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COMBINED HEAT AND POWER SYSTEM FOR THE POTASH MINING INDUSTRY AND WASTE HEAT USE FOR THE MUNICIPAL FACILITIES

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"Be master of your petty annoyances and conserve your energies for the big, worthwhile things. It isn't the mountain ahead that wears you out – it's the grain of sand in your shoe."

Robert Service

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Abstract

This master thesis presents a study which aimed to develop the best-suited and most sustainable Combined Heat and Power (CHP) system so as to provide the heat and electricity necessary in the extraction and processing of the potash deposits for a mining industry. It aimed also to make use of the waste heat (heat losses) resultant from the mineral processing of the current situation (natural gas boiler and electricity from the grid) in the warming of the close municipal facilities by a district heating, to be applied in the context of the potash mining industry in the center of Catalonia (Barcelona).

An energy simulation was developed, using the simulation tool *DesignBuilder*, with the goal of supplying the heat and domestic hot water demands by that energy losses. The results showed that the 10% of heating losses are sufficient to supply the proposed district heating for the eight municipal facilities considered.

On the other hand, a state of the art of some CHP technologies was made, and the matrix modeling methodology for cogeneration systems is presented. A comprehensive cogeneration system operation was implemented in *Matlab* © and using the Excel, and was carried out to develop the best topology design, in a number of eleven proposed systems (cases A to K), on the selection of a CHP system focusing on economic and environmental parameters (costs and carbon dioxide emissions).

The final results show that, in terms of environmental analysis, the cases D to J (Case D: PTC and Solar PV system; Case E: LFR and Solar PV system; Case F: Biomass combustion and Solar PV system, Case G: PTC and PTC with steam turbine, Case H: LFR and LFR with Steam turbine, Case I: PTC and Biomass combustion and Steam turbine and Case J: LFR and Biomass combustion with Steam turbine) are all advantageous because they have no CO_2 emissions. In terms of economic analysis the case D and G are the most advantageous. The case D has positive validation for energy costs and intermediate validation for the investment costs while case G has positive validation for both the energy and investment costs. An attempt to find the best cogeneration system in economic and environmental terms was made, allowing to suggest the case G, which seems to be the one that has the best results.

In conclusion, the final decision should be taken by *CTM* and, naturally, according to the interests of the mining industry where this project will be applied.

Keywords: Combined Heat and Power system, potash mining industry, heating losses, district heating, matrix modeling methodology for cogeneration systems.

Resumo

Esta dissertação apresenta um estudo cujo intuito é desenvolver o sistema de cogeração mais adequado e mais sustentável, de modo a fornecer o calor e eletricidade necessários na extração e processamento dos depósitos de sais de potