *Conditions* are fulfilled. For each condition, the following operators can be used: • = equal to • > higher than • < lower than • ^ different from

```
| General Values |

{SF} GV_SFEnergy      ! {SF}*{N}*{HxP} = {Energy} N and Energy in the u
{SFw} GV_SFEnergyFromW ! {SFw}*{N, W} = {Energy} Energy in the units ind
{SFp} GV_SFPrice      ! {SFp}*{Energy}*{Price}={Total price, €} Energy
{RxP} GV_RxP(j)       ! Repetitions factors, how many times an hour (or

| Variable indexes |

{N}      ValueFrom["Nominal";"Data";]     ! Nominal capacity
{HxP}    ValueFrom["HxP";"Data";]         ! Working hours per time period
{Fuel}   ValueFrom["InputFuel";"Energy";] ! Input fuel
{Elec}   ValueFrom["Elec";"Energy";]      ! Electricity out
{HighT}  ValueFrom["HighT";"Energy";]     ! High T out
{LowT}   ValueFrom["LowT";"Energy";]      ! Low T out
{ExGas}  ValueFrom["ExGas";"Energy";]     ! Exhausts Gas
{YTP}    ValueFrom["ytp";"Data";]         ! Y binary for all TP
{Y}      ValueFrom["y";"Data";]           ! Y binary

| Conditional indexes - From Master |
! Investment costs must be calculated?
{InvCosts_Yes} Option[#MCN#;InvCosts] = 0
{InvCosts_No}  Option[#MCN#;InvCosts] = 1

! Maintenance cost must be calculated?
{MantCosts_Yes} Option[#MCN#;MantCosts] = 0
{MantCosts_No}  Option[#MCN#;MantCosts] = 1
```

Figure 5.8 Example of indexes declaration including variables and conditionals

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The syntax to declare the variables or parameters that will be included in the GAMS model are detailed in table 5.5. **Declare[]** instruction can be used only in the **Process** section of the GUM file. The first row of the table shows the complete syntax for this instruction, the possible value for each parameter of the instruction is detailed in the following rows. **Declare[]** is used to define parameters or variables included in the GAMS model, **DeclareOut[]** is used to declare parameters after the GAMS model and the GAMS Solve statement, where several operations with the GAMS results can be done and do not take part in the optimisation process. Figure 5.9 shows an example of how to declare two parameters using **Declare[]** and **DeclareOut[]**.

Table 5.5 Declare[] and DeclareOut[] instructions used to define variables or parameters in GAMS

Declare[Type; VarName; (Label); (Output index); (Output filter)**]** **DeclareOut[**Type; VarName; (Label); (Output index); (Output filter)**]**	
Type	Indicates the type of variable, the possible values are the following: • Variable type • P: parameter • PV: positive variable • NV: negative variable • FV: free variable • IV: integer variable • BV: binary variable
VarName	Internal name of the variable, used to create the name of the variable that will be added to the GAMS model.
Label	Optional parameter. If it is not empty, the resulting value of the variable will be available from the MGEOS results window after the optimisation with the name written for this property. The keyword #NAME# displays the name of the unit where the variable or parameter is defined.
Output index	Optional parameter. Used to filter the values that will be displayed in MGEOS after the optimisation (obsolete, usually is not filled).
Output filter	Optional parameter. Used to filter the values that will be displayed in MGEOS after the optimisation (obsolete, usually is not filled).

```
if[ {OPct_Yes} ]
  ! Electrical
  Declare[P;#CN#_ID_#i2#_ElecEff;"#NAME# Electrical efficiency (%)";;]
  ! OP calculated in output section
  DeclareOut[P;#CN#_ID_#i2#_OP(j);"#NAME# Load (%)";;]
Close
```

Figure 5.9 Example of Declare[] and DeclareOut[] placed inside a conditional

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The keywords **#CN#** and **#i2#** in the figure 5.9 are used to create variables with a unique name for each unit of the flowsheet. Inside a **For[]** instruction, **#i2#** represents the second index of the **For[]** instruction (the identifier, an unique number of each unit added to the flowsheet and assigned automatically by MGEOS). **#CN#** means the CodeName of the current GUM file. If the **Declare[]** and **DeclareOut[]** instructions are placed inside a GUM file with CodeName "CHP", and two units corresponding to this GUM file are included in the flowsheet, one with identifier = 1 and another with identifier = 2, the following parameters will be declared in the GAMS file by MGEOS (from the intructions in figure 5.9):

- CHP_ID_1_ElecEff
- CHP_ID_1_OP(j)
- CHP_ID_2_ElecEff
- CHP_ID_2_OP(j)

The values assigned by the user to the input parameters (third section of the GUM file) can be read using the **Value**[] instruction (table 5.6). **Write[]** instruction (table 5.7) to write the values of single values or arrays or to define equations with parameters that are evaluated before the optimisatin process.

Table 5.6 Value[] instruction used to read the values assigned by the user to the input parameters

Value[VarName; Index TP; Array Column; Unit**]**	
VarName	VarName is one of the input parameters declared in the **#INPUT** section.
Index TP	Only for arrays. In this case the **Value[]** instruction must be placed inside a **For[all_tp;#CN#]** instruction. **Index TP** must be equal to **#i1#** that correspond to the first index of the For instruction (the time period)
Array Column	Only for arrays. Indicates the column of the array to be read.
Unit	Indicates from which unit is going to be read the variable, this parameter must be **#i2#** (the second index of the For[] instruction that identifies each unit).

Table 5.7 Write[] instruction that allows the user to write the content of the instruction in GAMS

Write[Params**]**	
Params	Params will be written in the GAMS model. If **Value[]** instruction is included inside Params, the value read will be written in the GAMS file.

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An example of application of **Write[]** and **Value[]** instructions is shown in figure 5.10. These instruction are used to write the values from the input parameters of the unit for a single value (line 326) and for an array (line 331) as a function if the value to be written: a constant value for all the time periods, or a different value for each time period.

```
319 |  SO2 emissions  |
320 For[;#CN#]
321   {SO2_Factor} #CN#_ID_#i2#_SO2prod(j)
322   if[{SO2_Yes}]
323     Declare[P;{SO2_Factor};;;]
324   Close
325   if[{SO2_Yes} AND {SameSO2_Yes}]
326     Write[{SO2_Factor} = Value[ConstSO2;;;#i2#];]
327   Close
328 Close
329 For[all_tp;#CN#]
330   if[{SO2_Yes} AND {SameSO2_No}]
331     Write[{SO2_Factor}('#i1#') = Value[VarSO2;#i1#;1;#i2#];]
332   Close
333 Close
```

Figure 5.10 Example of Write[] inside several loop and conditionals

Value[] can be used also in conditionals expressions like the example in figure 5.11, two indexes are defined using the **Value[]** instructions, these indexes can be used after in conditional evaluations.

```
! Fix minimum load?
{MinLoad_Yes} Value[MinLoadV;;;#i2#] ^ 0
{MinLoad_No}  Value[MinLoadV;;;#i2#] = 0
```

Figure 5.11 Index with Value[] and conditionals

Table 5.8 shows a conditional expression that returns one if the specified connector of the specified unit (or block) is connected to any other unit, otherwise the expression returns zero. Usually **IsConnected[]** is used to evaluate if optional connectors are connected to include different parameters, variables or equations.

Table 5.8 IsConnected[] instruction used to check if a connector defined in the GUM file is attached

IsConnected["Connector Code Name"; Unit**]**	
Connector Code Name	Connector Code Name is the internal name of one of the connectors defined in the GUM file. For this connector will be checked if it is connected to any other unit at the moment of the creation of the GAMS model.
Unit	Indicates to which unit is going to be check the connector. Unit must be equal to **#i2#**.

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The **Option[]** expression is used to read the value of and Option section of the specified unit. For example, once the Option value for "Calculate the investment costs?" is fixed in the master unit (see 5.3.3), **Option[]** can be used in each slave unit to decide if the equations and parameters regarding to the calculation of the investment costs must be added to the GAMS model. Table 5.9 shows the syntax for this instruction.

Table 5.9 Option[] instruction to read the value assigned to an Option of a GUM file (section 5.3.3)

Option[Unit; Option Name**]**	
Unit	Unit is the GUM file from where the option value must be readed. Usually refers to the master of the current unit, #MCN# the CodeName of the master for the current GUM file.
Option name	Indicates the name of the option that must be readed. This option is placed in the Unit (or GUM file) specified in the previous field.

The variables declared (**Declare[]** instruction) can be "attached" to one or several of the connectors of the GUM file. Other units connected to those connectors can use the variables attached. This is the way in which the information "flows" from one unit to the others. Several variables can be attached to the same connector. For example, to one connector can be attached only a variable that accounts for the energy input/output. In other cases, to consider material flows, to the same connector can be attached a variable for the temperature, another for the enthalpy, etc. Several variables attached to the same connector are distinguished using a **Label** (see table 5.10).

Table 5.10 Link[] instruction used to attach variables to a connector so is avaliable to others blocks

Link[VarName;"Connector Name";"Label"**]**	
VarName	VarName is one of the variables or parameters declared inside the GUM file.
Connector Name	Name of the input/output connector declared in the GUM file at which the variable will be attached.
Label	Is the type of information attached to the input/output connector. Currently the available labels are listed below: • Data • Energy • Mass • Temperature • Water ratio • Specific enthalpy • Total enthalpy

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For example if connector AC1 in unit A is connected to connector BC1 in unit B, A can use the variables defined in B and linked to connector BC1 using **ValueFrom[]**. These linked variables defined in B can be used in the equations of the GUM file in A. This instruction can be used in the **Process** section to declare indexes and in the **Equations** section to use the attached variables in the equations defined in the GUM file. **Label** indicates which variable must be read.

Table 5.11 ValueFrom[] instruction used to retrieve variables linked to connectors of other blocks

ValueFrom["Connector Code Name"; "Label"; ("Operator")**]**	
Connector Code Name	Name of one of the input/output connector declared in the GUM file.
Label	Label is one of the Data Types described in the table 5.10
Operator	(Optional) Determines the arithmetic operation to be performed when a multiple connector has several connections. The most common operators is +. In that case all the values read from the several connections will be summed.

Message can be used only in the **Process** section and it raises a message when MGEOS is creating the GAMS model (table 5.12). **Message** can be used to raise warning messages about the values of the input parameters, the connections performed or other options.

Table 5.12 Message[] instruction used to show a text during the creation of the GAMS model

Message[Params**]**	
Params	Params will be displayed by MGEOS during the creation of the GAMS model, Message[] can be used with conditional expressions to show warning messages.

Stop[] can be used only in the Process section and it interrupts the creation of the GAMS model. **Stop[]** can be used to check the input values, to check if an optional connector is connected or not in the case that connector is required, or any other verification.

Table 5.13 Stop[] instruction, used to interrupt the creation of the GAMS model by MGEOS

Stop[Params**]**	
Params	Params will be displayed by MGEOS during the creation of the GAMS model. Stop[] can be used with conditional expression to check certain conditions and interrupt the creation of the model.

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WriteEqn can be used only in the **Equations** section, the purpose of **WriteEqn** is to write the equations in the GAMS model, using the parameters or variables declared inside the GUM file or the variables from other units or energy flows using **ValueFrom**. The parameters required are detailed in table 5.14

Table 5.14 WriteEqn[] instruction used to declare and write the equations of the GAMS model

WriteEqn[(NameEqn); (Index); (Filter); Equation**]**	
NameEqn	Name of the equation used for the GAMS file.
(Index)	Index of the equation, if the equation is going to be repated for each time period, Index = (j)
(Filter)	Filter to be used for the equation.
Equation	Equation to be written in the GAMS file.

WriteEqnOut can be used only in the **Equations** section, **WriteEqnOut** writes equations in the GAMS file but after the model and solve statement. This means that the equations defined with **WriteEqnOut** do no take part of the optimisation process, and all the operations made are done with the solution of the model. These equations can be used to perform additional calculations which results are not used in the GAMS model. The parameters required are detailed in table 5.15.

Table 5.15 WriteEqnOut[] instruction used to declare and write equations after the solve section

WriteEqnOut[(NameEqn); (Index); (Filter); Equation**]**	
(NameEqn)	Empty. It is not necessary to write a name.
(Index)	Index of the equation, if the equation is going to be repeated for each time period, Index = (j)
(Filter)	Filter to be used for the equation.
Equation	Equation to be written in the GAMS file.

Examples of **WriteEqn[]** and **WriteEqnOut[]** are shown in figure 5.12, from line 282 to 285 there is an example of **WriteEqn[]**, from line 242 to 253 the WriteEqn[] is enclosed inside conditionals instructions. Finally from line 348 to 351 there is an example of **WriteEqnOut[]**.

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```
For[;#CN#]
  WriteEqn[ElecProd_E;(j);;{OutFlow} =l= {N}*{HxP}*{SF}]
  WriteEqn[FuelCon_E;(j);;{Fuel}*{OutEff} =e= {OutFlow}]
Close

For[;#CN#]
  if[ {yCon_No} and {ytpCon_No} ]
    if[ {HxPCon_Yes} and {Nominal_Yes} ]
      WriteEqn[QGDDT_E11;(j);;{Drive} =e= {N}*{InHxP}*({QG_TG}*{TG}+{QG_TE}*{TE}+
      WriteEqn[QEDDT_E11;(j);;{Chill} =e= {N}*{InHxP}*({QE_TG}*{TG}+{QE_TE}*{TE}+
    Close
    if[ {HxPCon_Yes} and {Nominal_No} ]
      WriteEqn[QGDDT_E10;(j);;{Drive} =e= {InHxP}*({QG_TG}*{TG}+{QG_TE}*{TE}+
      WriteEqn[QEDDT_E10;(j);;{Chill} =e= {InHxP}*({QE_TG}*{TG}+{QE_TE}*{TE}+
    Close
  Close
Close

For[;#CN#]
  WriteEqnOut[;(j);;if({Drive} > 0,{COP} = {Chill}/{Drive})]
  WriteEqnOut[;(j);;if({Drive} = 0,{COP} = 0)]
Close
```

Figure 5.12 WriteEqn[] and WriteEqnOut[] examples inside several loop and conditionals

5.4 MGEOS interface

MGEOS is the interface that represents each GUM file as a unit or block that can be add to a flowsheet an can be connected to other units or blocks. With MGEOS the user creates the flowsheet and introduces all the input parameters, like energy demand, energy prices, costs, efficiencies, etc. MGEOS is an interface to GAMS and is the responsible to create the GAMS model using the flowsheet defined by the user, the GUM files and all the input information introduced by the user. Once the model is created, MGEOS executes GAMS to solve the model and reads the results for all the variables with a label name defined. When the user select a unit of the flowsheet, MGEOS displays all the variables defined belonging to that unit. The user can chose one of the variable to obtain the results of the optimisation. All the results can be exported to other applications like Microsoft Excel.

MGEOS has been created with Borland Delphi 2006 and has almost 89,000 lines of code. "Diagram Studio" from TMS Software is also required for the development of MGEOS. Figure 5.13 shows a screenshot with the summary window of a MGEOS project. This window is used to introduce the main information like a name for the project, several comments or a "To do" list. The right panel is used to specify the energy magnitudes to be used in the model. Conversion factors are created so the energetic results of the model will be in the specified units. Figure 5.14 shows the flowsheet window. The central panel is used to place the units and perform the connections. The left panel shows all the units that have been added to the flowsheet organised in a tree structure.

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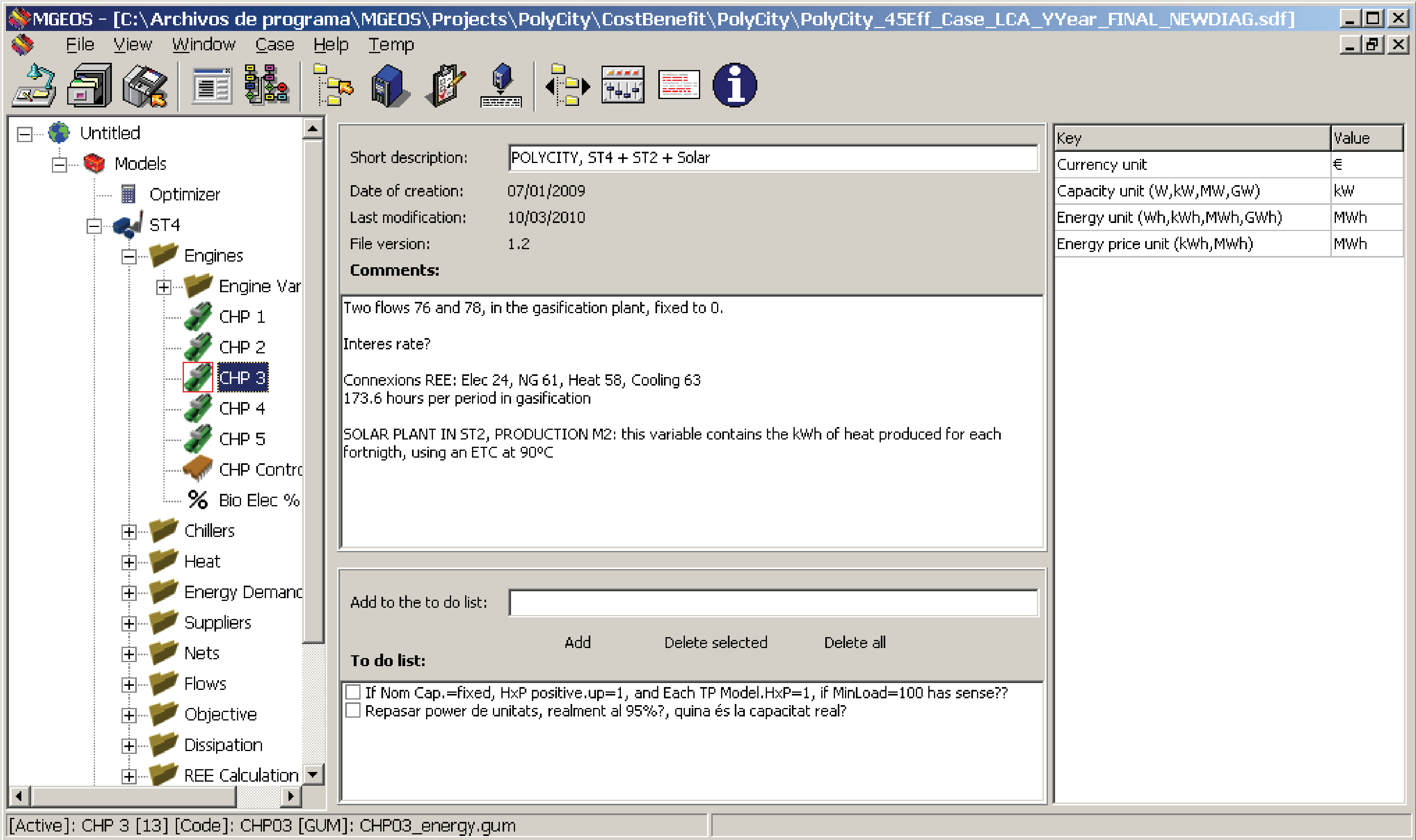

Figure 5.13 Screenshot of MGEOS with the initial window where general information can be stored

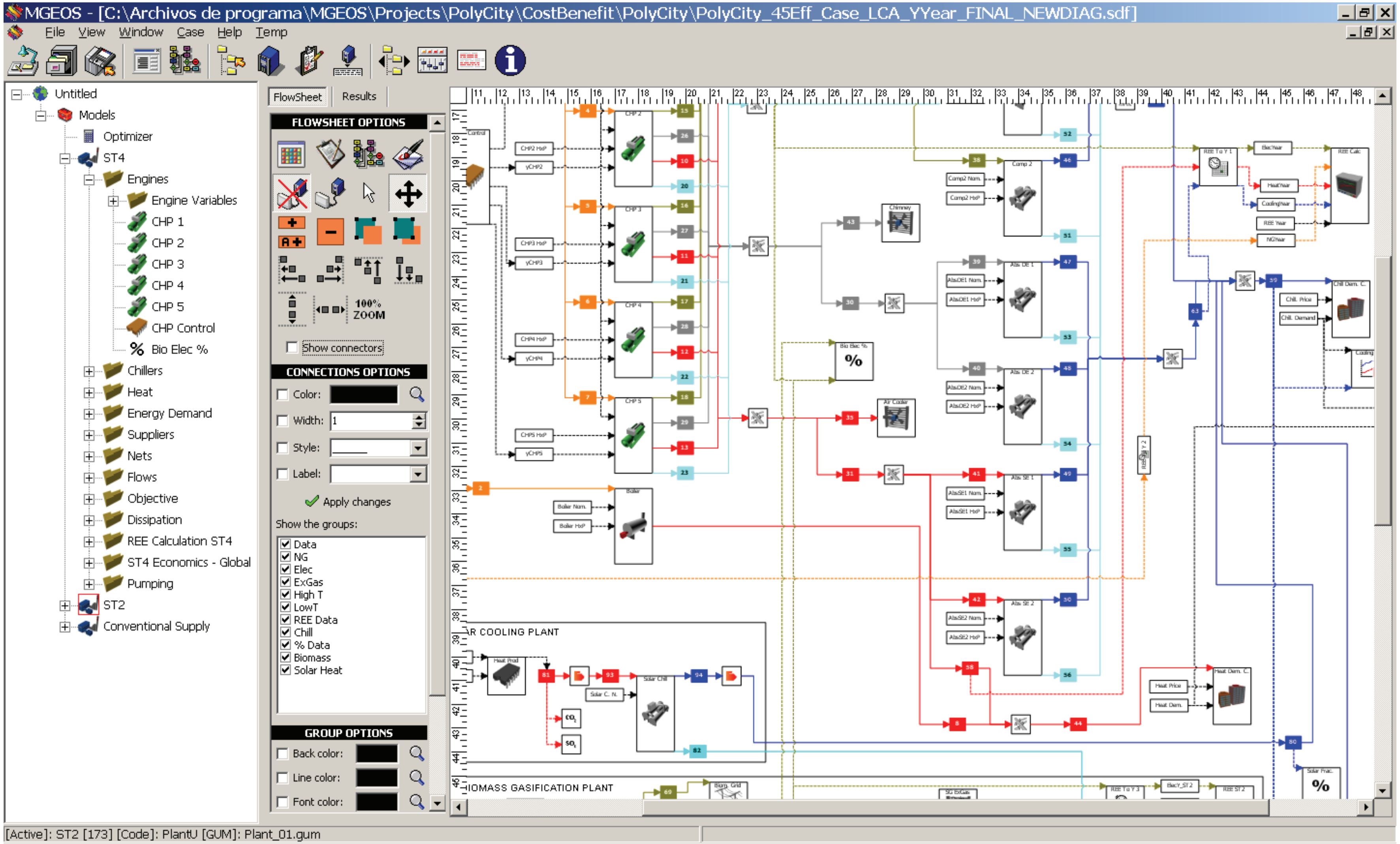

Figure 5.14 Screenshot of MGEOS with the diagram window to create the energy system flowsheet

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MGEOS read all the GUM files when is started and a units library is created (figure 5.15). The library shows all the units that the user can add to the flowsheet to create the configuration of the energy supply system. Each unit of the library is represented by a GUM file visible from the bottom-right panel of the library. The brief description of the unit can be read from the upper-right panel. The tree structure that appears in the library corresponds to the **"Classification"** field of the **#DESCRIPTION** section of the GUM file. If a GUM file has some **Options** defined (section 5.3.3), these **Options** are available inside the unit, and the user must indicate a value for these **Options** (figure 5.15, **Options** inside Plant) in the library. If an error is produced while MGEOS is reading the GUM files, the library is not created and an error message is raised. Errors and other messages can be reviewed in another window (figure 5.16). The error must be fixed and the library must be reloaded (Reload button).

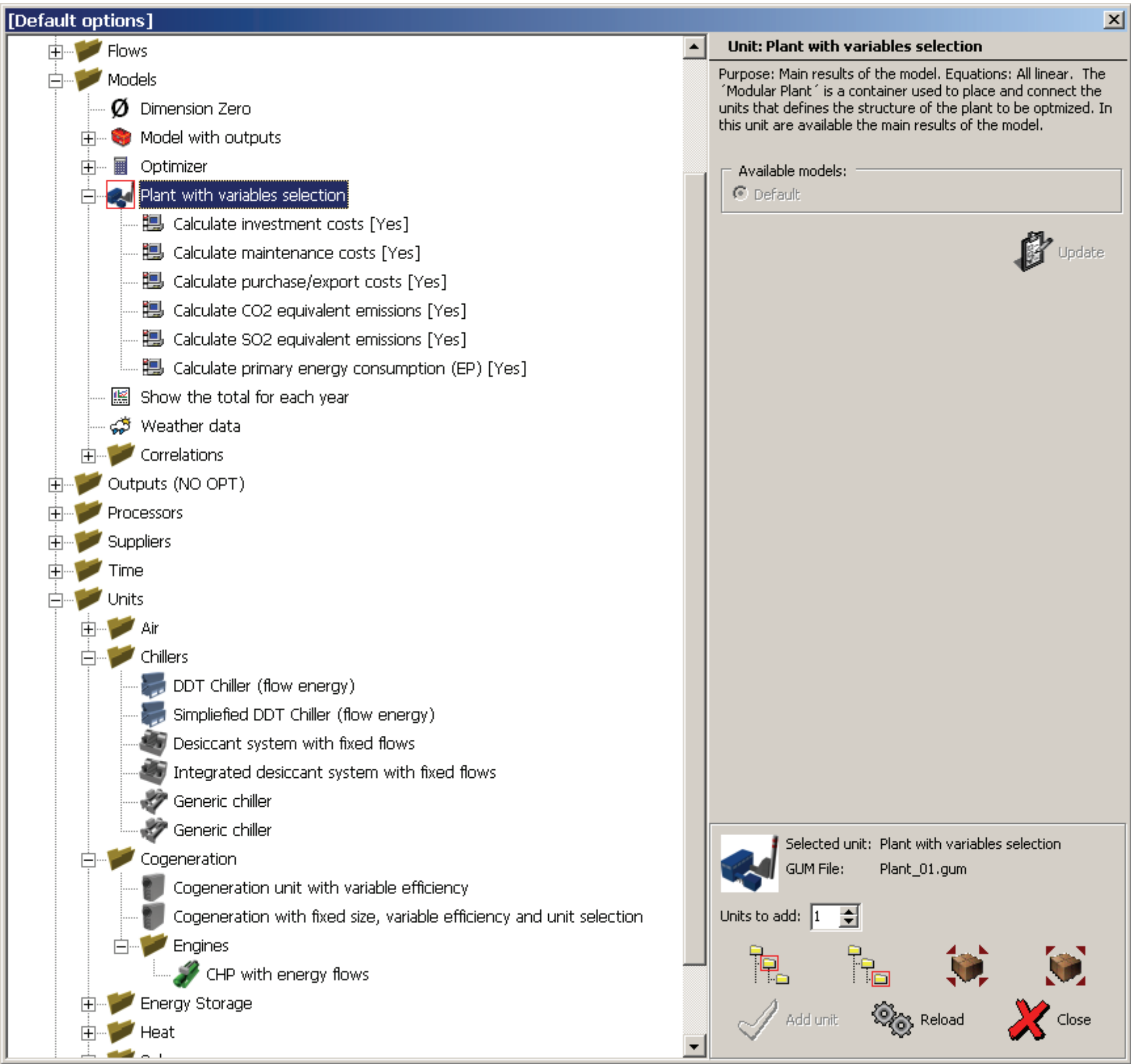

Figure 5.15 Library created by MGEOS with some of the available units represented by GUM files

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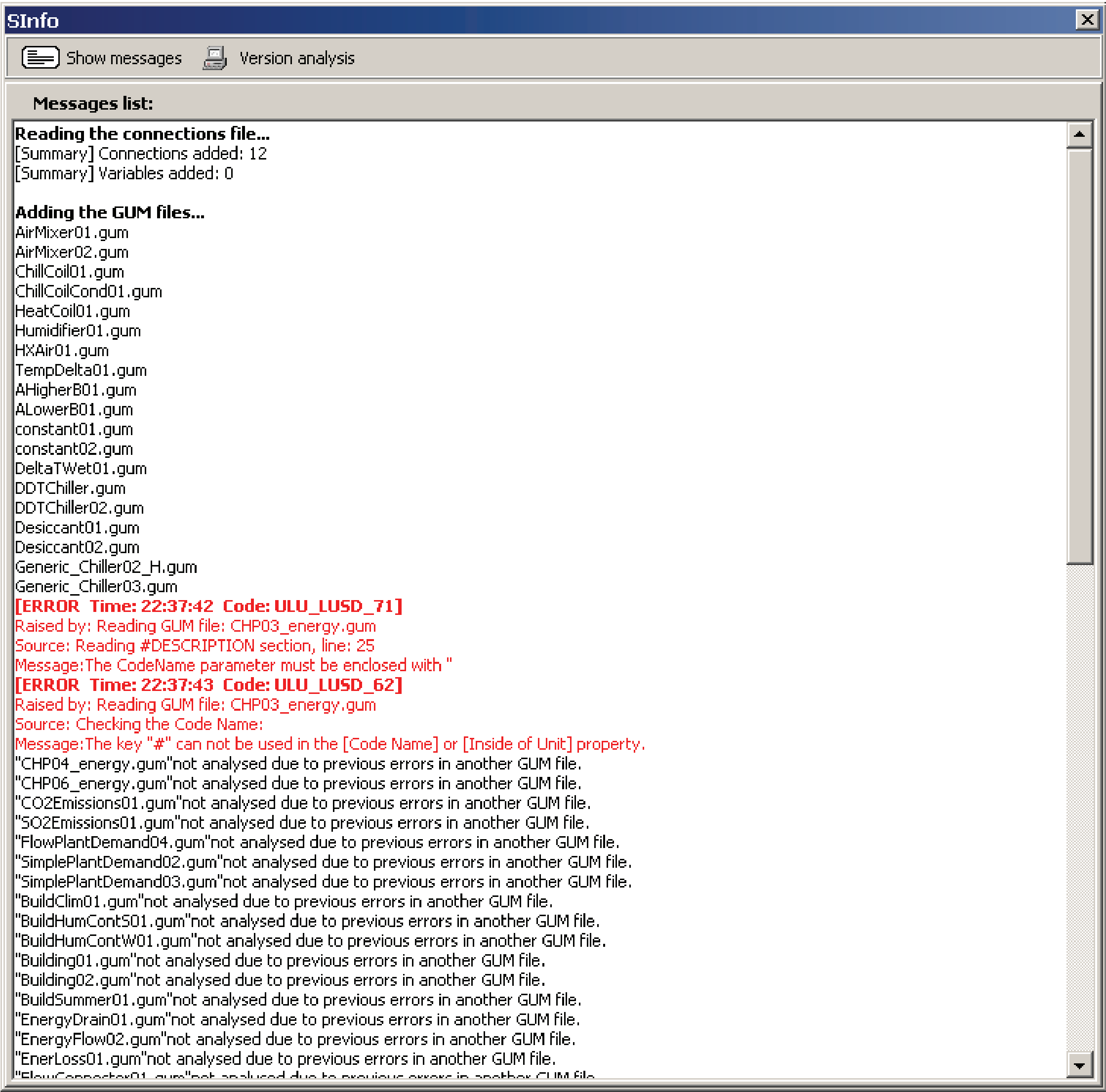

Figure 5.16 Window with the GUM files loading process into MGEOS (an error is marked in red)

Once the library is created, the user can add the units of the library to the flowsheet. When a unit is added to the project it appears in the flowsheet and is added inside the selected node of the tree (figure 5.17, left panel). The organisation of the tree (figure 5.18) is important because determines to which plant belongs each unit, this means to which plant will be charged the costs, emissions and primary energy consumption of each unit of the flowsheet. If the connection button  is active, when a unit is selected its connections appears in the lower panel (figure 5.17). This panel is used to perform the connections between the units.

Folders (figure 5.18) can be used to order the units inside the tree. Folders are not units and do not have any functionality, only contains units in the tree structure.

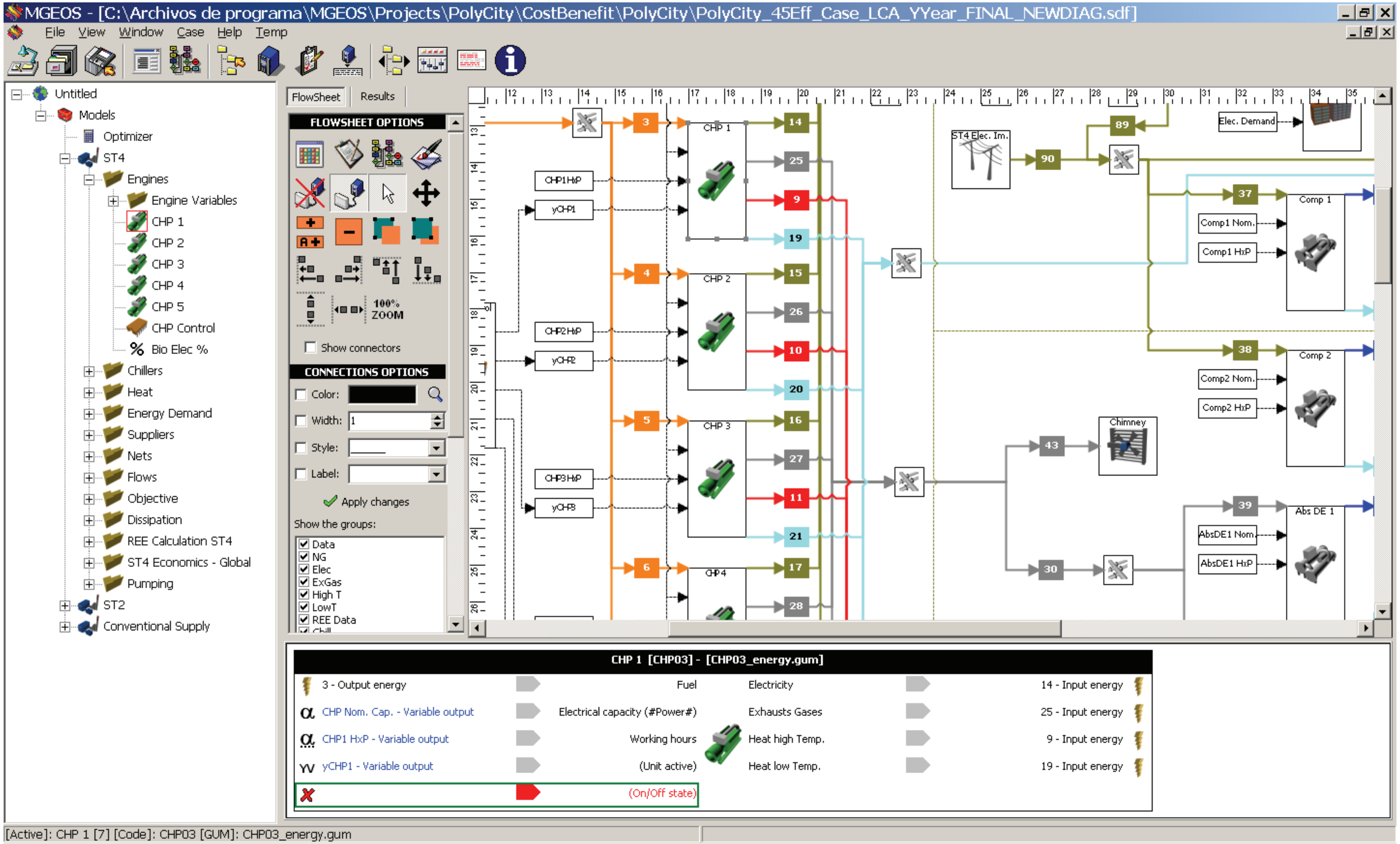

Figure 5.17 Screenshot of MGEOS showing the procedure to perform the connections (lower panel)

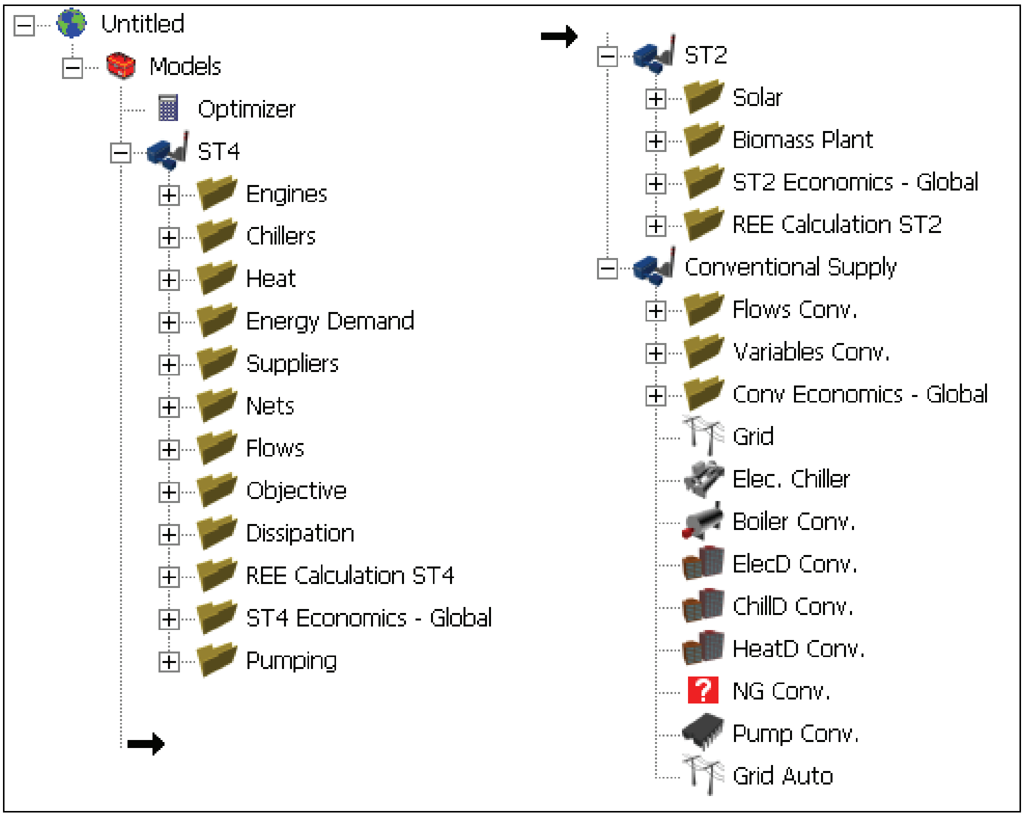

Figure 5.18 Example of the hierarchy organisation of several units in the tree (left panel)

With double-click or using the “Properties” button appears a dialog with the input parameters for the selected unit (figure 5.19). In this dialog the user can introduce the required parameters defined in the GUM file (**#INPUT** section, table 5.3). If one of the input parameters is an array, the dialog shown in figure 5.20 will be displayed with the corresponding fields of the array. The required magnitudes (€, kW, kWh, MWh, etc.) of the units will be in accordance with the defined values in the initial window of MGEOS (figure 5.13).

Although several units of the flowsheet belong to the same GUM file, with the same input parameters, each unit has its own vales different from the other units. When an input parameter is added or modified in a GUM file, the next time a *.SDF file is opened, the changes performed in the GUM file are updated for each unit of the flowsheet belonging to the modified GUM file. The same update process is made for all the other characteristics of the GUM file.

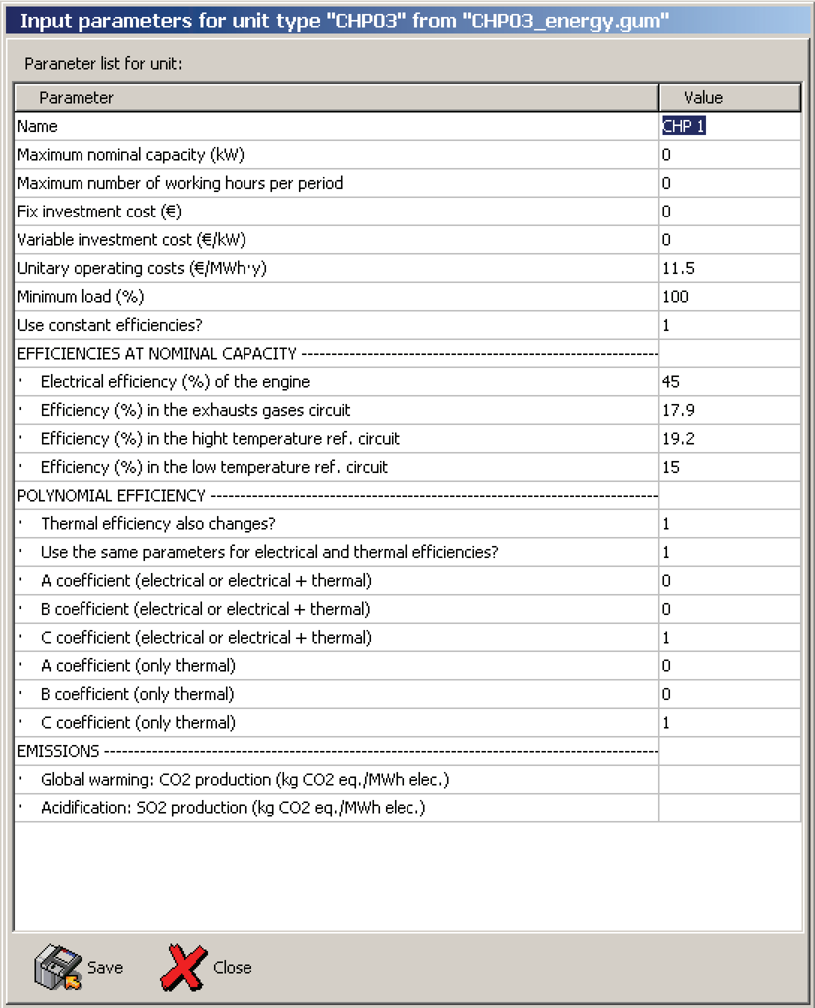

Figure 5.19 Example of input parameters

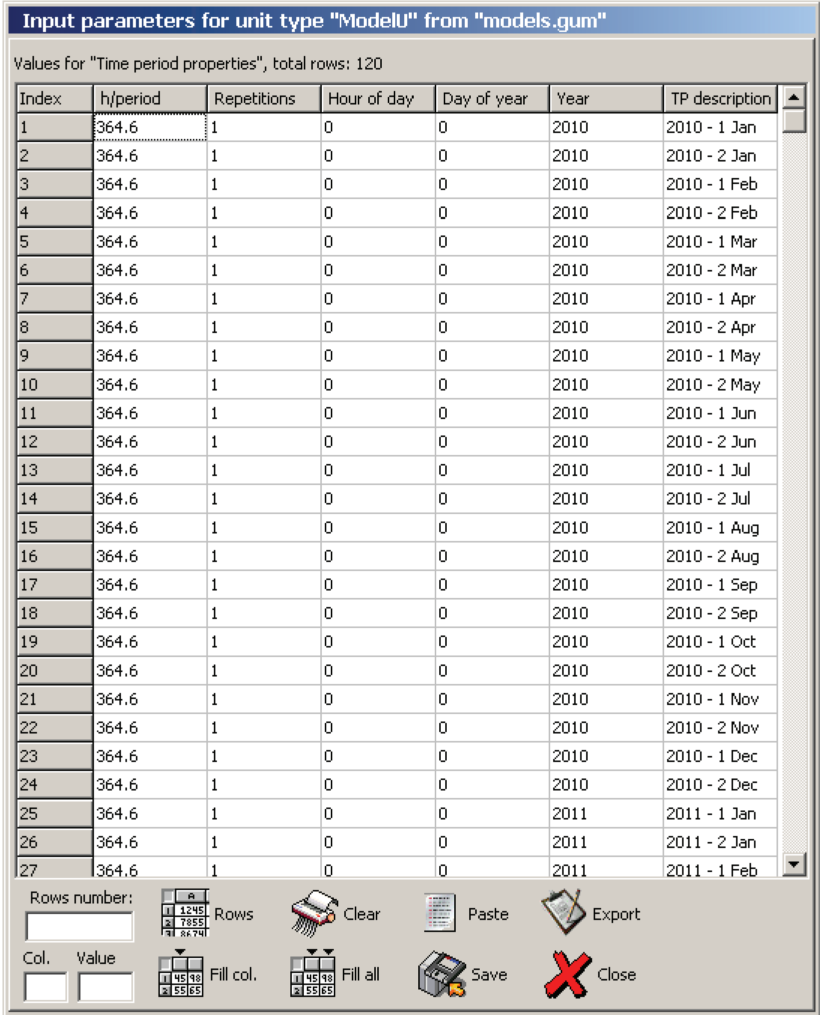

Figure 5.20 Example of input array parameter

When the flowsheet is completed and all the input data is introduced, MGEOS create the model by pressing the compiling button . Figure 5.21 appears when the GAMS models is created, in this dialog is stablished the type of model as a function if integer variables has been found during the creation of the GAMS model. The solver must be specified and it is possible to fix an iteration or time limit for GAMS and also the desired relative tolerance. If these values are not fixed, GAMS uses the default values. The equations and the variables added to the model can be reviewed by pressing (figure 5.23 and 5.24).

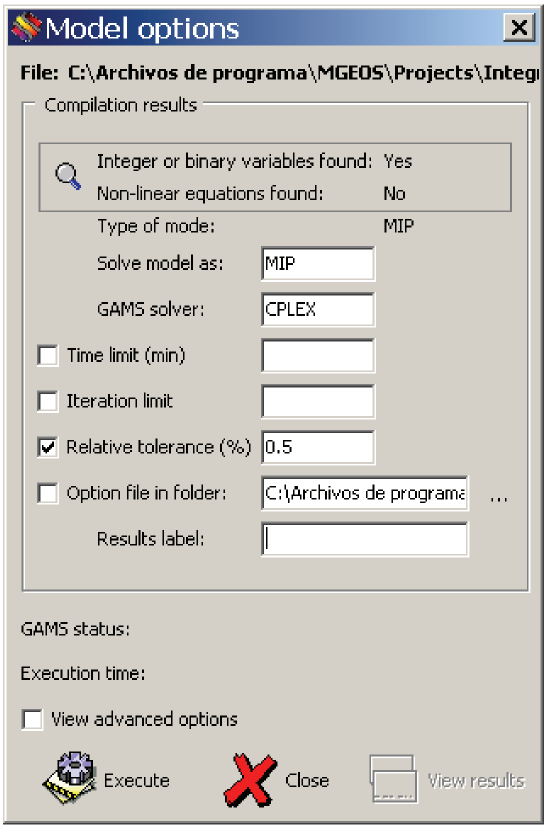

Figure 5.21 Execution GAMS dialog in MGEOS

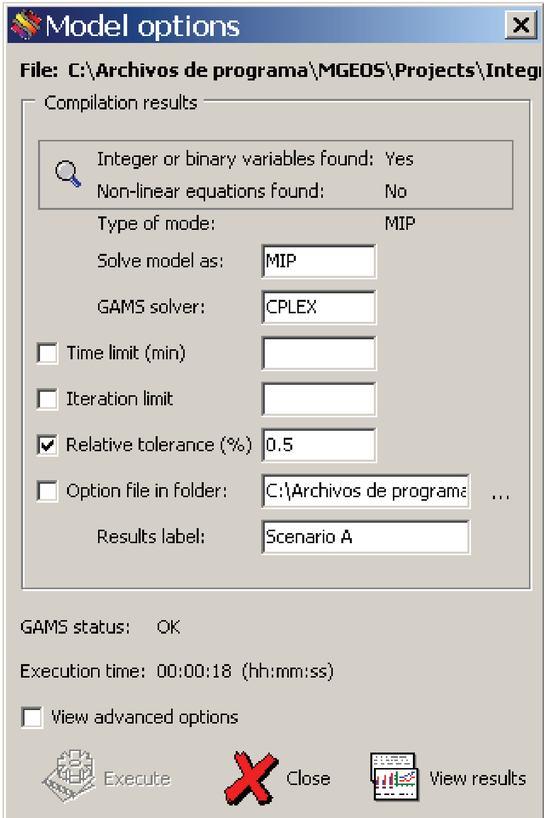

Figure 5.22 Reading the results from GAMS

The model is solved by pressing “Execute”, then GAMS is called and executed in background (figure 5.25). Once GAMS is finished, the solver status and the solving time are show in “GAMS status” and “Execution time” in figure 5.22. The results obtained from GAMS can be loaded into MGEOS by writing a name for the solutions in “Results label” and pressing the “View results”. The results that will be loaded into MGEOS will be the values of those variables that have been declared in the GUM files with a label (table 5.5). Each time the model is solve, the solutions are stored in MGEOS with a new name, the previous solutions are not deleted and are available by selecting the corresponding name.

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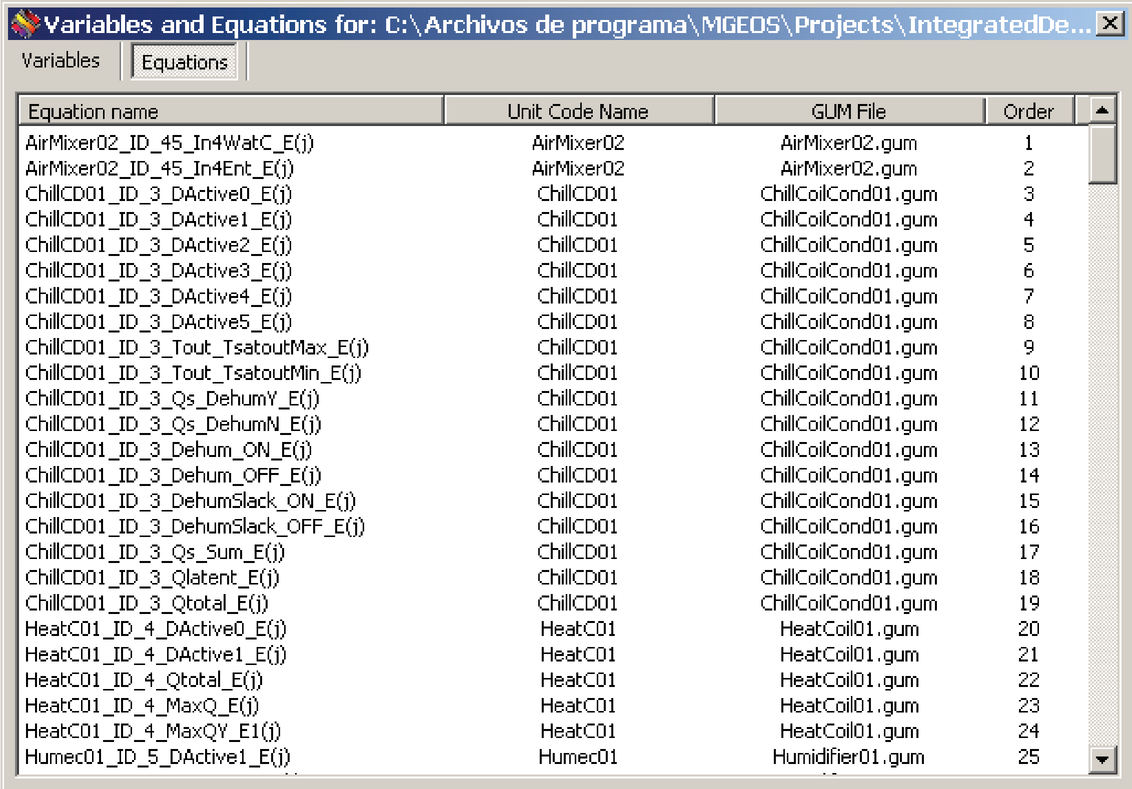
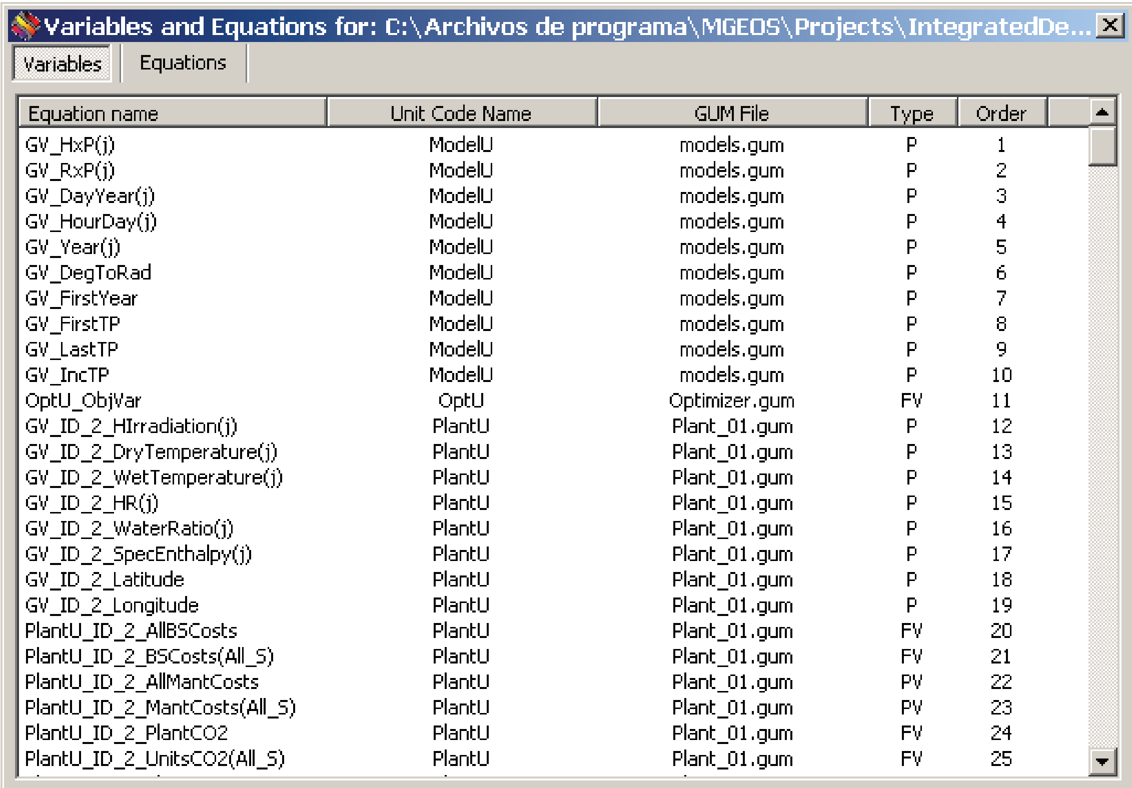

Variables and Equations for: C:\Archivos de programa\MGEOS\Projects\IntegratedDe...

Variables | Equations

Equation name	Unit Code Name	GUM File	Order
AirMixer02_ID_45_In4WatC_E(j)	AirMixer02	AirMixer02.gum	1
AirMixer02_ID_45_In4Ent_E(j)	AirMixer02	AirMixer02.gum	2
ChillCD01_ID_3_DActive0_E(j)	ChillCD01	ChillCoilCond01.gum	3
ChillCD01_ID_3_DActive1_E(j)	ChillCD01	ChillCoilCond01.gum	4
ChillCD01_ID_3_DActive2_E(j)	ChillCD01	ChillCoilCond01.gum	5
ChillCD01_ID_3_DActive3_E(j)	ChillCD01	ChillCoilCond01.gum	6
ChillCD01_ID_3_DActive4_E(j)	ChillCD01	ChillCoilCond01.gum	7
ChillCD01_ID_3_DActive5_E(j)	ChillCD01	ChillCoilCond01.gum	8
ChillCD01_ID_3_Tout_TsatoutMax_E(j)	ChillCD01	ChillCoilCond01.gum	9
ChillCD01_ID_3_Tout_TsatoutMin_E(j)	ChillCD01	ChillCoilCond01.gum	10
ChillCD01_ID_3_Qs_DehumY_E(j)	ChillCD01	ChillCoilCond01.gum	11
ChillCD01_ID_3_Qs_DehumN_E(j)	ChillCD01	ChillCoilCond01.gum	12
ChillCD01_ID_3_Dehum_ON_E(j)	ChillCD01	ChillCoilCond01.gum	13
ChillCD01_ID_3_Dehum_OFF_E(j)	ChillCD01	ChillCoilCond01.gum	14
ChillCD01_ID_3_DehumSlack_ON_E(j)	ChillCD01	ChillCoilCond01.gum	15
ChillCD01_ID_3_DehumSlack_OFF_E(j)	ChillCD01	ChillCoilCond01.gum	16
ChillCD01_ID_3_Qs_Sum_E(j)	ChillCD01	ChillCoilCond01.gum	17
ChillCD01_ID_3_Qlatent_E(j)	ChillCD01	ChillCoilCond01.gum	18
ChillCD01_ID_3_Qtotal_E(j)	ChillCD01	ChillCoilCond01.gum	19
HeatC01_ID_4_DActive0_E(j)	HeatC01	HeatCoil01.gum	20
HeatC01_ID_4_DActive1_E(j)	HeatC01	HeatCoil01.gum	21
HeatC01_ID_4_Qtotal_E(j)	HeatC01	HeatCoil01.gum	22
HeatC01_ID_4_MaxQ_E(j)	HeatC01	HeatCoil01.gum	23
HeatC01_ID_4_MaxQY_E1(j)	HeatC01	HeatCoil01.gum	24
Humec01_ID_5_DActive1_E(j)	Humec01	Humidifier01.gum	25

Figure 5.23 List of equations added to the GAMS model created by MGOES


Variables and Equations for: C:\Archivos de programa\MGEOS\Projects\IntegratedDe...

Variables | Equations

Equation name	Unit Code Name	GUM File	Type	Order
GV_HxP(j)	ModelU	models.gum	P	1
GV_RxP(j)	ModelU	models.gum	P	2
GV_DayYear(j)	ModelU	models.gum	P	3
GV_HourDay(j)	ModelU	models.gum	P	4
GV_Year(j)	ModelU	models.gum	P	5
GV_DegToRad	ModelU	models.gum	P	6
GV_FirstYear	ModelU	models.gum	P	7
GV_FirstTP	ModelU	models.gum	P	8
GV_LastTP	ModelU	models.gum	P	9
GV_IncTP	ModelU	models.gum	P	10
OptU_ObjVar	OptU	Optimizer.gum	FV	11
GV_ID_2_HIrradiation(j)	PlantU	Plant_01.gum	P	12
GV_ID_2_DryTemperature(j)	PlantU	Plant_01.gum	P	13
GV_ID_2_WetTemperature(j)	PlantU	Plant_01.gum	P	14
GV_ID_2_HR(j)	PlantU	Plant_01.gum	P	15
GV_ID_2_WaterRatio(j)	PlantU	Plant_01.gum	P	16
GV_ID_2_SpecEnthalpy(j)	PlantU	Plant_01.gum	P	17
GV_ID_2_Latitude	PlantU	Plant_01.gum	P	18
GV_ID_2_Longitude	PlantU	Plant_01.gum	P	19
PlantU_ID_2_AllBSCosts	PlantU	Plant_01.gum	FV	20
PlantU_ID_2_BSCosts(All_S)	PlantU	Plant_01.gum	FV	21
PlantU_ID_2_AllMantCosts	PlantU	Plant_01.gum	PV	22
PlantU_ID_2_MantCosts(All_S)	PlantU	Plant_01.gum	PV	23
PlantU_ID_2_PlantCO2	PlantU	Plant_01.gum	FV	24
PlantU_ID_2_UnitsCO2(All_S)	PlantU	Plant_01.gum	FV	25

Figure 5.24 List of variables added to the GAMS model created by MGEOS

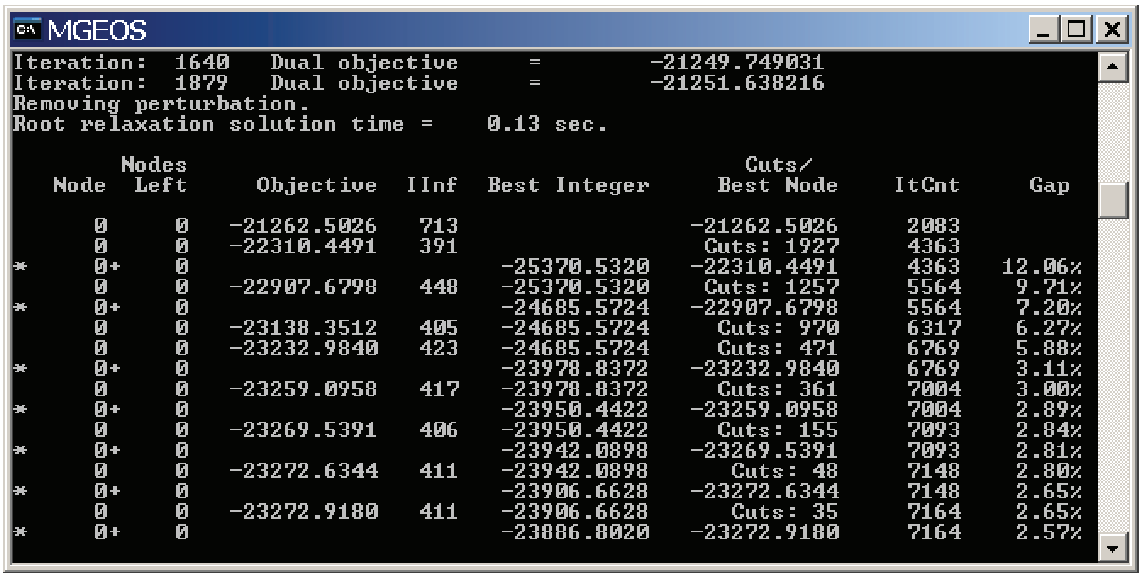


Figure 5.25 GAMS called from MGEOS solving a model in background

Figure 5.26 shows an example of several solutions with different names stored in MGEOS in the "Results" tab. In the list there are all the optimisation performed and the name used to solve the results. Each time the MGEOS project is saved in a *.SDF file, all the results are saved along with the flowsheet and al the input data introduced. The solution will be always available until a set of solutions is deleted by the user. Once a name of the list is selected, the results are show using the units of the flowsheet.

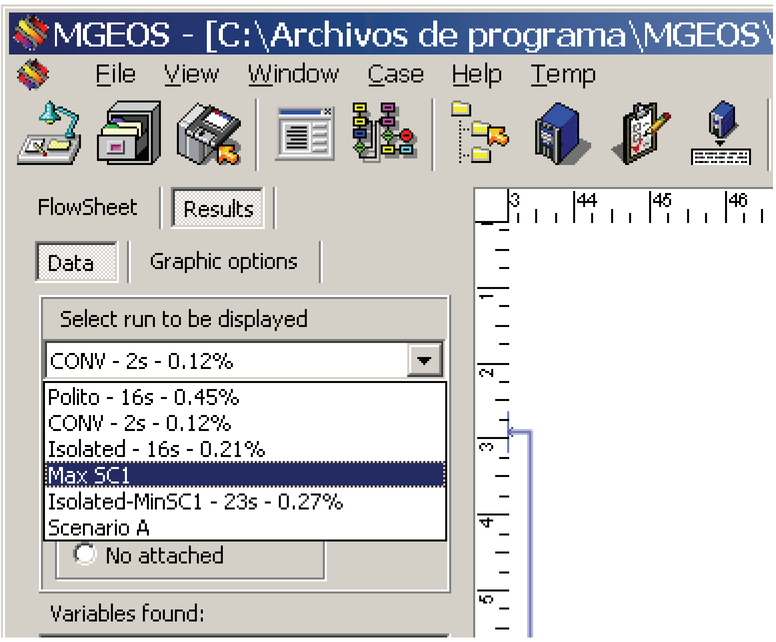


Figure 5.26 List of results stored in MGEOS

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Figure 5.27 shows an example of how the results are read. Once a name from all the solutions stored is selected, an option can be chosen in “Display results”:

- All: shows all the variables stored
- Attached to a unit: only shows the variables belonging to the selected unit in the flowsheet.

The example in the figure shows the results for the plant unit, the economical and environmental results. The variables found for the selected unit of the flowsheet are shown in the “Variables found” list. When a variable of the list is selected the results are show in “Values” list to the bottom. Each time a unit is selected in the flowsheet the “Variables found” list is updated.

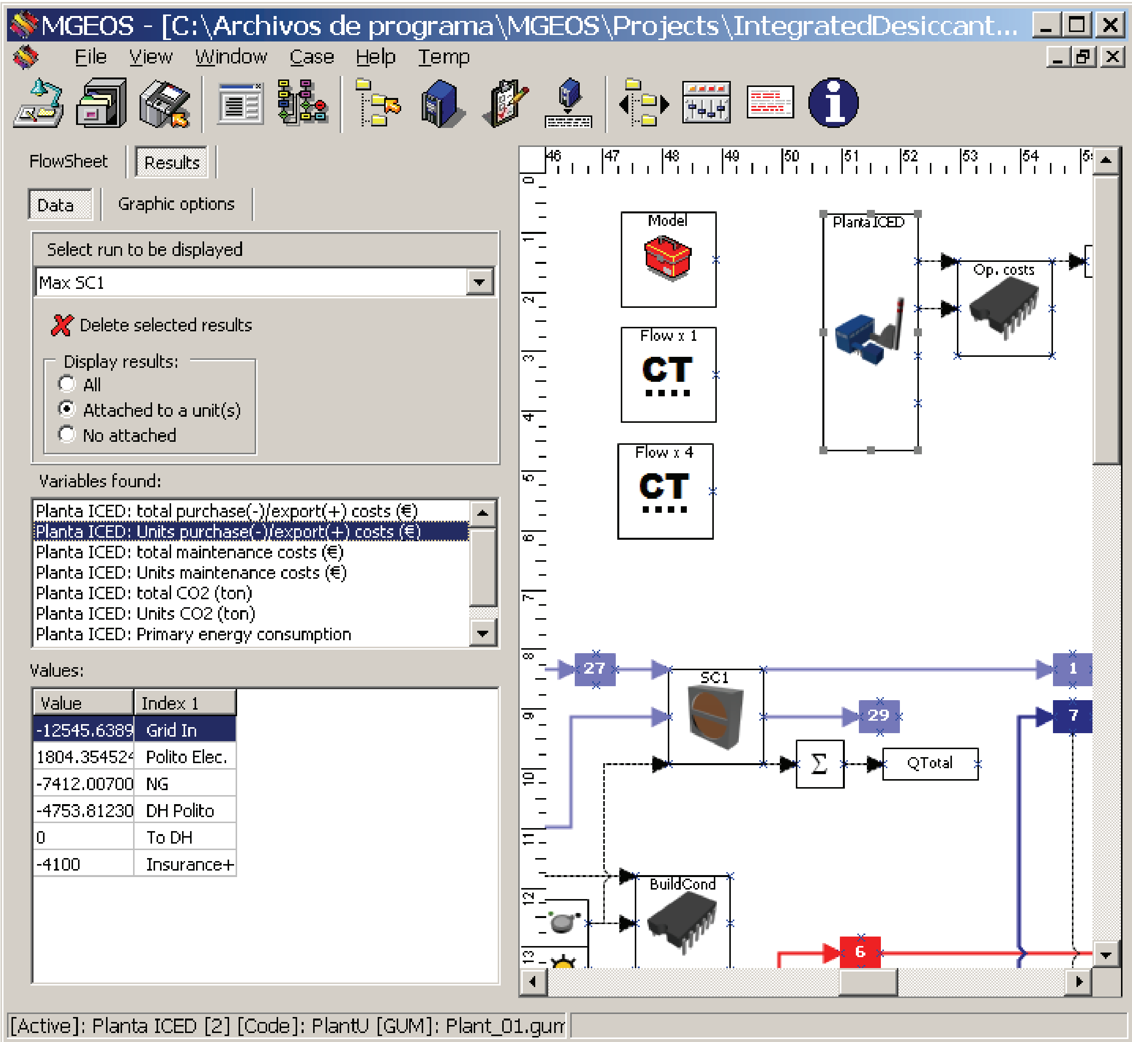

Figure 5.27 Available results for the plant unit for the optimisation saved as “Max SC1”

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Most of the variables has some indexes, for example the time periods or the years defined for array variables, or units for economic and environmental variables. The results shown in figure 5.27 are the operating costs resulting of purchase and sell energy. The values in euros are show for each unit that purchases or exports energy (natural gas, electricity or heat). In that case ”Index1” is the name of the units of the flowsheet.

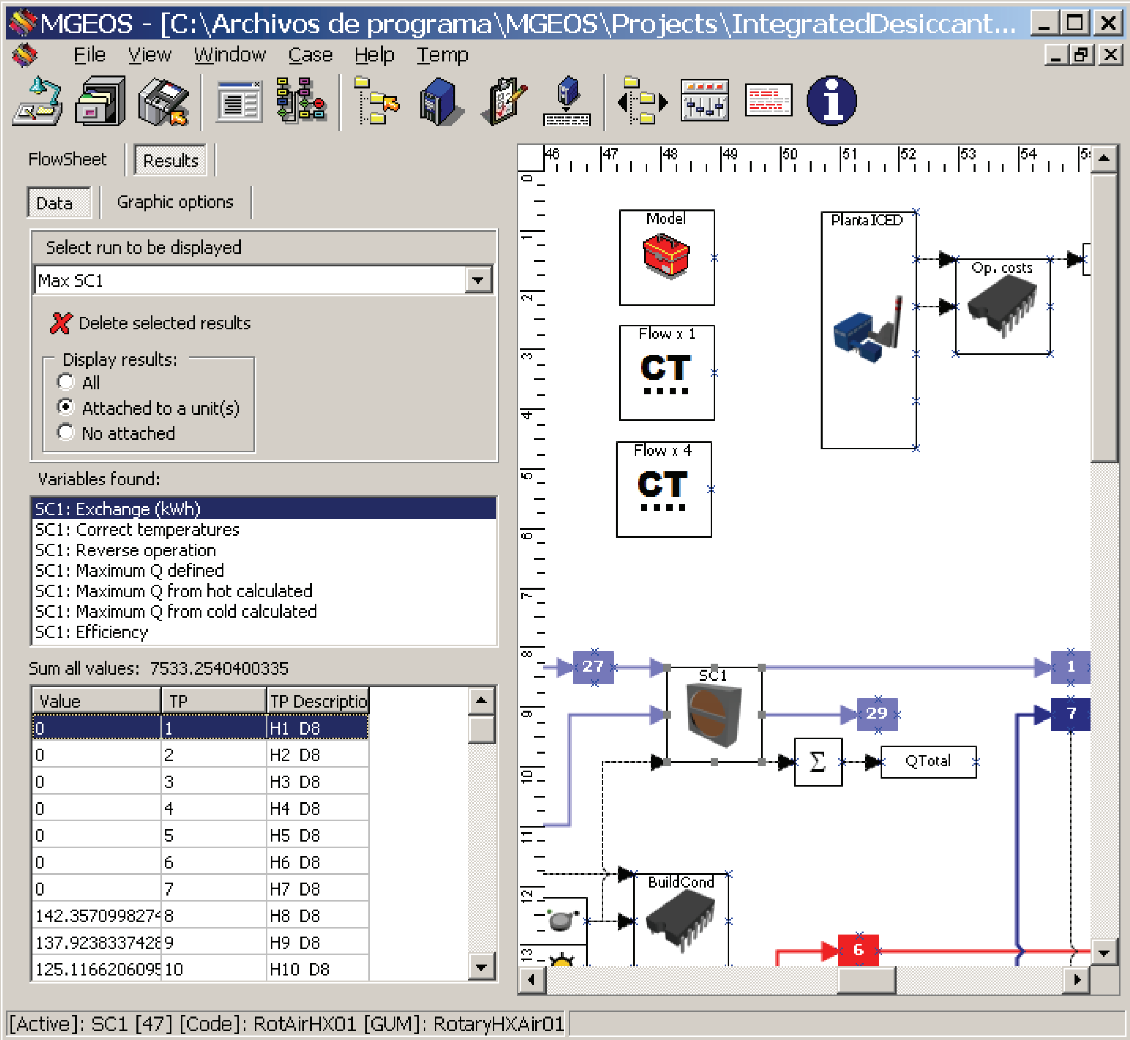

Figure 5.28 Available results for the SC1 unit for the optimisation saved as “Max SC1”

Figure **5.28** shows the results for the selected unit SC1 in the flowsheet. From all the variables found “SC1: Exchange (kWh)” is selected, this variable is the amount of energy exchanged with this unit. In that case, this variable is an array variable with a different value for each time period. “TP” means the time period, “TP Description” is a name assigned to each time period. In this example, the name is the hour of the time period (H) and the day of the year (D).

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Figure 5.29 show an example for the results of an air flow unit that represents an air stream with the corresponding mass flow rate, temperature, humidity and enthalpy. The flow 27 is selected from the flowsheet and the results for the temeperature are selected. Like in the previous case, the temeperature is an array with different values for each time period.

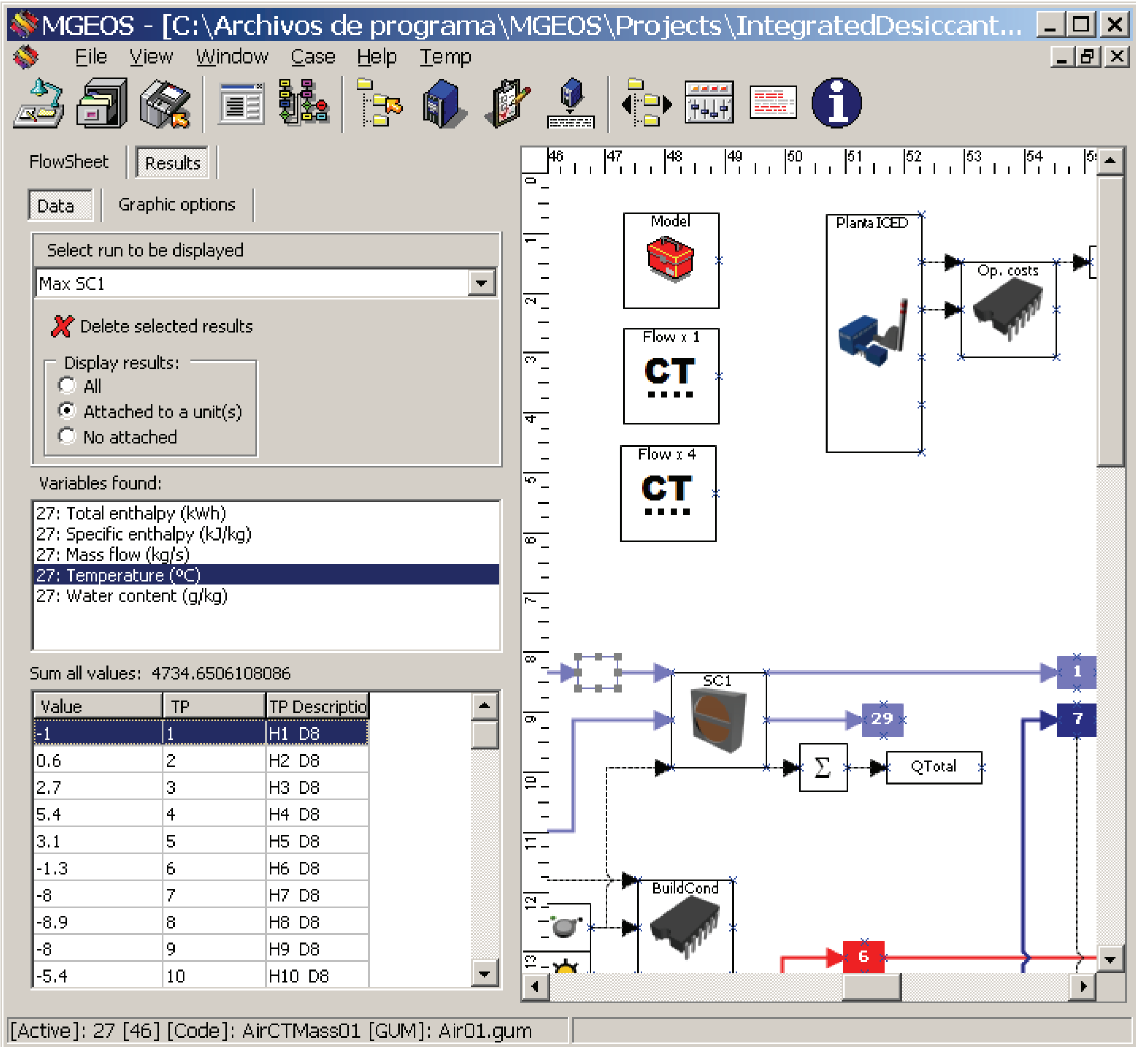

Figure 5.29 Available results for an air flow

An example of an energy flow (that contains just the energy value) is shown in figure 5.30. Flow 31 is selected and the corresponding values are listed in “Variables found”. In this case only the energy value is available. “Flow 31: Energy” is the energy value for each time period for the flow 31. “Flow 31: RPF Energy” is the energy value obtained when the energy of each time period is multiplied by the repetition factor (RPF). RPF is how many times a time period is repeated because typical days are used to represent the whole year. “Sum all values” shows the sum for all the time periods. In this case the value obtained is for the whole year.

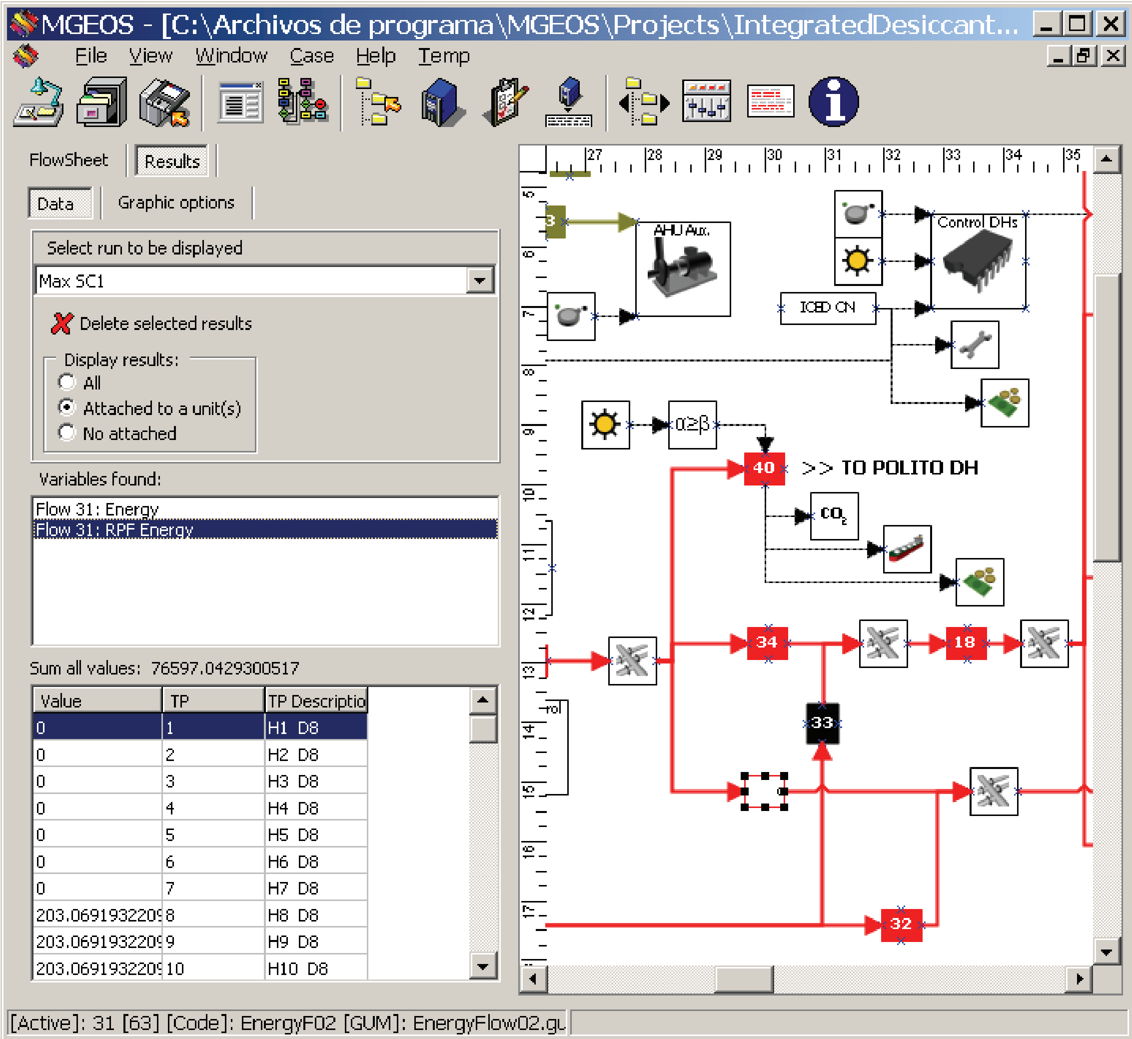

Figure 5.30 Available results for an air flow

The way in which the results are stored and managed facilitates the revision and comprehension of the results by selecting just the units or variables to obtain the results. All the results are saved in the *.SDF file, this means the solutions are always available and that is not necessary GAMS to see the results saved in a MGEOS project.

The results are show always in a table that can be exported easily to other programs like Microsoft Excel. MGEOS still is not able to present the results using plots or to write the results in text files.

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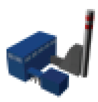
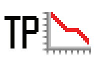
5.5 Developed units in MGEOS

A description of the developed units will be presented in this section. Because new units can be added, or the existing units can be modified, only a brief description is presented, without detailing connectors, input parameters or options. The units are grouped in functional groups, as can be found in the MGEOS library. The picture show in the table is the image that identifies each unit in MGEOS. Some of the units described are "containers", meaning that are able to contain other units inside when are placed in the MGES tree structure (Figure 5.18).

Table 5.16 contains some of the units that must be placed first when a new flowsheet is created. The unit **"Model"** is the first unit that must be placed in the flowsheet, and will contain all the other units inside. It is also the unit that has the main information about the model, like time periods, description of time periods, number of years, how the time periods are distributed in each year, time periods and the properties of each time period. Only one unit of this type can be added to each flowsheet. Inside the unit **"Model"** can be placed **"Optimiser"** that will determine the variable to be maximized or minimized, and **"Plant"** that will contain all the units that defines an energy supply system.

Table 5.16 List for plants and models units

	PLANTS AND MODELS
	**Model** is main unit, where are defined the main properties of the model. There are two temporal scales, time periods and years. In this unit is fixed the number of time periods, the repetitions of each time period, the number of years, how the time periods are distributed for the years defined, etc (see section 5.6). Is the container for **Plant** and **Optimiser** units.
	**Plant** is the container for almost all the other units. This unit contains the meteorological and the location information of the plant that is representing. All the outputs of this unit are global results, for all the time periods and years considered. The outputs are listed below: • Investment costs • Maintenance costs • Operational costs • CO2 emissions • SO2 emissions • Primary Energy Consumption
	**Show total for each TP**: the outputs of this unit are the same output than the **Plant** unit, but the results are available also for each time period. This unit must be placed inside a **Plant** type unit.
	**Optimiser** has only one input. The variable connected to this input will be maximized or minimized.

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Variables are also added to the flowsheet as a block. These variables can be single values or arrays with a different value for each time period. The type of variable is fixed by the user (TypeVar in table 5.3). These variables can be used to determine nominal capacities, operating hours, ON/OFF states, limiting values for other calculations, etc. The variables are listed in table 5.17.

Table 5.17 List of variables

VARIABLES	
α	**Single variable** is used to add a variable to the flowsheet. In this case is only a value (it is not an array with a value for each time period). Once the unit is added to the flowsheet, the user can chose the type of variable to be implemented in the input parameters dialog (figure 5.19). The types are the following: Positive variable, Negative variable, Free variable, Binary variable, Integer variable and Parameter. Minimum, maximum and initial values can be fixed.
α	**TP variable** is used to add an array variable to the flowsheet with a value for each time period. The types of variables are the same with respect to the **Simple variable** unit. Minimum, maximum and initial values can be fixed for the desired time period.
α β	**Data link** is a linking unit that makes a virtual connection between a single variable and other units. It is used to do more readable flowsheets by connecting units that if were connected in the traditional way these units would create confusing connection lines. Linking units are explained in more detail in the next table 5.18 and figure 5.31.
α β	**Data link TP** is a linking unit like Data link used to connect TP variables with other units.
	**3 section binary variable** includes three binary array variables for each time period. Usually to linearise a non-linear function using three sections.
YV	**Year variable** is used to add a variable to the flowsheet; in this case the variable is an array with a value for each year defined. The types of variables are the same with respect to the **Simple variable** unit. Minimum, maximum and initial values can be fixed for the year desired.
Y	**TP to year** connects a **TP variable** (A) with a **Year variable** (B). The value in B for each year will be the sum of A for each corresponding year.
TP	**Year to TP** connects a **Year variable** (A) with a **TP variable** (B).
CT	**Constant value node** can be used to fix a value for several variables placed inside. For example can be used in airstrem flows when the mass flow rate is constant. This unit fixes only one value.
CT	**Constant value node for each TP** can be used to fix a value for several variables placed inside. For example can be used in airstrem flows when the mass flow rate is constant. This unit can fix a different value for each time period.

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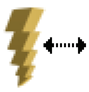
Currently almost all the units of the library use energy flows (except the "Liquid desiccant" unit and all the units in the "Air" group). This means that the flows between the units are modelled just as energy, without considering mass flow, temperatures, pressures, etc. Table 5.18 summarizes the units related to energy flows.

Table 5.18 Units to represent energy flows

	ENERGY FLOWS
	**Energy** is a unit that represents an energy flow between two units. It has an energy input/output connection that are attached to the units, and also an input/output data connection. The data connections can be attached to other units to perform additional calculations using the energy value.
	**Energy link** is a linking unit that must be placed inside an **Energy** unit. This linking unit can be connected in the flowsheet to other units stablising a virtual connection between the **Energy** unit where is placed and the unit connected to the **Energy link** unit. This unit is used to make more readable flowsheets avoiding confusing connection lines between two units. Figure 5.31 shows and example of the use of the linking units. The flow 52 must be connected to the input electrical demand of the building, but both units are not placed close and a conventional connection will create a connection lines that can make the flowsheet hard to understand.
	**Energy valve** allows the "circulation" of energy through an energy flow when the energy content of another energy flow is below a certain value fixed by the user. Can be used to allow the "circulation" of energy when the energy content of another energy flow is almost zero.
	**Net** is used to split or join energy flows.
	**Losses** has a constant losses coefficient that indicates the amount of energy lost. There is no cost or emissions associated to this unit. The losses coefficent can be the same for all the time periods or can have different values for each time period.

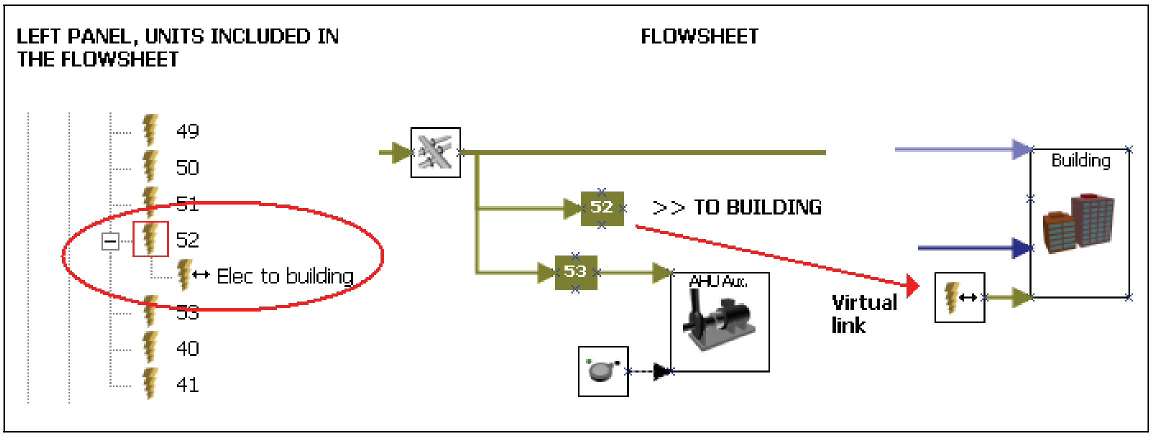


Figure 5.31 Example of the use of the linking unit, establishing virtual connections between units

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In table 5.19 there are the list of the main units that defines an energy supply system. These units are the responsible to "transform" one type of energy into another, for all these units, investment costs can be fixed or calculated as a function of the nominal capapcity. Maintenance cost can be calculated as a function of the energy production. Binary variables can determine when the unit is selected in the solution or in which time periods the unit is working. Other variables and units can be used to fix or to optimise the number of hours the units are working in each time period. Environmental factors accounts for the CO_2, SO_2 emissions and primary energy consumption as a function of the input fuel or the energy produced.

Table 5.19 Main units to transform energy

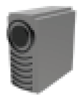
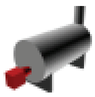
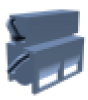
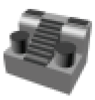
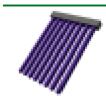
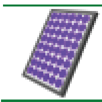
UNITS	
	**Cogeneration engine** represents an internal combustion engine with several outputs. The unit has linear relations of each output with the fuel consumption. A minimum load for the engine can be fixed.
	**Gas turbine** has an electrical and a thermal output. The fuel consumption is a linear relation of the electrical production and the temperature of the air. The maximum capacity of the gas turbine is also related with the temperature of the air.
	**Boiler** connects two energy flows; output is related to the input through a constant efficiency.
	**Chiller** produces cooling using a constant COP value. The cooling requirements of the chiller and the input driven energy are also calculated.
	**Absorption** produces cooling, usually applied to represent thermal driven chillers. The power in the generator and the evaporator is calculate using linear regressions of three temperatures (generator, condenser/absorber and evaporator).
	**Liquid desiccant** is a unit used for air conditioning. The unit cools and dehumidifies an air stream. The degree of dehumidification and the change of temperature of the conditioned air is calculated using linear regression of the input air temperature, input air humidity and temperature of the cooling water.
	**Thermal solar collector** produces heating from the meteorological information available in the **Plant** unit where is placed.
	**Photovoltaic** produces electricity from the meteorological information available in the **Plant** unit where is placed.

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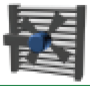
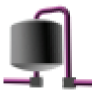
Table 5.20 shows additional units to storage or dissipate energy. "**Energy drain"** associates a cost or energy consumption as a function of wasted energy that must be dissipated (an energy flow that is connected to this unit). "**Dimension zero"** is a special unit that can be used only when in the flowsheet there is a plant without units inside, or without any unit that returns a value for a certain indicator that must be calculated. For example if in the flowsheet there is a plant without units with maintenance costs, but maintenance cost must be calculated for all the plants, "**Dimension zero"** can be added to the plant without units with maintenance cost to be able to return a zero value for at least, "**Dimension zero"** unit.

Table 5.20 Units related with environmental calculations

	ENERGY STORAGE AND DISIPATION
	**Energy drain** can be used to associate a cost to the wasted energy**.**
	**Dimension zero** is a unit to ensure a zero value for the main indicators calculated in the **Plant** unit if there are no units inside the **Plant** unit.
	**Energy storage** can be used to accumulate energy. The charge/discharge depends on the optimisation but a certain energy level can be fixed for any time period. The temporal relation for all the time periods defined in the model can be determined in this unit, this means that the unit is able to storage energy from the first to the last time period of the model sequentially. In other cases, for example if the model is composed of several typical days, the energy storaged inside one day must be consumed during that day and can not be transferred to other days or time periods.
	A nominal capacity can be calculated as well as investement and maintenance costs. A minimum level can be defined to assure the discharge of the storage for certain periods. There are two types of energy storage, one with one energy input and one energy output, and another with the same input/output but with a bypass, so the input energy can be storage or can be bypassed to the output.

The main units (table 5.19) have its own parameters to calculate investment costs, maintenance cost, energy price costs, environmental emissions and the primary energy consumption as a function of the input or the output of each unit. Table 5.21 lists several units that can be used to calculate additional costs or environmental emissions as a function of the energy content of an energy flow or any other variable of the flowsheet. Costs, emissions or primary energy consumption calculated with these units will be charged to the **Plant** where these units are placed (the same that for the main units in table 5.19 or suppliers in table 5.22).

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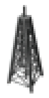
Table 5.21 Units related with environmental calculations

ENVIRONMENT AND ECONOMICS	
CO_2	**CO_2** can be connected to a variable or energy stream to calculate the associated CO_2 emissions.
SO_2	**SO_2** can be connected to a variable or energy stream to calculate the associated SO_2 emissions.
	**PEC** can be connected to a variable or energy stream to calculate the associated primary energy consumption.
	**Buy/Sell cost** adds additional costs besides the buy and sell costs of other units.
	**Maintenance cost** adds additional costs beside the maintenance costs of the other units.

The units listed in table 5.22 supplies resources to the energy supply system or to the energy demand units. Energy can be also exported to the national electrical grid. Costs, emissions and primary energy consumption can be associated to the imported/exported resources (energy).

Table 5.22 Units to related to the extraction or supply of resources

SUPPLIERS	
	**Resource extraction** accounts for the production of a resource, CO2 and SO2 emissions as well as operational costs can be calculated as a function of the energy "extracted".
	**Resource supplier** is used to fix a cost to the consumption of a certain type of energy.
	**"Grid"** represents the electrical national grid. It has an input connection to export energy to the grid and output connection to import energy from the grid. A binary variable can be used to calculate or to fix the sense of the grid (import or export). If only one connection is used, the binary variable is not necessary. CO_2, SO_2 emissions, PEC and costs associated to the imported or exported energy can be calculated.

The units listed in table 5.23 can be used to add custom equations to the flowsheet or to calculate global results from several values. Custom equations can be added directly in the flowsheet in MGEOS with the **"Processors"** units, using the variables connected to this unit and a memo variable where several equations can be written. More details of this unit will be presented in the first case study (section 6.4.3). **"Sum all"** returns a value that is the sum for all the time periods of the input variables connected to this unit.

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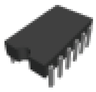
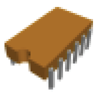
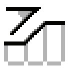
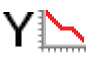
The units **"Linear"**, **"3 section linearise"** and **"Section linearise"** can be used to implement a linear relation using just one line, or using several sections and binary variables to discretise a non-linear function. The last units of the table calculate global results. These results are calculated after the optimisation process and for this reason **"Reduction ratio"**, **"Ratio"** and **"Totals"** do not take part in the optimisation process.

Table 5.23 Processors and units to calculate global results

PROCESSORS CORRELATIONS AND TOTALS	
 	**Processors** are used to add custom equations to the flowsheet. There are two types of processors: one that can be connected only to variables TP (black) and the other that can be connected only to yearly variables (yellow). Once several variables of the flowsheet are connected to the processor, these variables can be used to write custom equations. These units can be used when the users want to add some equations to the flowsheet but they do not want to create a new unit. Often these units are used for control purposes or to calculate global values from several variables. Figure **¡Error! No se encuentra el origen de la referencia.** shows and example of the custom equations included in a Processor unit.
	**Sum all** sums the variables for all the time periods connected to the input, the result is assigned to the variable attached to the output connector. Optionally the RPF factor (repetitions of each time period) can be applied to obtain overall results for all the year.
	**Linear** implements an linear function.
	**3 section linearise** represents a non-linear function using three lines representing each one a section of the non-linear function.
	**Section linearise** represents a non-linear function using lines representing each one a section of the non-linear function. Up to ten sections can be defined.
	**Reduction ratio** calculates the % of reduction of one value compared to another. The ratio is calculated after the optimisation process.
	**Ratio** calculates the % that one value represents respect another value. The ratio is calculated after the optimisation process.
	**Totals** calculate the sum for each year using the "TP variables" connected at its inputs. These totals are calculated after the optimisation process.

The behaviour of the units can be controlled using the units listed in table 5.24. Some of these units are attached to binary variable that controls the ON/OFF states of the units. Other units are attached to several energy flows imposing a constraint that must be fulfilled.

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Table 5.24 Control units to regulate the behaviour of the units

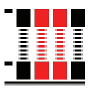
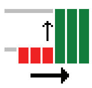
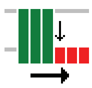
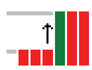
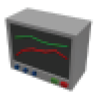
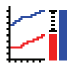
CONTROL	
	**Avoid 1 ON** avoids an ON value placed between OFF values (010). Usually this unit is attached to a TP binary variable controling the ON/OFF state.
	**Avoid 1 OFF** avoids an OFF value placed between ON values (101). Usually this unit is attached to a TP binary variable controling the ON/OFF state.
	**Avoid 2 ON** avoids two ON values placed between OFF values (0110). Usually this unit is attached to a TP binary variable controling the ON/OFF state.
	**Avoid 2 OFF** avoids tow OFF values placed between ON values (1001). Usually this unit is attached to a TP binary variable that controling the ON/OFF state.
	**Avoid 1 ON-OFF** avoids an isolated ON (010) value or an isolated OFF value (101). Usually this unit is attached to a binary TP variable controling ON/OFF state.
	**Avoid 2 ON-OFF** avoids two isolated ON (0110) values or two isolated OFF values (1001). Usually this unit is attached to a binary TP variable controling the ON/OFF state.
	**Keep ON** usually connected with a binary variable, once the binary variable changes from 0 to 1, **Keep ON** maintain the value to 1.
	**Keep OFF** usually connected with a binary variable, once the binary variable changes from 1 to 0, **Keep OFF** maintain the value to 0.
	**Find ON** uses a binary variable (A) to indicate when another binary variable (B) changes from 0 to 1. For each transition, the value in A is 1, otherwise is 0.
	**REE** establishes a minimum or/and maximum REE (*Rendimiento Electrico Equivalente)* that must be fulfilled. It is also able to calculate the REE value but after the optimisation.
	**Start-up control** counts how many times a binary variable changes from 0 to 1. Usually is connected with a binary variable that controls the ON/OFF operation of a unit.
	**Total operating TP** count the total number of time periods that the unit is ON. Usually the input binary variable connector of this unit is associated to a binary variable that controls the operation of a unit (ON/OFF) this unit is used to
	**Limiting relation for all TP** establishes a minimum value for one variable (A) respect to another variable (B) considering all the time periods. The limited value (A) must be greater or equal than the maximum value (B) multiplied by a percentage.
$\alpha \leq \beta$	**"A higher B"**: the variable A must be lower or equal than B.
$\alpha \geq \beta$	**"A higher B"**: the variable A must be greater or equal than B.

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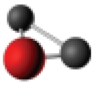
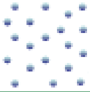
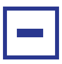
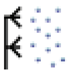
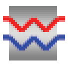
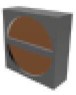
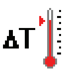
Table 5.25 shows the units which connections require an **"Air flow"** stream, so the main input and output are not modelled just as energy flows. The main properties of **"Air flow"** are the mass flow rate, temperature, humidity and enthalpy. The units listed have been developed for one of the case study in Chapter 6.

Table 5.25 Units those are associated to air streams

AIR	
	**Air flow** is an air stream, if it is placed inside a **Constant value node** the mass flow is fixed with the same value specified in the **Constant value node** unit. The enthalpy is calculated using the dry temperature (ºC) and the humidity ratio (g/kg).
	**Temperature** is a linking unit that must be placed inside an **Air flow** unit. This unit has available for other units in the output connector the temperature of the **Air flow** unit.
	**Humidity ratio** is a linking unit that must be placed inside an **Air flow** unit. This unit has available for other units in the output connector the humidity ratio of the **Air flow** unit.
	**Air mixer** joins several **Air flow** calculating the corresponding output temperature and humidity. Condensation is not considered in this unit.
	**Heating coil** heats an air flow stream using the energy content of an **Energy flow**.
	**Cooling coil with dehumidification** cools an air flow using the energy content of an **Energy flow**. A binary variable determines when is dehumidifying or when is only cooling. If there is dehumidification the output air is saturated.
	**Cooling coil** cools an air flow using the energy content of an **Energy flow**.
	**Humidifier** is used to add water to a air stream. A binary variable can control its state (ON/OFF).
	**Power to air** increases the temperature of the air by a fixed power and efficiency. Can be used to consider the heat produced by a fan.
	**Heat exchanger**. A constant efficiency is fixed to determine the energy exchanged between the two air streams. A binary variable can control the state of the heat exchanger (ON/OFF)
	**Rotary wheel** is a heat exchanger with a fixed maximum efficiency. As the efficiency of a rotary wheel depends of the velocity of ration, the real efficiency of this unit is variable and depends of the optimisation process, but must be equal or lower than the maximum fixed efficiency. The velocity of rotation is not considered in this unit.
	**Temperature increase** is used to increase the temperature of an air stream by a fixed temperature increment.

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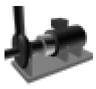
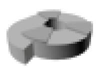
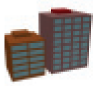
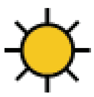
The energy demand is allways and input parameter in MGEOS. Currently there are no units able to calculate the energy demand of a building from the definition of the building and the behaviour of the occupants. The energy demand must be calculated previously and introduced in MGEOS as an input parameter. From the optimisation point of view, the energy demand can be fulfilled completely or not, or some buildings can be supplied with energy and others not as a function of economic or environmental aspects, but in all the cases the energy demand is a constant parameter that must be supplied by the user.

Table 5.26 shows the units used to specify an energy demand. Units like **"Auxiliary demand"** and "**Simple energy demand"** fix a demand for a certain type of energy. **"Building demand"** can be used to fix the typical demand of a building, including electrical, heating, sensible and latent cooling. The units **"Climatisation"** and **"Summer season"** that must be placed inside the **"Building demand"** can be used for control purposes for other units responsible to supply the energy demand of the building.

Table 5.26 Energy demand units

ENERGY DEMAND	
	**Auxiliary demand** requires an input energy demand that can be calculated as a function of other energy flows or variables (usually binary variables for ON/OFF states).
	**Simple energy demand** With this unit the user introduces a demand (energy or power) in the flowsheet. The user also introduces a price and chose if the energy demand must be fulfille or not.
	**Building demand** represents the energy demand of a one-zone building. An energy demand can be specified for electricity, heating, sensible cooling and latent cooling. Beside the energy demand, the following parameters must be specified for each time period: • Climatisation state (ON/OFF) • Summer season (TRUE/FALSE)
	**Climatisation** is a linking unit that must be placed inside **Building demand**. This unit is used to acces to the *Climatisation state* parameter defined inside **Building demand** at any place of the flowsheet, without the necessity to connect the **Building demand** block to the required unit directly. The purpose of this unit is to create more readable flowsheets.
	**Summer season** is a linking unit that must be placed inside **Building demand**. This unit is used to access to the *Summer season* parameter defined inside **Building demand** at any place of the flowsheet, without the necessity to connect the **Building demand** block to the required unit directly.

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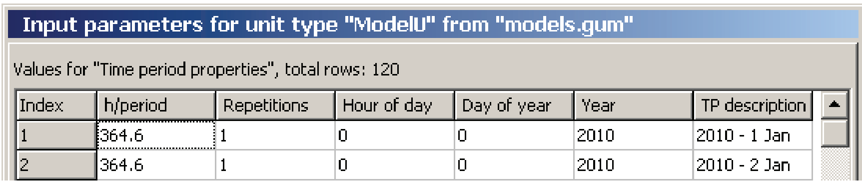
5.6 Temporal scales of the models

The unit **"Model"** contains the main information of the model, specially the temporal scales. Currently, only two temporal scales can be used: time periods and years. Time periods are any temporal division in which are evaluated all the energy balances and operational conditions of the units. Array variables and energy or material flows will contain a value for each time period defined. Each time period has several properties like the number of hours that has each time period or how many times the time period is repeated (if the methodology explained in Chapter 3 is applied to the model). If only one year is defined in the unit **"Model"**, all the time periods are included in that year, otherwise the user must indicate the which year belong each time period. The number of time periods and years will depend of the type of model to be implemented. For example if ten typical days (with 24 hours) must be used for one year, the time periods ranges from 1 to 240 and years range from 2010 to 2010. If ten typical days for each year must be used during five years, a total of 1200 time periods must be defined and five years from 2010 to 2014. Then the first 240 time periods belongs to 2010, the next 240 time periods belongs to 2011 until the last 240 periods that belongs to 2014. The number of hours for each time period can be used to define time steps different from one hour, for example each time step could represent a complete day, a week, a month, etc. as a function of the number of hours assigned.


Input parameters for unit type "ModelU" from "models.gum"

Values for "Time period properties", total rows: 120

Index	h/period	Repetitions	Hour of day	Day of year	Year	TP description
1	364.6	1	0	0	2010	2010 - 1 Jan
2	364.6	1	0	0	2010	2010 - 2 Jan

Figure 5.32 Properties of time periods in unit "Models"

5.7 Conclusions

The optimisation environment developed in this thesis is composed of the tools GUME and MGEOS. GAMS is the calculation engine that solve the models. The principle of the environment developed is the modularity of the optimisation model for each type of unit or technology. This modularity facilitates the development, use and maintenance of the models. Each unit is developed and used with independency of other units already existing. This modularity makes the environment flexible and it can be used easily in different case studies to optimise not only economic or environmental factors, but also any variable of the model like the energy production of a specific unit, the efficiency of the system, energy savings, etc.

The indicators included in the Plant unit are the investment cost, operational costs, maintenance cost, CO_2 emissions, SO_2 emissios and primary energy consumption. These indicators cover most of the cases or scenarios where economic and environmental factors are optimised. The indicators can be used also to calculate and optimise the payback period or the net present value. As mentioned previously, any variable of the flowsheet can be selected as objective to perform the optimisation. This makes very easy to perform different type of analysis for the same flowsheet. Althought multiobjective optimisation is not implemented with a specific unit that makes all the process automatically, multiobjective techniques like the weighting method or the constrained method can be applied easily using a processor unit and solving the model several times.

All the units currently developed and the possibility to add custom equations in the flowsheet allows the evaluation of very specific energy polygeneration systems in MGEOS. Although non-linear functions are not used, some of them can be linearised using units that discretise the curve in several linear sections. Furthermore most of the units are represented efficiently using linear relations (taking into account the scope of the models presented in this thesis). The tools and the models developed are able to represent efficiently energy polygeneration system and modelise non conventional configurations.

An important limitation of the models presented in this thesis is the dificulty to modelise configurations including material flow with mass flow, temperatures and enthalpies. Several units has been developed to work with material flows, but to maintain the linearity of the models a variable (usually the mass flow rate) must be fixed. The aim of MGEOS is not the development of very detailed models. Simulation tools like TRNSYS, INSEL would be more suitable for this purpose.

All the units presented in this section are available in the MGEOS library and allows defining a high variety of configurations and scenarios. Some of these units will be used in the case studies to optimise the yearly operation of a small scale polygeneration system and to perform a scenario analysis of a high capacity DHC polygeneration system. Due to the lack of experimental data most of the models has not been validated yet but has been developed in accordance with other optimisation or simulation models found in the literature (internal combustion engines, absorption chillers, energy storage, solar collectors, etc.).

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Chapter 6 – Case study 1

Polygeneration with liquid desiccant cooling system

6.1 Introduction

During the progress of this thesis, a three month stay has been done in the Politecnico di Torino (Italy) in the Department of Energetics (DENER) in the group of Professor Marco Badami. The research activity of Professor Badami has been mainly focused on theoretical and experimental analysis of internal combustion engines (combustion process, pollution formation, 1D-3D simulation), injection systems (cavitation, sprays, transitory system simulation), and Fluid-machines simulation and optimisation. Moreover he has carried out theoretical and experimental studies on small scale cogeneration systems both with internal combustion engines and with turbogas generators. The task performed during the stay was the experimental study of four liquid desiccant units to provide air conditioning to a classroom building. These desiccants units are integrated into a trigeneration plant with a novel 120 kW electrical cogenerator engine with a high efficiency at partial load. During the stay were analysed the preliminary results of the desiccant units.

Section 6.2 introduces the trigeneration plant installed in Politecnico di Torino. Section 6.3 presents some of the monitored results obtained and some correlations are tested to predict the temperature and the humidity of the output air from the dehumidification column. The COP is estimated indirectly using some of the measures. Finally, MGEOS is used to analyse several scenarios in order to calculate some economic and environmental indicators to evaluate the viability of the polygeneration system. The methodological approach is presented in section 6.4. The implementation of the polygeneration plant in MGEOS is discussed in section 6.4.3. The energy demand of the building is calculated in section 6.4.4 and the scenarios are presented in section 6.5. The results are discussed in section 6.6.

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6.2 Overview of the polygeneration plant in Politecnico di Torino

Small-scale cogeneration plants are systems that are able to simultaneously produce electricity and heat in a 50 – 200 kWe power range for most applications. Interest in these plants has been increasing steadily over the last few years, since they are able to provide a significant primary energy consumption reduction, with respect to separate generation of the same amount of electrical and thermal energy, using traditional equipment. For this reason, cogeneration is also one of the technologies that has been promoted by the European Union (EU) as a way of achieving energy efficiency and energy savings in the industrial, tertiary and residential sectors. An EU Directive has been issued on this subject with the purpose of facilitating the installation and operation of cogeneration systems, in order to save energy and combat climate changes (Directive 2004/8/EC).

Trigeneration plants seem to be even more interesting, since the thermal energy produced during the summer season, and not directly used as the final energy vector, can easily be converted into cooling energy, by means of specific equipment, such as absorption chillers or desiccant cooling systems. This possibility also allows the cogeneration plant to be operative during the summer season, with a consequent increase in its yearly running hours that is favourable for the economic proficiency of the plant (Badami et al 2009a).

Many studies have been conducted on trigeneration plants made up of internal combustion engines or microturbines coupled to single stage absorption chillers for example in (Maidment et al 2002, Badami et al 2009, Moya et al 2009). Desiccant cooling systems have also been investigated extensively in literature. Some state-of-art technology reviews of these systems are available in Daou et al 2006 and Jain et al 2007. Other studies have focused on the systems using a $CaC1_2$ solution as a liquid desiccant (Kinsara et al 1996), or on solid desiccants regenerated by thermal energy obtained from solar collectors (Davangere et al 1999, Henning et al 2001). A study of an aqueous lithium chloride desiccant system has been presented in Fumo et al 2002, while a solar powered air conditioning system, using liquid desiccant, has been proposed in Kabeel et al 2007. An innovative trigeneration plant constituted by an internal combustion engine coupled to a liquid desiccant system is presented in this chapter. The main purpose of the plant installed in the Politecnico di Torino (Turin, Italy) is to provide air conditioning to a building dedicated to educational activities. Preliminary experimental tests have been conducted for the desiccant systems, and the results are here presented, together with the description of the measurement instruments that were adopted.

6.2.1 Plant description

The main components of the plant are the CHP unit and the liquid desiccant system. The cogenerator was developed and set up by the FIAT Research Centre (Turin, Italy). The cogeneration engine can provide 126/220 kW of electrical and heating, respectively. The cogenerator is provided with an electronic power unit, made up of an AC/DC-DC/AC converter, which allows the engine to operate at a variable speed, while delivering 50 Hz AC to the grid. Thanks to this strategy, the engine can work at a higher partial load efficiency than similar equipment as shown in figure 6.2 (Badami et al 2007). Finally, two humidifiers, a rotary heat exchanger and a cooling tower are also needed to complete the installation. A schematic layout of the installation is shown in figure 6.3.

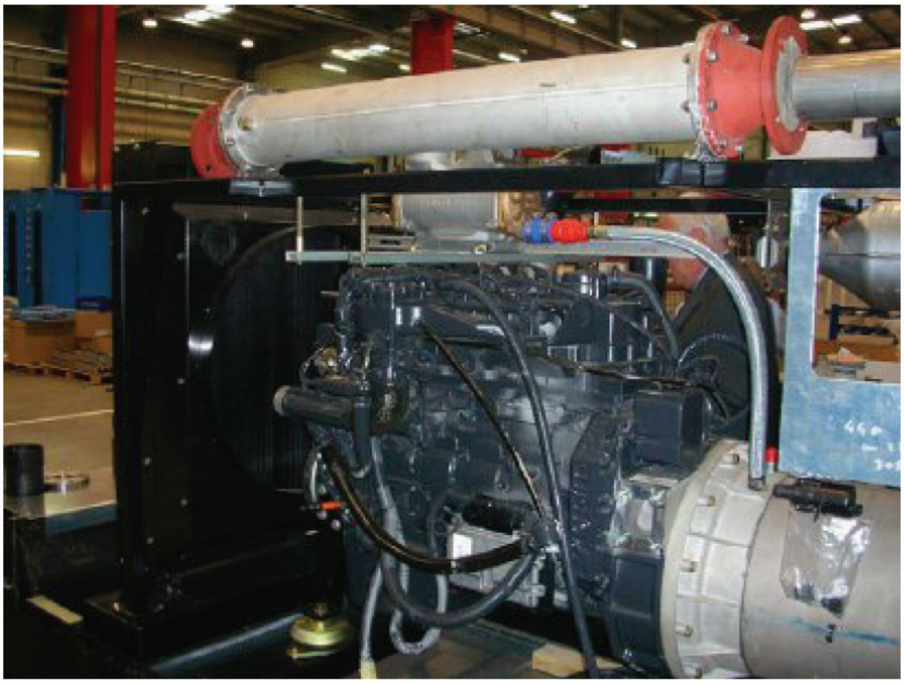

Figure 6.1 FIAT research centre cogeneration engine (Badami et al 2009)

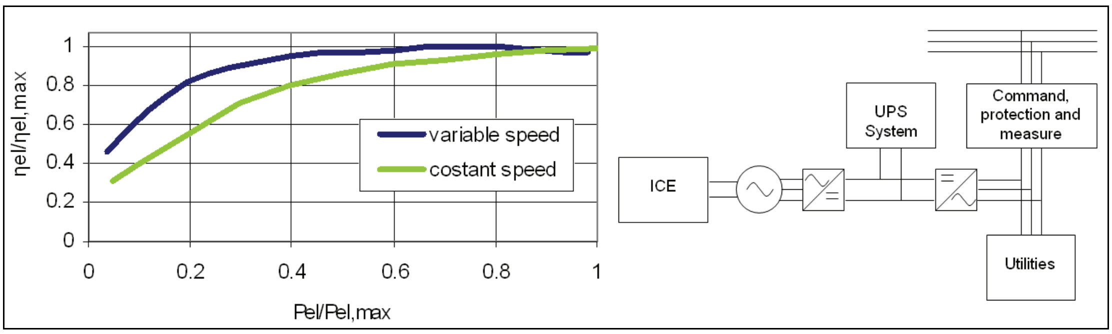

Figure 6.2 Electrical scheme of the small-scalle cogeneration engine (Badami et al 2007)

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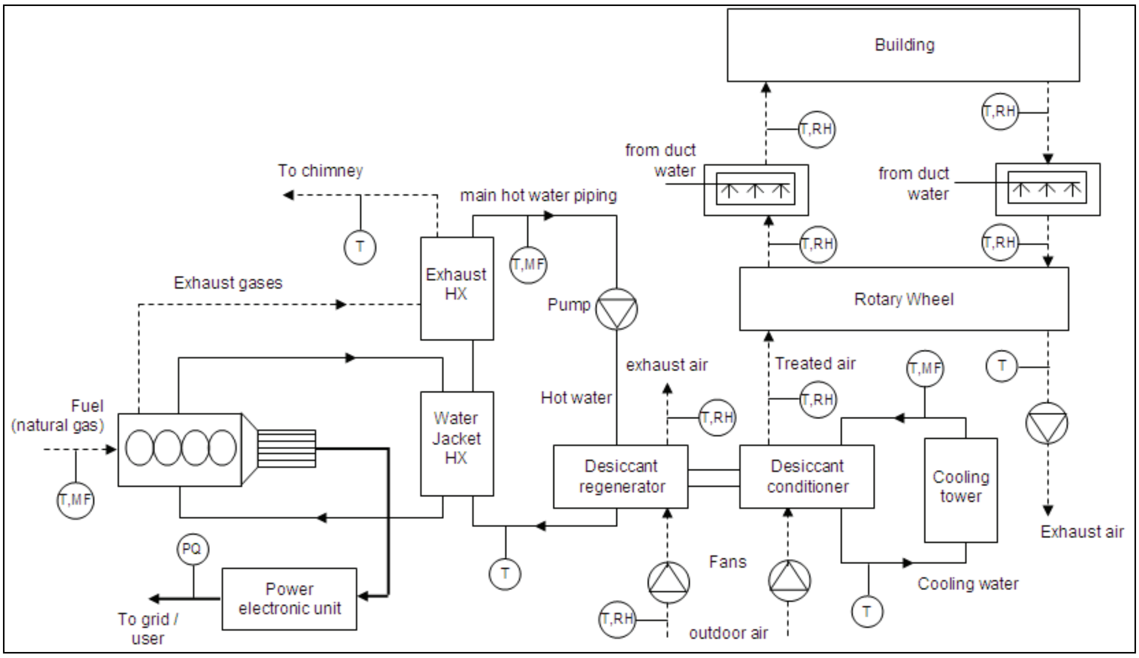

Figure 6.3 Schematic configuration of the trigeneration plant installed in the Politecnico di Torino

The thermal power is recovered from the engine through two heat exchangers, one recovering waste heat form the engine cooling water and the other from the flue gases. Using these exchangers, hot water can be produced at 90°C, and can be employed inside the desiccant system regenerator. The purpose of the regenerator (*regeneration phase*) is to evaporate the water absorbed from the air into the solution in the conditioner side (*dehumidification phase*). The absorption of the water from the outdoor air is done by means of the contact between the cooled LiCl solution, dripped over the honeycomb column, and the air which passes through the column in counter-flow mode. As the solution attracts the moisture from the air, its level tends to increase, and therefore the water in excess flows from the conditioner to the regenerator, thanks to the communicating vessel effect.

Figure 6.4 shows a simplified scheme of a liquid desiccant cooling unit. The cooling media to extract the condensation heat from the dehumidifier is the cool water from the cooling tower (streams 3 and 4). The hot media for the regenerator is hot water from the cogeneration system (streams 1 and 2). The desiccant solution drips at the top of the honeycomb media through the dehumidification pump (PP). The pump (RP) in the regeneration section drips the desiccant solution at the top of the honeycomb media to evaporate some water and concentrate again the solution. Both pumps are always working, maintaining the honeycomb media wetted all the time. The operation of the desiccant unit is controlled by:

- The regeneration fan (RF)
- The dehumidifier fan or process fan (PF)
- Hot water valve (HW) in the regeneration side
- Liquid Desiccant level (HL, ML and LL)

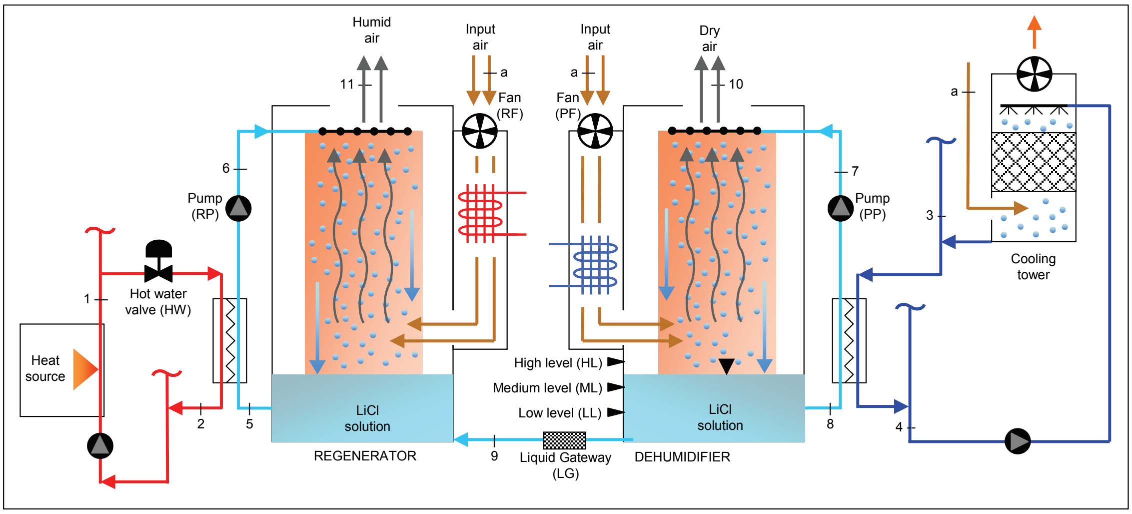

Figure 6.4 Simplified scheme of one of the desiccant units installed in the Politecnico di Torino

The desiccant cooling units have been tested in manual mode. In this mode of operation, the pumps, the process fan and the cooling tower are allways working. When humidity is removed from the air in the dehumidifier, the level of the desiccant solution rises. The desiccant level in the dehumidifier and the regenerator is expected to be the same. Both systems are connected through the Liquid Gateway (LG), which allows the circulation of water from the dehumidification to the regeneration section by diffusion due to the concentration difference between the two subsystems. The quantity of salt in each subsystem is constant. When the solution level rises, the regeneration is activated (RF is turned ON) decreasing the level of the desiccant solution.

The hot water valve is opened when it is necessary independently of operation of the regeneration fan (ON/OFF). The purpose of the hot water valve is to heat the desiccant solution in the regeneration side when is required. The regeneration fan is working until the regeneration solution is concentrated again and the level of the desiccant solution decrease to the medium level. Under normal operational conditions, the low level (LL) is never reached. The general data for each desiccant unit are reported in table 6.1 and the capacity data are reported in table 6.2.

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Table 6.1 General characteristics for each desiccant unit (manufacturer data)

Number of units	4
Desiccant solution type	LiCl-water
Nominal air capacity	5000 m^3/h
Maximum air capacity	5780 m^3/h
Hot water operating temperature range	50 – 90 °C
Hot water flow	250 l/min
Cold water operating temperature range	-10 – 35 °C
Cold water flow	250 l/min
Minimum ΔT between the hot and cold water	25 °C
Desiccant solution volume	175 l
Operating weight (including LiCl)	690 kg
Dimensions (L/W/H)	2240/1420/1575 mm

Table 6.2 Cooling capacity for each unit at two different ambient conditions (manufacturer data)

Conditions	Ambient 30 ºC, 70 % R.H., 18.8 g/kg Hot water 85 ºC, cold water 6 ºC	Ambient 30 ºC, 70 % R.H., 18.8 g/kg Hot water 65 ºC, cold water 17 ºC
Sensible cooling	25.3 kW	9.7 kW
Latent cooling	49.1 kW	35 kW
Total cooling	74.4 kW	44.7 kW
Moisture extraction	70 lt/h	52 lt/h
Temperature reduction	13 °C	6 ºC

Figure 6.5 shows the building heated and air-conditioned with the trigeneration plant. The building is composed of several classrooms and the main air handling unit (AHU2) and the desiccant units are installed in the utilities building (figure 6.6).

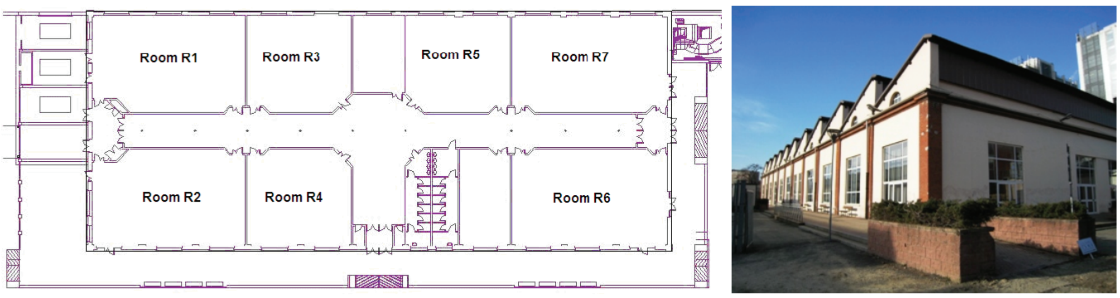

Figure 6.5 Layout of the building heated and air-conditioned by the desiccant trigeneration plant

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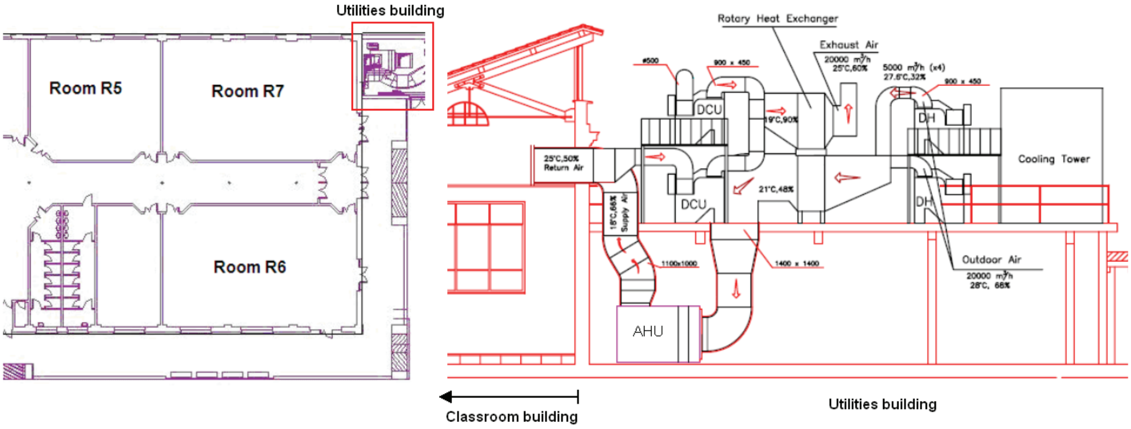

Figure 6.6 Utilities building containing the desiccant units placed next to the classroom building

Figures 6.7 and 6.8 show the desiccant cooling units installed on the roof of the utilities building that is placed next to the classroom building (left image in figure 6.6). The cooling tower, the air desiccants inlet/outlet and the air ducts are shown in the pictures. These air ducts (at the left of the figure 6.7) drives the output dehumidified air of the desiccant units into the main air handling unit (AHU2) showed in figure 6.9.

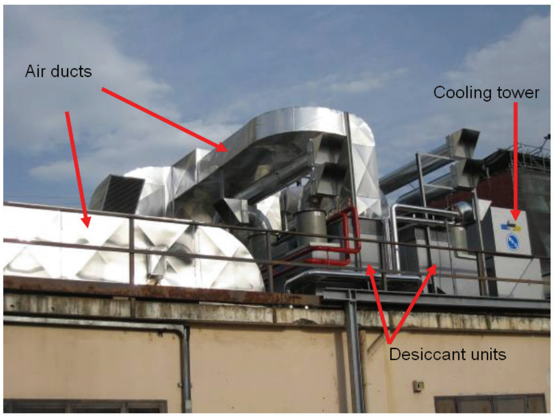

Figure 6.7 Desiccant units and cooling tower

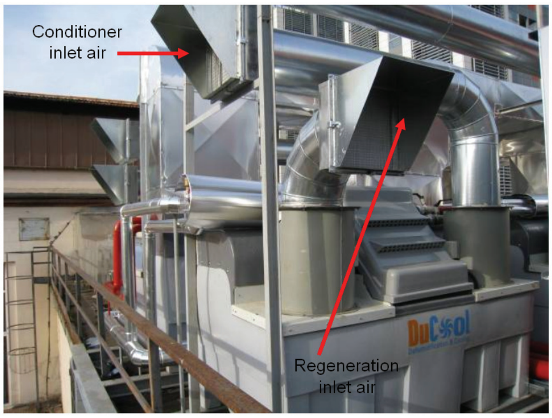

Figure 6.8 Inlet/outlet of one of the four units

The main air handling unit is placed inside the utilities building between the rotary wheel heat exchanger and the classrooms building (figure 6.3). This air handling unit is composed of a cooling coil, a heating coil a humidifier and the main fan. The purpose of this unit is to supply all the ventilation air in the required conditions and supply additional cooling when the power cooling of the desiccant units is not enough. This additional cooling is supplied using the compression chillers cooling plant installed in Politecnico di Torino. Figure 6.9 shows the air duct from the desiccant units (righ) and the air duct to the building (left).

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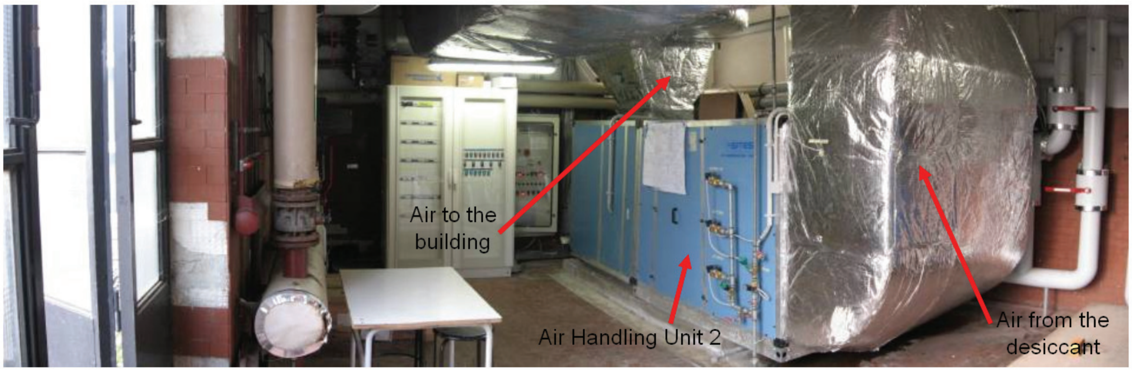

Figure 6.9 Control system and main air handling unit (AHU2) placed inside the utilities building

6.2.2 Experimental facility

An overview of the measurement system installed in the plant is presented in this section. All signals are collected in a Compact Field Point controller that communicates, via Ethernet, with a data acquisition system developed in Labview™. In this way, the most important operating variables are sampled and stored, and they can then be processed in the data analysis. Table 6.3 lists the type of sensors used for the monitoring and their accuracy.

Table 6.3 List of sensors installed: parameters monitored, typology and accuracy of the sensors

Variable	Sensor typology	Sensor Accuracy
Gas input to engine volume flow (Nm^3/h)	Mass-thermic flow sensor (Nm^3/h)	+/- 3% of measured value
CO_2, NO_x, CO, O_2 and SO_2 concentrations in the exhaust gases (mg/Nm^3)	CO_2, NO_x, CO: Non Dispersive Infrared technique; O_2: electro-chemical method	CO, NO_x: 0–100 ppm 10% of reading O2 : ±0.3%
Flue gas temperature (°C)	Iron-constantan thermocouple	±1°C to 199°C ±0.5% of reading > 199°C
Water temperature (°C)	4 wires RTD sensors, class A	±0.15°C @ 0°C ±0.35°C @ 100°C
Mass flow of water	Ultrasonic static mass flow meter	±1% of reading
Air temperature (°C)	Humidity / Temperature Transmitter (Hygrometer / class A RTD sensor)	±0.25°C @ -10°C ±0.20°C @ 20°C ±0.28°C @ 40°C
Relative humidity of the air (%)		-15 – 40°C < 90% RH: ± (1.3 + 0.3%*mv) % RH -15 – 40°C > 90% RH: ± 2.3% RH
Electric power produced by alternator (kWel) Power Quality	Power meter and Grid Analyser	Voltage: ±0.25% FS Current: ±0.25% FS Power: ±0.50% FS Power factor: ±1% FS

A combined humidity and RTD temperature sensor was also installed at the conditioner outlet of each unit. Its accuracy is ± 3% RH, ± 1°C (treated air in figure 6.3). In the following section, the main monitored data are reported and discussed.

6.2.3 Regeneration temperature

The desiccant cooling system was tested at the beginning of October using the district heating network of the Politecnico di Torino for the regeneration side. The temperature in the regeneration side must be high enough to evaporate the same or more water than the water condensed in the dehumidifier, otherwise, the level would increase and the PF would be stopped and no more conditioned air would be produced. The nominal operational conditions given by the manufacturer are calculated at 85 ºC and 65 ºC for the regeneration side (table 6.2). The temperature obtained from the district heating network is low ranging from 57 ºC to 65 ºC. The effect of the temperature in the regenerator respect to the conditions of the output air is represented in figure 6.10. The solid lines are the output humidity ratio (flow 11, figure 6.4) of the air in equilibrium (meaning dehumidification efficiency = 100%) with the desiccant solution at a certain concentration. The dashed lines are the output humidity ratio with an efficiency of the 80 %. It is assumed a drop of 4 ºC between the hot water (T_1) and the temperature of the desiccant solution dripped in the regenerator (T_6).

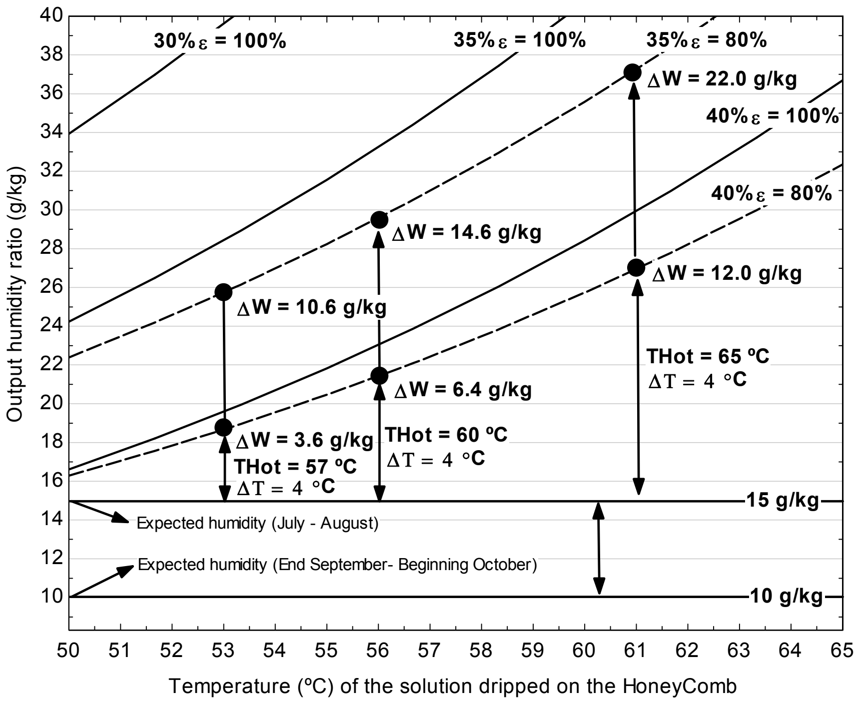

Figure 6.10 Effect of the temperature solution on the regeneration rate

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The bottom horizontal lines represent the expected humidity ratio in Torino for July-August (15 g/kg) and September-October (10 g/kg) (meteorological file of EnergyPlus for Torino). The water evaporated in the regenerator per kg of dry air, is the difference between the humidity of the input air to the regenerator (a) and the humidity of the output air (flow 11). Table 6.4 shows the expected humidity removal in the regenerator as a function of the hot water temperature, the desiccant concentration and the month. From figure 6.10 and table 6.4, as higher is the temperature, higher is the quantity of water evaporated. With respect to the concentration of the desiccant solution, as lower is the concentration, higher is the water evaporated.

Table 6.4 Maximum theoretical water removal in the regeneration side at different conditions

Hot water temperature (T1, ºC)	Concentration LiCl	July-August	September-October
57	40%	3.6	8.6
	35%	10.6	15.6
60	40%	6.4	11.4
	35%	14.6	19.6
65	40%	12.0	17.0
	35%	22.0	27.0

The use of lower activation temperature (57-65 ºC) in the regeneration side can be justified from the previous table, as the humidity ratio is lower in autumn, at the same regeneration temperature, more water can be removed. Even with the lower temperature considered (57 ºC in T_1) in autumn the regeneration side will be able to evaporate between 8 and 15 g/kg of water, considering that the expected ambient humidity is around 10 g/kg, it can be concluded, that for this temperature and ambient conditions, the theoretical evaporation rate is greater than the maximum possible condensation rate in the dehumidifier. It is expected that the low temperature in the regenereation side does not affect the cooling performance.

6.3 Monitored data in the desiccant units

Desiccant cooling system was tested from 1th until 5th of October 2009, and the measurements were registered every five minutes. The results shown corresponds from the 1th of October at 21:15 to the 5th of October at 9:15, with a total of 1007 monitored points. From the four units, two units worked continuously during this period. Figure 6.11 shows the status (ON/OFF) of the two units for the 2nd of October, from 8:30 (hour 0 in the plot) to 16:45 (hour 8.15 in the plot). PF is the process fan (dehumidifier) status, RF is the regenerator fan status and HW is the hot

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water valve status in the regenerator. If a point is represented for these three items, it means the item is ON (or open), otherwise it is OFF (or closed). The level of the desiccant has also been plotted, where 1 means low level, 2 means medium level and 3 means high level. Some preliminary results were presented in Badami et al 2010.

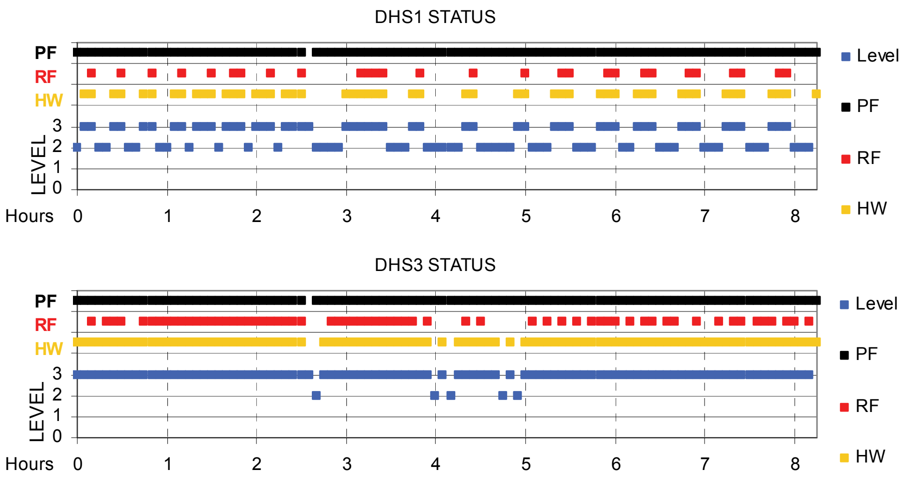

Figure 6.11 Operational status for the dehumidification and regeneration process in desiccant units DHS1 and DHS3 on 2nd October (8:30 – 16:45)

Figure 6.12 shows the hot water temperature at the regenerator inlet for the same day. A lower activation temperature than the nominal one (90 °C) has been obtained using the district heating network (between 55-65 ºC), but due to the moderate ambient humidity it is expected that this temperature will be enough to operate the desiccant units (section 6.2.3). The operation of the conditioners was set to manual, which means that the conditioners were operated removing the maximum possible humidity and under the current operational conditions: ambient humidity and temperature, hot water temperature, and temperature of the water from the cooling tower. The ambient humidity ratio oscillates between 9 and 11 g/kg.

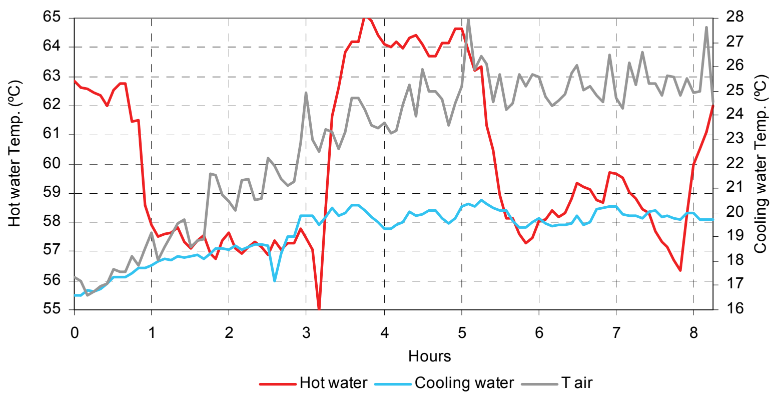

Figure 6.12 Hot water temperature input to the conditioners

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Figure 6.13 shows the input and output air condition for DHS3 unit in two periods for the 2nd October. The points corresponding to morning operation, between 8:30 and 9:30, are plotted on the left. All the points measured in the afternoon, from 13:30 to 15:00, are on the right, and they present higher temperatures. In the morning air is heated because of the low input temperature of the air, compared to that in the afternoon. The output absolute humidity is roughly the same for all the points, but the output relative humidity is lower in the afternoon, due to the difference in the output temperature.

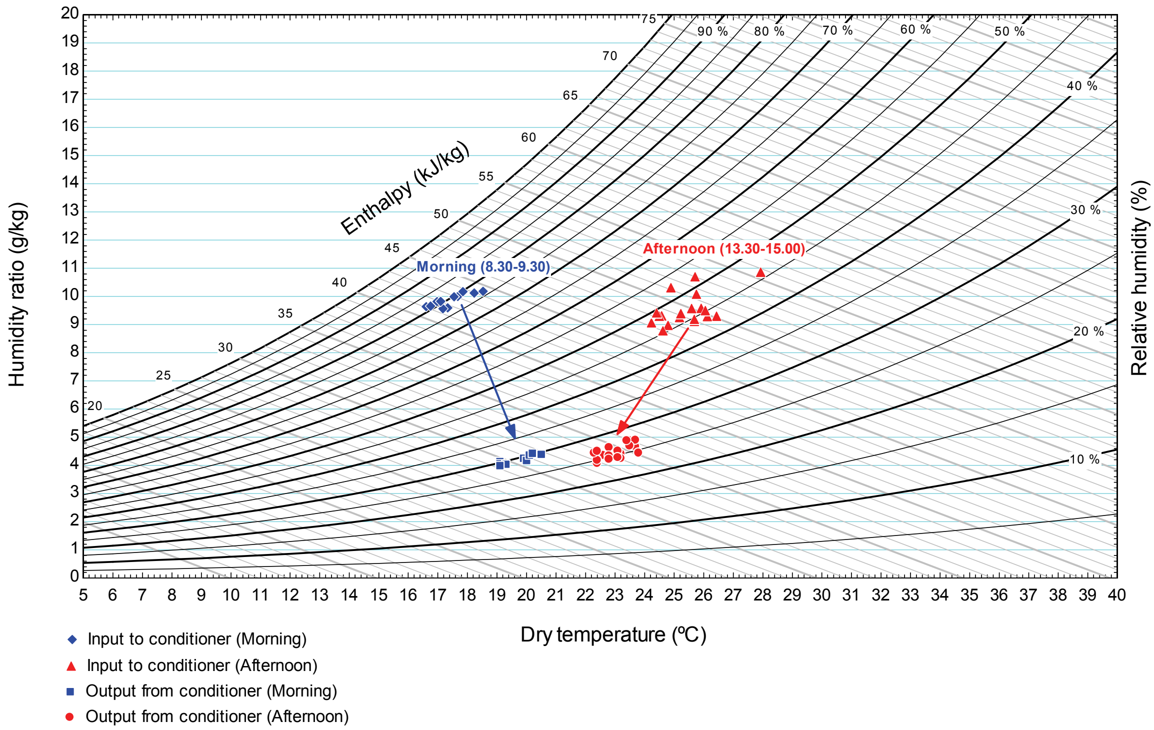

Figure 6.13 Dehumidification process for the DHS3 conditioner on 2nd of October

The dehumidification and regenerator columns are made of corrugated cellulose, and the volume-to-surface ratio measured using sheets form this packet is 425 m^2/m^3 (figures 6.14, 6.15 and 6.16). This value is in accordance with the values presented in Chung et al 1996. Due to the wetting properties of the water and cellulose, the honeycomb column is always completely wet (the circulation pumps dripping the water at the top of the column are always working). For this reason, no equations, like the one proposed in (Onda et al 1968), were considered to calculate the effective wet area. The dehumidifier efficiency is defined as follows (Martin et al 2000):

$$\varepsilon = \frac{W_{in} - W_{out}}{W_{in} - W_e} \tag{6.1}$$

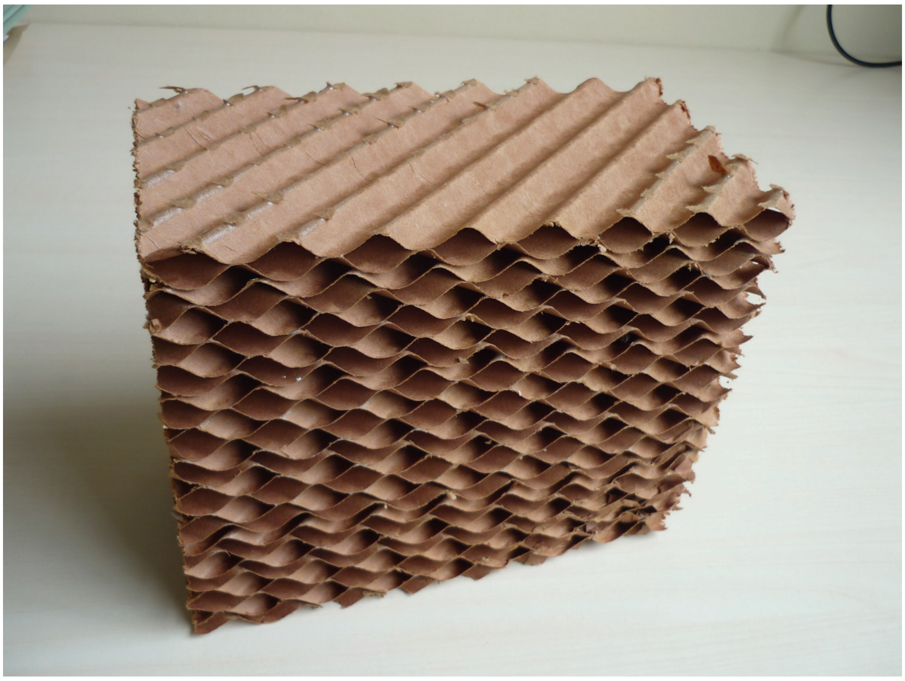

Figure 6.14 Celullose packet used in the dehumidifer and regenerator columns

Figure 6.15 View of the crossed channels of the packet

Figure 6.16 One of the sheets used to measure the volume-to-surface ratio

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Where W_{in} and W_{out} are the humidity ratios of the air at the inlet and outlet of the desiccant units, respectively, and can be calculated from the monitored temperature, relative humidity and pressure. W_e is the humidity of the air when the outlet of the air of the dehumidifier is in equilibrium with the dripped solution at the top of the column. This occurs when the vapour pressure of the water in the air ($P_{vap\_w,air}$) is the same as that the vapour pressure of water of the desiccant solution ($P_{vap\_w,LiCl}$):

$$P_{vap\_w,LiCl} = P_{vap\_w,air} \quad (6.2)$$

The vapour pressure of the desiccant solution has been calculated using the correlation presented in Chaudari et al 2002. According to the desiccant manufacturer's specifications the following assumption has been made:

$$T_7 = T_3 + 3.5\ °C \qquad \text{(according to the nomenclature in figure 6.4)} \quad (6.3)$$

Although the LiCl concentration changes according to the desiccant level, a constant mass fraction of 40% has been considered. Dehumidification efficiency (ε) has been calculated for all the measured points, and is reported in Figure 6.17 for DHS1 and DHS3 units. The shadowed zones in the figure correspond to the time between 8:30 and 18:00 for each day. There are some differences between the two units, but unit three always shows better performance than unit one. Figure 6.18 shows the cooling capacity of each unit, calculated by the difference in enthalpy between the input and the output air in the dehumidification column, and the nominal air mass flow rate (5.000 m^3/h for each unit). The obtained cooling capacity is lower than at of nominal conditions (44.7 kW, table 6.2, with hot water = 65 ºC), because the ambient humidity is lower and the temperature of the cooling tower water is higher with respect to the nominal conditions.

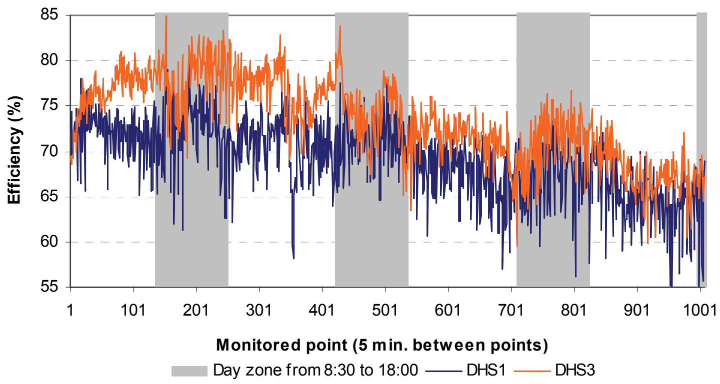

Figure 6.17 Dehumidification efficiency for DHS1 and DHS3

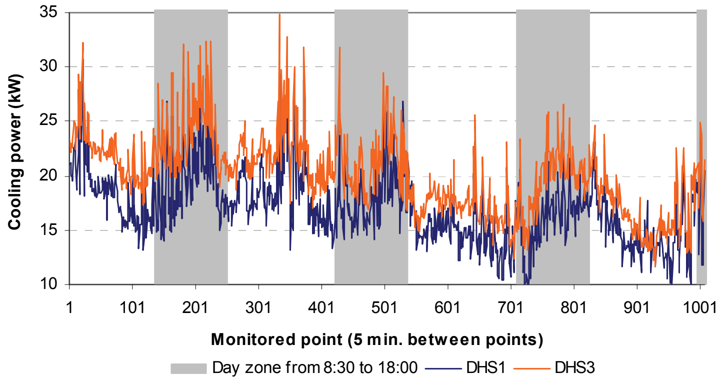

Figure 6.18 Calculated cooling capacity for DHS1 and DHS3

6.3.1 Output temperature of the dehumidifer

The temperature of the output air from the conditioner is required to calculate the total cooling capacity of each conditioner. This temperature is also useful to calculate the energy required by the auxiliary units (UTA2) to deliver the air to the desired conditions into the building. There are no correlations to predict this temperature. When detailed simulations using finite difference equations are not used, usually a dimensionless temperature difference ratio is assumed for the dehumidification column (Gandhidasan, 2004). With the nomenclature of the figure 6.4 the thermal efficiency is defined as:

$$\beta_{th} = \frac{T_a - T_{10}}{T_a - T_7} \tag{6.4}$$

Figure 6.19 and 6.20 shows the calculated thermal efficiency with equation 6.4 using the monitored data. The efficiency is not constant, but sometimes seems to oscillate around the same value. This value is more clear for the DHS3 unit that for the DHS1 unit.

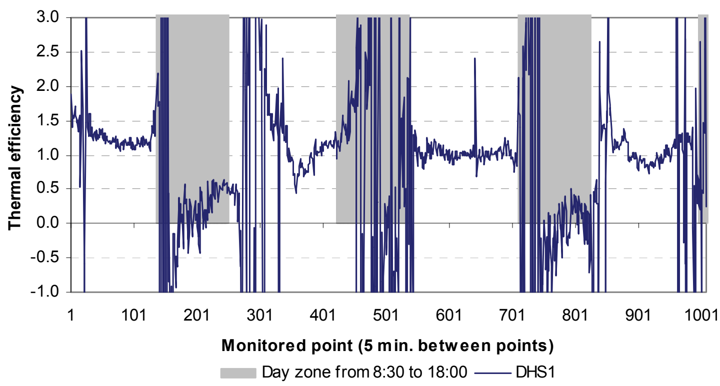

Figure 6.19 Experimental thermal efficiency for DHS1

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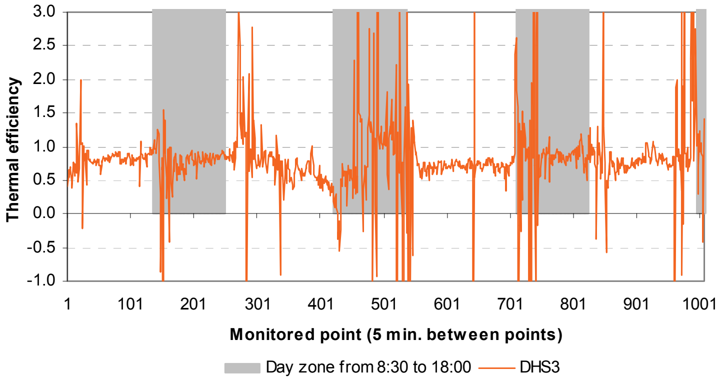

Figure 6.20 Experimental thermal efficiency for DHS3

To calculate the temperature difference ratio of the dehumidifier, a regression has been made using the 1007 measured values minimizing the sum of the square differences. The output temperature can be calculated with equation 6.5:

$$Tcalc_{10,j} = Texp_{a,j} - \beta_{th} \cdot \left(Texp_{a,j} - Texp_{7,j}\right) \quad (6.5)$$

$$SSD = \sum_{j=1}^{n} \left(Texp_{10,j} - T_{10,j}\right)^2 \quad (6.6)$$

Where $Texp_{a,j}$ and $Texp_{10,j}$ are the monitored input and output temperatures of the air in the dehumidifier. $Texp_{7,j}$ is the temperature of the solution dripped on the top of the honeycomb media (equation 6.3). $Tcalc_{10,j}$ is the calculated output temperature of the air. Minimizing the value of SSD can be found the value for the thermal difference ratio of the honeycomb media β_{th}. The calculated values are shown in table 6.5. The average error is calculated comparing for each point the experimental value of T_{10} with respect to the calculated value of T_{10} using the efficiency value shown in the table. The maximum error is the maximum for all the 1007 points.

Table 6.5 Thermal efficiency in the dehumidifier

	DH1	DH3
β_{th} value	0.870	0.769
Average error	4.3%	1.5%
Maximum error	22.5%	12.2%

Figures 6.21 and 6.22 compare the experimental output temperature with the temperature calculated with equation 6.5 and the β_{th} value presented in table 6.5. The prediction for the unit DHS3 is better respect the unit DHS1.

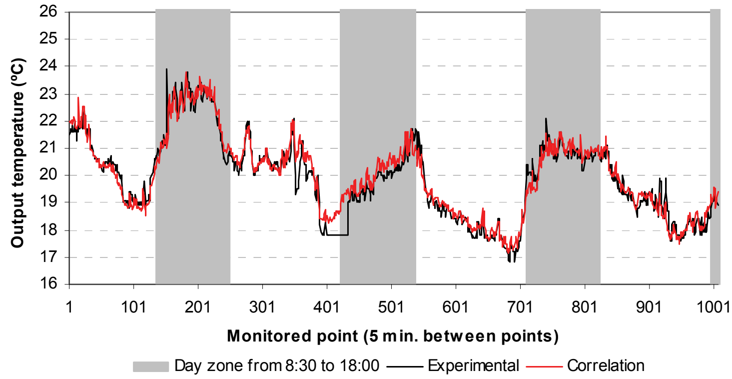

Figure 6.21 Prediction of the temperature for DHS1 η_{th} = 0.870

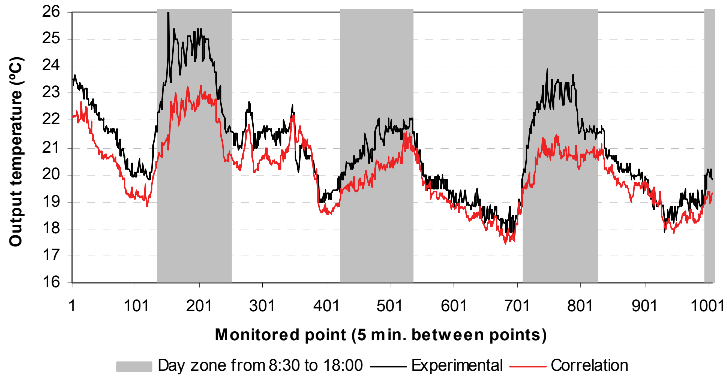

Figure 6.22 Prediction of the temperature for DHS3 η_{th} = 0.769

A linear regression is proposed using the monitored data to improve the prediction of the temperature of the output air using the equation 6.7, where A, B, C and D are coefficients calculated minimizing the sum of the square differences between the predicted temperature with the linear correlation and the monitored value of T_{10}. This equation is based in the modelling of the absorption chillers presented in Chapter 4. In this case are included in the correlation the temperatures of the input air to the dehumidifier (T_a in figure 6.4), the temperature of the cooling tower water (T_3) and the water content of the input air (W_a).

$$T_{10,j} = A \cdot Texp_{a,j} + B \cdot Texp_{7,j} + C \cdot Wexp_{a,j} + D \qquad (6.7)$$

The regression is made using 152 selected points from the 1007 points available. These 152 points are shown in the figure 6.23, and has been selected according to the following criteria: select the zones where the parameters (specially the hot water temperature) are quite constant, and select several zones along the 1007 points to be able to “capture” the behaviour of the unit during these four days of operation.

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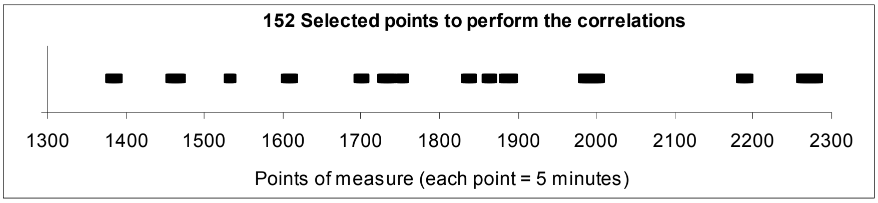

Figure 6.23 Selected points from the monitored data used in the correlations

The values for the parameters of the regression made for the 152 points are shown in table 6.6 for the units DH1 and DH3. Figures 6.24 and 6.25 compare the monitored output temperature with respect to the predicted value with the equation 6.7 for all the 1007 points.

Table 6.6 Parameters obtained for equation 6.7

	DHS1	DHS3
A	$-7.403 \cdot 10^{-1}$	$8.579 \cdot 10^{-1}$
B	$9.823 \cdot 10^{-1}$	1.098
C	$-4.431 \cdot 10^{-2}$	$-1.516 \cdot 10^{-1}$
D	$2.445 \cdot 10^{-2}$	$3.562 \cdot 10^{-1}$

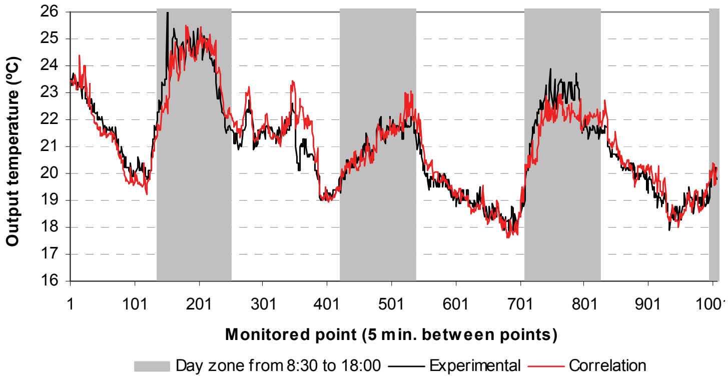

Figure 6.24 DHS1 output temperature with linear correlation

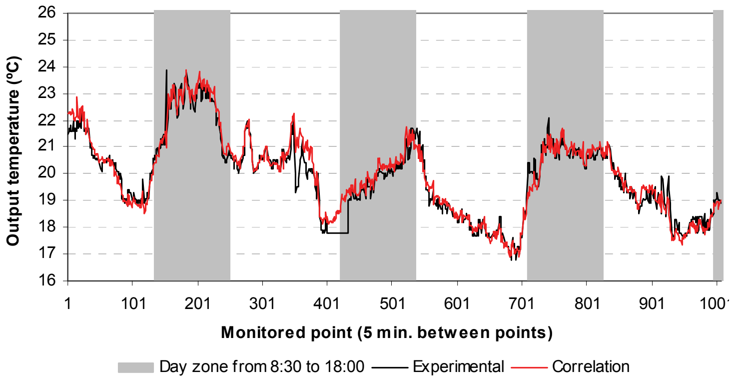

Figure 6.25 DHS3 output temperature with linear correlation

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The average and the maximum errors of the predicted temperature with equation 6.7 with respect to the monitored values for the 1007 points are presented in table 6.7. The error for unit DHS3 is very similar with the linear correlation with respect to the use of a constant efficiency (table 6.5). Respect the unit DHS1, the linear correlation works better. As mentioned previously, the thermal difference ratio of the unit DHS1 is not so constant respect the unit DHS3, and the use of the linear correlation is recommended.

Table 6.7 Prediction error for the linear correlation

	DHS1	DHS3
Average error	1.89%	1.38%
Maximum error	17.7%	12.2%

6.3.2 Calculation of the COP

Due to a problem with the control system of the cogeneration engine, the temperature of the return hot water (T_2 in figure 6.4) and the mass flow rate has not been recorded, only the temperature of the input water is available (T_1). The energy required in the regenerator and the COP can not be calculated and are estimated using the experimental data. To estimate the energy requirements of the regenerator the following hypothesis has been assumed:

- Neglect the energy associated with flow 9 (figure 6.4).
- There are no energy losses to the ambient through the walls.

With the hypothesis listed, the regenerator can be modelled as:

$$Q_{reg} = m_1 \cdot (H_1 - H_2) \tag{6.8}$$

$$m_1 \cdot (H_1 - H_2) = m_{11} \cdot (H_{11} - H_a) \tag{6.9}$$

H_1 and H_a can be calculated from the monitored data, H_{11} is not monitored and must be estimated in order to obtain the value of Q_{reg}. To estimate the value of H_{11} the temperature and the humidity at the output of the regenerator must be determined. Since the operation on the regenerator is not constant (in contrast to the dehumidifier), an average Q_{reg} value for each hour is calculated during eight hours. Equations 6.10 and 6.11 are used to calculate the total water condensated in the dehumidifier between each sample (i) and during each hour (h). The average output humidity for each hour ($\overline{W}_{11,h}$) is calculated with the equation 6.12. $\overline{W}_{a,h}$ is calculated from the experimental data. $\overline{W}_{e\,reg,h}$ is the humidity ratio in equilibrium calculated with the equations 6.13 and 6.14. The vapour pressure of the water in the air (equation 6.13) is calculated using data from a psychrometric chart. The vapour pressure of water in the desiccant solution (equation 6.14) is calculated with an Antoine type equation (equation 6.15, Chaudari et al 2002). A_{LiCl}, B_{LiCl}, C_{LiCl} are coefficients that depend on the concentration of LiCl in the desiccant solution. An increment of temperature (ΔT_{reg}) is assumed to calculate the temperature of the desiccant solution in equation 6.16. With the equation 6.17 is calculated $t_{reg\,c,h}$. This is the theoretical regeneration time (seconds) required in each hour if all the condensate water in the dehumidifier during that hour is evaporated in the regenerator. $t_{reg\,c,h}$ does not indicate how the regeneration time is distributed inside each hour. $TS_{reg\,e}$ (experimental) and $TS_{reg\,c}$ (calculated) are the total regeneration time for the eight hours. The concentration of LiCl, $\varepsilon_{W,reg}$ and ΔT_{reg} must be adjusted in order to be equal to TS_{rec} calculated with the experimental value (equation 6.21). With this procedure $\overline{W}_{11,h}$ and the regeneration time are estimated.

$$C_{cond,i} = \left(W_{a,i} - W_{10,i}\right)\cdot m_{air,d} \cdot \Delta t_i \tag{6.10}$$

$$H_{cond,h} = \sum_{i=i_o}^{i_f} C_{cond,i} \tag{6.11}$$

$$\varepsilon_{W\,reg} = \frac{\overline{W}_{11,h} - \overline{W}_{a,h}}{\overline{W}_{11,h} - \overline{W}_{e\,reg,h}} \tag{6.12}$$

$$\overline{P}_{vap\,air,h} = A_{air} \cdot \overline{W}_{e\,reg,h} + B_{air} \tag{6.13}$$

$$\overline{P}_{vap\,LiCl,h} = \overline{P}_{vap\,air,h} \tag{6.14}$$

$$\log\left(\overline{P}_{vap\,LiCl,h}\right) = A_{LiCl} + \frac{B_{LiCl}}{\overline{T}_{LiCl.h}} + \frac{C_{LiCl}}{\overline{T}^2_{LiCl,h}} \tag{6.15}$$

$$\overline{T}_{LiCl,h} = \overline{T}_1 + \Delta T_{reg} \tag{6.16}$$

$$t_{reg\,c,h} = \frac{H_{cond,h}}{\left(\overline{W}_{11,h} - \overline{W}_{a,h}\right)\cdot m_{air\,reg}} \tag{6.17}$$

$$TS_{reg\,c} = \sum_{h=1}^{N} t_{reg\,c,h} \tag{6.18}$$

$$t_{reg\,e,i} = ST_{RF} \cdot \Delta t_i \quad (6.19)$$

$$TS_{reg\,e} = \sum_{h=1}^{N} \sum_{i=h_o}^{h_f} t_{reg\,e,i} \quad (6.20)$$

$$TS_{reg\,e} \approx TS_{reg\,c} \quad (6.21)$$

To calculate the average temperature of the air at the output of the regenerator, a temperature difference ratio is assumed in the equation 6.22. The value of β_{th} obtained for the dehumidifier (table 6.5) has been used to estimate $\beta_{th,reg}$. Once $\overline{T}_{11,h}$, $\overline{W}_{11,h}$ and $t_{reg,h}$ are calculated for each hour, Q_{reg} and the COP value can be calculated with the equations 6.23 to 6.25.

$$\beta_{th,reg} = \frac{\overline{T}_{11,h} - \overline{T}_{a,h}}{\overline{T}_{11,h} - \overline{T}_{6,h}} \quad (6.22)$$

$$\overline{Q}_{reg,h} = \left(\overline{H}_{11,h} - \overline{H}_{a,h}\right) \cdot m_{air,reg} \cdot \frac{t_{reg\,c,h}}{3600} \quad (6.23)$$

$$Q_{dehum,h} = \frac{1}{3600} \cdot \sum_{i=h_o}^{h_f} \left(H_{a,i} - H_{10,i}\right) \cdot m_{air,dehum} \cdot \Delta t_i \quad (6.24)$$

$$\overline{COP}_h = \frac{Q_{dehum,h}}{\overline{Q}_{reg,h}} \quad (6.25)$$

Figure 6.26 shows the cooling capacity and the estimated average COP for units DHS1 and DHS3. The cooling capacity is calculated using experimental data (figure 6.18). Table 6.8 shows the values for the parameters obtained in order to obtain the same value of $TS_{rec\,c}$ respect the experimental data ($TS_{rec\,e}$)

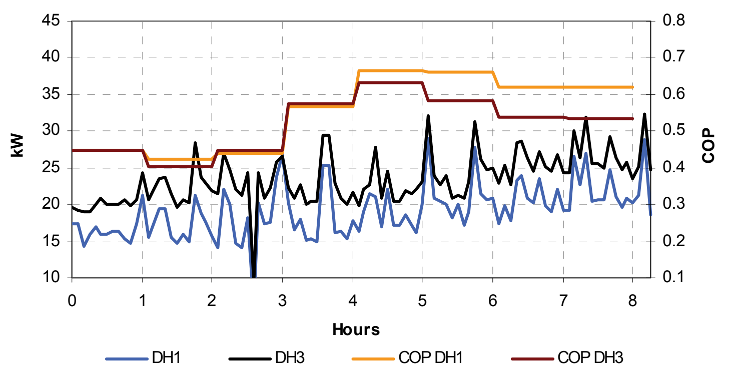

Figure 6.26 Cooling power and COP

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Table 6.8 Parameters assumed to calculate the energy requirement in the regenerator

	DHS1	DHS3
ΔT_{reg} (ºC)	3.5	5.3
ε_T	0.87	0.77
$\varepsilon_{W\ reg}$	0.85	0.65
Conc LiCl in regenerator to calculate A_{LiCl}, B_{LiCl}, C_{LiCl} (mass fraction)	0.365	0.390

It is important to underline that the values of table 6.8 are not experimental values, these are values adjusted to obtain (from a theoretical point of view) the same regeneration time along eight hours with respect to the real regeneration time monitored. As can be seen from figure 6.11, the unit DHS3 is almost all the time in high level, whereas the level of the unit DHS1 oscillates between the high and medium level. This behaviour is reflected in the values obtained in the table 6.8 (higher ΔT_{reg} and lower $\varepsilon_{W,reg}$ in DHS3). From the point of view of the regeneration process, unit DH3 works worst in comparison with unit DHS1, because is not able to decrease the level of the desiccant solution to the medium level. Another contribution to the desiccant high level in DHS3 could be the higher quantity of water condensed in the dehumidifier during the eight hours in DH3 (250 kg) respect DHS1 (232 kg). It is important to keep in mind that a measurement is taken each five minutes, and the calculation of the regeneration time ($t_{reg\ e,h}$) could be not very precise, since it is not possible to know exactly when the regeneration fan signal changes from ON to OFF and vice versa. Figure 6.26 can be compared with the figure 6.12 to see the temperatures of the hot water, the ambient air, and the cooling water from the tower. Figure 6.27 shows the ambient humidity of the air (W_a). The oscillations of the measured humidity could be caused because some of the output air from the regenerator could be introduced in the dehumidifier as fresh air due to the placement of the inlet duct to the dehumidifier and the outlet duct from the regenerator.

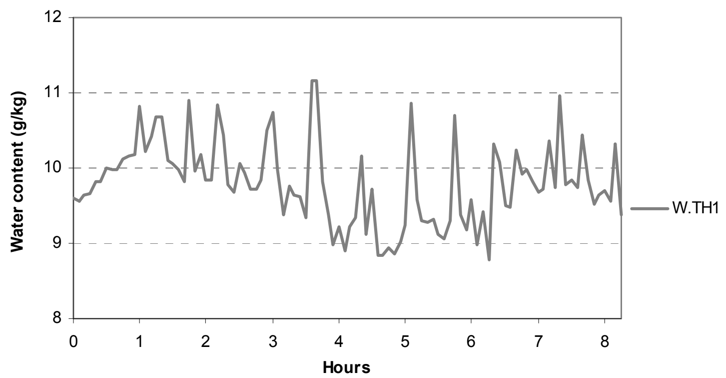

Figure 6.27 Ambient humidity ratio for the calculation of COP

6.3.3 Prediction of the dehumidification rate

There are several empirical correlations available in the literature to predict the efficiency of the dehumidifier (equation 6.1). These correlations have been proposed for desiccant solutions using LiCl, LiBr or TEG and for both structured and random packing. An analysis of the use of these correlations can be found in Jain et al 2007. In particular, Chung's and Chung&Luo's correlations have been compared with the obtained experimental results. The different variables and parameters are reported in table 6.9.

$$\varepsilon_{Chung} = \frac{1-\dfrac{0.205\cdot GL^{0.174}\cdot \exp\left[0.985\cdot TGTL\right]}{\left[A\cdot Z\right]^{0.184}\cdot PVR^{1.68}}}{1-\dfrac{0.152\cdot \exp\left[-0.686\cdot TGTL\right]}{PVR^{3.388}}} \qquad (6.26)$$

$$\varepsilon_{Chung\,Luo} = \frac{1-\dfrac{0.024\cdot GL^{0.6}\cdot \exp\left[1.057\cdot TGTL\right]}{\left[A\cdot Z\right]^{-0.185}\cdot PVR^{0.638}}}{1-\dfrac{0.192\cdot \exp\left[0.615\cdot TGTL\right]}{PVR^{-21.498}}} \qquad (6.27)$$

Table 6.9 Parameters appearing in Chung's and Chung Luo's correlations

Parameter	Description	Value
GL	Air mass flow / solution mass flow ratio	0.917
A	Pack column volume-to-surface ratio	425.7 m^3/m^2
Z	Tower column height	0.79 m
TGTL	Air temperature / solution temperature ratio	variable
PVR	Vapour pressure difference: ($P_{vap\_w,air}$ - $P_{vap\_w,LiCl}$) /	variable

The humidity at the outlet air predicted with Chung's and Chung Luo's correlations can be calculated with equations 6.28 and 6.29:

$$W_{out,Chung} = W_i - \varepsilon_{Chung}\left(W_{in} - W_e\right) \qquad (6.28)$$

$$W_{out,Chung\,Luo} = W_i - \varepsilon_{Chung\,Luo}\left(W_{in} - W_e\right) \qquad (6.29)$$

Several hypotheses were considered when applying the correlations for the calculation of the efficiency for the dehumidifier: a constant LiCl mass fraction of 40% was considered; the temperature of the LiCl solution was calculated from the cooling tower water temperature, and the temperature of the input air was the measured ambient temperature (equation 6.3); the air and LiCl solution mass flow rates were considered constant, although the mass flow rate of the

LiCl solution dripped at the top of the column can vary slightly, mainly as a function of the concentration of the solution.

Another correlation applied, is an equation of the form of equations 6.26 and 6.27 that can be used to fit the experimental data by nonlinear regression (Liu et al 2006). The equation 6.30 can be fitted to the experimental data to find the values of the parameters B0, B1, B2 and B3. In this case, as the concentration is assumed to be constant, X_{LiCl} is constant and the variable X_{LiCl}^{B3} can be grouped inside B0. In the same way, as the mass flows (air and liquid desiccant) is considered also constant, the variable GL^{B1} can be grouped also inside B0. With these assumptions, equation 6.30 can be rewrite as shown in equation 6.31.

$$\varepsilon_{chung''} = \frac{1 - \dfrac{B0 \cdot GL^{B1} \cdot \exp\left[B2 \cdot TGTL\right]}{X_{LiCl}^{B3}}}{1 - \dfrac{W_e}{W_{in}}} \tag{6.30}$$

$$\varepsilon_{Chung''} = 1 - \frac{B0 \cdot \exp\left[B2 \cdot TGTL\right]}{1 - \dfrac{W_e}{W_{in}}} \tag{6.31}$$

B0 and B2 are fitted minimizing the sum of the square differences. The regression is made using 152 points (from the 1007 monitored points, figure 6.23). Once the equation is fitted, the predicted efficiency calculated with equation 6.31 is compared with the experimental data for all the 1007 points. The values for the parameters are presented in table 6.10.

Table 6.10 Parameters of equation 6.31

	DH1	DH3
B0	$4.2675 \cdot 10^{-1}$	$3.9629 \cdot 10^{-1}$
B2	$1.6624 \cdot 10^{-1}$	$1.7248 \cdot 10^{-1}$

A linear correlation (equation 6.32) similar to the multiregression model for absoprtion chillers (Chapter 4) has been used also to predict the humidity removal of the dehumidifier. Like in the previous case, 152 from the 1007 points have been used to do the regression. Table 6.11 shows the parameters obtained from the regression.

$$m_{regDH,j} = A \cdot T\exp_{a,j} + B \cdot T\exp_{7,j} + C \cdot W\exp_{a,j} + D \tag{6.32}$$

$$W_{10,j} = W_{air,j} - m_{regDH,j} \tag{6.33}$$

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Table 6.11 Parameters for the linear correlation (equation 6.32)

	DH1	DH3
A	$4.0922 \cdot 10^{-2}$	$5.4829 \cdot 10^{-2}$
B	$-1.2394 \cdot 10^{-1}$	$-1.3167 \cdot 10^{-1}$
C	$8.8685 \cdot 10^{-1}$	$9.4482 \cdot 10^{-1}$
D	-2.3547	-2.7785

Summarising, four correlations have been applied to the 1007 points of operation. Table 6.12 shows the average absolute error, and the maximum absolute error comparing the result of the correlations with respect to the experimental data (figures 6.28 to 6.35).

Table 6.12 Absolute average and maximum error

Absolute error	DH1				DH3			
	Chung&Luo	Chung	Liu	Lineal	Chung&Luo	Chung	Liu	Lineal
Average	9.23	26.9	5.52	4.21	7.0	19.9	5.73	4.76
Maximum	40.8	67.6	27.0	26.1	28.6	53.8	23.6	22.5

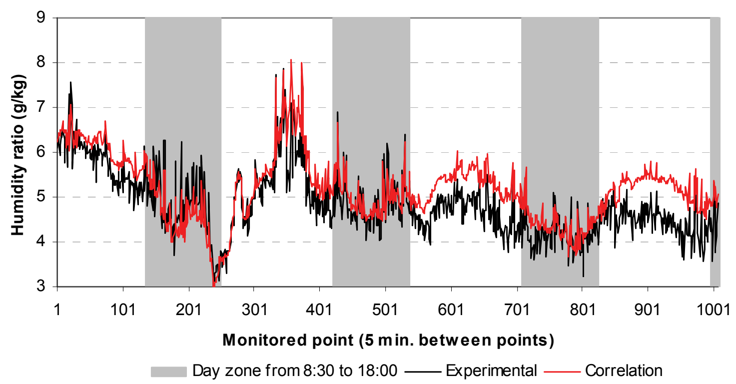

Figure 6.28 Comparison of Chung&Luo correlation with DHS1

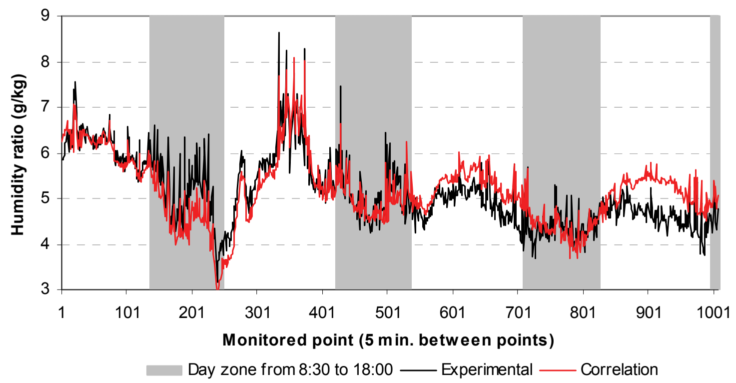

Figure 6.29 Comparison of Chung&Luo correlation with DHS3

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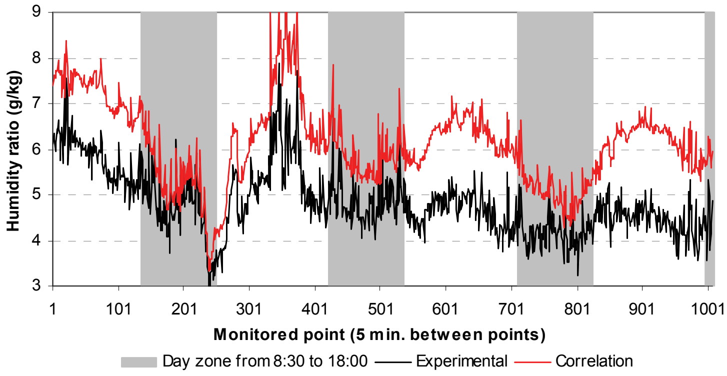

Figure 6.30 Comparison of Chung correlation with DHS1

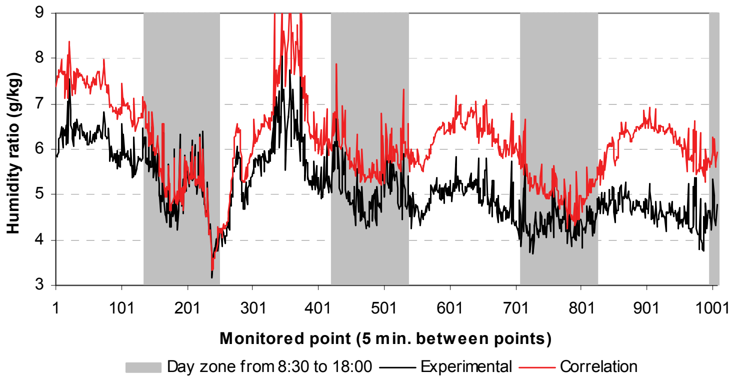

Figure 6.31 Comparison of Chung correlation with DHS3

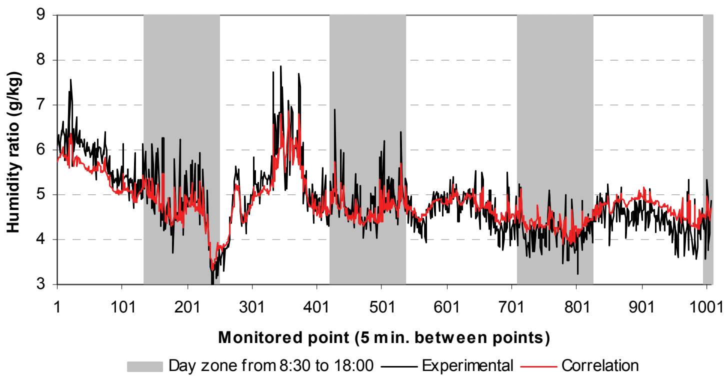

Figure 6.32 Comparison of eqn. 6.31 fitted to DHS1

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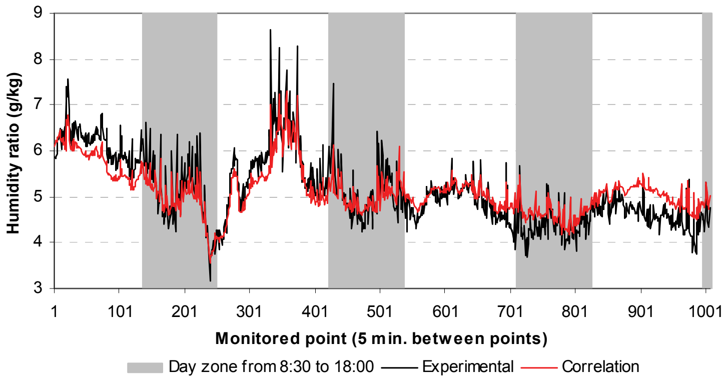

Figure 6.33 Comparison of eqn. 6.31 fitted to DHS3

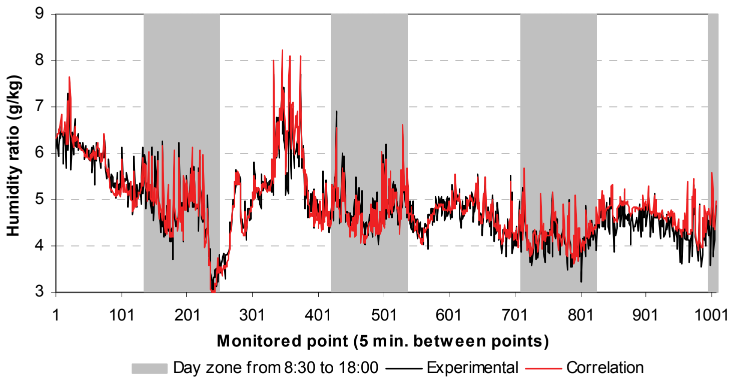

Figure 6.34 Comparison of the linear correlations with DHS1

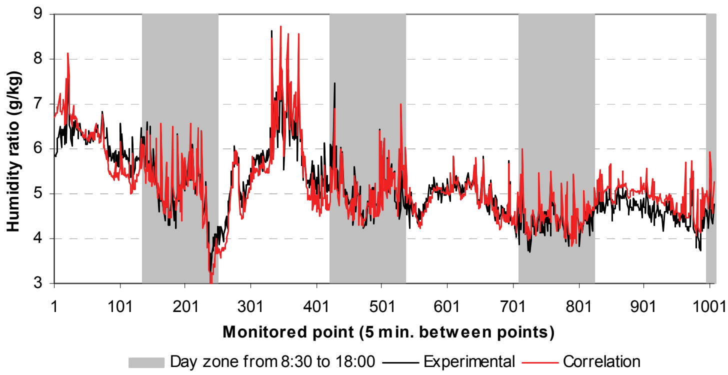

Figure 6.35 Comparison of the linear correlations with DHS3

6.3.4 Transient behaviour of the desiccant units

As it is usual in all the thermal cooling systems, there is a transient behavior until the stationary condition is reached each time the unit is started or turned off. This transient behavior occurs due to the capacitance of the materials and fluids that constitutes the system. Usually this behavior is more pronounced as higher is the capacity of the system (higher cooling capacity). Of the four desiccant units, two units (DHS1 and DHS3) have been working uninterrupted for almost four days. Due to technical problems, DHS2 has not been working. Unit DHS4 worked only during few hours and the transient behaviour has been monitored. Figures 6.36 and 6.37 shows the start-up and shut-down process for two different days. For each figure, the upper plot shows the output humidity ratio (g/kg) of the conditioned air at the output of each desiccant unit. The lower plot shows the status of the desiccant unit DH4. "Level" indicates the level of the desiccant solution inside the unit; the typical values during the operation are 2 and 3. All the other signals indicate the status ON/OFF of different items of the unit. When nothing is plotted, it means OFF, when a point is plotted, it means ON. The items represented are the following:

- Alarm: indicates if there is an alarm in the desiccant unit.
- Proc pump: indicates if the process pump (PP in figure 6.4) is working.
- Reg pump: indicates if the regeneration pump (RP in figure 6.4) is working.
- PF: indicates if the process fan (PF in figure 6.4) is working.
- RF: indicates if the regeneration fan (RF in figure 6.4) is working.
- HW: indicates if the hot water valve (HW in figure 6.4) is opened.

The grey line in the upper plot of each figure is the humidity ratio of the ambient air. As mentioned above, the unit DHS2 is not working. The monitored value of humidity ratio at the output of DHS2 is not relevant, since it is turned OFF and the process fan is also off, the measure of the humidity ratio corresponds to the suspended air inside the unit. Units DHS1 and DHS3 are working and are used as reference to know when the unit DH4 reaches stationary conditions. This means that when the unit DHS4 is ON or OFF, the output humidity of DH4 will change from the ambient humidity to the output humidity of DHS1 and DHS3 and vice versa. In the two cases, DHS4 is turned ON at +1 hour, and is working for almost four hours. In the two cases the behavior is very similar. When the unit is turned ON the output humidity decrease quickly reaching the stationary conditions before one hour. When it is turned OFF, if the PF is working the dehumidification of the air continues but increasing the water content.

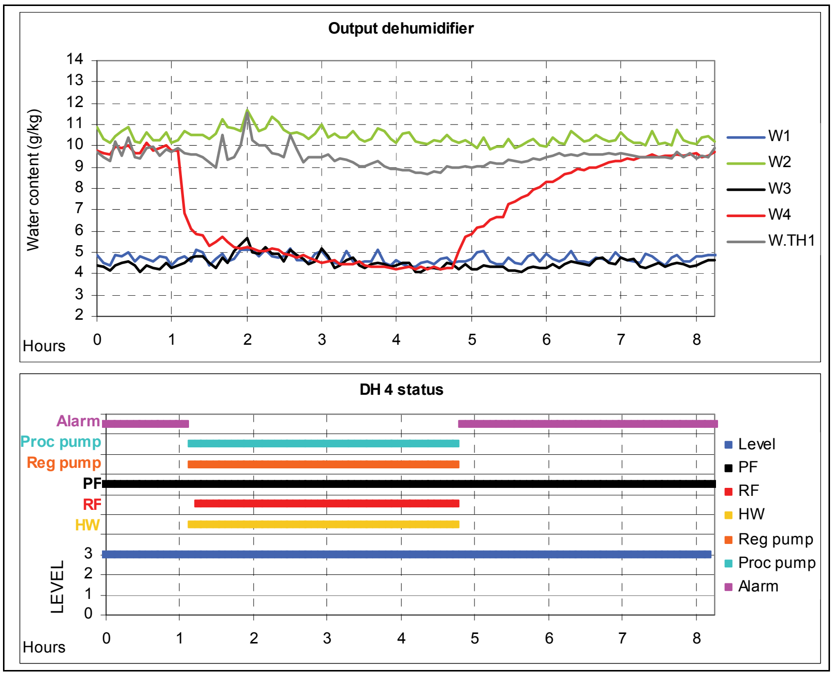

Figure 6.36 Transient behavior of DH4, Hour 0 = 03/10/2009 – 15:30

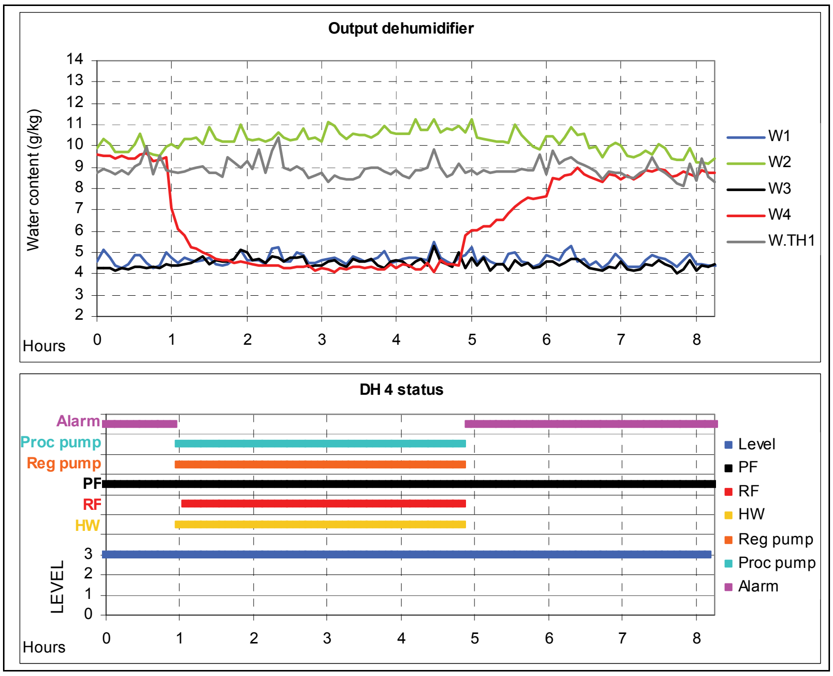

Figure 6.37 Transient behavior of DH4, Hour 0 = 04/10/2009 – 6:30

The transient behaviour of the desiccant units is not considered in the model implemented in MGEOS. Firstly, because the units are able to reach the stationary conditions quickly and secondly because there is no monitoring of the heating requirements in the regenerator and there is no measure of the heating required during the start-up period until the stationary conditions.

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6.4 Methodological approach for the optimisation model

The polygeneration plant presented was finished at the end of summer in 2009. Due to some technical problems the entire system including the cogeneration engine, the desiccant units and the main air handling unit (AHU2) has not been tested working together. There is only some experimental data for some of the desiccant units and for the cogeneration engine working separately. The objective of this case study is to implement the polygeneration system in MGEOS and evaluate the economic and environmental performance of the system for several scenarios with different type of operation and different possibilities to import and export energy from/to the polygeneration system considering the analysis boundary detailed in section 6.4.2. The scenarios will be presented in section 6.5. Beside the economic and environmental evaluation, the purpose of this case study is also to show how MGEOS can be used to implement a specific polygeneration system using the existing units or developing new units.

The modelling of the main units in MGEOS will be made using the experimental data for the cogeneration engine and the desiccant units. The engine will be represented with the model presented in section 4.3.1 and the unit "Cogeneration engine" in section 5.5. The desiccant unit will be modelled using a modified version of the model presented for the "Absorption chiller" in section 4.5 in order to include the ambient humidity and using the correlations obtained in sections 6.3.1 and 6.3.3. Other units without available experimental data are modelled with theoretical models. The compression chiller and the boiler have been modelled using the units "Chiller" and "Boiler" with constant COP and efficiency value, respectively. Other necessary units to represent the air handling units, the building demand and other auxiliary elements has been developed using GUME and are summarized in table 5.25.

Regarding to the energy demand of the classroom building, some calculations has been done previously in the framework of the HEGEL project to estimate the monthly heating demand. For the cooling demand only the peak cooling demand is available. In order to estimate hourly profiles, the annual energy demand of the classroom building has been estimated using Designbuilder, defining a building similar to the classroom building. Afterwards the methodology for the selection of typical days described in Chapter 3 has been applied to select 14 typical days from the annual energy demand obtained. The calculation of the energy demand and the selection of typical days is described in section 6.4.3.

The investment costs and the energy price described in Badami et al 2009a has been used in this case study, as well as other characteristics of the polygeneration plant like electrical

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consumption of the auxiliary units, maintenance costs or personal costs. Regarding to the CO_2 emission and the primary energy consumption, only the emissions produced by the use of the fuels has been considered. The emissions due to the extraction, transformation and transporations have not been included. Energy costs and emission factors are presented in section 6.4.5.

The configuration of the plant, the energy demand, the energy prices and emissions has been implemented in MGEOS to create the model of the polygeneration system solved with GAMS. How the polygeneration plant is implementation in MGEOS is detailed in section 6.4.3.

6.4.1 Characterization of the units

In this section will be presented the sources and methodology used to characterize the units of the polygeneration system. Some new units have been developed: the desiccant liquid, all the units working with air flow in table 5.25 and almost all the units in table 5.26. The rest of the units like the internal combustion engine, boiler, compression chiller, processors and other auxiliary units have been implemented with the existing previous units in the MGEOS library.

The linear correlations obtained from the monitored data (table 6.11) for the prediction of the temperature and the humidity of the output air from the dehumidifier have been used to characterise the operation of the desiccant units. A constant COP value of 0.65 (figure 6.26) calculated using monitored data from the regeneration times and liquid levels will be used to calculate the energy requirements in the regenerator. This constant COP value has been assumed because there are no direct monitored data of the output temperature and mass flow (only the nominal flow of the pump) of the hot water in the regenerator. For this reason the temperature in the regenerator is not considered in MGEOS and it is assumed that is high enough to guarantee the correct operation of the conditioners.

The temperature of the water from the cooling tower (flow 3 in figure 6.4) has been calculated as a contant temperature increment with respect to the ambient wet temperature. Figure 6.38 shows the average temperature increment during each hour from 8:00 to 20:00 of the flow 3 (figure 6.4) respect to the wet bulb ambient temperature. Almost all the time only two desiccant units are working, but in some periods where three desiccant units are working, temperature increments around 2 ºC are reached. It is expected that when four units will be working and with the ambient conditions of June and July the temperature increase will be higher. A constant temperature increase of 3 ºC will be considered for the optimisation model.

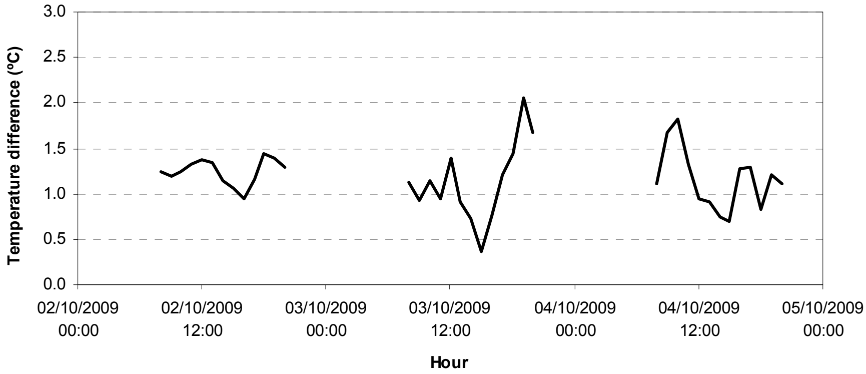

Figure 6.38 Cooling temperature difference respect to wet bulb temperature

The cogeneration engine is modelled using the experimental data presented in Badami et al 2007 and 2008. Figures 6.39, 6.40 and 6.41 show the experimental data obtained at several engine loads. The relation between the gas consumption and the electrical and thermal production are linear, like the examples presented in section 4.3.1. The models presented in Chapter 4 will be implemented using the unit "Internal combustion engine" shown in table 5.19.

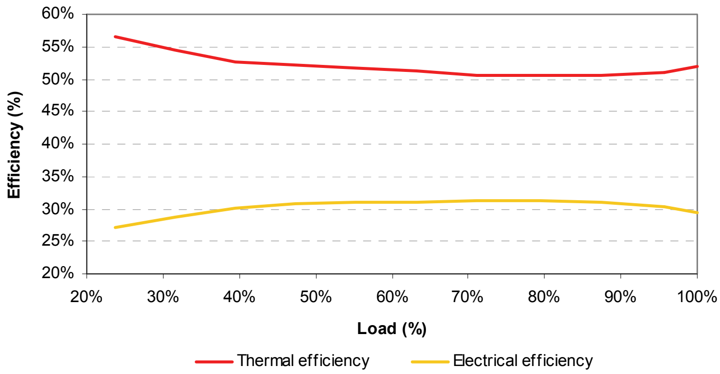

Figure 6.39 ICE electrical and thermal efficiencies

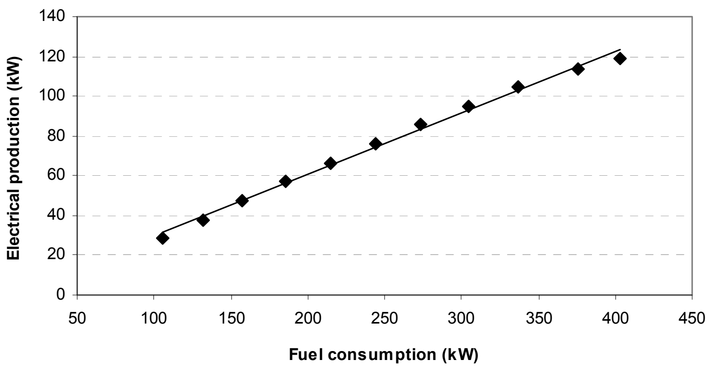

Figure 6.40 ICE electrical production as a function of the fuel

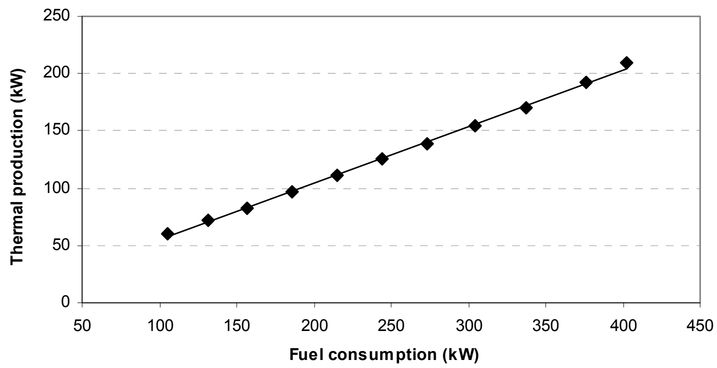

Figure 6.41 ICE thermal production as a function of the fuel

The Air Handling Unit (AHU2, figure 6.9) is modelled using the units listed in table 5.25. A cooling coil, a heating coil and a humidifier are connected in sequence to represent the AHU2. The first cooling coil is able also to dehumidify when it is necessary. The heating coil is used for heating in winter or to reheat the air flow after a dehumidification process in the cooling coil. After the humidifier a "Power to air" unit is connected to simulate the temperature increase of the main fan in AHU2. If the dehumidification of the desiccant units is not enough, the first cooling coil is able to dehumidify using a cooling source from a backup compression chiller.

The cooling coil and the humidifier require the calculation of the saturation temperature for the input and the output air. The unit "3 section linearise" (table 5.23) has been used to calculate the saturation temperature because is a non-linear function of the humidity ratio. Figure 6.42 shows the saturation temperature (black points) of the air calculated with the temperature fluid property function for AirH2O in EES at 1 atm as a function of the humidity ratio. The three correlations presented with different colours (Section 1, Section 2 and Section 3) has been used in the unit "3 section linearise" to calculate the saturation temperature.

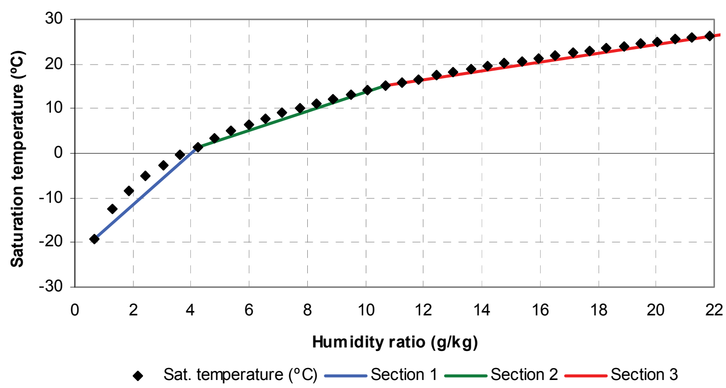

Figure 6.42 Saturation temperature at 1 atm

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The humidifier at the output of the building is not implemented in MGEOS because it is only used in summer to dehumidify the air of the building. An input air stream from the building is required for the rotary heat exchanger, so instead of the humidifier, the conditions of the air after the humidifier has been fixed in summer (90% humidity) and winter temperature (20 ºC) when conditioned without considering the temperature inertia of the building. The rotary wheel has been simulated with a constant maximum efficiency according to the manufacturer and using the unit “Rotary wheel” in table 5.25. The hourly average efficiency is optimised in each case (in a rotary wheel the efficiency depend of the rotation velocity).

The energy demand of the building is calculated using DesigBuilder and selecting some typical days using the methodology of Chapter 3. The energy demand for the selected typical days is introduced in the “Building demand” unit (table 5.26). Along with the energy demand, the conditioning state is fixed to 1 for those hours with occupation and energy demand. The summer state is fixed to 1 for the typical days representing summer days.

Other auxiliary units are implemented with constant efficiencies, and the electrical demand for lighting and other auxiliary units has been considered constant (table 6.13).

6.4.2 System boundaries

In this section will be described the overall energy supply system of the Politecnico di Torino (Polito) that has been implemented in MGEOS and the interaction with the polygeneration system. Figure 6.43 show a simplified scheme of the energy supply system considered. The lines represent natural gas, electricity, heating and cooling streams distinguished by using the colours orange, yellow, red and blue, respectively. On the left there are the main energy suppliers to Polito: the national electrical grid and a district heating plant with natural gas boilers. Politecnico di Torino is represented to the right, divided in two parts, the upper “Polito Buildings” represents the whole university except the classroom building conditioned with the polygeneration system analysed in this case study (bottom). The green dashed lines indicate the system boundaries considered. Inside the boundary there are the polygeneration plant and the classroom building. The energy demand that must be supplied is listed bellow:

- Electricity for lighting in the classroom bulding.
- Electricity for the air handling units and the desiccant units.
- Heating in winter and summer (if reheat is required)
- Cooling in summer.

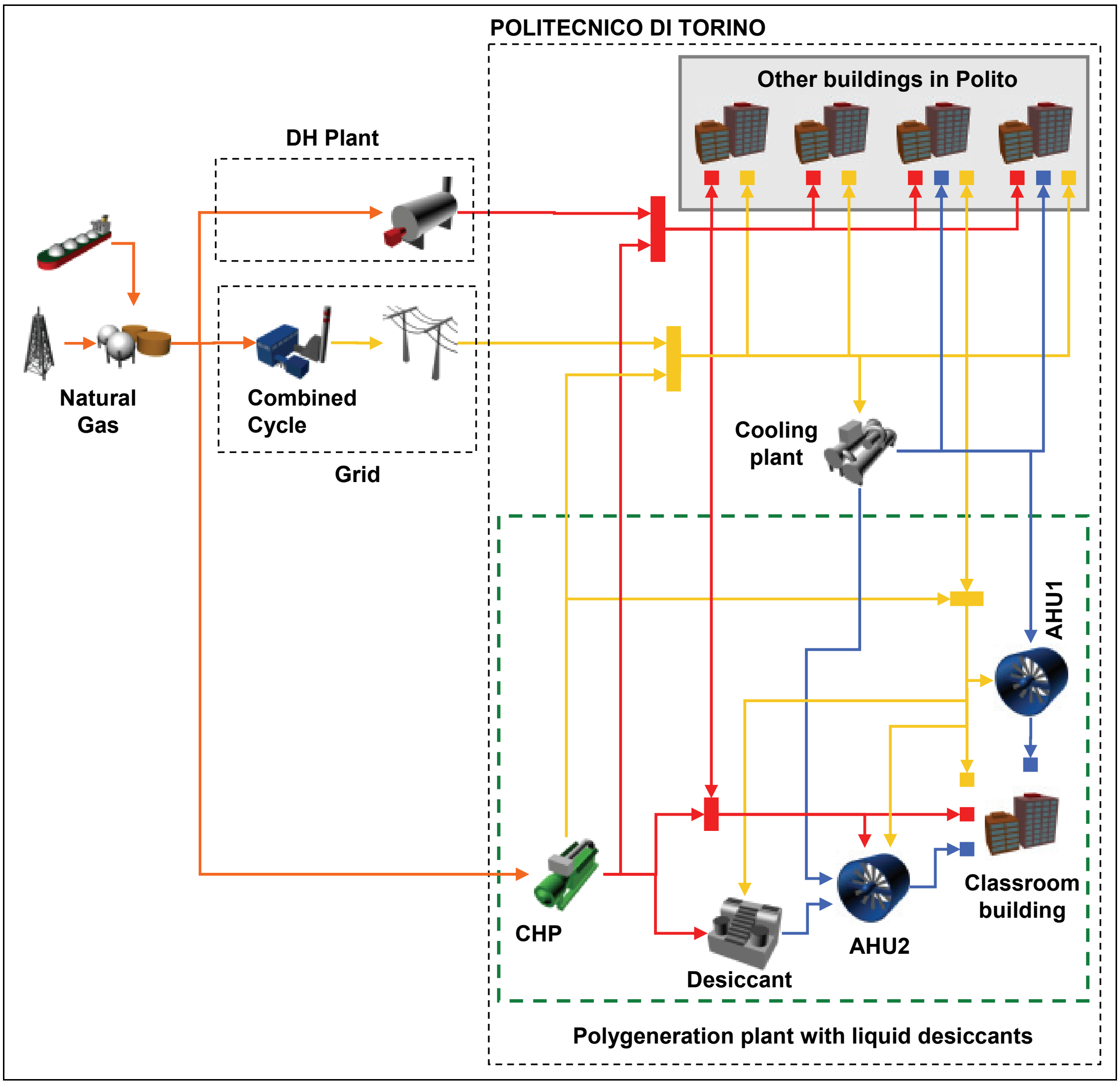

Figure 6.43 Simplified energy supply system for the Politecnico di Torino implemented in MGEOS

The electrical production of the engine is consumed entirely inside Polito, for the classroom building, air handling units, desiccant units or in other buildings in Polito. In winter, the heating production of the engine is consumed in the classroom building and / or is exported to the district heating. In summer is assumed that is not possible to export heating to the DH network and all the heating production must be consumed to produce cooling using the desiccant units.

The air conditioning system (Desiccant units + AHU2) is a constant volume all air ventilation. Additional cooling from the cooling plant can be used in AHU2 when the desiccant units are not able to fulfil the cooling demand. All the heating and cooling requirements must be supplied through the ventilation air and a minimum supply temperature of 17ºC has been fixed to avoid non confort conditions air to the occupants.

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Due to the 17ºC temperature limit, when the sensible cooling demand is higher than the cooling capacity of the air, an auxiliary air handling unit (AHU1) can be used. AHU1 recirculates the air of the building and is composed of cooling coils using chilled water from the cooling plant.

Figure 6.44 shows in more detail the main air conditioning system (desiccant units and AHU2). The air is represented by the blue light and pink lines (supply air and exhaust air, respectively). The air is dehumified in the desiccant units, the temperature of the conditioned air at the output of the desiccant units is close to the temperature of the cooling water from the cooling tower. This air is cooled in the rotary heat exchanger using the humidified output air from the building. The output air of the building is humidified approximately up to 90% of saturation obtaining a temperature around 19ºC.

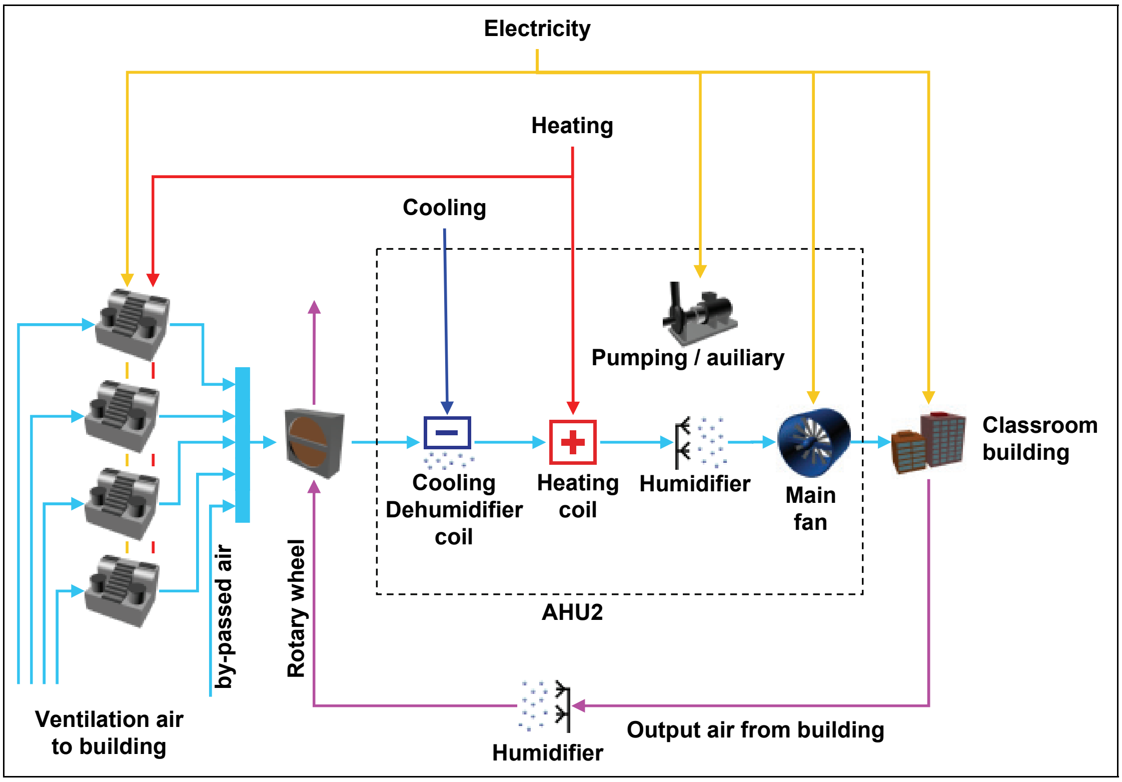

Figure 6.44 Schematic of the air conditioning process including the desiccant and the main AHU2

The conditioning of the air until the desired conditions is done with AHU2. This air handling unit is composed of a cooling/dehumidifier coil, a heating coil, a humidifier and the main fan that supply 20.000 m^3/h of air. The cooling coil is used to produce additional cooling or to dehumidify the air when the desiccant units are not able to produce all the latent cooling demand. This coil works with chilled water from the Polito cooling plant.

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The heating coil is used in winter to heat the air or in summer to reheat the air when is dehumidified in the cooling coil. The humidifiers can be used to cool the conditioned air when the latent cooling power of the desiccant units is higher respect to the latent demand of the building. In that case, when the air is humidified in isenthalpic conditions, sensible cooling increase and the water content of the air also increase. In MGEOS a global efficiency for the main fan has been considered in order to calculate the increase of temperature of the air. This fan is responsible to supply all the ventilation air. It is assumed that when a desiccant unit is OFF, the system takes some air from the outside (by-passed air in figure 6.44) to maintain the 20.000 m^3/h because the air flow trough the desiccant units can not be increased to avoid carry-over of the desiccant solution by the air.

All the heating requirements in winter and summer of the heating coil come from the cogeneration engine or from the district heating network. The electrical demand is supplied by the cogeneration engine or by imported electricity from the grid. The national grid has been considered as a combined cycle using natural gas with a global electrical efficiency of 49.8 %, calculated according to the European Comission Decision of 21 December 2006.

The energy flows that cross the boundary (green line in figure 6.43) of the system analysed in this case study are shown in figure 6.45. The input energy carriers to the polygeneration system are the natural gas for the cogeneration engine, electricity from the grid, heating from the district heating and cooling from the Polito cooling plants. The output energy carriers from the polygeneration system that are not consumed in the classroom building are electricity and heating that will be used in other buildings inside Politecnico di Torino.

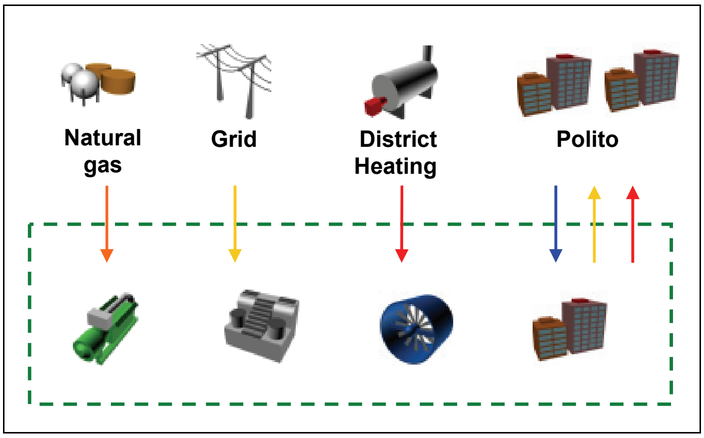

Figure 6.45 Energy carries that cross the system boundary

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From the economical and environmental point of view each energy flow that crosses the boundary has some credits that must be considered. When an energy carrier is imported inside the boundary analysis, a cost and some emissions and primary energy consumption are incorporated to the overall balance. When an energy carrier is exported outside the boundary analysis, some economic benefits are calculated, and the emissions and primary energy consumption equivalent to the avoided energy consumed from the grid or the district heating is discounted. The costs and the emissions are described in section 6.4.5.

6.4.3 Implementation of the polygeneration system in MGEOS

In this section is described how the whole energy supply system (figure 6.43) is implemented in MGEOS using the new developed units for this case study and some of the already available units in the MGEOS library. Due to the high energy demand of the Polito buildings in comparison with the energy production of the polygeneration plant, the Polito buildings (grey shaded box in figure 6.43) are not implemented in MGEOS and are considered just as heating and electrical sink where the polygeneration plant can export the energy produced. All the other units presented in the figures 6.43 and 6.44 are implemented in the optimisation model.

Figure 6.46 shows the complete energy system (or flowsheet) implemented in MGEOS. Each section of the flowsheet will be analysed in more detail. The energy flows are represented using the colors orange, green olive, red and navy blue for natural gas, electricity heating and cooling. The air flows are represented with the colour light blue. Energy flows only contains the energy value of the flow (in this case kWh). The air flows contain the temperature, humidity and enthalpy for the air. The mass flow is constant because the air conditioning system is a constant volume all air ventilation. The flow throught the desiccant units is also constant, the process fan (PF in figure 6.4) has only a constant velocity when is working. The dashed black lines indicate data connections to perform different types of operations.

Figure 6.47 shows the main energy systems in the Politecnico di Torino considered in this case study: the cogeneration engine (ICE), the electrical grid (Grid in) and the district heating network represented with a boiler (Boiler). The natural gas source for ICE and Boiler are not the same because the prices are different (section 6.4.5). The imported electricity can be used in the compression chiller to produce cooling (flow 46) or can be used for the classroom bulding, AHU or the desiccant unit's requirements (flow 47). The electrical production of the engine (flow 37) can be used also for the classroom building, AHU and desiccant units (flow 43) or can be exported for other buildings in Polito (flow 42 to Polito Elec.)

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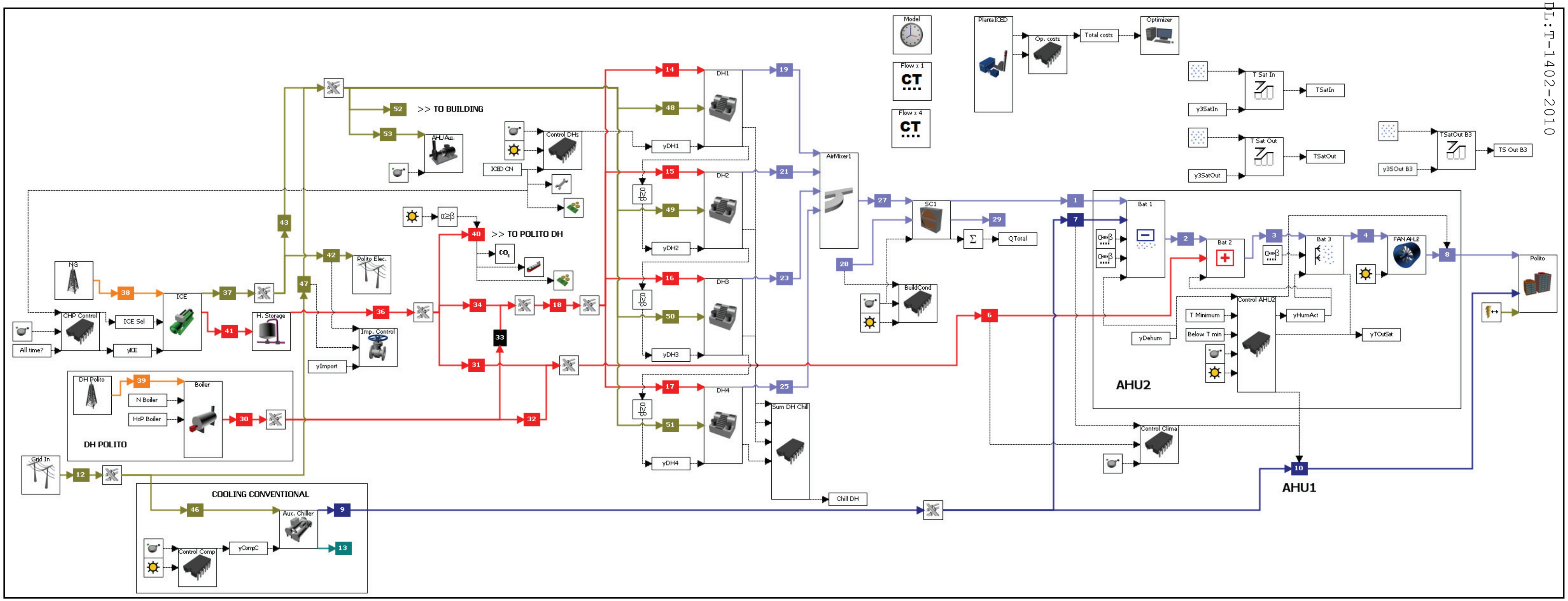

Figure 6.46 Polygeneration plant and energy supply system of Politecnico di Torino implemented in MGEOS

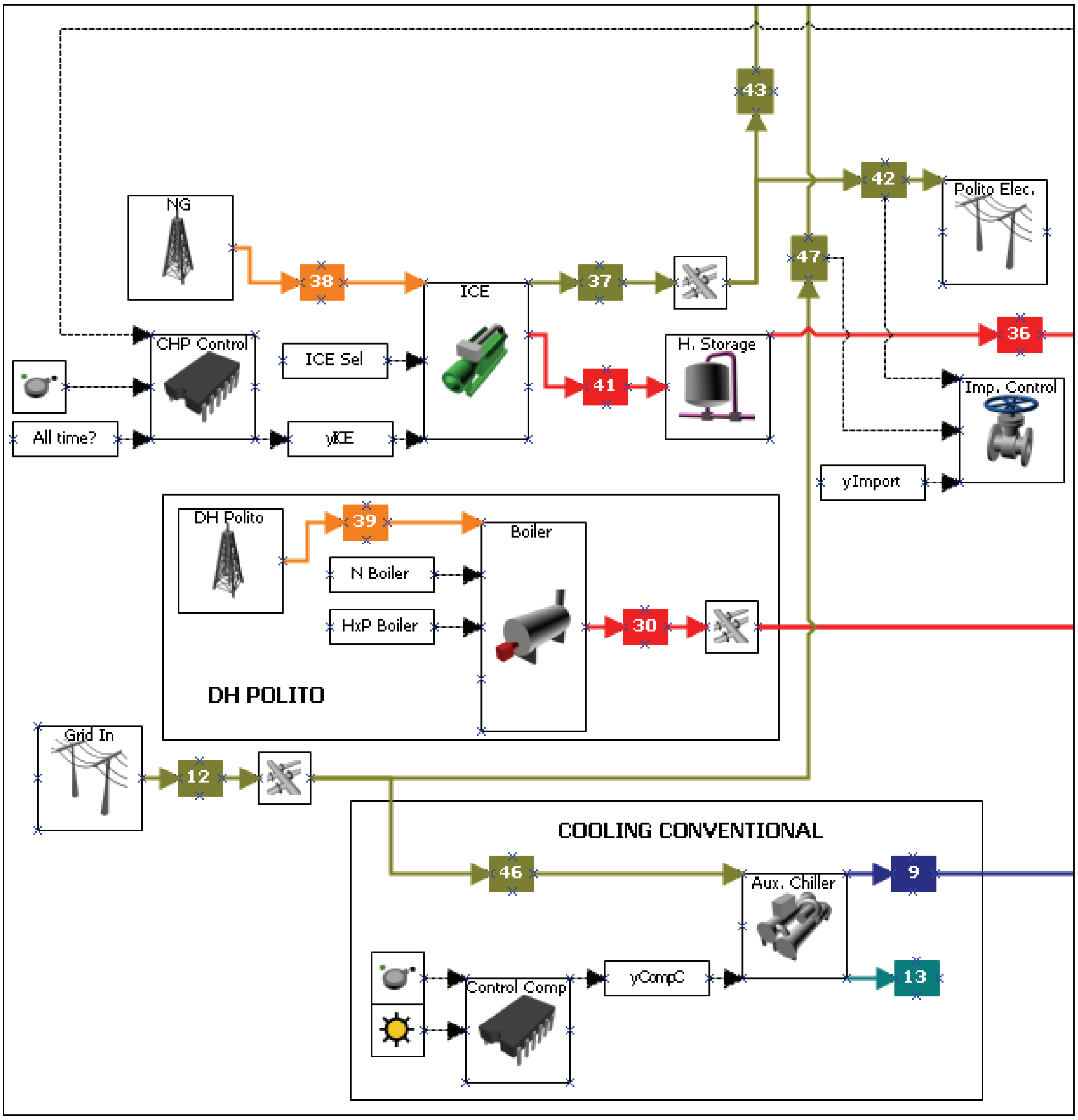

Figure 6.47 Main energy systems: the national grid, the district heating and the cogeneration engine

"Imp. Control" allows the circulation of energy in flow 47 only when flow 42 is almost zero. This means that the cogeneration engine will be able to export electricity only when it is able to fulfil all the electrical demand inside the boundary analisys (figure 6.45). In other words, electricity from the grid will be imported only when the cogeneration engine is not able to supply all the demand. "Imp. Control" is usefull for example when the model maximise economical benefits and imported and exported electricity has the same price. In that case, from the optimisation point of view, there is no difference between importing and exporting electricity and a priority (first supply demand) must be fixed. The heating from DH (flow 30) can be used in the heating coil (AHU2), and optionally can be used to drive the desiccant units.

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With "CHP Control" is determined how the cogeneration engine is working. If "All time?" is zero, the engine can work only when the classroom building is open and conditioned , if "All time?" is one, the cogeneration engine can work at any time. The compression chiller "Aux. chiller" from the Polito cooling plant is used in this case to supply the additional cooling to AHU2 or AHU1. Accumulation for cooling has not been considered, so the compression chiller can work only when the classroom building is conditioned and is summer . "yICE" and "yCompC" are the binary variables that indicates the state of the unit (ON when the variable is one and OFF when the variable is zero). Inside the building unit is fixed when it is conditioned or when is summer along with the heating and cooling demand. and can be placed inside the building unit and can be used in any place of the flowsheet to avoid connection lines from the building that makes the flowsheet hard to understand.

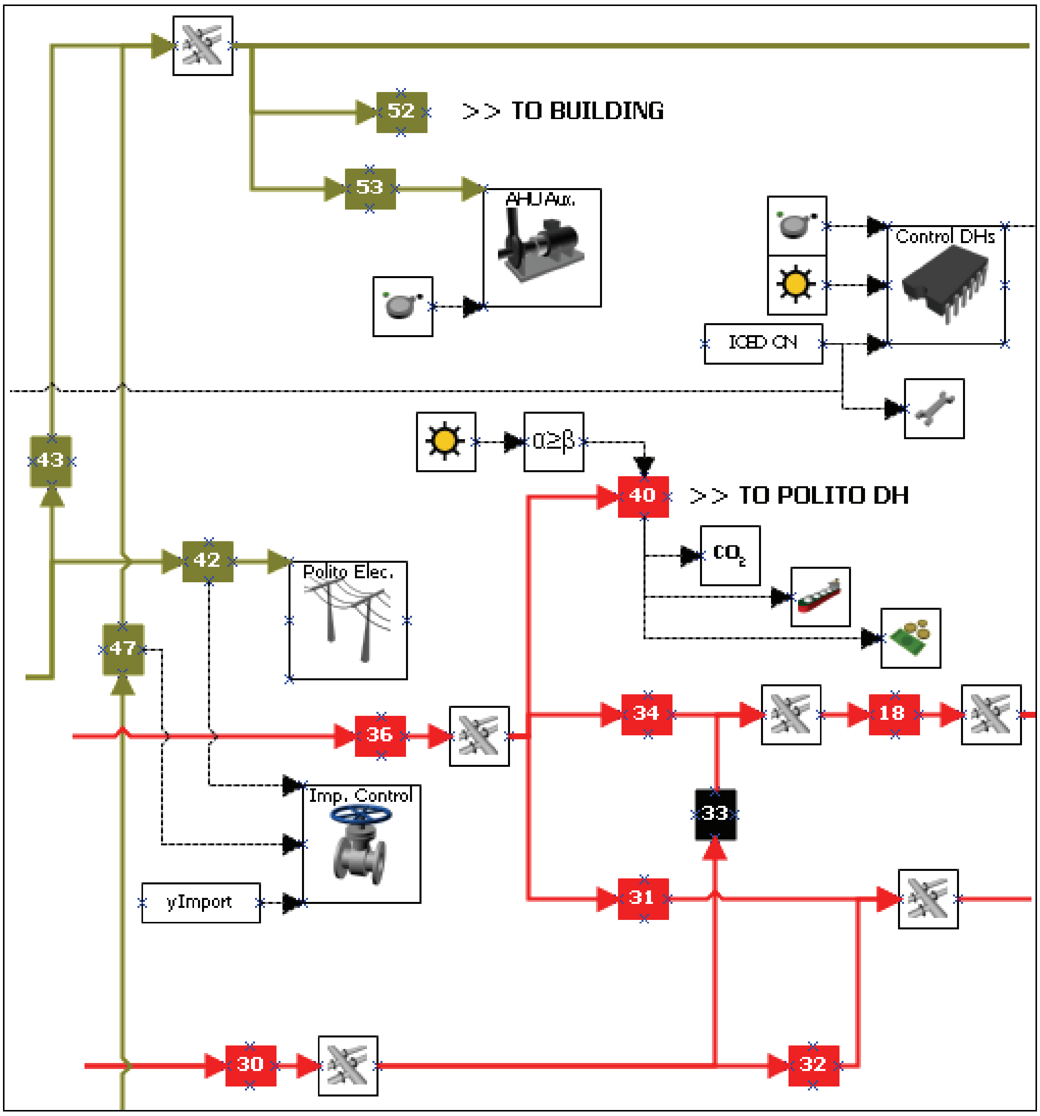

Figure 6.48 Distribution of electricity and heating

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The heating energy storage “H.Storage” does not exists in the real plant installed in Polito, but has been included in the model to study the effect of the heating storage. “H.Storage” can be disabled when an optimisation without energy storage must be carried out.

Figure 6.48 shows how electricity and heating is distributed. In all the figures the unit allows to join and/or split several energy flows. The heating from the district heating (flow 30) can be used in the heating coil in AHU2 (flow 32) or optionally can be used to drive the desiccant units (flow 33). For each flow, a nominal, minimum or maximum value can be fixed. For example flow 33 can be fixed equal to zero to avoid supplying the desiccant units with heat from the district heating. The heating from the cogeneration engine (flow 36) can be used in the heating coil in AHU2 (flow 31), in the desiccant units (flow 34) or can be exported to the district heating of Polito (flow 40). Units and α≥β are used to indicate that in summer heating can not be exported to the district heating.

When heating energy is exported to the district heating, some economic benefits are calculated considering the avoided heating purchased from the DH plant. In the same way, some CO_2 emissions CO_2 and primary energy consumption are discounted. The costs and emission factors for each type of energy carrier that cross the system boundary (described in figure 6.45) are detailed in section 6.4.5.

The unit “AHU Aux.” is included to take into account the auxiliary electrical consumption of the AHU when is working. Flow 52 is the electrical consumption of the classroom building. Flow 52 is connected indirectly to the building to avoid an excessive number of connection lines. A linking unit ↔ like and can be placed inside flow 52 in the left panel of MGEOS (left in figure 5.14) and this linking unit can be connected to the input electrical demand connector of the building as shown to the right in figure 6.49.

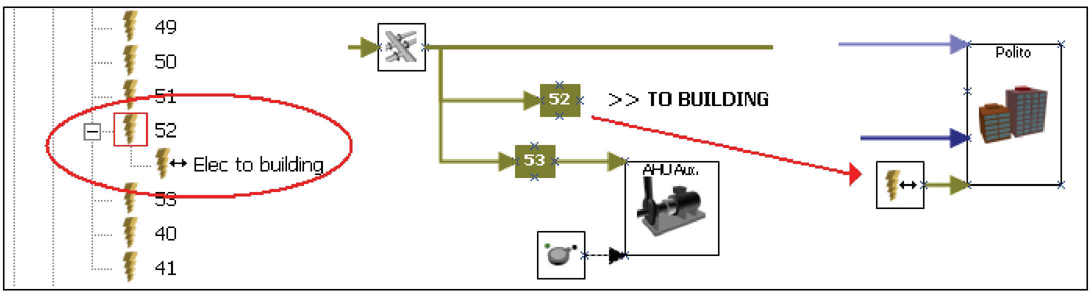

Figure 6.49 Connection of the electrical energy flow 52 to the building using a linking unit

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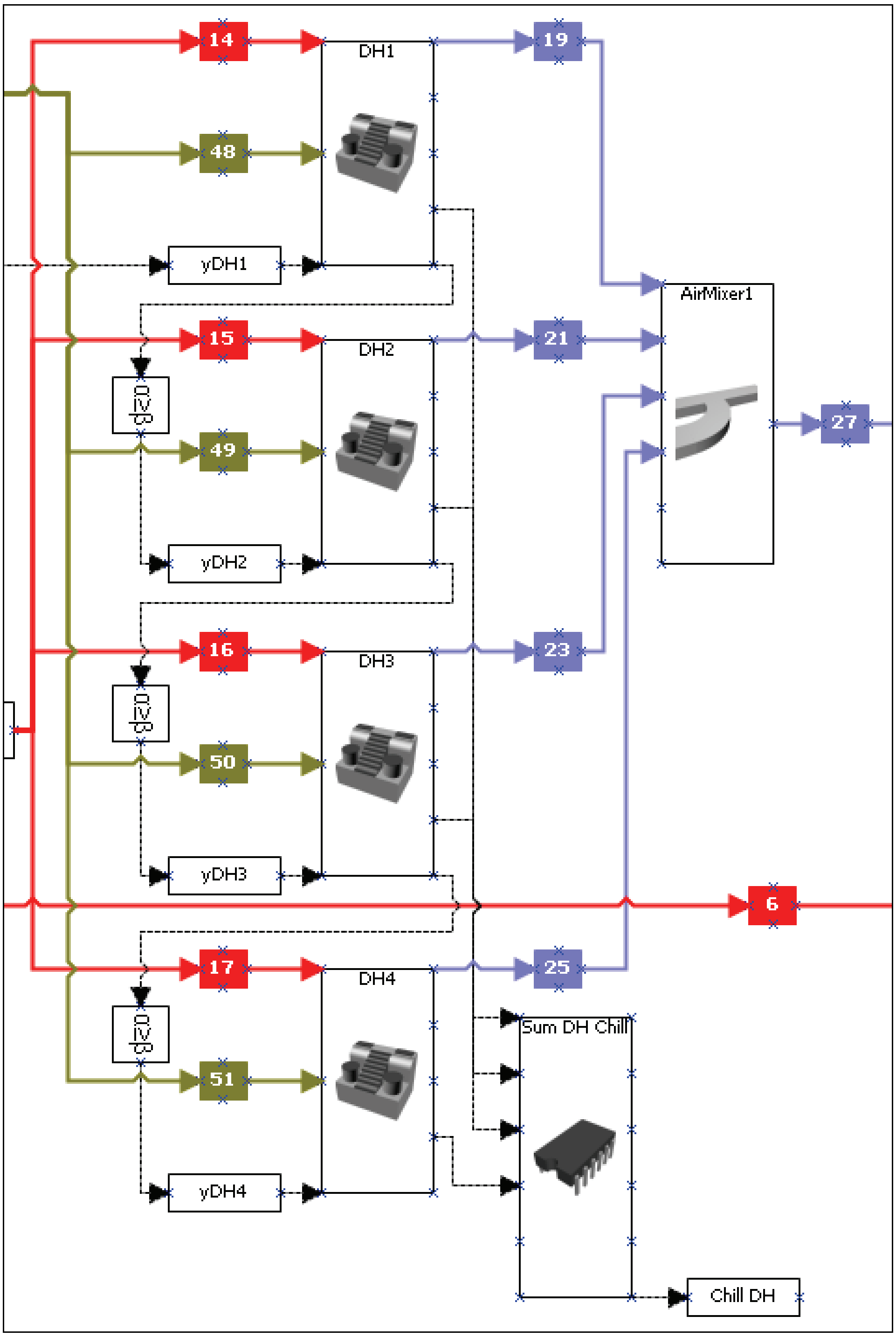

Figure 6.50 Connection for de desiccant units DHS1 to DHS4

Figure 6.50 shows the connections of the desiccant units with the names DHS1 to DHS4 (DuHandling Series from DuCool). The inputs to these units are electrical and heating consumption and ON/OFF state indicated by yDHS1 to yDHS4 binary variables. The ambient air properties are taken from the metereological data defined in the Plant unit (table 5.16).

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In this case study, all the input data to calculate the humidity ratio and the temperature of the output air from the dehumidifier are parameters (constant values: ambient temperature, ambient humidity ratio and temperature of the water from the cooling tower calculated as the ambient wet temperature plus an constant increment) meaning that the maximum dehumidification rate for each hour is also a parameter. As the velocity of the process fan in the dehumifier is constant, for each hour is optimised how much time in average (from 0 to 1) the process fan is working and the average output conditions of the air. The operating time of the fan is available in the last output to the right of each desiccant unit. The unit $\alpha \geq \beta$ is used to establish that a desiccant unit can operate during a concrete hour only when the previous desiccant unit in the cascade has the process fan working all the time that hour.

The input data to yDHS1 comes from the unit "Control DHs" in figure 6.48. "Control DHs" specifies that the desicant units can work only when the building is conditioned is summer and the operation of the trigeneration system is enabled ("ICED ON" binary variable). Flows 19, 21, 23 and 25 are the dehumidified air from the desiccant units with fixed mass flow, each air flow is joined in "AirMixer1" and a new temperature, humidity ratio and enthalpy is calculated for the total flow (flow 27). The flow 6 is the heating flow that goes to the heating coil in AHU2. "Sum DHs C" sums the total cooling effect produced by the four desiccant units, that is available in the fourth output connection to the left of the desiccan units.

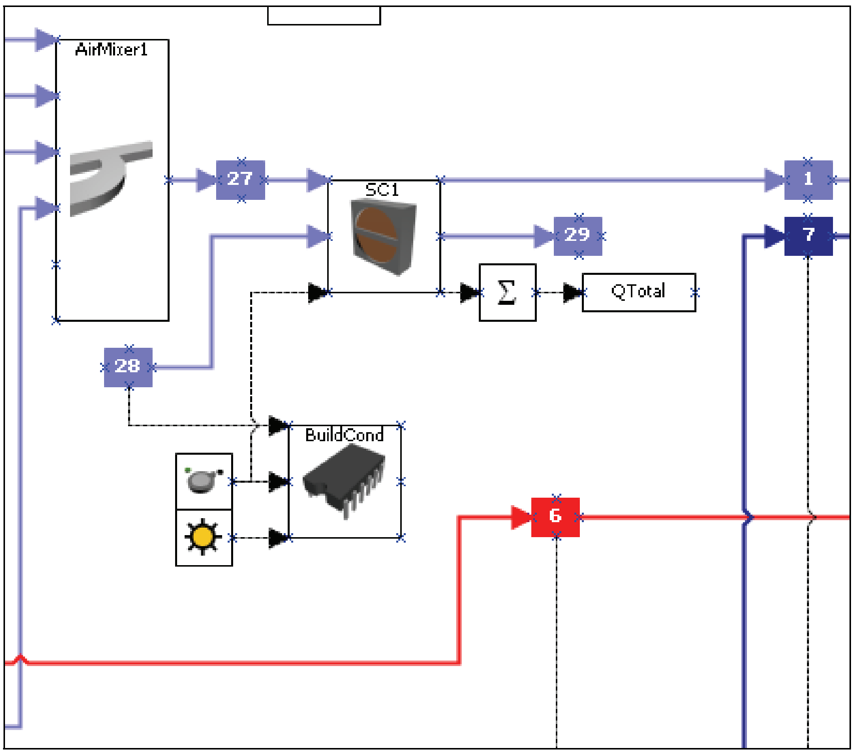

Figure 6.51 Rotary wheel and the output air from the building

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Figure 6.51 shows the rotary wheel (SC1) with a maximum efficiency of 75% according to the manufacturer. SC1 can work only when the building is conditioned . "QTotal" is the annual heat and cooling recovered with SC1. "BuildCond" determines the conditions of the output air from the building after a humidifier. The purpose of this humidifier is to cool the output air of the building to recover some sensible cooling in the rotary wheel. As this humidifier is not implemented, in summer the temperature of flow 28 is set to 19 ºC (90 % relative humidity). In winter the temperature in flow 28 is set to 20 ºC. A simplification has been made neglecting the inertia of the building, this means that while the building is conditioned in winter, temperature in flow 28 is 20 ºC even in the firsts hours in the morning.

Figure 6.52 shows the main Air Handling Unit (AHU2). The components that integrates AHU2 are a cooling coil, a heating coil, a humidifier, the main fan and the control of AHU2 responsible to operate correctly all these components. The cooling coil ("Bat1") has an air flow input (first input to the left, figure 6.53) and a cooling input (second input to the left). This unit is able to cool and dehumidify the air if it is necessary. "Bat1" needs the saturation temperature of the input and output air as a function of the humidity ratio. These saturation temperatures are calculated externaly to "Bat1" to be able to use the adequate correlation for each case of application. In this case the saturation temperatures are calculated using the linearized curve explained previously (figure 6.42). The unit "3 section linearise" in table 5.23 can be used to implement a curve using three lines adjusted to tree diferent sections of the curve.

Figure 6.54 shows the units that calculates the saturation temperature at the input and output of the unit "Bat1" and also at the output of the humidifier ("Bat3"). The units  are linking units that take the humidity ratio value from the flows 1 (input to "Bat1"), 2 and 4. The unit  is also a linking unit that returns the saturation temperature calculated availabe in "TSatIn", "TSatOut" and "TS Out B3" to the units "Bat1" and "Bat3" without a direct connection line to make the flowsheet more clear. The last input connector to the righ in "Bat1" is a binary variable that indicates if the cooling coil is dehumidifying (ON/OFF).

The connections of the heating coil are the air flow input/output, heating and operation (ON/OFF). The humidifier has the air flow input/output, the saturation temperature and operation (ON/OFF). For the humidifier, if the operation is ON it means that is allowed to humidify, but it does not mean that is humidifying. The second output of the humidifier indicates if the output air is saturated.

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Finally the unit "Fan AHU2" is added in order to consider the heating effect produced by the main fan. In this case it is assumed a global efficiency of the fant to calculate how much power is transferred to the air as sensible heating. The fan operates only when the building is conditioned. The flow 8 is the conditioned air that is introduced in the classroom building.

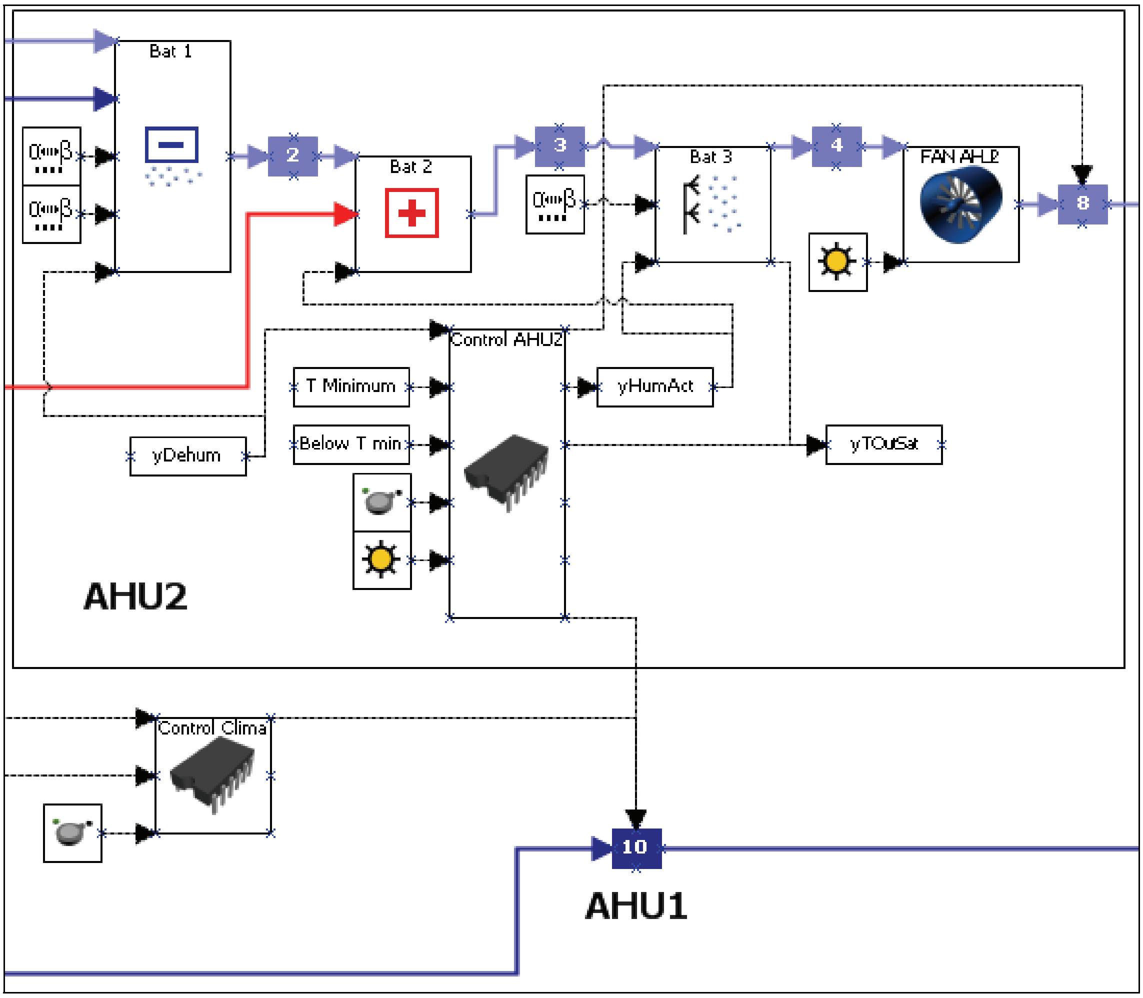

Figure 6.52 Air Handling Unit 2 including the cooling and heating coil, the humidifier and the fan

Bat 1 [ChillCD01] - [ChillCoilCond01.gum]			
1 - Output flow	Input air	Output air	2 - Input flow
7 - Output energy	Cooling		
TSatIn Link - Data TP	Input temp. saturation		
TSatOut Link - Data TP	Output temp. saturation		
yDehum - Variable output	Dehumidifier ON/OFF state		

Figure 6.53 Connections of the cooling coil in the AHU2

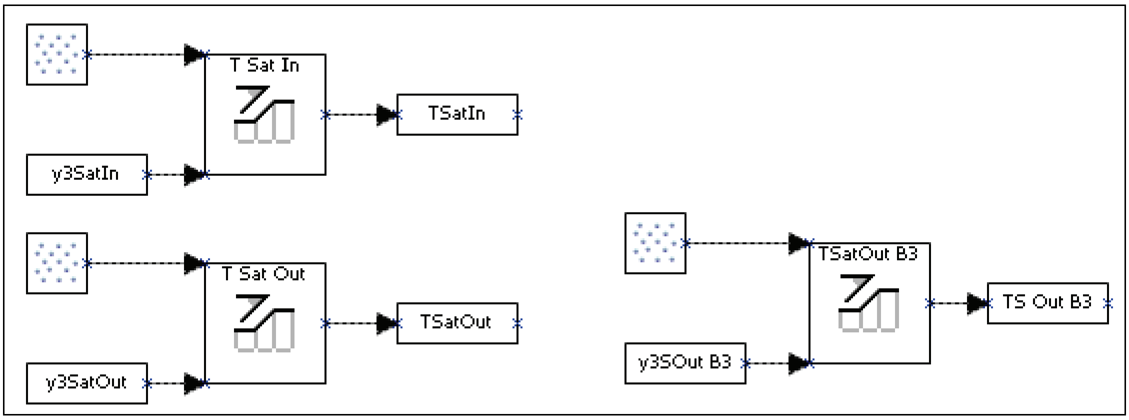

Figure 6.54 Calculation of saturation temperatures of the air as a function of the humidity ratio

The unit "Control AHU2" is a "Processor" unit (table 5.23) with some custom equation to assure the correct operation of all the elements that integrate AHU2. Figure 6.55 shows the input and output connections for this unit. "yDehum" is the binary variable that indicates if the cooling coil is dehumidifying. "T Minimum" is a fixed value that indicates the minimum input temperature of the air to be introduced in the building (in this case 17 ºC). "yBelow" indicates when the temperature of the air introduced to the building (flow 8, connection S) is equal to "T Minimum". "yHumAct" indicates if the humidifier is allowed to work (figure 6.54) and is also connected to the heating coil but in reverse mode (Input parameters in heating coil, figure 6.56). This means that for the same hour, only the heating coil or the humidifier can work (the air can not be heated to be humidified after). "yOutSat" indicates if the output air from the humidifier is saturated and finally Z is connected with the energy flow 10 that represents the cooling requirements in AHU1. "Control AHU2" also determines when AHU1 can be used.

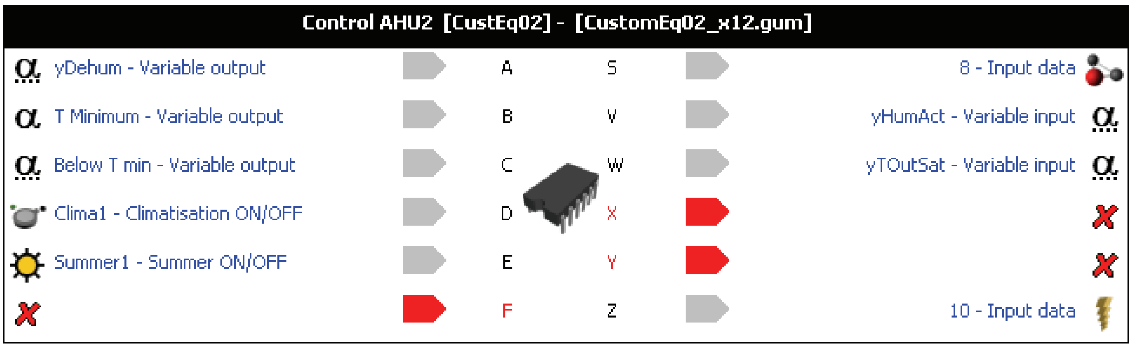

Figure 6.55 Input (left) and output (right) connections of the unit "Control AHU2" in figure 6.54

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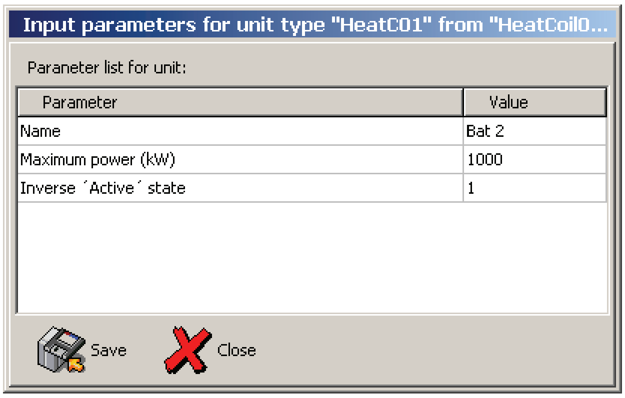

Figure 6.56 Input parameters for the heating coil

The custom equations introduced in "Control AHU2" are shown in figure 6.57. From line 1 to 9 are given the names that will be used in the custom equations, and for each name which type of variable is read and from which connector (figure 6.55). Equation in line 11 indicates that AHU1 can work only if the input air to the building is saturated or has the minimum temperature fixed by the user. Equation in line 12 stablishes that when the building is climatised, the temperature of the input air must be greater or equal (= g =) than the minimum temperature. Equations 13 and 14 are used to determine when the air temperature introduced to the building is equal to the minimum temperature (in that case yBelow = 1). The last two equations indicate when the humidifier is able to work: when there is no dehumidication in the cooling coil (line 16) and in summer and the building is conditioned (line 17).

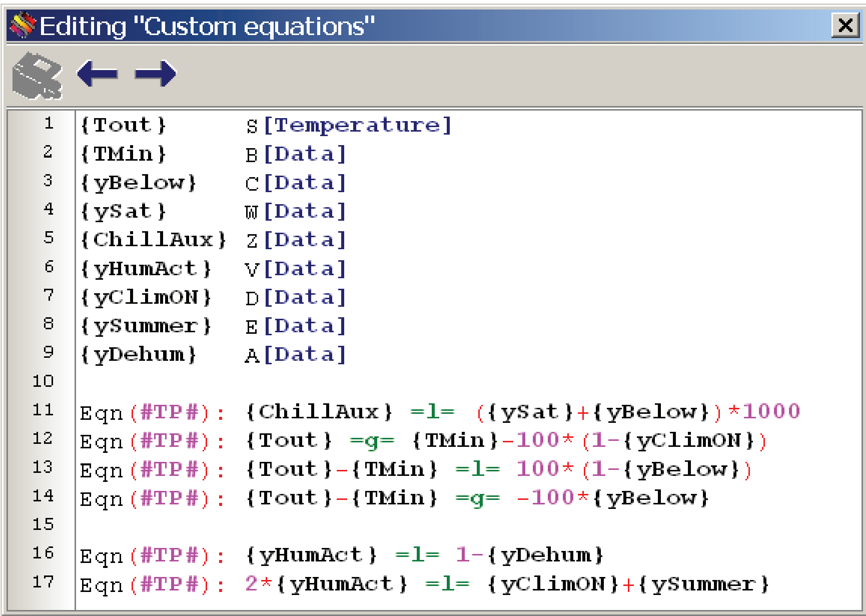

Figure 6.57 Custom equations in the processor "Control AHU2"

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The energy demand of the classroom building is introduced in the “Building demand” unit (Polito unit in figure 6.58). The required inputs for this unit are the input ventilation air flow to the building and two auxiliary inputs, one for heating and another for cooling. The model implemented in the building assumes that all the heating and cooling demand must be supplied with the ventilation air (input air flow to the unit). The auxiliary inputs are used to supply sensible heating or cooling respectively when the ventilation air flow is not able to supply all the energy demand. This auxiliary input for sensible cooling is used to implement AHU1, modelled just as cooling energy required represented by the flow 10 in figure 6.52 that is connected to the building. The last input connection to the building (the fourth connection to the left in figure 6.58) is used to supply the electrical demand. In this case a linking unit is used to connect the flow 52 with the building.

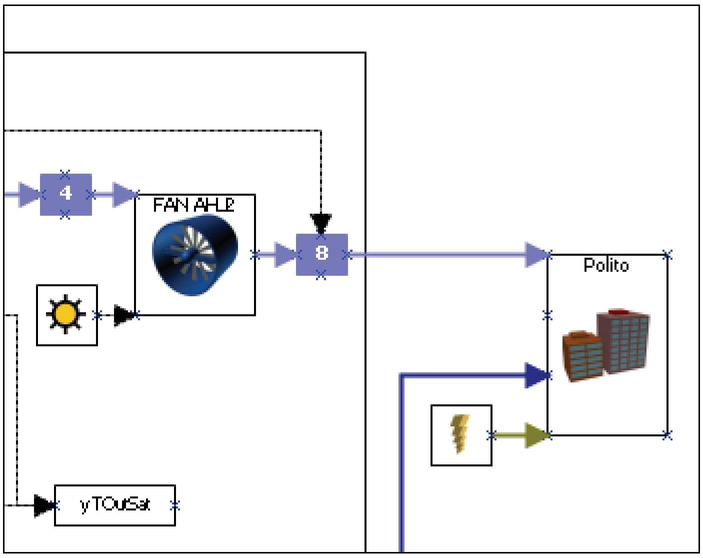

Figure 6.58 Classroom building connections

Figure 6.59 shows the plant unit with the name “Plant ICED”. Inside this plant are placed all the units and flows that defines the polygeneration system presented in the previous figures. Three plants could be used in this flowsheet, for example one plant for the polygeneration system, a plant for the district heating and finally another for the cooling plant of Polito. But in our case of all the costs are calculated for the polygeneration system considering the district heating plant and the cooling plant as energy suppliers and/or energy sinks, so all the systems has been included inside the same plant unit. “Flow x 1” and “Flow x 4” contains the constant air mass flow rate used in the model. “Flow x 1” for the air flows in each desiccant unit and “Flow x 4” for the air flows after “AirMixer1” unit (figure 6.50).

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"Model" unit contains the main information regarding to the time periods: how many time periods the model has, how many years has the model, how are distributed the time periods in each year, the number of hours and repetitions for each time period and other parameters.

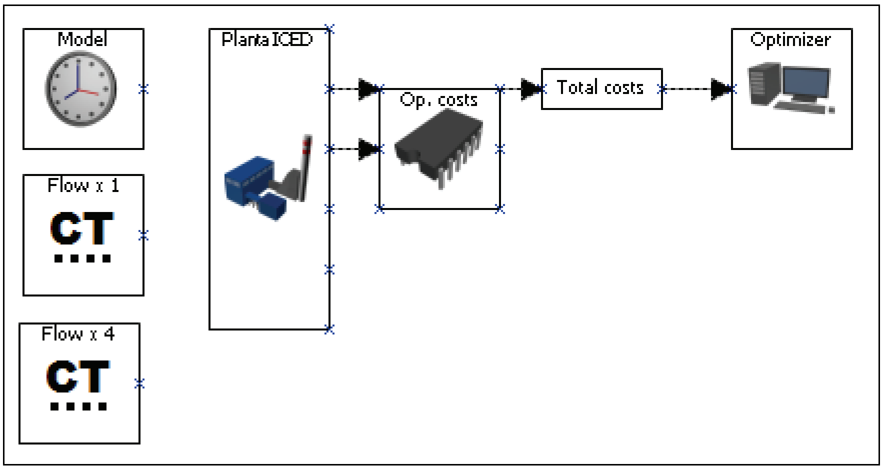

Figure 6.59 Plant unit and calculation of the total operational costs

Figure 6.60 shows the output connectors for the plant unit. In this case study, the available options are the maintenance costs, purchase/export costs, CO_2 emissions and primary energy consumption. Although the connections for the CO_2 emissions and the primary energy consumption are not connected to other units (labels in red in figure 6.60), these values are calculated and are available in the plant units results. The selection of which indicators in the plant unit must be calculated is made using the available options inside the plant unit in the MGEOS library (figure 5.15). The processor "Op. costs" connected to the plant unit is used to calculate the cash flow using the benefits/costs from the energy and the maintenances costs. The results are the "Total costs" variable that is connected to the "Optimiser". The model will maximise or minimise any variable connected to the "Optimiser" unit. Finally, table 6.13 shows a summary of the main characteristics of each unit.

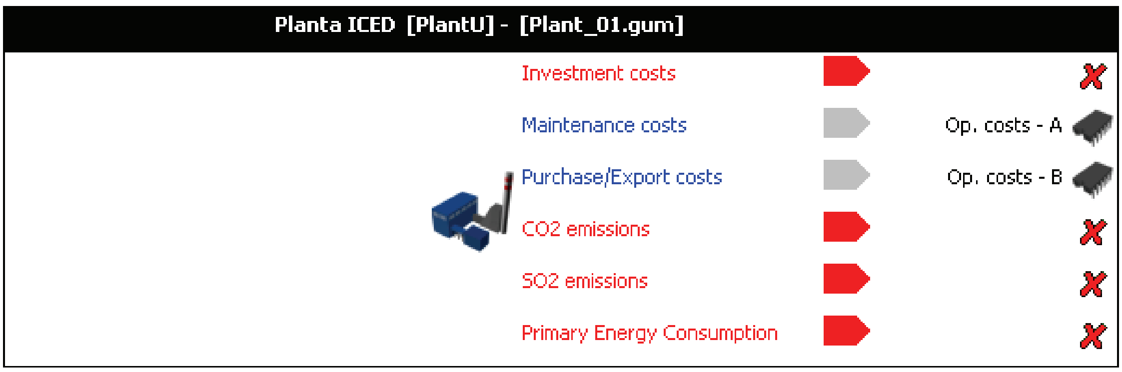

Figure 6.60 Available output from the plant unit

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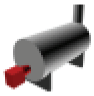
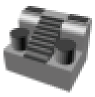
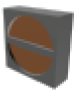
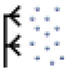
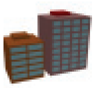
Table 6.13 Main characteristics of the MGEOS units used to build the Polito trigeneration system

	**Grid** Import electricity	Combined cycle, overall efficiency = 49.8%
	**Cogeneration unit** Electricity and heating	Fuel consumption as a function of the electrical production from experimental data. Fuel consumption as a function of the heating production from experimental data. Minimum load if the unit is ON: 30%
	**Boiler** Heating	Efficiency: 90%
	**Compression chiller** Cooling	COP = 3
	**Desiccant liquid** Cooling	Linear correlation from experimental data. With the correlations the output temperature and humidity of the conditioned air is calculated, as well the cooling produced. The energy required in the regenerator is calculated using a constant COP value of 0.65, obtained from experimental data. The temperature in the regenerator is not considered.
	**Rotary heat exchanger**	Maximum efficiency fixed to 75 %, the real efficiency (or the heat exchanged) is optimised by the model
	**Cooling coil**	Saturation temperature calculated with the correlations presented in figure 6.42
	**Humidifier**	Saturation temperature calculated with the correlations presented in figure 6.42
	**Fan**	Nominal power of the fan: 11 kW. It is assumed a global efficiency of 60 %.
	**Classroom building** Electricity Heating Cooling	Electrical demand for lighting calculated as 10 W/m^2 Electrical demand for AHU = 19.5 kW Heating demand calculated with DesignBuilder Cooling demand calculated with DesignBuilder

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6.4.4 Demand characteristics

The heating and cooling energy demand of the building has been estimated using DesigBuilder and EnergyPlus. For simplicity, all the windows have been grouped and a pitched roof has been considered instead of the step roof (figure 6.5). A screenshot of DesignBuider with a render of the building is shown in figure 6.61.

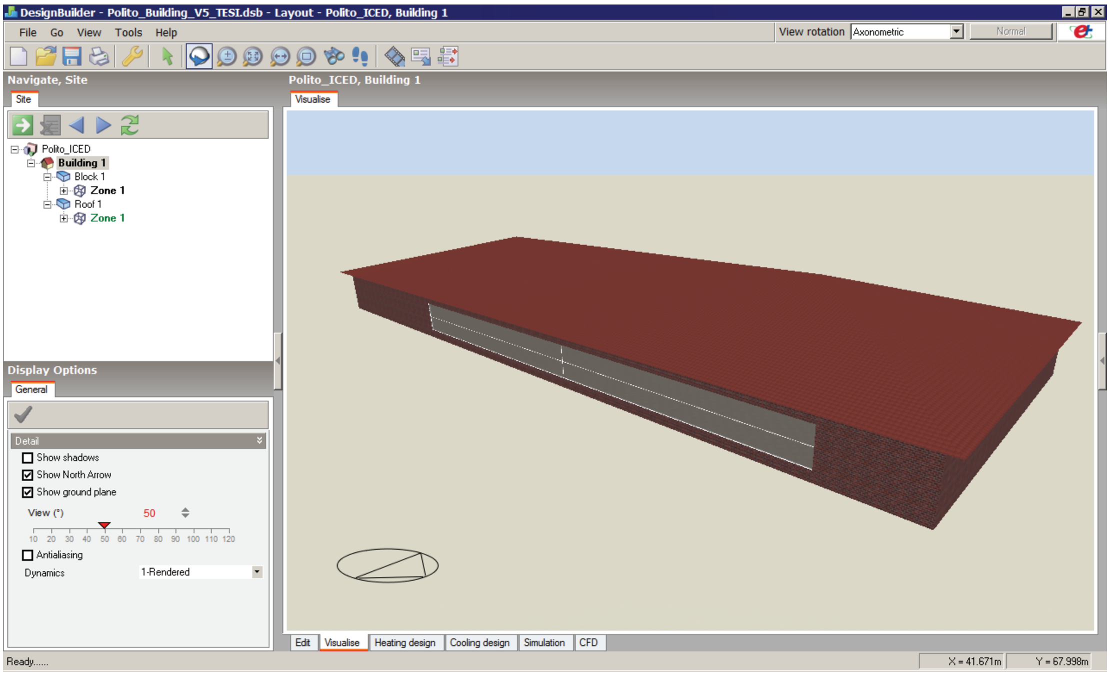

Figure 6.61 Screenshot with the building simulated to estimate the heating and cooling demand

The main properties of the building simulated are presented in table 6.14. The building has similar characteristics to the real building conditioned with the trigeneration system. The simulation has been made for the city of Torino, with the building oriented to the North-South direction (the arrow in figure 6.61 indicates the direction. The schedule shown in figure 6.62 has been assumed to consider the variation in the occupation. A maximum occupancy (100%) indicates that all the classrooms are occupied (around 500 persons). In August there is no occupancy and the building is closed. The winter season has been fixed from January-May and October-December, and the summer season for June, July and September.

An annual simulation has been carried out to calculate the heating and cooling demand. Heat recovery has been disabled in Designbuilder. The energy demand obtained is the heating and cooling demand that must be supplied for the conditioning of the ventilation air and to fulfil the loads of the buildings to maintain the set point temperatures and relative humidity in summer.

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Table 6.14 Main characteristics of the building simulation with DesignBuilder

Location	Torino, Italy. Meteorological data file for Torino/Caselle. Ground monthly temperatures at 0.5 m in the statistics file for Torino/Caselle
Building	Floors: 1 Surface: 2046 m^2 Orientation: North-South
Occupancy	0.25 person/m^2, from Monday to Friday (distribution in figure 6.62) In August the building is closed and there is no energy demand.
HVAC system	Constant Volume with dehumidification control, heat recovery off. HVAC schedule of the from Monday to Friday from 7:30 to 20:00
Setpoints	Heating season: January-May, October-December Cooling season: June, July and September Winter 20 ºC Summer 25 ºC

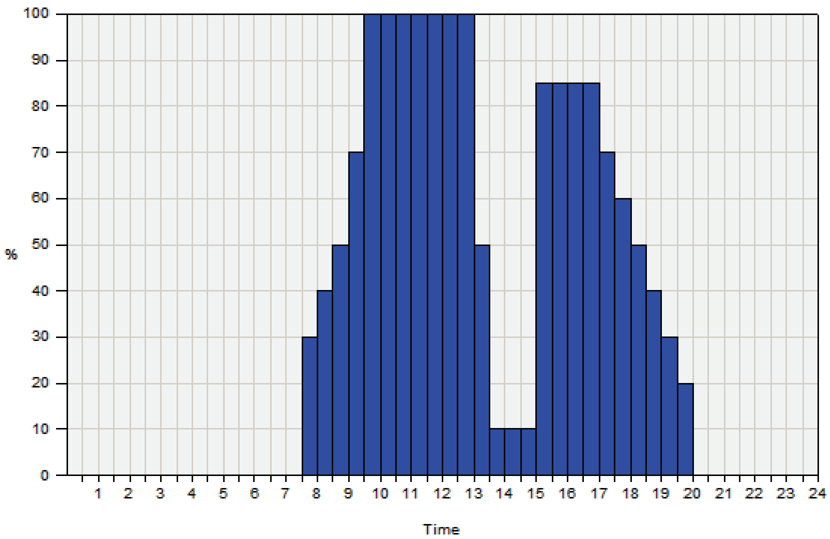

Figure 6.62 Occupancy 100% indicates that all classrooms are occupied

Besides the energy demand of the building, the metheorological conditions are also important in order to calculate the performance of some units like the desiccant units or the rotary wheel. The annual results can not be used in the optimisation model due to the high number of time periods, for this reason the methodology detailed in Chapter 3 has been applied to the energy demand and metheorological data in order to characterise the entire year. TipDay has been used to select the typical days analysing the following data from the simulation results and the DesignBuilder meteorological data base:

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- Heating demand
- Total cooling demand
- Sensible cooling demand
- Ambient dry temperature
- Ambient wet temperature
- Ambient humidity ratio

The ambient conditions are included in the typical days because are necessary to calculate the performance of the desiccant system and the rotary heat exchanger (figure 6.3). The profiles of the energy demand are shown in figures 6.63, 6.64 and 6.65. In order to apply the methodology to select the typical days these figures show the data corresponding to the working days (Monday to Friday except August), for the rest of the days all the values (temperatures and humidity) are considered zero.

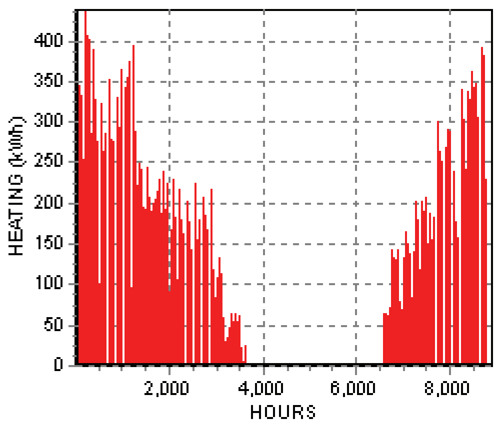

Figure 6.63 Whole year heating demand

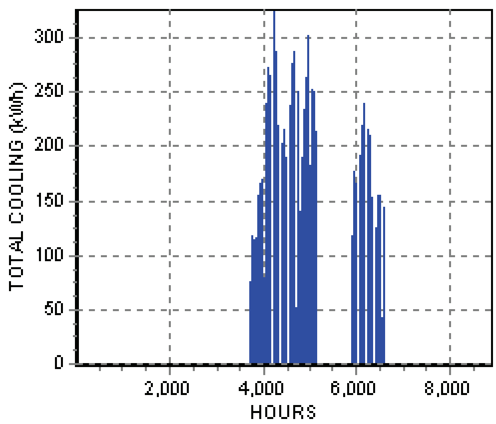

Figure 6.64 Total cooling demand

Figures 6.66, 6.67 and 6.68 shows the ambient dry-wet temperature (ºC) and the humidity ratio (g/kg) from the meteorological file used in DesignBuilder for Torino/Caselle. The heating (red), total cooling (blue) and sensible cooling (blue light) of the selected typical days are shown in figure 6.69. Fourteen typical days have been selected, including the peak day for heating and cooling demand. Of them there are six days with heating demand and eight days for cooling demand. The cooling demand is more irregular than the heating demand, moreover it is important to characterise properly the temperature and humidity ratio in summer. For this reason there are more summer than winter typical days.

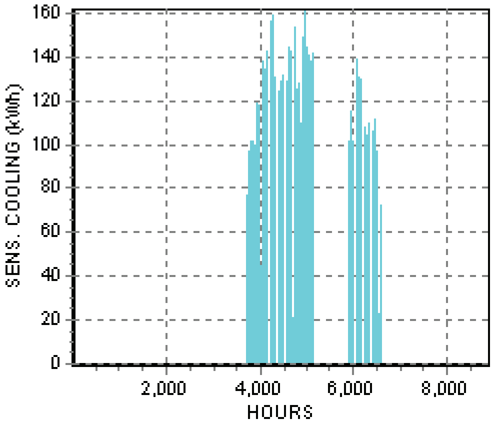

Figure 6.65 Sensible cooling demand

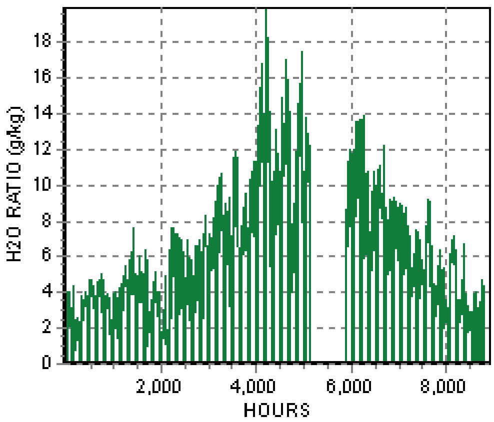

Figure 6.66 Ambient humidity ratio

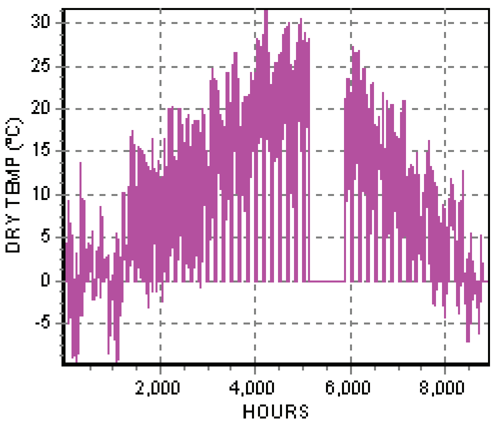

Figure 6.67 Ambient dry temperature

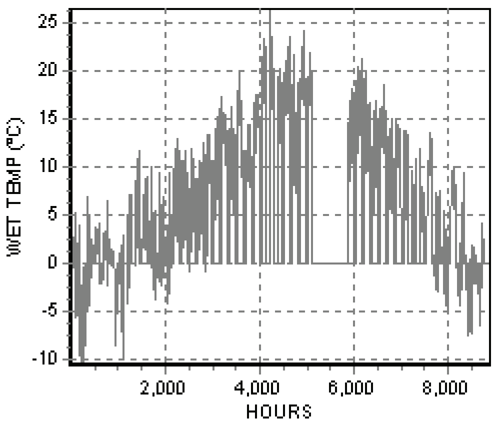

Figure 6.68 Ambient wet temperature

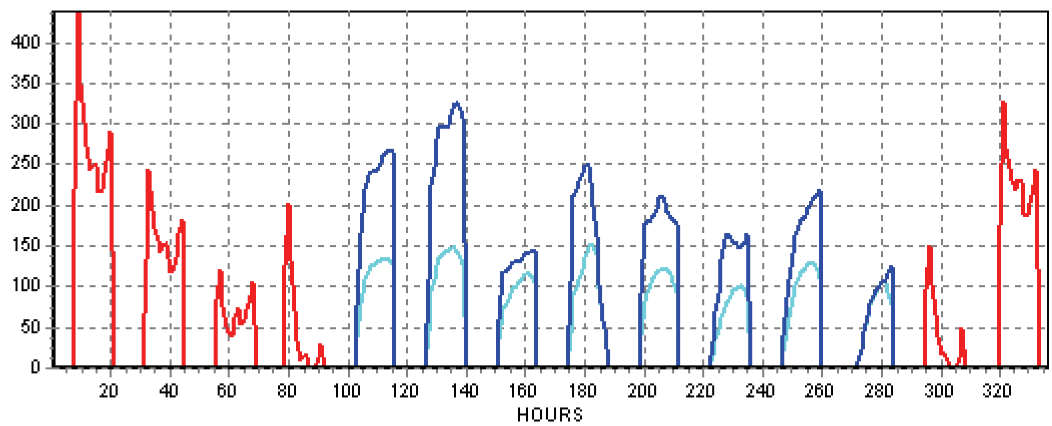

Figure 6.69 Selection of typical days, including heating demand and total cooling demand

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Figure 6.70 shows the ambient dry (fuchsia)-wet (grey) temperature and the humidity ratio (green) profiles in the typical days. The days with the minimum and maximum temperature correspon also to the peak demand days for heating and cooling. In figure 6.69 and 6.70 these days are the first (1-24h) and the sixth day (120-148h) in the sequence. Although in these figures all the typical days are shown together, in the optimisation model each day has no temporal relation with the other days, for example if an energy storage is used in the model, the energy accumulated in one day is consumed during the same day, and can not be used in other days.

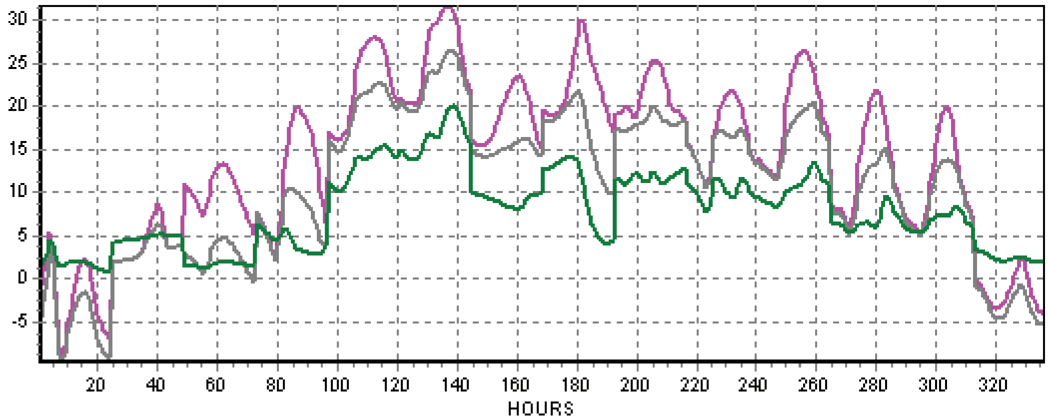

Figure 6.70 Selection of typical days, including dry-wet temperatures and humidity ratio

The reproduced cumulative curves obtained when the methodology to select the typical days is applied, are shown bellow. Figures 6.71, 6.72 and 6.73 show the reproduced curves for the heating, total cooling and sensible cooling demand respectively. The reproduction of the cumulative curve is quite good in the three cases, with only small differences in some regions.

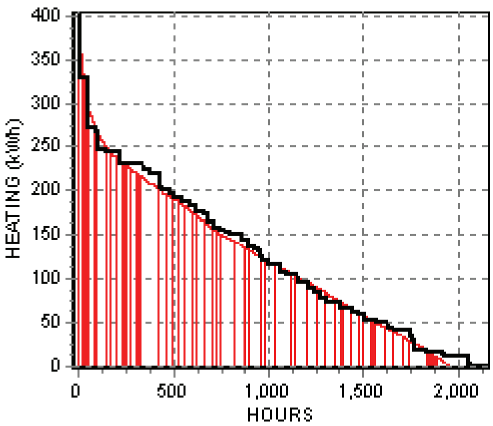

Figure 6.71 Cumulative curve reproduced for heating demand using 14 typical days

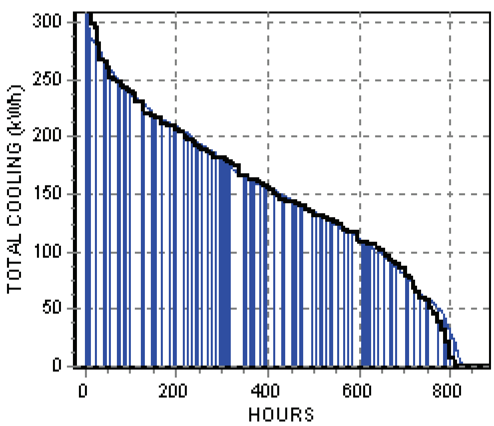

Figure 6.72 Cumulative curve reproduced for cooling demand using 14 typical days

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Figures 6.74, 6.75 and 6.76 show the reproduced curves for the ambient conditions that will be used to calculate the performance of the desiccant units. In this figures the reproduction of the cumulative curves is not so good compared with the energy demand curves, especially for medium and low values of wet bulb temperature and humidity ratio. But these curves will be useful only in summer for the desiccant units, and the agreement in this period is quite good (sumper period is represented by the highest values of temperature and humidity).

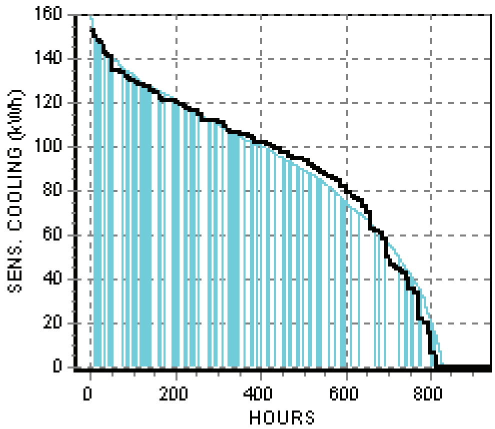

Figure 6.73 Cumulative curve reproduced for sensible cooling using 14 typical days

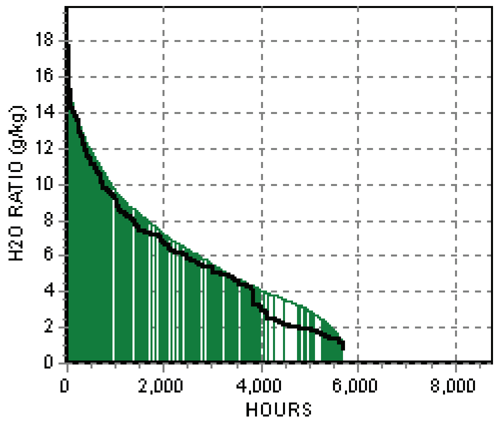

Figure 6.74 Cumulative curve reproduced for humidity ratio using 14 typical days

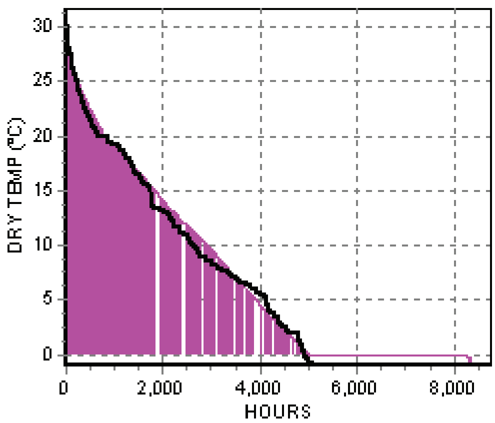

Figure 6.75 Cumulative curve reproduced for dry temperature using 14 typical days

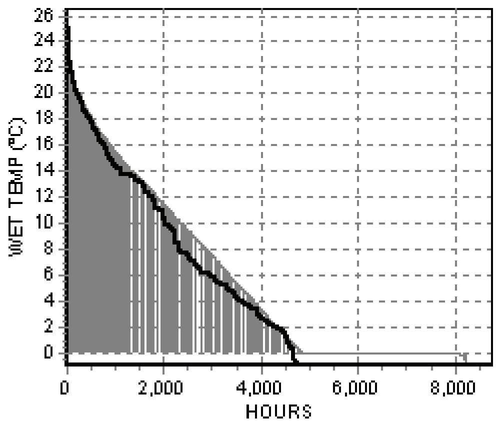

Figure 6.76 Cumulative curve reproduced for wet temperature using 14 typical days

Table 6.15 shows the week, day and number of repetitions (RPF) for each typical day. The RPF values indicates how many times each typical day is repeated in order to calculate the energetic, economic and environmental global results. These global results can be used in the model to calculate the payback period, the net present value, the energy savings or to fix other energetic or environmental constrains imposed by law.

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Table 6.15 Repetitions for the selected typical days

RPF	Week	Day
3	2	1
29	5	4
31	13	5
10	15	2
6	25	2
3	26	1
11	27	4
8	29	1
7	31	2
7	36	5
11	37	2
10	39	2
62	43	2
40	51	2

6.4.5 Energy costs and emissions by technology

The energy and maintenance costs considered in this case study has been calculated according to Badami et al 2009a. The authors fix a price for natural gas, imported electricity and imported heating from the district heating plant of 30, 140 and 58 €/MWh, respectively. There are no prices for the exported electricity or heating from the polygeneration plant. When electricity or heating produced by the polygeneration plant is consumed in other buildings inside the Politecnico di Torino, the benefits considered are equal to the avoided energy consumed. This means that the exported electricity and heating to other buildings of Politecnico di Torino has the same price that the electricity and heating imported by the university. The situation is the same in order to calculate the CO_2 emissions and the primary energy consumption. The emissions calculated in this case correspond only to the use of the fuel, without considering additional emissions due to the extraction, transportation and transformation of the fuel until the final user. The national grid has been considered as a combined cycle according to the European Comission Decision of 21 December 2006 (section 7.3.4). The district heating plant has been modelled as a boiler with 90 % efficiency using natural gas. A summary of all the costs and the emissions and primary energy factors considered are presented in table 6.16.

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Table 6.16 Operational costs and energy emissions

Grid Import electricity	Combined cycle, overall efficiency = 49.8% Price of imported electricity: 140 €/MWh (*) Primary energy consumption: 172 ktoe/MWh_e CO_2 emissions: 402 kg/MWh_e
Natural Gas Resources	Price: 30 €/MWh (*) Primary energy consumption: 86 ktoe/MWh CO2 emissions: 201 kg/MWh
Cogeneration unit Electricity and heating	Maintenance costs: 16.5 €/kWh_e (*)
District Heating Heating	Price: 54.3 €/MWh_t (*) Emissions: as a function of the natural gas consumption. No maintenance costs considered
Compression chiller Cooling	Price: as a function of the electricity consumed from the grid. Emissions: as a function of the natural gas consumption to produce the required electricity No maintenance costs considered
Desiccant liquid Cooling	Maintenance costs: 8.0 €/MWh_c
Maintenance costs	Personnel costs: 3,100 €/year (*)
Investment costs **Other costs**	Investment (ICE+Desiccants): between 195,000 and 216,000 € Insurance: 2,600 €/year (*) General costs: 2,600 €/year (*)
Subsidies	Primary Energy Saving Certificates: 1,100 €/year (*)

(*) Prices from Badami et al 2009a

Regarding the CO_2 emissions and primary energy savings some considerations can be made comparing the conventional alternative with the polygeneration system. In order to assest the potential energy savings of this system the production of 1 MWh of heating and cooling produced with the polygeneration system is compared respect to the conventional system.

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Figure 6.77 shows the energy balances for the production of 1 MWh cooling considering the conventional system as a compression chiller with COP = 3 and the grid as a combined cycle with 50% global efficiency and using natural gas. Figure 6.78 shows the energy balances using the polygeneration system and considering that the electrical production is exported to the grid. The exported electricity discounts the CO_2 emissions and primary energy consumption required by the reference system (combined cycle) to produce the same quantity of exported electricity. The nominal efficiencies of the cogeneration engine (Badami et al 2009a) have been used to perform the energy balances. Considering only the cooling production, the CO_2 emissions and the primary energy consumption of polygeneration system is 84 % higher than the conventional system. The increase of emissions for the polygeneration system is due to the low COP of the desiccant units in comparison with the compression chillers the high efficiency considered for the electrical grid.

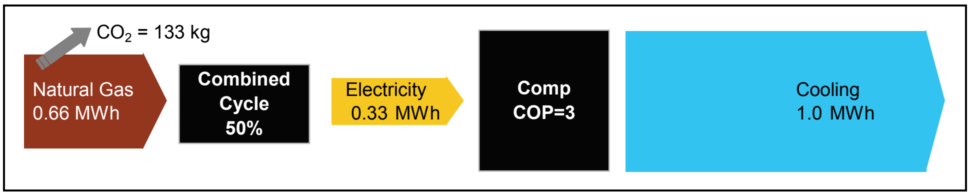

Figure 6.77 CO_2 emissions and primary energy consumption for conventional production of cooling using compression chillers with COP = 3

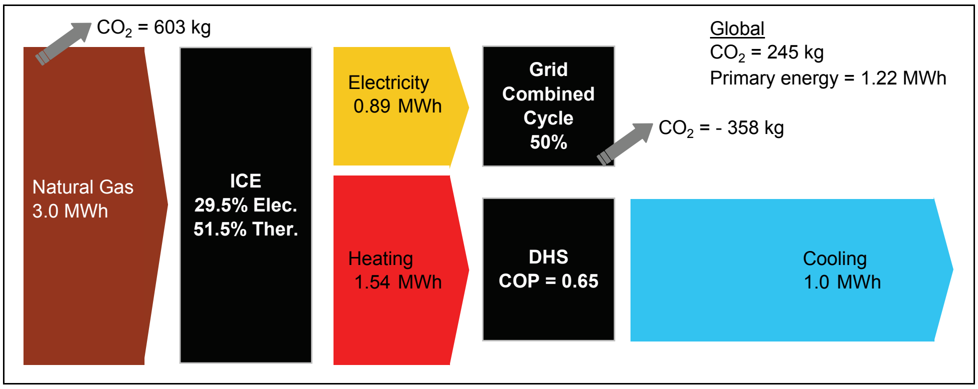

Figure 6.78 Emissions and primary energy consumption for cooling production using the polygeneration system with desiccant liquid for cooling and COP = 0.65

Figure 6.79 shows the conventional system for heating production using a boiler with 90 % efficiency. Figure 6.80 show the heating production with the cogeneration engine. In this case the cogeneration engine reduces the CO_2 emissions and the primary energy consumption by 28 % respect to the conventional system considering the avoided emissions and natural gas consumption due to the exported electricity.

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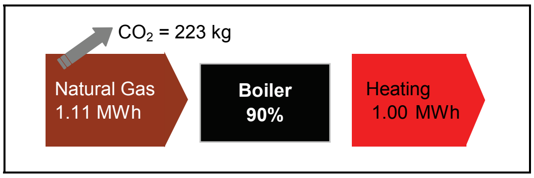

Figure 6.79 Emissions and primary energy consumption for heating production

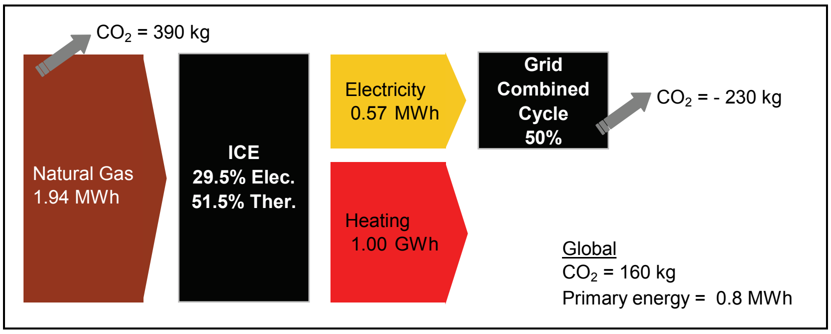

Figure 6.80 Emissions and primary energy consumption for heating production using the cogeneration engine

Using the examples presented it is clear that when the polygeneration system is compared with a conventional system composed of combined cycle, boiler and compression chillers not always a reduction in CO_2 emissions and primary energy consumption will be achieved. To reduce emissions and primary energy consumption the best configuration is the use of the cogeneration engine only in winter, but this is not the best option from the economical point of view. If economic benefits are maximised, the degree of emission reduction with respect to the conventional system will be a function of the ratio between the heating produced in winter and the cooling production in summer. It is important to underline that the separate production of electricity in the conventional system is represented by state-of-the art technologies with high electrical efficiencies like combined cycles.

6.5 Scenarios definition

In this section different situations or scenarios are defined to calculate which units are working and the type of energy that can be imported or exported. The objective is to evaluate the economic viability and the environmental impact of the polygeneration system under several possible configurations. In all the scenarios the economic and environmental evaluation is made considering the analysis boundary shown in figure 6.45. This means that all the balances are made as if the classroom building was an independent building from all the other buildings of the university. All the other buildings are considered like a heating or electrical sink.

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The conventional scenario (**CONV**) is shown in figure 6.81. This scenario is the typical configuration to supply electricity, heating and cooling to the classroom building. The engine and the desiccant units are disabled, and only AHU1 and AHU2 work with the cooling coming from the Polito cooling plant and the heating from the district heating plant. All the electricity is imported from the grid.

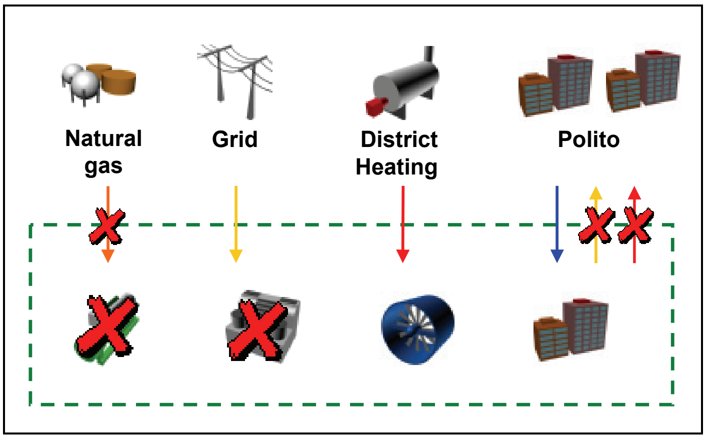

Figure 6.81 Conventional scenario, importing electricity heating and cooling, air conditioning provided with AHU2

Figure 6.82 shows the current situation (**PolyExport**): the polygeneration system produce electricity, heating and cooling that is consumed in the classroom building. The surplus of electricity can be consumed in other building of the university. The surplus of heating can be exported to the university DH only in winter. In summer the heating produced by the engine must be consumed in the desiccant units to produce cooling. The air conditioning is provided to the classroom building through AHU2 that is able to use cooling from the politecnico cooling plant when it is necessary. Additional sensible cooling (AHU1) can be provided.

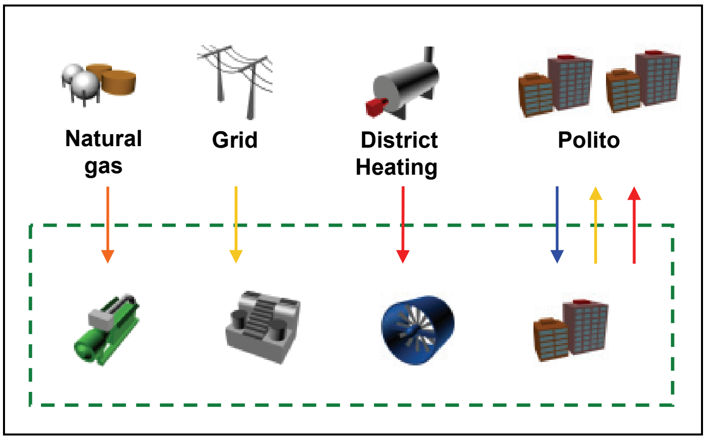

Figure 6.82 Current scenario using the polygeneration plant with the desiccant liquids for air conditioning

Figure 6.83 shows another scenario in which it is not possible to export heating to other buildings of the university. This means the classroom building is an isolated building without relation with others. The district heating plant continues supplying heating to the classroom building. The cooling plant has been maintained because backup cooling is necessary to fulfil all the cooling demand. The objective of this scenario is to evaluate the economic feasibility of this polygeneration system to fulfil the energetic demand of a building without the possibility to export all the surplus heating, meaning that the operation of the engine must follow the classroom building energy demand.

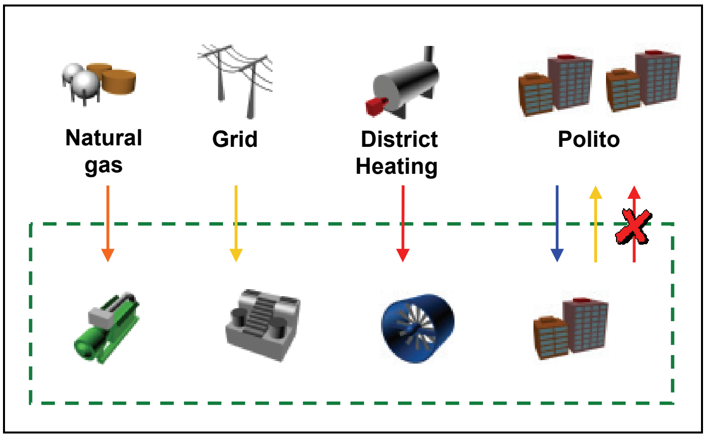

Figure 6.83 Scenario without heat sink, all the thermal production must be consumed in the classroom building

In the scenario of figure 6.83 it is very important the operation of the rotary wheel. In **PolyExport** scenario is possible to export all the heating production and the cogeneration engine is able to work all the time, so the heat and cooling recovered with the rotary wheel does not compete with the cogeneration engine production. The situation is different in the scenario of figure 6.83 and the energy recovered by the rotary wheel will decrease the economic benefits of the polygeneration system, for this reason two scenarios are defined with the configuration presented in figure 6.83: **Isolated1** and **Isolated2**.

In scenario **Isolated1** the operation of the rotary wheel is free and the solver will find the optimal operation considering the optimisation criteria. In **Isolated2** a minimum quantity of energy recovered with the rotary wheel is fixed. This minimum fixed is very close to the maximum annual energy that can be recovered with the rotary wheel. The maximum recovery of energy with the rotary wheel can be found solving the model by maximizing the variable "QTotal" in figure 6.51.

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Figure 6.84 shows the maximum energy recovered by the rotary wheel (shaded zone) compared with the total heating and sensible cooling demand. The total heating and sensible cooling demand is 337 MWh/year and the maximum energy recovered is 144 MWh/year. These results will be used in each scenario to check how the rotary wheel is working.

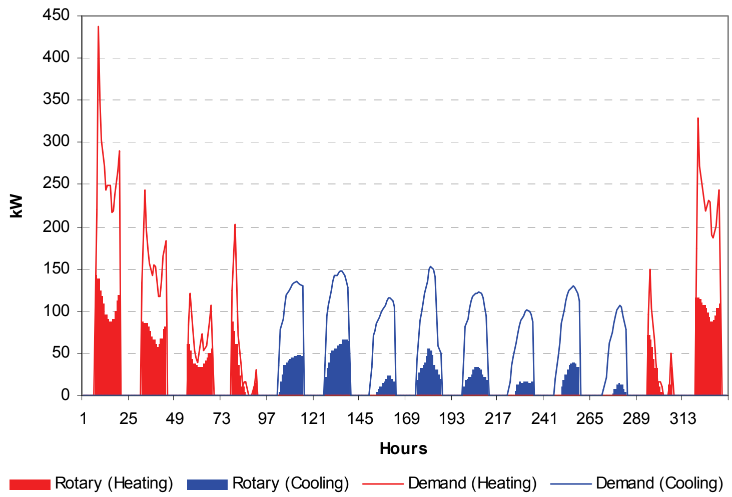

Figure 6.84 Maximum energy recovered with the rotary wheel

A summary of the four scenarios defined is presented as follows. In all the cases flow 33 in figure 6.48 is fixed to zero meaning that heating from the district heating can not be used to drive the desiccant units. The heat storage in figure 6.47 is disabled in the four scenarios. The flowsheet developed in MGEOS is the same for all the scenarios, fixing the appropiate values in some variables or energy flows to perform the optimisation for each scenario.

- **CONV** is the conventional supply of electricity, heating and cooling using the boundary system defined in figure 6.81.

- **PolyExport** is the current configuration of the polygeneration system with the possibility to export the electrical and heating surplus. The scenario is presented in figure 6.82

- **Isolated1** is the polygeneration configuration without the possibility to export the heating surplus (figure 6.83). The operation of the rotary wheel is not constrained.

- **Isolated2** is the polygeneration configuration without the possibility to export the heating surplues (figure 6.83) and a minimum energy recovery by the rotary wheel is fixed. The value fixed is 142 MWh.

6.6 Scenario results

The main results for each scenario are shown in Table 6.17. In this table are presented the main energy flows (MWh/year), the annual cash flow, the CO_2 emissions and the primay energy consumption. The "Flow" columns indicate from which energy flow is read the value (respect to the figures in section 6.4.3).

Table 6.17 Main results from the scenario analysis (energy in MWh/year)

Flow		CONV	PolyExport	Isolated1	Isolated2
38	Natural gas for district heating plant	194.8	5.3	13.3	26.2
12	Imported electricity from the grid	154.8	33.0	58.2	70.9
30	Thermal consumption from the district heating	175.4	4.8	11.9	23.6
39	Natural gas for cogenerator	0	1,044.4	618,9	26.2
37	Electricity production	0	319.1	188.6	124.5
42	Electrical exported	0	208.9	103.6	52.0
31	Thermal production for heating	0	136.8	223.4	119.8
40	Thermal production exported	0	300.6	0	0
34	Thermal production for cooling	0	94.3	94.1	92.3
	Cooling produced with the desiccant units	0	61.3	61.1	60.0
9	Cooling imported from the cooling plant	128.0	64.6	64.7	66.0
6	Heating coil including reheat in summer	175.4	141.6	235.3	143.4
	% energy recovered respect to maximum	98.6 %	99.3 %	34 %	98.6 %
	Cash flow (€)	-31,205	-3,691	-23,662	-25,954
	Primary energy consumption (toe)	43.4	31.3	46.5	40.7
CO_2	CO_2 emissions (ton CO_2)	101.4	73.2	108.8	95.2

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Before to discuss the results for each scenario it is important to highlight that there are two types of results. The annual energy demand is represented with 14 typical days, from the operational point of view (for example power recovered with the recovery wheel, or heating power required) the results shows the profiles for 14 typical days (336 hours). For the annual energy and economical balances, the results of these 14 typical days are multiplied by the RPF factor, so the economical, energetic and environmental balances are results for all the year.

All the results presented must be compared respect to the CONV scenario in order to assest the viability of the implementation of the scenarios PolyExport, Isolated1 and Isolated2. The context for this comparison is that the CONV system already exists, and the other scenarios must be evaluated. From the economincal point of view PolyExport, Isolated1 and Isolated2 has lower negative annual cash flow with respect to the conventional system meaning economical savings. The economic and environmental saving respect to the CONV scenario are detailed in table 6.18. Only PolyExport scenario has a reasonable payback period. The economic saving in Isolated1 and Isolated2 scenarios are very low due to the impossibility to export heating from the cogeneration engine to the district heating network. The difference between Isolated1 and Isolated2 scenario is the operation of the rotary wheel.

Table 6.18 Economical and environmental savings with respect to the conventional system

Savings	PolyExport	Isolated1	Isolated2
Economic (€/year)	27,514	7,543	5,251
Payback (years)	7.3	26.5	38.1
Primary energy (%) CO_2 emissions (%)	27.9	-7.1	6.2

The energy recovered by the rotary wheel for the CONV and PolyExport scenarios are presented in figures 6.85 and 6.86, respectively. In these figures the shaded zone is the recovered energy and the lines represent the maximum energy that could be recovered (shaded zone in figure 6.48). Red means heating and blue means cooling. For the conventional scenario the operation of the rotary wheel is profitable from the economic and environemtal point of view avoiding purchase a certain quantity of heating and cooling. In that case the energy recovered is almost 99% of the maximum energy that could be recovered. This small difference could be due to the tolerance or to the different convergence process when different objectives are selected.

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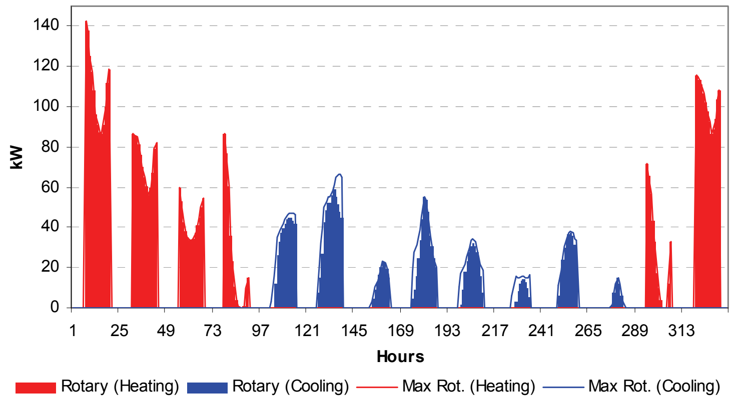

Figure 6.85 Energy recovered by the rotary wheel in CONV scenario

For PolyExport scenario, as higher is the heating recovered by the rotary wheel more heating can be exported to the district heating with the consequent economical and environmental benefits. In summer, the heating of the engine is used in the desiccant units to produce latent cooling, so the sensible cooling recovered does not affect to the performance of the cogeneration engine in summer. For this reason in this case the use of the rotary wheel is also profitable from all points of view. The energy recovered is 99% of the maximum.

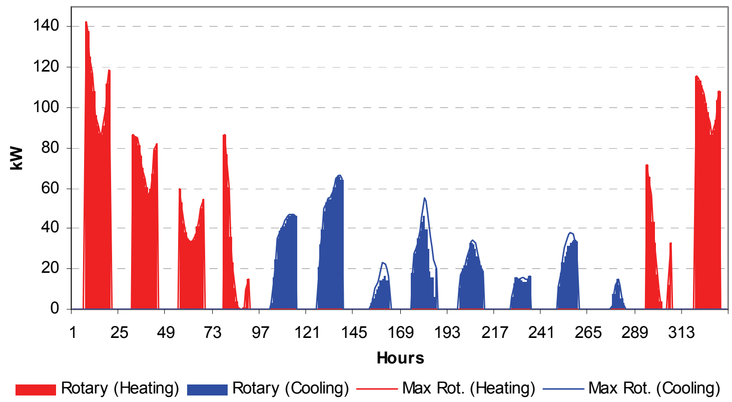

Figure 6.86 Energy recovered by the rotary wheel in PolyExport scenario

The situation is very different for the Isolated1 scenario. In this case there is no possibility to export heating to the district heating, so any device that is able to recover heating and decrease the heating demand is prejudicial from the economical point of view. Figure 6.87 shows the energy recovered that is 34% of the maximum energy recovable. In winter there is recovery of heating in that hours where the energy demand is higher respect to the thermal capacity of the engine. In this case, due to the heating/coolind demand ratio (section 6.4.5) the CO_2 emissions and primary energy consumption are higher respect to the conventional scenario.

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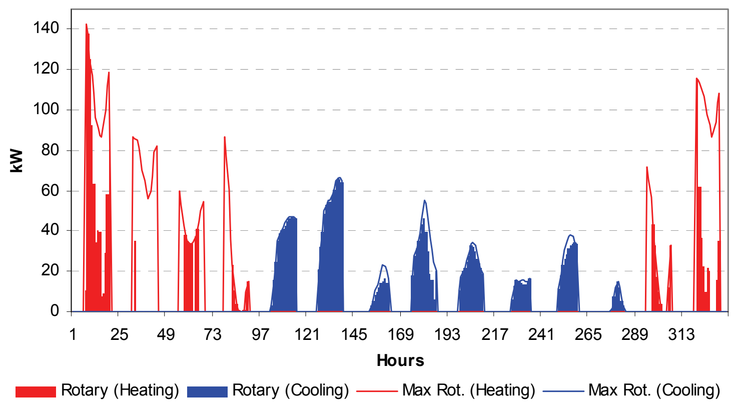

Figure 6.87 Energy recovered by the rotary wheel in Isolated1 scenario

Figure 6.88 shows the recovered energy for the Isolated2 scenario that is very similar to the CONV and PolyExport because the minimum recovered energy is fixed to 142 MWh/year. In this case the economical saving is lower compared to the Isolated1 scenario but the environmental savings are higher. As more energy is recovered, less electricity will be produced and lower economical benefits will be obtained; but the energy demand will be reduced and also the environmental emissions.

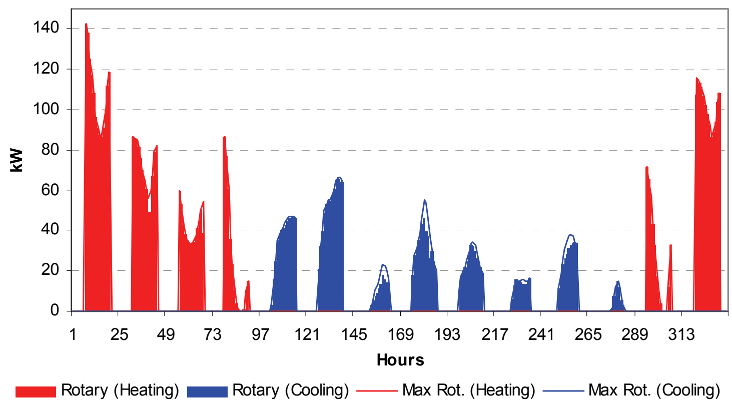

Figure 6.88 Energy recovered by the rotary wheel in Isolated2 scenario

The operation of the polygeneration system in summer is almost the same for PolyExport, Isolated1 and Isolated2 scenarios. The cooling production with the desiccant units and the cooling imported from compression chillers is almost the same in these scenarios. The use of the desiccant units decrease the heating demand in summer for reheating purposes, because the dehumidification is produced without the necessity to cool the air until the saturation temperature. This reheat is necessary because a minimum temperature of 17 ºC is fixed to avoid an uncomfortable supply of air.

The heating consumption in the heating coil is 175.4 MWh/year for the CONV scenario and 141.6 MWh/year for the PolyExport scenario. Figure 6.89 show the power required in the heating coil for heating in winter (red) and for reaheat in summer (orange). From the figure reheat in summer is necessary almost all the time and the average power is around 50 kW.

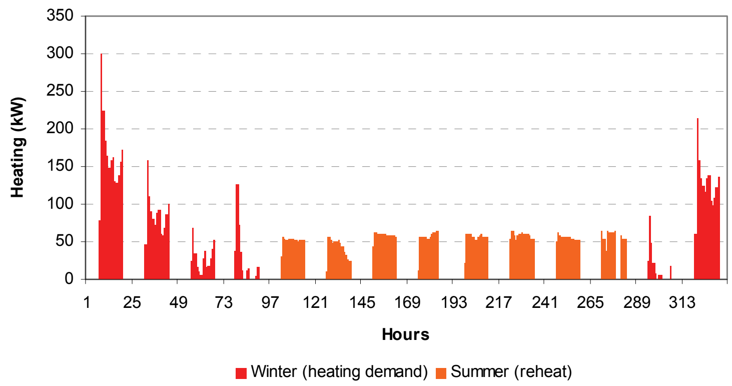

Figure 6.89 Heating coil power in CONV scenario

Figure 6.90 shows the power in the heating coil for PolyExport scenario, the capacity of the desiccant to dehumidify the air without decreasing the temperature reduce reheating requirements in summers.

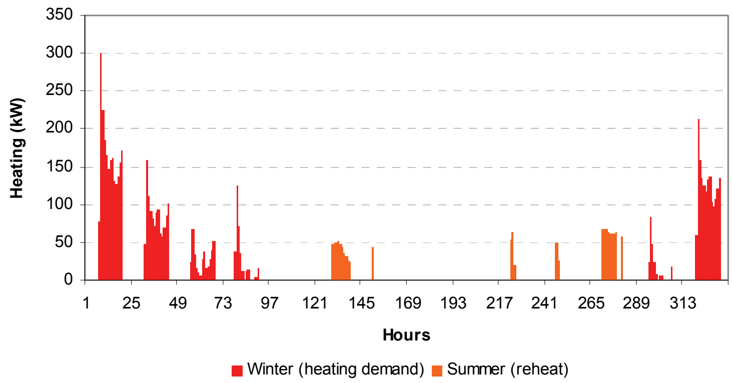

Figure 6.90 Heating coil power in PolyExport scenario

The power requirements for the heating coil for Isolated2 are very similar respect to PolyExport due to the fixed energy recovered with the rotary wheel. For Isolated1 scenario the lower energy recovered with the rotary wheel increase the heating power required in winter of the heating coil. (for example first and last day in figure 6.91).

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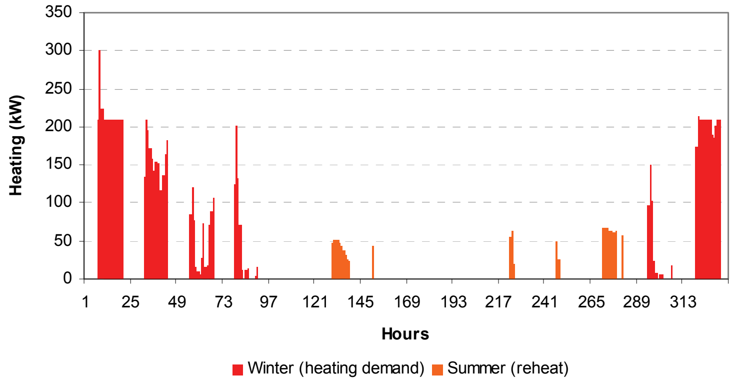

Figure 6.91 Heating coil power in Isolated1 scenario

The total cooling produced by the conditioning system (desiccant + compression) is almost the same in PolyExport, Isolated1 and Isolated2 (126 MWh/year), while in the conventional system is 128 MWh/year. The total cooling demand calculated with DesignBuilder is 125.8 MWh/year.

The higher cooling production in CONV respect to the other scenarios is due to the dehumidification-reheating process, this difference increase if the minimum temperature of the air also increases. For example if the minimum temperature is fixed to 18ºC, the total cooling produced for CONV is 133.0 MWh/year and for PolyExport is 126.7 MWh/year.

6.7 Conclusions

A polygeneration plant with an internal combustion engine, a desiccant cooling system and two air handling units has been presented in this chapter. In summer thep lant supply conditioned air to a clasroom building. In winter all the heat production is exported to a district heating network. Due to some technical problems only the desiccant units were tested. Although the activation temperature was lower (55-65 ºC) compared with the nominal (65-85 ºC) the units worked correctly obtaining a cooling power for each unit between 15-25 kW. It is important to highliht that the units were tested at the beginning of October 2009 when the ambient humidiyt is lower with respect to July or August.

The monitored data from the desiccant units has been used to test several correlations and propose a linear correlation for their use in optimisation models. Other units of the polygeneration plant have been modeled using previous experimental data or manufacturer data. With this information several units has been developed with GUME in order to implement the polygeneration plant in MGEOS.

With the optimisation model proposed, several scenarios has been analysed including a conventional scenario (CONV) the current operation of the polygeneration plant (PolyExport) and two scenarios in which the polygeneration plant is not able to export all the heating surplus (Isolated1 and Isolated2). The results are compared with respect to the CONV case in order to assest the viability of the polygeneration plant.

From the economical point of view, only the PolyExport scenario justifies the installation of this polygeneration system. Considering the size, the characteristics of the units installed and the energy demand of the building, the system is not desiderable if all the heating must be consumed by the classroom building and the plant is not able to export the heating surplus in order to increase the number of working hours. Moreover, the operation of some units like the rotary wheel competes with the cogeneration engine decreasing the load and the number of working hours (Isolated2). If the polygeneration system presented in this chapter must work isolated, it would be economically feasible only for building with a higher energy demand.

From the environmental point of view, the conventional system (CONV) is defined as a combined cycle for electrical production, compression chillers for cooling and boilers for heating. Considering only the nominal efficiencies of the polygeneration plant, energy savings are achieved for heating production but not for cooling production. When the polygeneration plant is compared with the conventional system in summer, the conventional system is more efficient. The annual energy savings of the polygeneration system will depend of the heatind-cooling demand ratio. Since the heating production in the PolyExport scenario is high, important energy savings are achieved with the polygeneration plant. When the plant is isolated, if economical benefits are maximized (Isolated1) more primary energy is consumed with respect to the conventional scenario. If the operation of the rotary wheel is increased (Isolated2), economical benefits are reduced but small energy savings are achieved with respect to the conventional system.

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Chapter 7 – Case Study 2

Polygeneration plant in the Polycity project

7.1 Introduction

The purpose of this section is to apply the developed environment to the polygeneration plant of the PolyCity project and to present the assessment analysis performed. POLYCITY is a project of the CONCERTO initiative, co-funded by the European Commission. In the course of the POLYCITY Project, three large urban areas in Germany, Spain and Italy have been developed by applying new measured in the field of energy optimisation and the use of renewable energies. The Spanish project consists in the development of a new urban area located in Cerdanyola del Vallès near Barcelona. This new area is a technological park, which will incorporate high efficiency polygeneration plants (ST4 and ST2 plants) connected to district heating and cooling networks. A scenario analysis will be presented to perform an economic, energetic and environmental assessment for different scenarios from 2010 to 2014. The scenarios considered have been evaluated using the availabe information from technical reports because there are no monitoring data available yet (at May 2010). The analysis is based on the comparsion with conventional alternatives estimating environmental benefits and assests possible future pathways to a more clean energy supply system. The scenarios can be used also to evaluate the impact when the energy prices or the rate of occupancy change respect the initial hypothesis.

Section 7.2 introduces the Spanish project in Cerdanyola del Vallès, with an overview of the main energy supply plants ST4 and ST2. The methodological approach is presented in section 7.3 detailing the emissions by technology, the investment and energy costs, the system boundary and how the energy supply system is implemented in MGEOS. Four scenarios have been defined in section 7.4 to compare the economic and environmental performance of different configurations. Finally the results are discussed in section 7.5

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7.2 Overview of the Spanish project in Cerdanyola del Vallès

The Polycity project is developed in a new area of 340 hectares in growth located in *Cerdanyola del Vallès* near Barcelona that at the end will comprise a roof area of 1,890,000 m^2, with a residential area for 15,000 inhabitants and an activity area that will create 40,000 jobs. A high efficiency energy system is to be implemented in the new urban development called Directional Centre, in order to produce electricity, heating and cooling. This polygeneration system will comprise high-efficiency natural gas cogeneration plants with an electrical output of about 16 MW_e, in a first stage, with thermal cooling facilities and a district heating and cooling network to connect the plant with the Science and Technology Park, which represents the core of the Directional Centre.

As mentioned above, the area will include a Science and Technology Park with the Synchrotron Light Facility (ALBA) as well as residential buildings. The ST4 plant will provide electricity, heat and cold energy for the Synchrotron and the technological park buildings through a district heating and cooling network of four tubes. The facility development is managed by the "Consorci del Centre Direccional" hereinafter called ConsCd, formed by the city council of Cerdanyola del Vallès and the "Institut Català del Sòl". The area has the following distribution:

- Synchrotron and Science and technology Park: 64.6 ha
- Parks, gardens and biologic corridor: 157.7 ha
- Dwellings, services and commercial area: 46.7 ha

The development of the Science and Technological Park in Cerdanyola del Vallès is divided in two phases:

- Phase I: construction of an energy production plant ST4 located in the technological park, to supply energy to the Synchrotron Laboratory (ALBA) and other users of the park (442,700 m^2 of offices and 62,000 m^2 of equipments). The end of this phase is planned by 2010. The ST4 will use a district heating and cooling network to provide hot and cold water simultaneously.
- Phase II: construction of three new energy supply plants (ST2, ST3 and ST5).

ConsCd launched a Call for Tenders to build and operate the polygeneration plant published in the OJEU (Official Journal of the European Union), BOE (Boletin Oficial del Estado) and DOGC (Diari Official de la Generalitat de Catalunya) in July 2006. The deadline was closed at

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the end of November 2006. The received proposals were reviewed by ConsCd with the help of CREVER and awarded on March 1st, 2007 to the joint venture formed by Tecnocontrol and Lonjas Tecnología, hereinafter called Lonjas. Figure 7.1 shows the Spanish site with the location of the four energy production plants, and the associated DHC network. The development of the second phase will be carried out as the territorial occupation grows.

Figure 7.1 Foreseen energy supply plants and DHC network in Alba park in Cerdanyola del Vallès

7.2.1 District heating and cooling network

District heating and cooling (DHC) is an integrative technology that can make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security. The fundamental idea of DHC is connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling. The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way.

DHC is no longer of importance only in northern latitude countries. Increasingly, in many parts of the world the DHC concept is being implemented for cooling, either through distribution of chilled water or by using the district heating network to deliver heat for thermal-driven chillers.

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DHC is important for implementing CHP because it expands the pool of potential users of recovered thermal energy beyond the industrial sector to include commercial, institutional and multi-unit residential buildings. The temperatures required by these users are relatively low, which allows CHP to operate at higher efficiencies compared to plants producing higher-temperature industrial process heat. In addition, as industry becomes more electrically intensive, large industrial heat sinks for low-grade energy are increasingly hard to find. Urban buildings, accessed through DHC, are a more stable long-term partner for CHP plants.

7.2.2 ST4 plant

The main units of the ST4 plant are the JMS 620 GS-N.L cogeneration engines, the main characteristics are presented in figure 7.2. The electrical nominal capacity is 3,354 kW with a recoverable thermal energy of 3,102 kW if the exhausts gases are cooled until 120ºC. The electrical efficiency is 45% and the total efficiency is 86.5%.

Jenbacher gas engines
Technical Specification

JMS 620 GS-N.L
Natural gas 3.354kW el.

CO-GEN Module data:

Electrical output	kW el.	3.354
Recoverable thermal output (120 °C)	kW	3.102
Energy input	kW	7.462
Fuel Consumption based on a LHV of 9,5 kWh/Nm³	Nm³/h	785
Electrical efficiency	%	45,0%
Thermal efficiency	%	41,6%
Total efficiency	%	86,5%
Heat to be dissipated (LT-Circuit)	kW	169

Emission values: NOx < 500 mg/Nm³ (5% O2)

Additional information:

Sound pressure level (engine, average value 1m)	dB(A)	101
Sound pressure level exhaust gas (1m, 30° off engin	dB(A)	123
Exhaust gas mass flow rate, wet	kg/h	18.221
Exhaust gas volume, wet	Nm³/h	14.373
Max.admissible exhaust back pressure after engine	mbar	60
Exhaust gas temperature at full load	°C [8]	383
Combustion air mass flow rate	kg/h	17.684
Combustion air volume	Nm³/h	13.680
Max. inlet cooling water temp. (intercooler)	°C	40
Max. pressure drop in front of intake-air filter	mbar	10
Return temperature	°C	70
Forward temperature	°C	90
Hot water flow rate	m³/h	133,2

Figure 7.2 Main characteristics of Jenbacher JMS 620 engines cogeneration installed in Alba park

Tables 7.1 and 7.2 show the main units to be installed in the ST4 plant, which is expected to be expanded as the energy demand grows. The ST4 plant is composed of cogeneration engines, simple and double effect water/LiBr absorption chillers, compression chillers and a backup boiler of 5 MW. Nowadays, only the units corresponding to the year 2010 and the boiler are installed. The operational conditions expected by Lonjas are listed in table 7.1.

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Table 7.1 ST4 plant foreseen installed cogenerators and expected operational conditions (Lonjas)

Year	Engines	Operation
2010	1 JMS620	16 hours/day – 5 days/week – 52 weeks
	2 JMS620	24 hours/day – 7 days/week – 38 weeks
2011	1 JMS620	16 hours/day – 5 days/week – 52 weeks
	2 JMS620	24 hours/day – 7 days/week – 38 weeks
2012	1 JMS620	16 hours/day – 5 days/week – 52 weeks
	2 JMS620	24 hours/day – 7 days/week – 38 weeks
2013	3 JMS620	16 hours/day – 5 days/week – 52 weeks
	2 JMS620	24 hours/day – 7 days/week – 38 weeks
2014	3 JMS620	16 hours/day – 5 days/week – 52 weeks
	2 JMS620	24 hours/day – 7 days/week – 38 weeks

Table 7.2 Foreseen installed cooling capacity for each type of chiller and year in ST4 plant (Lonjas)

Year	Installed capacity (kW)	Total capacity (kW)	Useful (5% loss) (kW)
2010	SE: 3,060	SE: 3,060	SE: 2,907
	DE: 5,028	DE: 5,028	DE: 4,776
	Comp: 5,000	Comp: 5,000	Comp: 4,750
2011	SE: 3,060	SE: 3,060	SE: 2,907
	DE: 5,028	DE: 5,028	DE: 4,776
	Comp: 5,000	Comp: 5,000	Comp: 4,750
2012	SE: 3,060	SE: 3,060	SE: 2,907
	DE: 5,028	DE: 5,028	DE: 4,776
	Comp: 5,000+5,000	Comp: 10,000	Comp: 9,500
2013	SE: 3,060+2,040	SE: 5,100	SE: 4,845
	DE: 5,028+3,352	DE: 8,380	DE: 7,961
	Comp: 5,000+5,000	Comp: 10,000	Comp: 9,500
2014	SE *: 3,060+2,040	SE: 5,100	SE: 4,845
	DE *: 5,028+3,352	DE: 8,380	DE: 7,961
	Comp *: 5,000+5,000	Comp: 10,000	Comp: 9,500

* SE: Absorption Simple Effect , DE: Absorption Double Effect, Comp: Compression chillers

Figure 7.3 shows the configuration of the ST4 plant for the year 2014. The double effect absorption chillers are fired directly with the exhausts gases of the engines. The simple effect absorption chillers use hot water produced by the engines and the compression chillers are used to cover peak demand periods. The electrical, thermal and cooling demand of the synchrotron is supplied by the ST4 plant and the surplus of electricity is sold to the grid. ST4 plant also produces heating and cooling to fulfil the energy requirements of the park.

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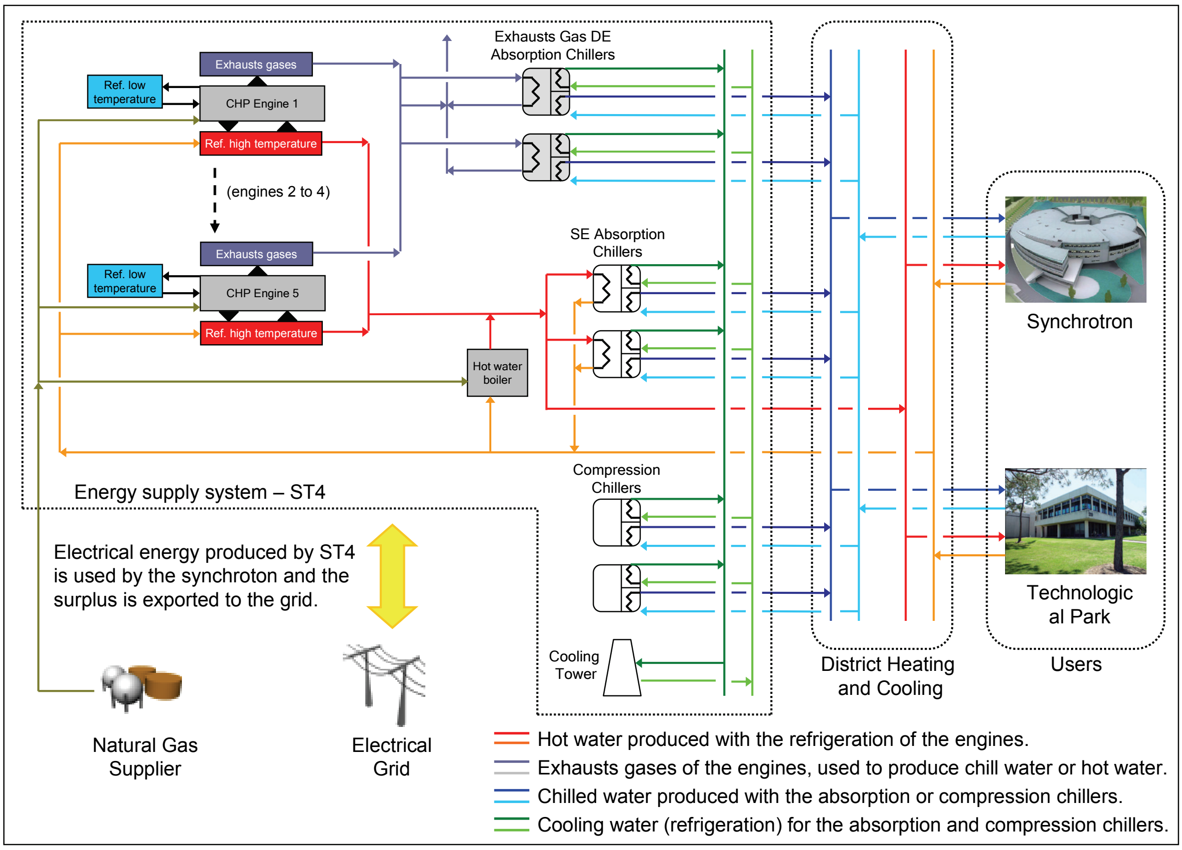

Figure 7.3 Foreseen configuration of the ST4 plant in park del Alba for the year 2014 (Lonjas)

The following figures show the different units during the construction phase of the plant ST4. Figures 7.4 and 7.5 show one of the three cogeneration engines currently installed. The former shows the alternator and the last shows the heat exchangers to recover the heat from the high temperature circuit.

Figure 7.4 One of the Jenbacher engines, with its electric generator at the front of the picture

Figure 7.5 Heat exchangers for the recovery of thermal energy at the high temperature circuit

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Figure 7.6 shows the double effect absorption chillers, fired directly with the exhausts gases of the engine (upper left part of the picture). Figure 7.7 shows the simple effect abortion chiller fired with the hot water produced with the engines.

Figure 7.6 DE absorption chiller activated with exhausts gases coming from the cogenerators

Figure 7.7 SE absorption chiller activated with the hot water produced with the cogenerators

Figure 7.8 shows the compression chiller of 5MW cooling used as a backup. Figure 7.9 shows the cooling tower used for the cooling requirements of the absorption chillers (DE and SE) and the compression chillers. The towers are used also for the cooling requirements of the low temperature circuit of the cogeneration engines.

Figure 7.8 Electric chiller before being installed

Figure 7.9 General view of the cooling towers

Figure 7.10 shows the backup boiler of 5MW. Figure 7.11 is a general view of the ST4 plant during the construction phase. The picture shows the section where are placed all the chillers, the backup boiler and the pumps. Figure 7.12 shows an external view of the ST4 plant finished, and figure 7.13 shows the location of the ST4 plant respect to the synchrotron ALBA.

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Figure 7.10 View of the backup boiler of 5 MW

Figure 7.11 ST4 plant during the construction

Figure 7.12 General view of the ST4 finished

Figure 7.13 Synchrotron ALBA and ST4 plant

7.2.3 ST2 plant

The ST2 plant is expected to be build after the ST4 will be finished and under operation. ST2 plant consists of a solar cooling plant and a gasification plant to produce synthesis gas for a cogeneration engine, the main characteristics of these plants in ST2 are:

- Solar cooling plant, with up to 2,000 m^2 of solar collectors. Using flat plate collectors with adsorption chillers, or evacuated tube collectors with absorption chillers.

- A gasification plant working with forestry residues or sub products from the local industry and other residues. The synthesis gas is used in a dedicated cogeneration engine to produce electricity and cooling using absorption chiller.

The biomass gasification plant is integrated with a cogeneration engine of 1 MWe and fed with wood biomass, with an estimated consumption of 1,000 kg/h of wood residues. For the present analysis, the production rate of synthesis gas is estimated according to the results from the

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biomass plant "*Energia Natural de Móra, S.L.*" (*Enamora,* figure 7.14). This plant is installed in the *Pere Escribà, S.A.* Company and works with almond rind producing 2,500 Nm^3/h of synthesis gas (LHV 5.319 kJ/Nm^3) for each 1,000 kg/h of biomass supplied. In the biomass gasification processes, air is used as gasifying agent and a low calorific value gas is generated. The biomass is converted into a gaseous fuel, the major components being carbon monoxide and hydrogen. These gas produced is used as a fuel for the generation of heat and electricity. The gas produced is usually contaminated with tar and dust that should be removed first.

Figure 7.14 ENAMORA gasification plant (Gasifier+synthesis gas treatment)

7.3 Methodological approach

The ST4 plant is finished but has not start yet thus there is no available monitoring data (at February 2010). Nowadays the ST4 plant consist of three cogeneration engines, 1 SE and 1 DE absorption chiller, 1 compression chillers and a backup boiler (tables 7.1 and 7.2). As no monitoring data is available, the expected operational conditions of the engines (table 7.1) have been considered in the scenario analysis. The energy demand for the Synchrotron is estimated in a fifteen days basis, for the electricity, heating and cooling. For the rest of the park, the energy demand has been estimated using the ratio of occupation for each year (% roof area occupied / total roof area in the park) from the Lonjas technical reports (Lonjas report). The energy demand is obtained applying the energy consumption ratios, the ratio of occupation for each year and the total roof area.

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The first step is the calculation of the expected energy demand for each fortnight with the available information from the technical information obtained from the Lonjas report (section 7.3.2).

The operation of the energy supply system will be evaluated from the energy, economic and environmental point of view. To perform this analysis an optimisation model has been developed using MGEOS and solved with GAMS to calculate all the operational parameters of the plant for each time slice maximizing the economical benefits. Figure 7.15 shows the framework to optimise the scenarios. Almost all the necessary information has been obtained from the Lonjas technical report. The CO_2 and the SO_2 equivalent emissions for each technology have been calculated using GEMIS 4.5 (Global Emission Model for Integrated System, Öko-Institute e.V.) and are presented in the section 7.3.4. With this information and the units available in MGEOS the flowsheet of the polygeneration system is implemented and all the system is solved maximising the economic benefits.

The objective of the scenario analysis is to compare the performance of energy supply system with different configurations (technologies), these configurations are listed from section 7.4.1 to 7.4.4. The different configurations are implemented in MGEOS, optimised and the results are compared in section 7.5. The general analysis boundary is presented in section 7.3.1. The economic and energetic savings of the polygeneration plant will be compared with the conventional energy supply system.

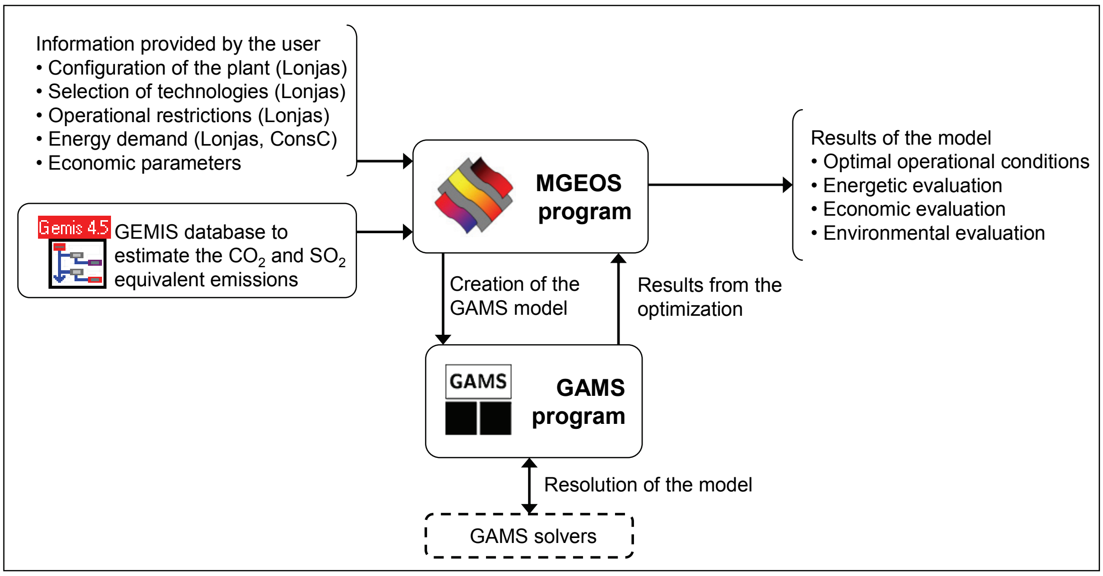

Figure 7.15 Framework implemented to solve the scenarios using MGEOS and GEMIS database

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7.3.1 System boundaries

Figure 7.16 shows the system boundaries (green line) used in the scenario analysis. This figure represents the ST4 plant, the ST2 plant (gasification and the solar cooling plant) and also the district heating and cooling network. Only the electrical consumption of the Synchrotron is considered, because the electrical demand for the other buildings will be always supplied with the national grid. For all the scenarios a reference technology is considered for the separate production of electricity (national grid, section 7.3.4).

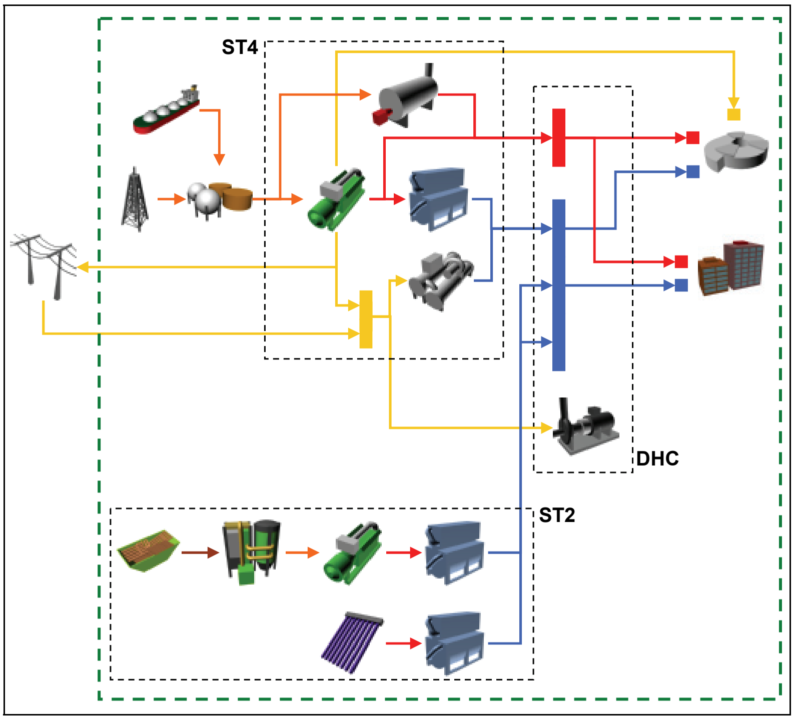

Figure 7.16 Boundaries fixed for the polygeneration system

As mentioned above, the GEMIS 4.5 database has been used to calculate the CO_2 and the SO_2 equivalent emissions. The extraction, transformation and transportation of resources (natural gas and biomass) are integrated into the equivalent emissions calculated with GEMIS 4.5, and all these process are included inside the boundary analysis. The national grid is outside the boundary analysis and the CO_2 and SO_2 equivalent emissions are charged for all the imported electricity. In the same way, some credits (avoided CO_2 and SO_2 emissions) are considered for all the exported electricity. The avoided emissions equal the emissions of the technology considered for the separate production of electricity.

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7.3.2 Implementation of the polygeneration system in MGEOS

In this section is presented how the polygeneration plant is implemented in MGEOS. As the implementation of the polygeneration plant with liquid desiccant has been presented in detail in section 6.4.3, only few comments will be presented in this section. Figure 7.17 and 7.18 presents the entire flowsheet for the PolyCity project (the flowsheet has been splited in the two figures). Figure 7.17 shows the main results obtained from the plants (economic and CO_2 and SO_2 emissions). The bottom blocks of in figure 7.17 calculate the results for each year.

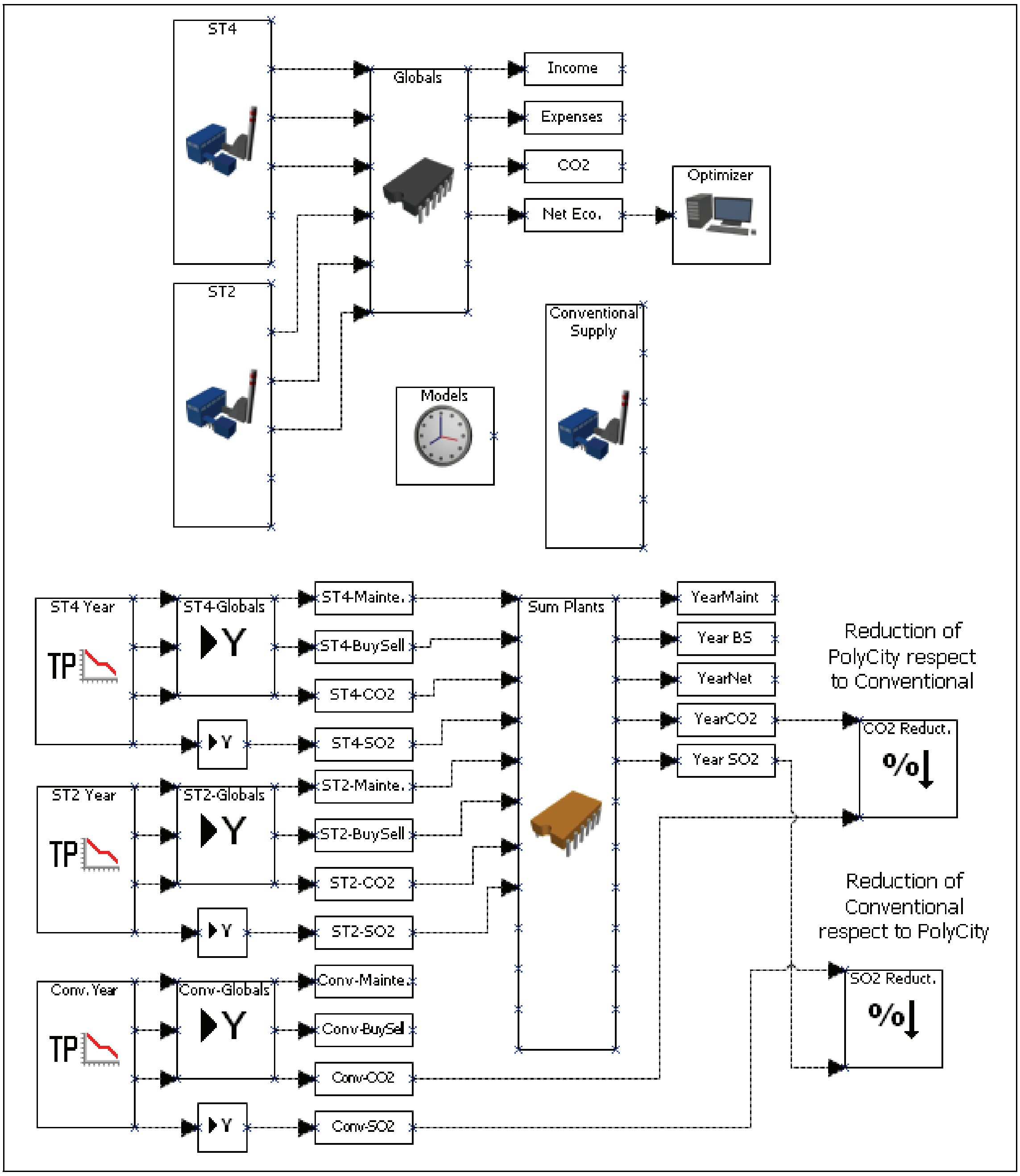

Figure 7.17 Global results

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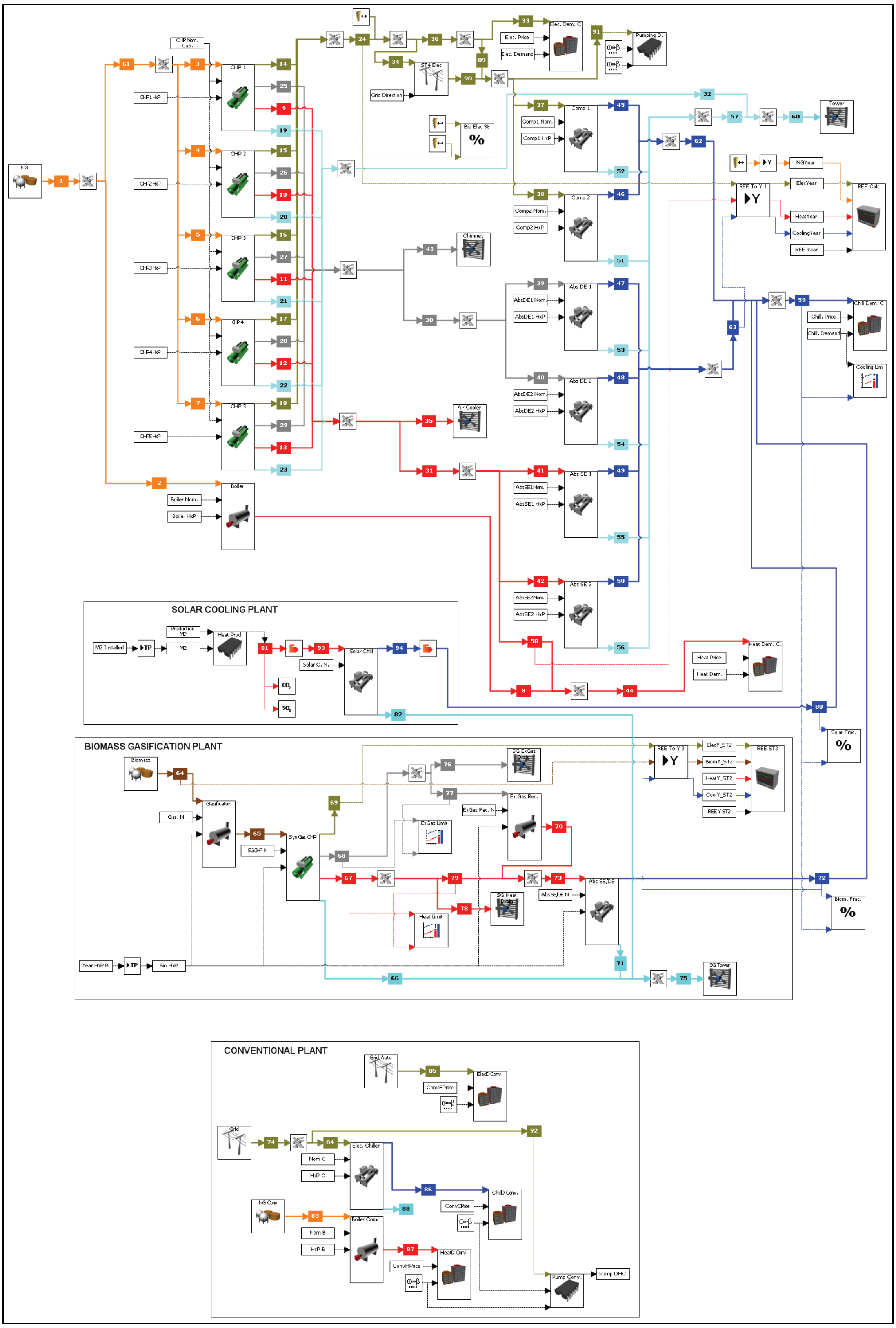

Figure 7.18 Overview of the MGEOS flowsheet for the PolyCity project

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Figure 7.18 shows all the other units placed inside the three plants (ST4, ST2 and conventional plant). Figure 7.19 shows four of the five engines in the ST4 plant. For each engine is calculated the electrical output (olive) and the thermal production from the exhausts gases (grey) and the hot water (red) from the high temeperature circuit of the engine. The heat to be dissipated from the low temperature circuit is represented in light blue and the energy consumed as natural gas in orange. The nominal capacity of the engines is represented by the variable "CHP Nom. Cap." and the number of working hours in each time period is represented by "CHP*n* HxP" where *n* is the number of the engine. The flows corresponding to the same type of energy are connected using the unit .

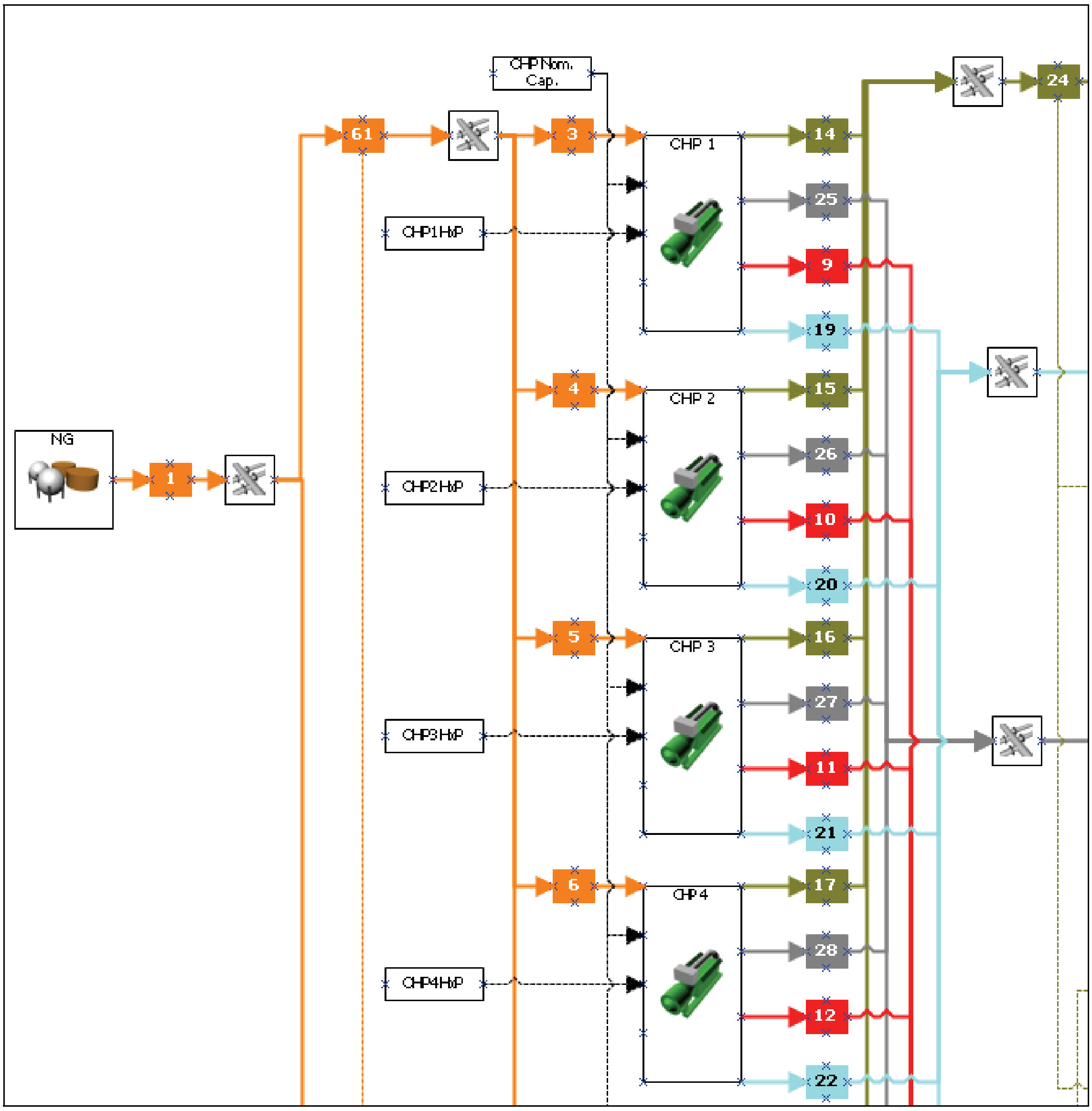

Figure 7.19 Cogeneration engines in the plant ST4

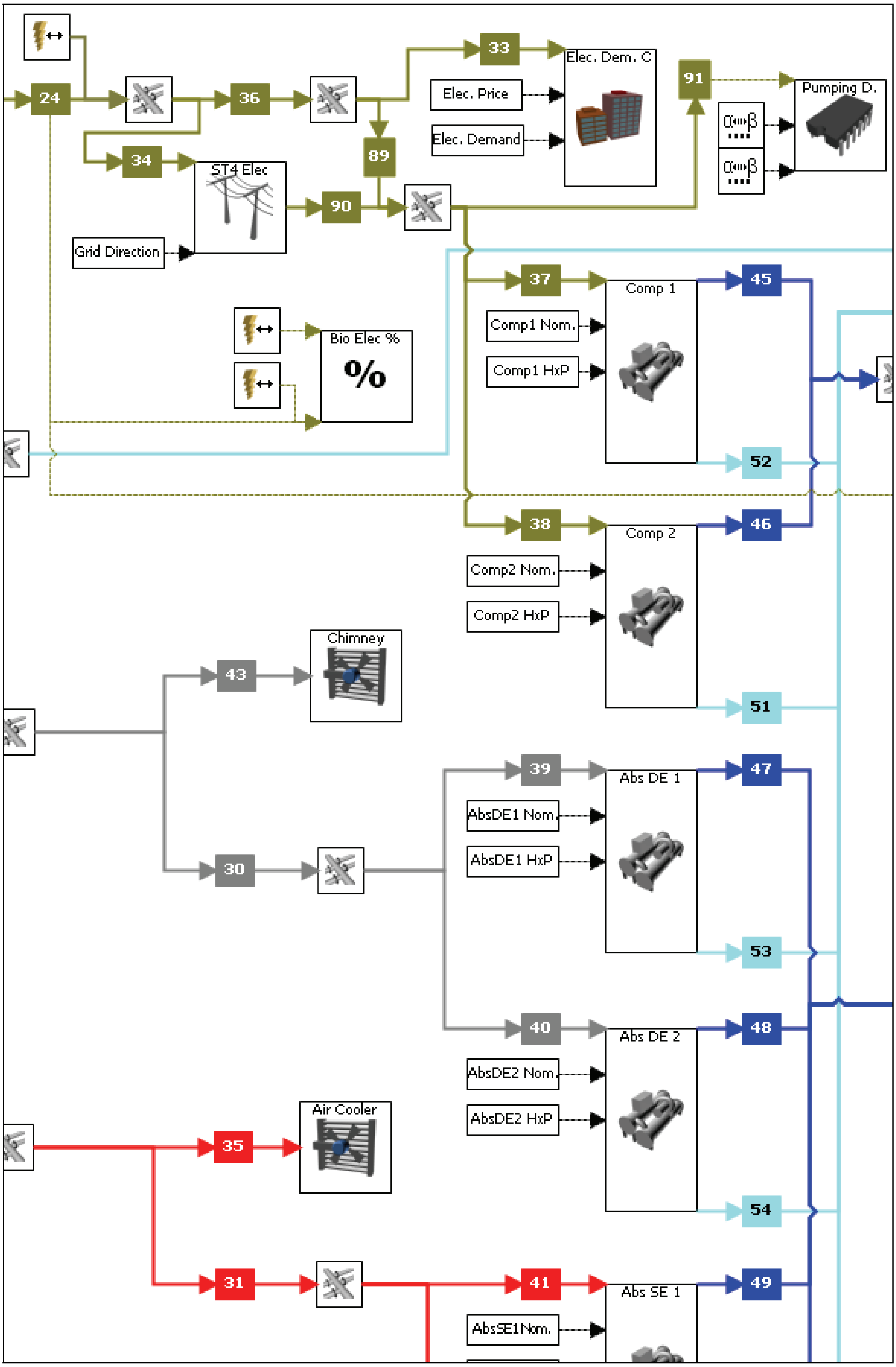

Figure 7.20 Implementation of the compression and double effect absorption chillers

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Figure 7.20 shows the compression and the double effect absorption chillers. Flows 30 and 43 are the total production of thermal energy with the exhausts gases, that can be dissipated (43) or used to produce cooling (30). Flow 24 is the electrical production of the engines with natural gas (ST4) and the energy link is the electrical production of the ST2 plant. All the electrical production can be exported to the grid (34) or can be used to cover the electrical demand from the users (33) or the electrical requirements of the ST4 plant (89). Electrical energy can be imported through the flow 90 for the requirements of the plant ST4. In the same time period, electrical energy can not be imported and exported simultaneously (variable "Grid Direction"). Flow 91 represents the electrical consumption for pumping calculated as a linear correlations of the heating and cooling consumption introduced with the linking units . These linking units are placed inside the variables that contains the cooling and heating demand. Simple effect absorption chillers are shown in figure 7.21. The energy from the hot water produced with the engines can be used in the chillers to produce cooling (31), to supply the heating demand of the users (58) or can be dissipated (35). Flow 8 is the heating production from the backup boiler. The heating demand of the users is represented in the block with the price "Heat Price" and the demand stablished in "Heat Dem.".

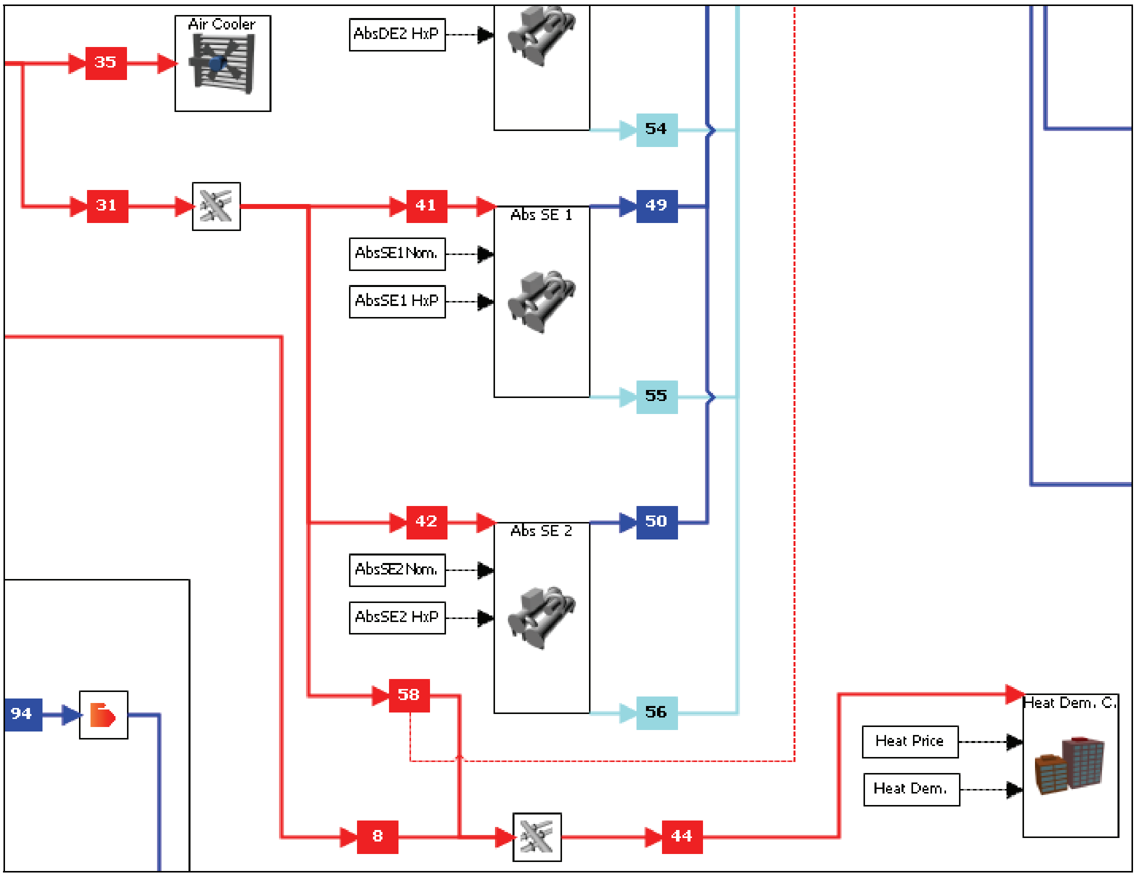

Figure 7.21 Implementation of the compression and double effect absorption chillers

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Figure 7.22 shows the calculation of the electrical equivalent efficiency for the plant ST4 for each year. Flow 60 represents the cooling requirements of the engines and the absorption chillers. Flow 62 is the cooling production with the compression chillers and flow 63 is the total cooling production with the absorption chillers. Figure 7.23 shows how the conventional system is represented. The results for this plant ("Conv Supply" and "Conv. Year" in figure 7.17) are used to compare the environmental savings of the polygeneration plant with respect to the conventional system. The conventional system is represented by the national grid, a compression chiller and a boiler. Pumping requirements can be calculated if the conventional system is represented by a centralised heating and cooling plant with district heating and cooling.

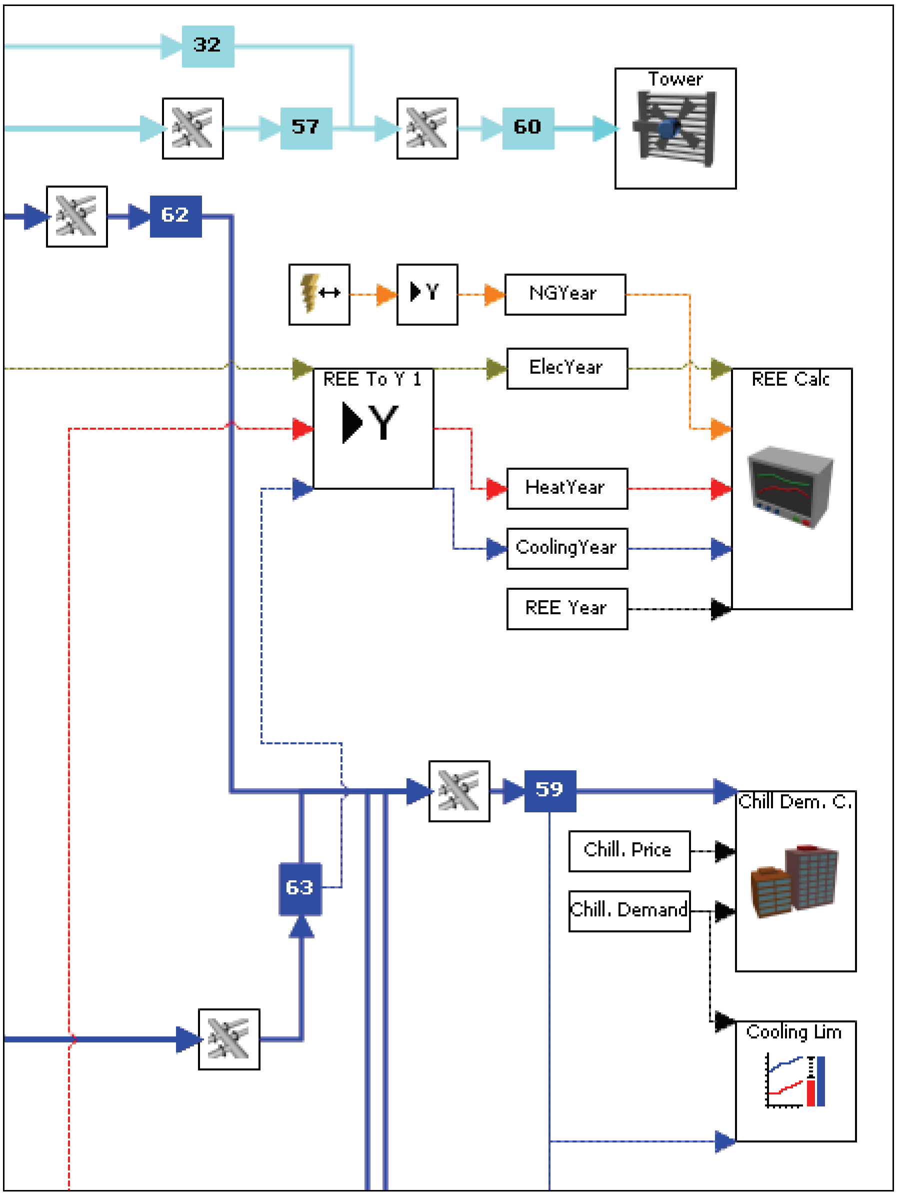

Figure 7.22 Cooling demand and equivalent electrical efficiency

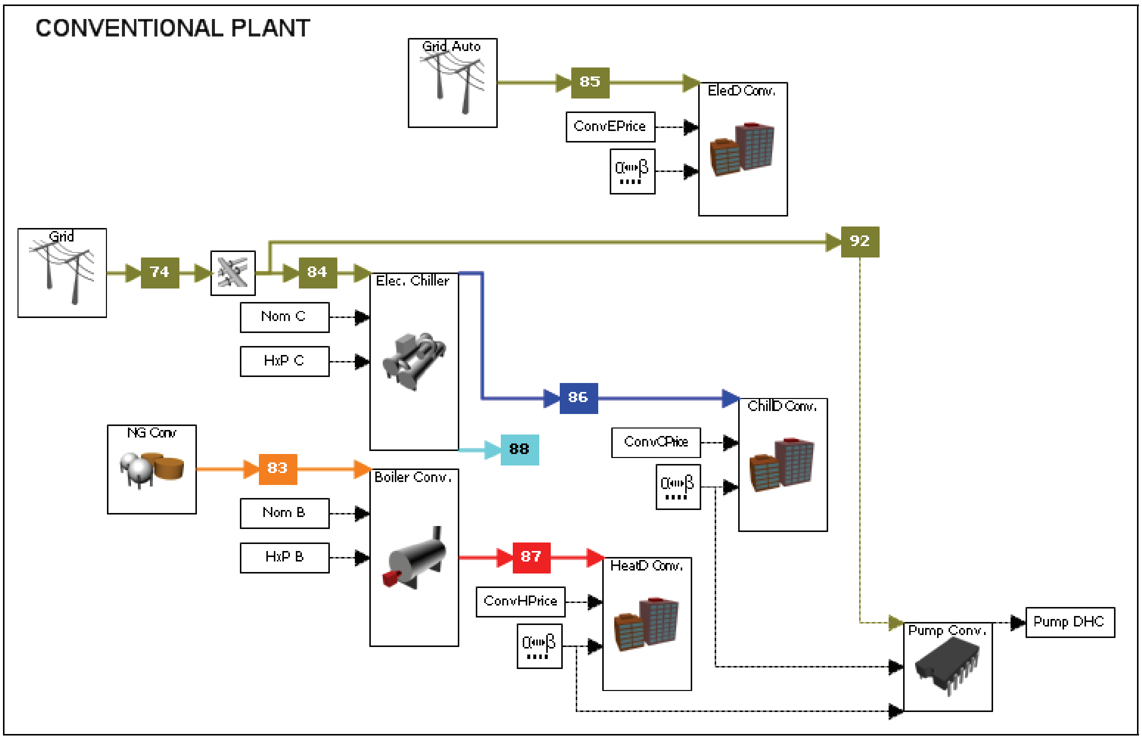

Figure 7.23 Implementation of the conventional plant

Figure 7.24 shows the solar cooling plant respresented by a fixed ammount of heating energy produced for each period and m^2 of solar thermal collector (Production M2). "M2 Installed" is the surface of thermal collectors installed for each year (2.000 m^2 from 2011 to 2014). The gasification plant is presented in the figure 7.25. The gasifier is represented using a boiler with a 80 % of efficiency. It is assumed that all the thermal production of the engine is used in an absorption chiller with a COP near one (a double effect chiller with the possibility to use also hot water in the intermediate stage). Due to the time step considered according to the available plant data (fifteen days) it is not necessary to implement more detailed models for the solar cooling and biomass plant.

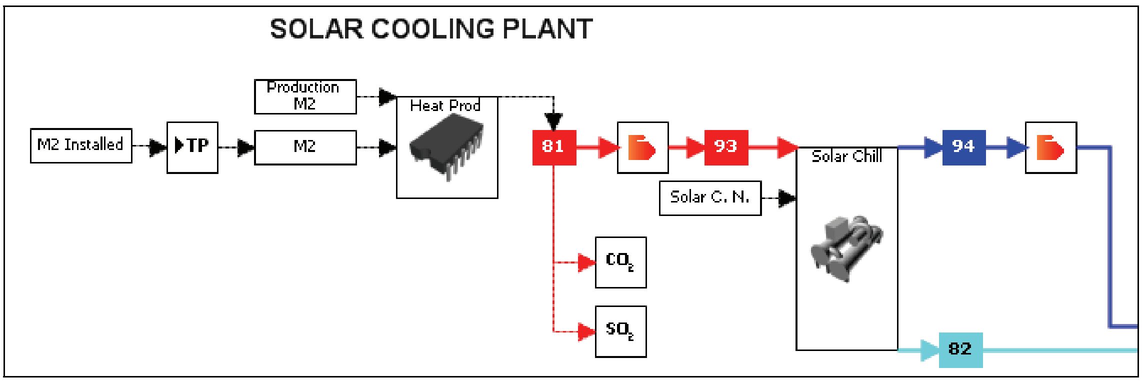

Figure 7.24 Solar cooling plant

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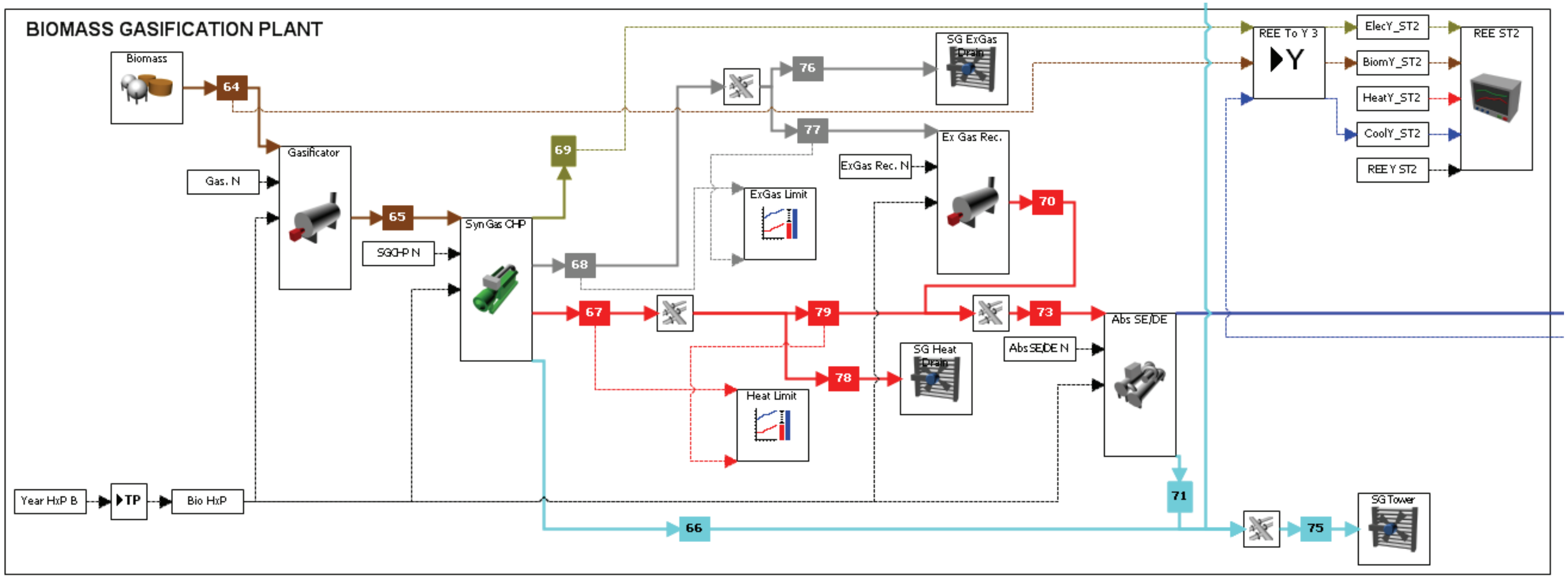

Figure 7.25 Implementation of the biomass gasification plant in MGEOS using a congeneration engine and a boiler to represent the gasifier

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7.3.3 Demand side characteristics

The energy demand profiles have been calculated for each fifteen days from the available information of the Lonjas technical report. Table 7.3 shows the expected occupancy ratio in the park as well as the number of call centers and equipment building. It is expected a full occupancy in 2014. The specific and total energy demand can be found in table 7.4. The calculated annual energy demand is distributed for each fortnight using the factors in table 7.5.

Table 7.3 Foreseen occupancy in Alba park for energy demand calculations (ConsCd, Lonjas)

	2010	2011	2012	2013	2014
Rate of occupancy (%)	10	25	50	70	100
Numbers of call centers	0	1	1	1	2
Equipment buildings	0	0	1	2	2

Table 7.4 Energy demand rations used to calculate the energy demand (ConsCd, Lonjas)

	Cooling demand	Heating demand
Tertiary sector buildings	115 $kWh/m^2 \cdot year$	55 $kWh/m^2 \cdot year$
Equipment buildings	100 $kWh/m^2 \cdot year$	80 $kWh/m^2 \cdot year$
Call centers	16,000 MWh/year	400 MWh/year

Table 7.5 Distribution (%) of the energy demand (ConsCd, Lonjas)

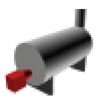
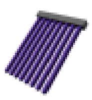
Period	Air conditioning	Heating and DHW	Cooling for call center
1 JAN	0.0	9.5	2.0
2 JAN	0.0	9.0	2.5
1 FEB	0.0	8.5	2.5
2 FEB	0.0	7.5	2.5
1 MAR	0.5	7.0	3.0
2 MAR	1.0	4.0	3.0
1 APR	1.5	4.0	4.0
2 APR	2.5	4.0	4.5
1 MAY	3.0	3.5	4.5
2 MAY	5.0	2.0	5.0
1 JUN	7.5	1.5	5.0
2 JUN	9.0	1.0	5.5
1 JUL	11.0	1.0	6.0
2 JUL	13.0	0.5	7.0
1 AUG	11.0	0.5	7.0
2 AUG	10.0	0.5	7.0
1 SEP	11.0	0.5	6.5
2 SEP	9.0	1.5	5.0
1 OCT	4.0	1.5	4.0
2 OCT	1.0	3.0	4.0
1 NOV	0.0	5.5	2.5
2 NOV	0.0	7.0	2.5
1 DEC	0.0	8.0	2.5
2 DEC	0.0	9.0	2.0

7.3.4 Costs and emissions by technology

The emission factors used in the scenario analysis has been obtained from the GEMIS 4.5 database, in order to include the emissions accounted for all the necessary processes to obtain the fuel, transformation and transportation, construction and operation of the equipment. Two emissions will be considered, the CO_2 equivalent emissions, which includes the main gases responsible of the global warming, and the SO_2 equivalent emissions, including the main gases responsible for acidification.

The reference system for the separate production of electricity is a combined cycle with a global electrical efficiency of 49.8%. This efficiency is calculated according to the European Comission Decision of 21 December 2006. The efficiency for a combined cycle built between 2006 and 2011 is 52.5%. A factor must be applied due to the transportation losses of the grid. For a system connected to 20 kV and exporting the 60% of the electrical production, this factor is 0.937. The reference efficiency of a boiler running with natural gas is 90%. Table 7.6 shows the emissions for each technology. The credits due to exported electricity are not considered in the table, this credits will be accounted in the optimisation model and will be equal to the emissions of the reference system for the separate production of electricity.

Table 7.6 CO_2 and NO_x emissions calculated using the GEMIS 4.5 database for each technology included in the scenario (credits corresponding to the exported electricity are not included here)

Technology		Equivalent emissions (g/kWh)	
		CO_2	SO_2
	Reference system for the separate production of electricity (Combined Cycle, $\eta_{overall}$ = 49.8 %) (as a function of the electricity production)	493	0.583
	Reference boiler (η = 90%) (as a function of the heating energy production)	270	0.302
	CHP engines with natural gas ($\eta_{CHP,elec}$ = 44.9 %) (as a function of the electricity production)	552	0.731
	Biomass gasification plant ($\eta_{gasifier}$ = 80%, $\eta_{CHP,elec}$ = 36.1 %)	82.4	1.01
	Solar thermal collectors (2000 hours/year, η_{avg}=42 %) (as a function of the thermal production)	13.3	0.068

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The investment and energy costs are obtained also from the Lonjas technical report (Lonjas report) and are presented in the following tables. Table 7.7 shows the unitary cost used to calculate the price of conventional equipments. These prices will be used in the conventional configurations composed of compression chillers to produce cooling and boilers to produce heating.

Table 7.7 Unitary costs to calculate the investment cost for the conventional scenarios

Unit	Unitary price
Boiler	100 €/kW
Compression chiller	100 €/kW
District heating network	210,000 € (Lonjas report)

Table 7.8 shows the total investment costs of the polygeneration plant in Cerdanyola del Vallès obtained from the Lonjas technical reports. The investment cost includes the district heating and cooling network. Finally the energy prices used in all the scenarios are presented in table 7.9.

Table 7.8 Total investment cost of the polygeneration plant from the Lonjas technical reports

Plants	Investment cost
ST4 plant	25,2 Million €
Renewables plant (ST2)	6,2 Million €

Table 7.9 Energy prices used in the optimisation model from the Lonjas technical reports

Energy	Price
Electricity imported from the grid	60.40 €/MWh
Electricity exported to the grid	97.40 €/MWh
Electricity sold to the users	82.30 €/MWh
Heating	31.11 €/MWh
Cooling	35.20 €/MWh
Maintenance cost (for each unit)	11.50 €/MWh

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7.4 Scenarios definition

In this section the base scenarios will be analysed. These scenarios are calculated using the following parameters obtained or calculated from the Lonjas technical reports:

- Energy costs.
- Operational costs.
- Rate of occupation.
- Specific energy demand ratios.

The differences between the scenarios considered are which technologies are used to supply the energy demand (electrical, heating and cooling). The scenarios are listed below:

- CONV: this scenario is the conventional configuration to supply electricity, heating and cooling. This configuration uses the national grid and an individual boiler for heating and a compression chiller for cooling for each user.
- CONV+DHC: the same units respect to the CONV scenario are used but centralised in a plant, to produce heating and cooling to be distributed for all the users using a district heating and cooling network. The main difference respect to the CONV scenario is the higher capacity of the units and the higher efficiency of the compression chillers. Pumping costs for the district heating and cooling network has been considered in the CONV+DHC scenario from the available data in the Lonjas technical reports.
- ST4+ST2: this is the scenario including the polygeneration plant ST4 and the biomass and solar cooling plant with the specifications indicated in the previous sections and the configuration shown in figure 7.16.
- ST4: in this scenario the ST2 plant is not installed, only the ST4 plant is working with the expected configuration and operational conditions (section 7.2.2).

Some simplifications have been applied:

- Constant energy costs.
- Constant operational costs.
- Devaluation not considered.

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The indicators analysed for these cases are:

- CO_2 equivalent emissions for the greenhouse gases, from GEMIS 4.5 including: SO_2, NO_x, HCl, HF, Particulates, CO, NMVOC, H_2S, NH_3, As(air), Cd (air), Cr (air), Hg (air), Ni (air), PAH (air), Pb (air), PCDD/F (air).
- SO_2 equivalent emissions for the gases responsible of acidification, from GEMIS 4.5 including: CO_2, CH_4, N_2O, Perfluoromethane, Perfluoroethane.
- Total RES installed capacity, including electrical and cooling production.
- % of electrical energy produced with RES.
- % of cooling energy produced with RES.
- Investment costs.
- Cash flow.

7.4.1 Conventional case without DHC (CONV)

This scenario is the conventional energy supply configuration. The conventional case is based on the reference values established by the Commission Decision of 21 December 2006. The rate of occupancy of the park is the one considered in the Lonjas technical report. Figure 7.26 shows the configuration for the conventional scenario. The green line is the analysis boundary, and the units included are listed in table 7.10.

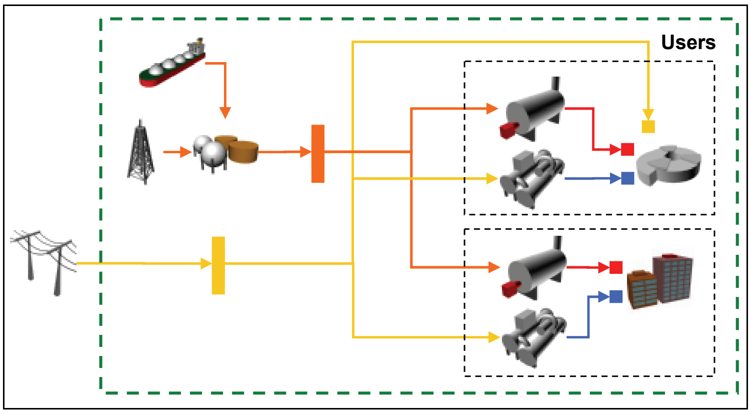

Figure 7.26 CONV scenario configuration and boundary

Table 7.10 Main parameters of the plant considered in the CONV scenario

	Electricity	Combined cycle, overall efficiency = 49.8%
	Heating	Boiler, η = 90%
	Cooling	Compression chillers, COP = 3

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Table 7.11 shows the main results for the CONV scenario. The cash flow is not calculated, because is supposed that each user buy and operates a boiler and a compression chiller, in contrast to the other scenarios (CONV+DHC, ST4+ST2 and ST4) where an ESCO install and operates the energy system and the users pay to the ESCO for the services received. The renewable capacity installed and the renewable production is zero in this scenario. The expected investment cost for this scenario is 3.1 M€.

Table 7.11 Main results for the CONV scenario for the analysed years

Year	CO_2 equivalent (ton/year)	SO_2 equivalent (ton/year)
2010	20,819	24.6
2011	23,503	27.7
2012	25,874	30.4
2013	28,369	33.3
2014	33,461	39.3

Figure 7.27 shows the energy flow for the year 2014 to supply the heating and the cooling demand, and also the electricity required by the synchrotron ALBA. The electrical demand of the other users is not considered. In figure 7.27 are represented the boilers and the compression chillers of the users and also the national grid represented with a combined cycle. All the fossil primary energy consumption is represented in the basis of natural gas.

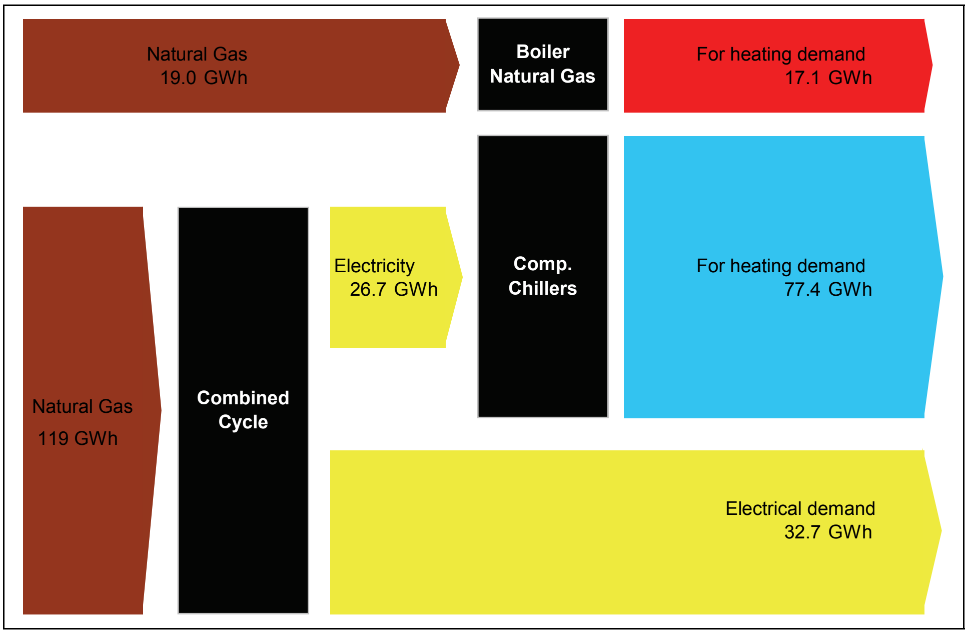

Figure 7.27 Global energy balances for the CONV scenario in 2014

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7.4.2 Conventional case with DHC (CONV+DHC)

In this scenario the DHC is included and the boilers and compression chillers are centralised. The differences with the previous case are a higher COP for the compression chillers and the pumping consumption for the DHC network. The compression chillers are of the same type than the compression chillers included in the ST4 plant. The pumping requirements are calculated in the basis of the Lonjas technical report. Figure 7.28 shows the configuration for the conventional scenario. The green line is the analysis boundary, and the units included are listed in table 7.12.

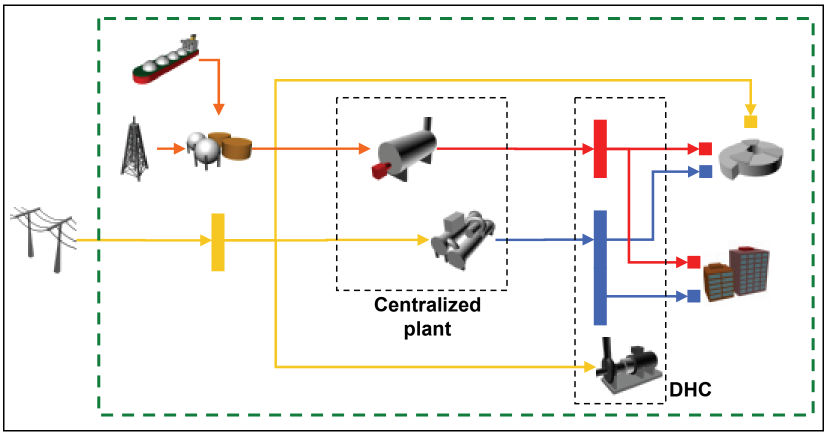

Figure 7.28 CONV+DHC scenario configuration and boundary

Table 7.12 Main parameters of the plant considered for the CON+DHC scenario

	Electricity	Combined cycle, overall efficiency = 49.8%
	Heating	Boiler, η = 90%
	Cooling	Compression chillers, COP = 5
	Pumping	As a function of the energy demand

Table 7.13 shows the results for the CONV+DHC scenario. The cash flow has been calculated with the energy prices considered in the Lonjas technical report and assuming that an ESCO manages the polygeneration plant and has some benefits due to the electricity, heating and cooling production. Like in the CONV scenario, the renewable capacity installed and the renewable production is zero and only the contaminant emissions and the cash flow are presented in table 7.13. The reduction of the CO_2 and SO_x emissions is due to the higher efficiency of the compression chillers compared to the CONV case.

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Table 7.13 Main results for the CONV+DHC scenario for the analysed years

Year	CO_2 equivalent (ton/year)	SO_2 equivalent (ton/year)	Cash flow
2010	19,415	22.9	$2.9 \cdot 10^5$
2011	21,426	25.2	$4.3 \cdot 10^5$
2012	23,408	27.5	$5.3 \cdot 10^5$
2013	25,527	29.9	$6.3 \cdot 10^5$
2014	29,636	34.8	$8.3 \cdot 10^5$

Figure 7.29 shows the energy flow for the year 2014 for the CONV+DHC scenario. In this case all the units are centralised and the national grid is considered as a combined cycle. The main difference respect to the CONV scenario is the lower electrical demand of the compression chillers to produce cooling, and the pumping requirements due to the district heating and cooling network. The same efficiency has been considered for the boiler for the scenarios CON and CON+DHC. The total fossil primary energy consumption is reduced 12% from 138 GWh for the CONV scenario to 121 GWh for the CONV+DHC scenario. The expected investment costs for this scenario is 3.3 M€, the cost of the district heating and cooling network has been obtained from the Lonjas technical reports. The main advantages of this scenario with respect to the CONV scenario is the higher efficiency obtained because of the higher COP of the compression chillers and the intrinsic benefits for the use of the DHC network.

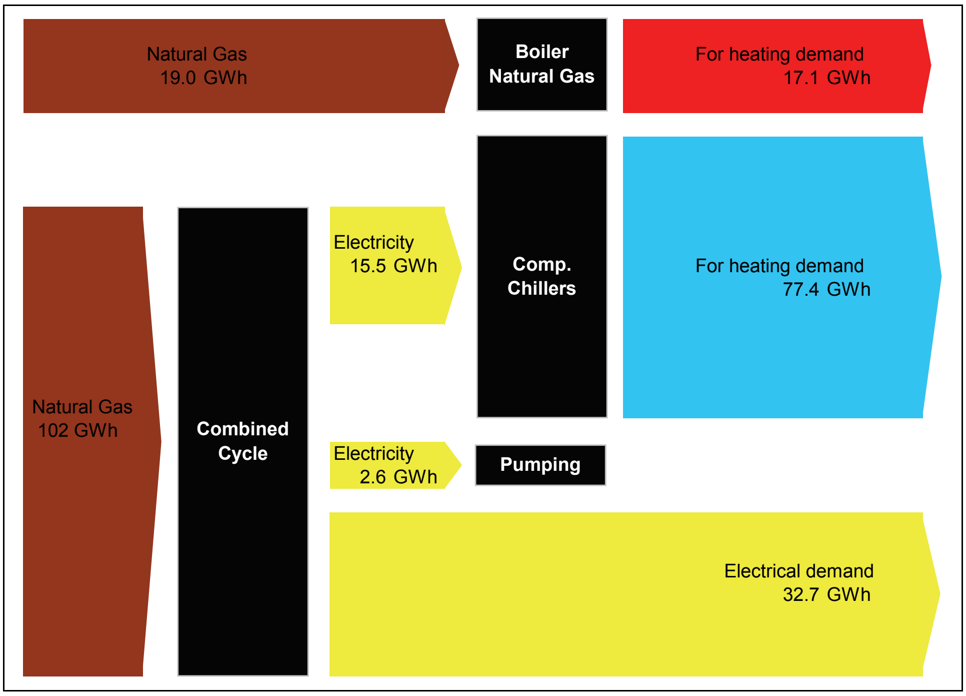

Figure 7.29 Global energy balances for the CONV+DHC scenario in 2014

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7.4.3 ST4+ST2 scenario

This scenario is the initial configuration, operation and load energy demand profiles included in the Lonjas technical reports, with the biomass gasification and the solar cooling plants in operation. The energy and operational costs are obtained from the Lonjas technical reports. Figure 7.30 shows the configuration in this scenario. The ST4 plant was presented in section 7.2.2 and the renewable plants ST2 in section 7.2.3. In figure 7.30 for simplicity the electrical production of the cogeneration engine in the ST2 plant is exported to the grid. From the optimisation point of view, with the configuration implemented in MGEOS, the electrical production of the ST2 plant can be used to fulfil the users demand, for the ST4 plant requirements (compression chillers or pumping) or can be exported to the grid.

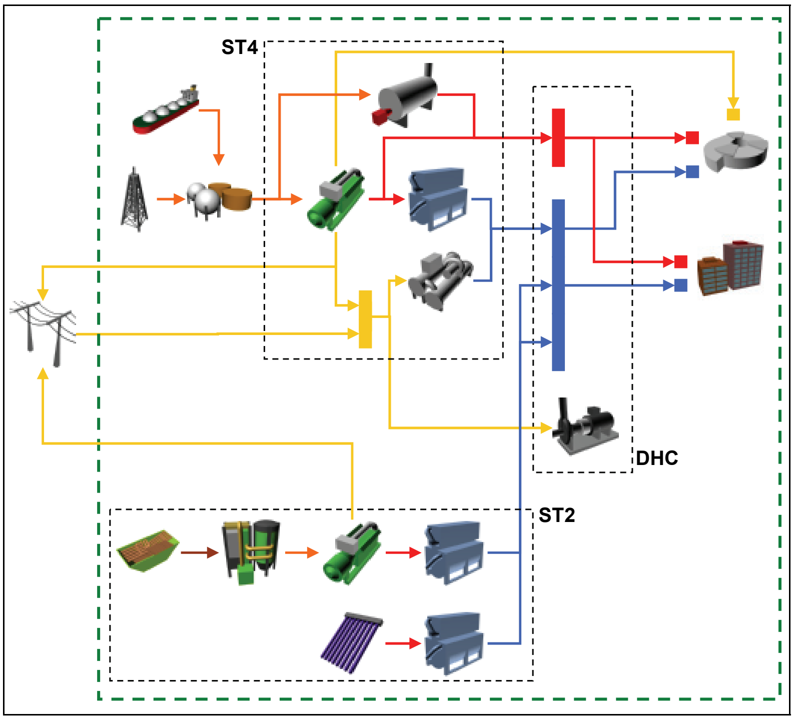
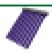


Figure 7.30 ST4+ST2 scenario configuration and boundary

Table 7.14 shows the main properties of the units included in the ST4+ST2 scenario. The national grid is considered as a combined cycle, like in the previous scenarios. The efficiencies of the natural gas cogeneration engines are calculated from the manufacturer data (figure 7.2) and the efficiencies of the synthesis gas cogeneration engines are calculated from the Lonjas technical reports. The efficiency of the gasificator is the average value obtained for the ENAMORA gasification plant (section 7.2.3). The COP of the chillers presented in the table are the expected values for this units (Lonjas).

Table 7.14 Parameters of the plant

	Import-Export Electricity	Combined cycle, overall efficiency = 49.8%
	ST4, Electricity and heating	Cogeneration engines η_{elec} = 45.0% $\eta_{hot\ water}$ = 23.5% $\eta_{exhaust\ gases}$ = 18.1%
	ST4, Cooling	SE Abs. Chillers COP = 0.75 DE Abs. Chillers COP = 1.3
	ST4, Cooling	Compression chillers COP = 5
	ST4, heating	Boiler, η = 90%
 	ST2, solar plant	Calculated with TRNSYS from previous studies (López et al 2007)
   	ST2, biomass plant	Biomass plant, consists of a gasifier, a cogeneration engine and an absorption chiller. $\eta_{gasifier}$ = 80% $\eta_{CHP,elec}$ = 36% $\eta_{hot\ water}$ = 24.4% $\eta_{exhaust\ gases}$ = 22.3% COP_{abs} = 1.0
	Pumping	As a function of the energy demand

The results of this scenario are presented in table 7.15. The main result is the reduction of the CO_2 equivalent emissions respect to the CONV and CONV+DHC scenarios. The SO_2 equivalent emissions are similar respect to the CONV scenario. It is important to note that the main gas that contributes to the SO_2 equivalent emissions is the NO_x. The result of the higher NO_x emissions of the internal combustion engines respect to the conventional system (using gas turbines in combined cycles) a similar SO_x equivalent emissions. The SO_x equivalent emissions in ST4+ST2 increases almost 10% respect to the CONV+DHC. Only the ST4+ST2 scenario has energy production from renewable sources, which represents around 5% and 8% for the total electrical and cooling production respectively. The total investment cost is around 31.4 M€ (the cost of the ST2 plant is around 6 M€). The expected payback period for all the system is quite high, between eight and ten years due to the high costs of the renewable plant ST2 compared to the production obtained from this plant.

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Table 7.15 Emission-economic results for the ST4+ST2 scenario for the analysed years

Year	CO_2 equivalent (ton/year)	SO_2 equivalent (ton/year)	Cash flow (€)
2010	19,164	27.0	2.1E+06
2011	17,776	29.9	2.6E+06
2012	18,833	31.1	2.8E+06
2013	20,248	35.0	4.0E+06
2014	22,960	38.2	4.2E+06

Table 7.16 Renewable sources results for the ST4+ST2 scenario for the analysed years

Year	Total Renewable capacity (kW)	Fraction of electrical renewable production (%)	Fraction of cooling renewable production (%)
2010	0	0	0
2011	2,930	8.1	15.0
2012	2,930	8.1	12.2
2013	2,930	5.6	10.4
2014	2,930	5.6	8.0

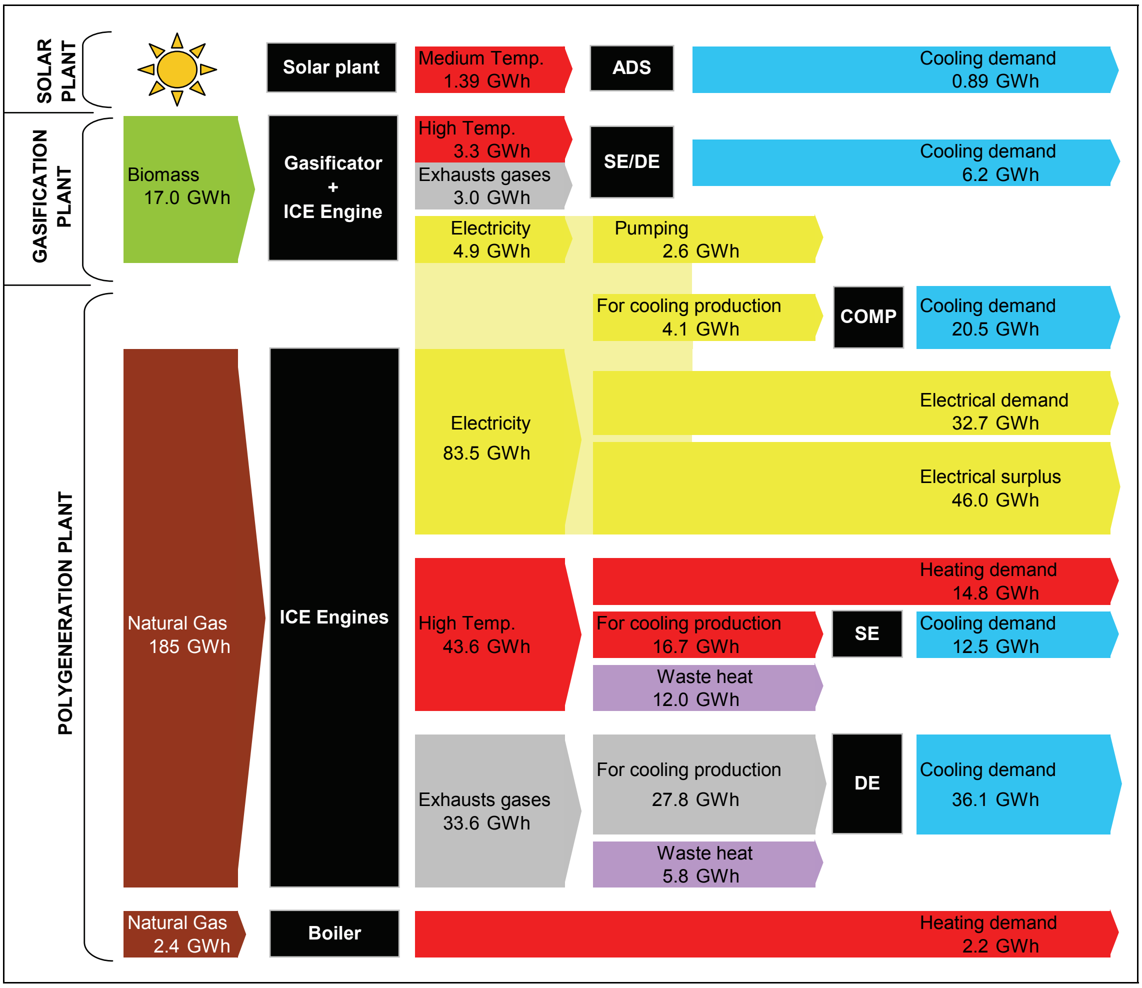


Figure 7.31 Global energy balances for the ST4+ST2 scenario in 2014

7.4.4 ST4 scenario

This scenario is the ST4+ST2 scenario but without the biomass gasification and the solar cooling plant. This is the currently configuration installed (at February 2010) with the expected expansions presented in section 7.2.2. The energy and operational costs are obtained from the Lonjas technical reports. Table 7.17 shows the main characteristics of the units included in this scenario, with the same properties respect to the ST4+ST2 scenario.

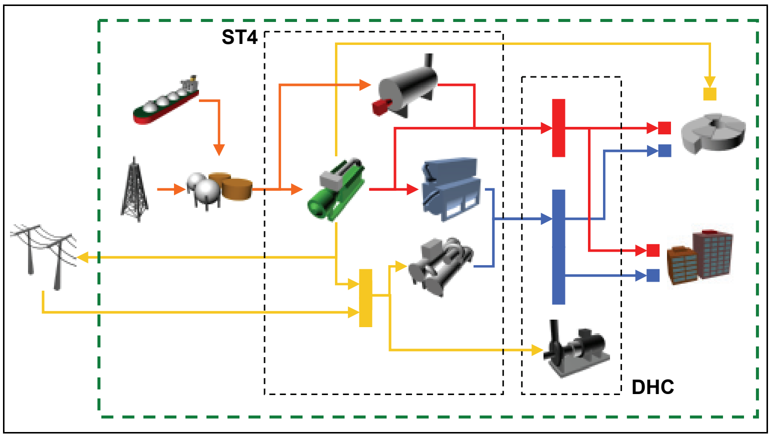
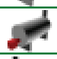
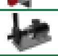


Figure 7.32 ST4 scenario configuration and boundary

Table 7.17 Parameters of the plant

	Import-Export Electricity	Combined cycle, overall efficiency = 49.8%
	ST4, Electricity and heating	Cogeneration engines η_{elec} = 45.0% $\eta_{hot\ water}$ = 23.5% $\eta_{exhaust\ gases}$ = 18.1%
	ST4, Cooling	SE Abs. Chillers COP = 0.75 DE Abs. Chillers COP = 1.3
	ST4, Cooling	Compression chillers COP = 5
	ST4, heating	Boiler, η = 90%
	Pumping	As a function of the energy demand

The main results are presented in table 7.18. In this scenario there is no energy production from renewable energy sources, only the results for contaminant emissions and cash flow are presented. The lower SO_2 equivalent emissions respect to the ST4+ST2 scenario is because there is one engine less (gasification plant). The CO_2 emissions in ST4 scenario are higher because in the ST4+ST2 scenario there are the electrical production of the gasification plant produced from renewable sources that is exported to the grid.

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Table 7.18 Main results for the ST4 scenario for the analysed years

Year	CO_2 equivalent (ton/year)	SO_2 equivalent (ton/year)	Cash flow (€)
2010	19,164	27.0	2.1E+06
2011	19,950	27.9	2.3E+06
2012	21,107	29.3	2.4E+06
2013	22,497	33.1	3.7E+06
2014	25,182	36.3	3.9E+06

Figure 7.33 shows the main energy balances for the year 2014. The yellow clear shaded area means that the electrical energy for the plant consumption and the compression chiller can belong to the imported electricity from the grid or to the electrical production of the cogeneration engines. Due to the fixed operation of the congeneration engines (section 7.2.2) the consumption of fossil primary energy is the same respect to the ST4+ST2 scenario. Regarding to the operation of the ST4 plant, the main difference respect to the ST4+ST2 plant is the higher cooling production with the compression chillers and the DE absorption chillers.

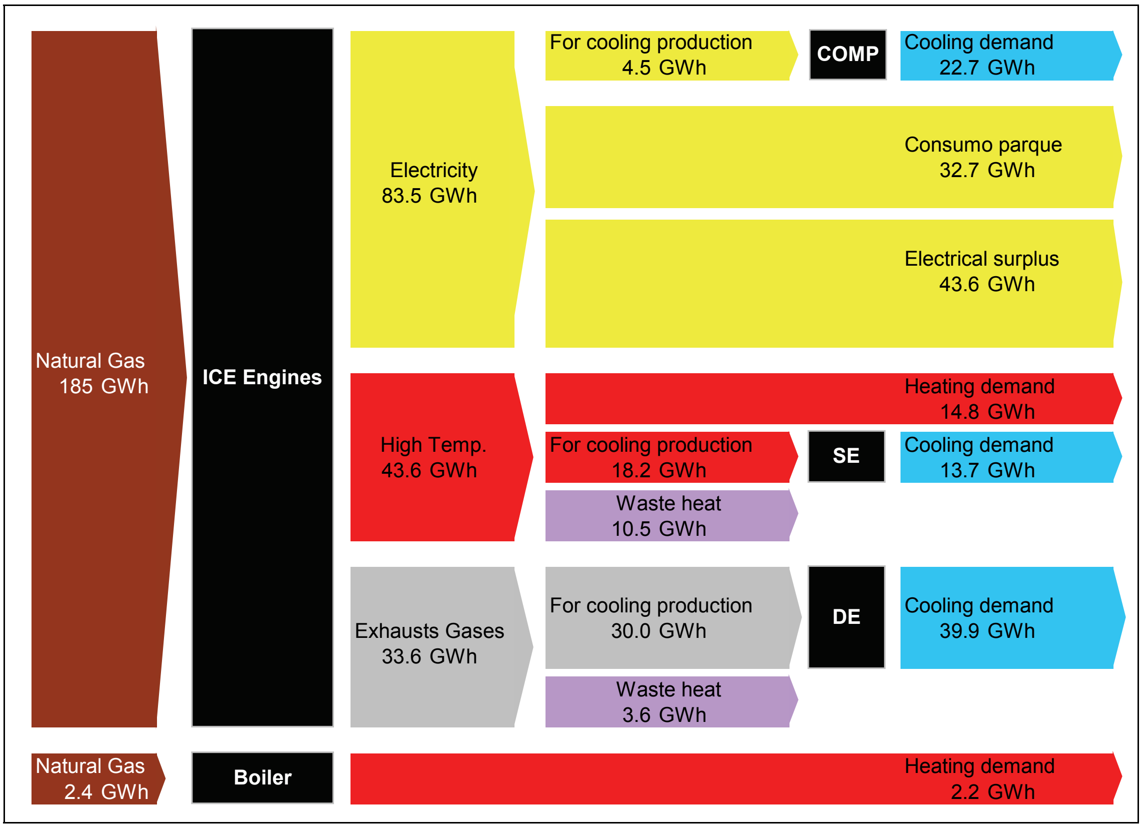

Figure 7.33 Global energy balances for the ST4 scenario in 2014

7.5 Scenario results

In this section the four scenarios are analysed using the results presented from section 7.4.1 to 7.4.4. All the information presented in tables 7.11, 7.13, 7.15, 7.18 for the year 2014 are summarised in the figure 7.34. Only the results for the year 2014 are analysed in this section because it is expected to be the year of full occupation of the park and the energy plants will be completed. The indicators described in section 7.4 are compared in figure 7.34. The meaning and the scale of each axis of the figure is presented below.

- CO_2 equivalent emissions, this axis range from 100% (scenario CONV) to the 50% of the maximum emissions value. Each division is a 5%.
- SO_2 equivalent emissions, this axis range from 100% (scenario CONV) to the 50% of the maximum emissions value. Each division is a 5%.
- % RES Capacity, total installed renewable capacity (electricity + cooling) respect the total installed capacity (electricity + cooling). 100% means all the installed capacity uses renewable sources. Each division is a 1%.
- % RES Elec., electrical production from renewable sources respect to the total electrical production. 100% means all the electrical energy is produced from renewable sources. Each division is a 1%.
- % RES Cool., cooling production from renewable sources respect to the total cooling production. 100% means all the cooling energy is produced from renewable sources. Each division is a 1%.
- Investment, total investment for each scenario, this axis ranges from 100% (31.4 M€ for the *ST4+ST2* scenario) to 0%. Each division is a 10%.
- Cash flow, this axis ranges from the maximum cash flow obtained for ST4+ST2 (3.7 M€) to 0%. Only for the CONV scenario the cash flow is not considered, because each user produces its own energy. For all the other cases, where the DHC is considered, an ESCO is expected to run the plant. Each division is a 10%.

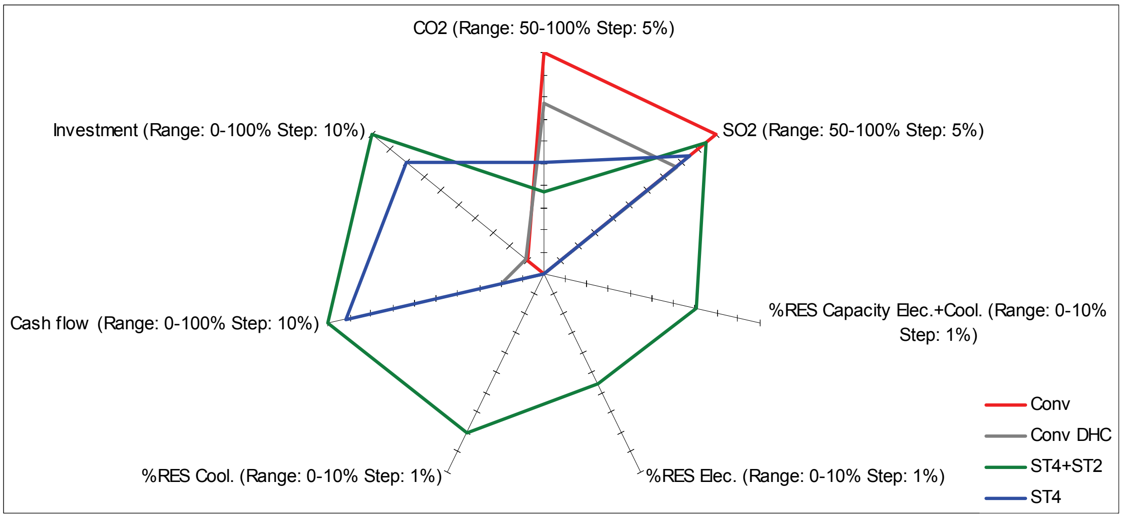

Figure 7.34 Comparison of the results for the analysed indicators for each scenario and year 2014

Only one scenario produces electricity and cooling from renewable sources (the heat from renewable sources is used to produce cooling). For the ST4+ST2 scenario the installed RES capacity is almost the 7 % of the total installed capacity. The renewable energy production is 6 % for electricity and 8 % for cooling. In spite of the low ratio of RES capacity installed, the reduction of CO_2 emissions respect the conventional case is considerable, even for the case without renewable (ST4). This reduction is achieved through the use of high efficiency cogenerators coupled with SE and DE absorption chillers. The reduction of CO_2 emissions for the ST4 scenario is 23 % respect the CONV case, for the ST4+ST2 the reduction is 30 %. A reduction of 11 % is also achieved for the CONV+DHC case due to the higher COP of the compression chillers.

The gases emissions with an acidification effect are represented using the SO_2 equivalent emissions. For the energy production systems analysed, the most important gas with more weight to calculate the SO_2 equivalent is the NO_x emissions. Between the technologies presented in section 7.3.4, the main difference are the higher NO_x emissions of the ICE cogenerators respect the reference system using a gas turbine in the combined cycle power plants. In general, the SO_2 equivalent emission of the ST4 and ST4+ST2 scenario are lower respect the CONV scenario, but higher respect the CONV+DHC. The higher SO_2 equivalent emissions of the ST4+ST2 respect the ST4 scenario is due to the addition of an engine in the biomass gasification plant. Although the gasification plant uses renewable energy resources, more NO_x is produced in the cogenerator. The lower SO_2 equivalent emissions are achieved in

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the CON+DHC scenario with a reduction of 11 % respect the most contaminant case (CONV). The reduction for the ST4 is 5.5 % and 1.0 % for the ST4+ST2 respect to the CONV scenario.

The investment cost is similar for the CONV and the CONV+DHC scenarios. The only difference is the addition of the DHC network. The increase in the investment cost of the ST4+ST2 respect the ST4 scenario is due to the addition of the solar cooling and the biomass gasification plant. The higher average cash flow is obtained for the ST4+ST2 due to the higher electrical production. The cash flow for the ST4 scenario is still high (7.4 % lower) but the investment is almost 20 % lower.

7.6 Conclusions

An scenario-analysis has been used to calculate the potential energy savings of the current ST4 plant in comparison with conventional strategies to supply electricity, heating and cooling. Scenario-analysis has been used also to asses the implications of installing a solar cooling plant and a gasification plant in addition to the current ST4 plant. The specifications from the technical reports have been used in the scenario-analysis because there is no monitoring data available.

The ST4 plant implies a significant reduction in primary energy consumption and CO_2 emissions (up to 24 %) respect to the conventional systems. The addition of the gasification plant increases the energy savings and the reduction of CO_2 (up to 31 %) but with a considerable increase of the investments costs (20 %). Due to the small size of the solar cooling plant compared with the ST4 plant capacity, the impact of the solar cooling plant are very small from the energetic point of view.

The results of the scenario-analysis show that the ST4 plant is an efficient way to reduce the primary energy consumption and CO_2 emissions. ST4 plant constitutes a good basis for an efficient and cleaner energy supply system. The addition of the ST2 plant has conflicting results: the energy savings and the economical benefits increase, but the increase of the investment costs are very significant compared with the production obtained from the ST2 plant.

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Chapter 8

Conclusions and future work

8.1 Conclusions

The optimal configuration and design of polygeneration technologies for residential and tertiary sector applications leads to complex models because of the high variability of the energy demand and the number of possible combinations when several technologies must be integrated to obtain high efficiency. The variability of the energy demand increases the number of time periods that must be considered, and the number of technologies that can define the polygeneration system increases the number of possible configurations. In the literature review, mathematical programming models are the most common technique for optimally configuring and designing polygeneration systems. Environments like GAMS or LINGO are commonly used to implement and solve optimisation models.

Binary variables are widely used in mathematical programming models and are necessary for unit selection, operational states (ON/OFF) and control purposes. The use of binary variables leads to mixed integer programming (MIP) and mixed integer non-linear programming (MINLP) optimisation problems, which are the most usual types of models found in the literature. MINLP models are more appropriate for detailed models, which have a lower number of time periods and possible configurations than MIP models. MIP models are more flexible than MINLP, although the level of detail that can be obtained with MIP models is lower than with MINLP models. In the literature most of the models for multiperiod operational optimisation are MIP.

For the design and optimisation of energy polygeneration systems MIP models are suitable when the following factors must be considered:

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- Economic viability
- Environmental evaluation
- Unit selection
- Operational optimisation
- Multiperiod
- Scenario analysis with long term optimisation
- High variability in the energy demand with hourly models that increase the number of time periods.

MIP models are less complex and have shorter resolution times than MINLP models so larger models can be implemented. This is useful in the first stages of a project when several configurations with different technologies must be evaluated and the optimal one selected. Although non-linear equations cannot be used in MIP models, binary variables can sometimes be used to discretise non linear functions into several linear sections. When material flows must be considered, the mass flow or the temperatures are usually fixed. For this reason MIP models are not the best option when a very detailed configuration is to be simulated (in these cases, simulation programs like TRNSYS, INSEL or EnergyPRO would be better options).

To maintain linearity the units have been modelled with binary variables when necessary so the technologies are characterized mainly with MIP models. The main units are cogeneration engines, gas turbines or absorption chillers and they can be modelled efficiently using linear relations with respect to the inputs (fuel consumption or temperatures). The manufacturer data has been used to perform the linear correlations for each unit and the agreement between the value predicted by the correlation and the manufacturer data is good.

One of the most important inputs of the optimisation models is the energy demand of the users. If no monitored data for energy consumption is available, engineering models can be used to calculate the energy demand from the definition of the building and the behaviour of the users. These tools calculate the energy demand for the whole year and cannot be used directly in the optimisation models because of the large number of time periods. The selection of typical days is a common practice that reduces the complexity of the model. Since user behaviour and meteorological conditions are often very similar for several days, several periods can be represented with only one day. From the economic and energy point of view, if the results obtained from the optimisation model for one typical day are multiplied by the number of days that this typical day represents, the results are very similar to when the whole year is included in the model. A comparison between the results of a model using the whole year and another model using typical days shows small differences that are no greater than the intrinsic uncertainty of the input data (e.g. energy prices, efficiencies or the energy demand itself). The methodology developed for selecting typical days is easy to apply but several days must be tested to ensure that they correctly represent the whole year. Meteorological data can also be included if this information is necessary for the optimisation models. Considering the results obtained from the optimisation cases, the method of selecting typical days is efficient because, in general, the results obtained are very similar to the results provided by the whole-year hourly demand. Furthermore, the method is robust, because the number of typical days selected has little influence on the results. The tool developed, TipDay, can be used to apply the methodology to any type of data.

The optimisation environment developed in this thesis is made up of two tools, GUME and MGEOS. GAMS is the calculation engine that solves the models. The principle of the environment developed is the modularity of the optimisation model for each type of unit or technology. This modularity facilitates the development, use and maintenance of the models. Each unit is developed and used irrespective of the other units that are already in existence. This modularity makes the environment very flexible and it can be used easily in different case studies to optimise not only economic and environmental factors, but also all the other variables of the model. All the units currently developed and the fact that custom equations can be added to the flowsheet facilitates the evaluation of very specific energy polygeneration plants. The environment is open so new units can be created or existing units modified to adapt the models to new cases.

Two cases of applications using the optimisation environment developed in this thesis have been presented. The first case is the evaluation of a polygeneration system using desiccant liquids that provide a classroom building with heating and cooling. The experimental data measured for the desiccant liquids were used to create a new unit to represent this type of process. The model developed for the desiccant units is in reasonable agreement with the experimental data and can be implemented easily in the optimisation environment. The conditions of the air at the output of the desiccant units are calculated using a correlation with the ambient temperature, humidity and temperature from the cooling tower. The environment developed is quite flexible: the existing units can be used or modified or new units created to represent particular energy supply systems, including the cogeneration engine, the desiccant units, the air handling unit and other auxiliary units.

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The results of the optimisation models show how important it is for the polygeneration system to be the right size and to work well to ensure the economic viability of the polygeneration system. Pay-back periods for the polygeneration system are reasonable only when the heating surplus of the cogeneration engine can be exported to a district heating network in order to increase the load and the number of working hours of the engine. When the polygeneration system works only to supply the heating and cooling demand of the classroom building, pay-back periods are long and some units, like the rotary wheel, compete with the cogeneration engine. Significant amounts of primary energy and CO_2 emissions are saved only when the polygeneration system can export the heating production.

In the second case the existing units have been used to perform a scenario analysis of a polygeneration plant in the framework of the PolyCity project. The conventional alternative for producing electricity, heating and cooling has been compared with the polygeneration system. The results for the complete polygeneration system show primary energy and CO_2 equivalent emissions savings of up to 30% with respect to the conventional system. In the case of the SO_2 equivalent emissions, the results are of the polygeneration and the conventional system are very similar because of the higher SO_2 emissions of the internal combustion engines.

8.2 Future work

For the future, two main future tasks can be identified: the validation of some of the models and the further development of the optimisation environment.

Some models that have been developed for some units have not been tested yet (e.g. the thermal and photovoltaic solar collectors). Moreover, other units that use renewable sources such as biomass or wind energy must be developed. Some monitoring data may become available in the coming months from the PolyCity project for the ST4 plant in Cerdanyola del Vallès. The monitored data will be used to validate the PolyCity case study and to improve the models already developed. As far as the polygeneration plant in Turin is concerned, some new monitored data about the operation of the whole system could be made available this summer. This data could be used to validate the correlations and models of the units presented in this thesis.

To develop the optimisation environment and complete the library units, some specific future tasks are listed below:

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- Continue with the development of units to complete the MGEOS library.
- Add plot capability to MGEOS so that the results obtained from MGEOS can be represented graphically.
- Test the thermal solar collector and the photovoltaic collectors to validate the models. Develop more units for renewable applications, such as biomass gasification or wind energy production.
- Make it possible for the user to define more than two time scales.
- Make it possible to use a specific unit to run multi-objective optimisation (like "Optimiser" for single-objective).
- Improve the methodology for selecting typical days by using the tool TipDay. Add an algorithm for the automatic selection of typical days.

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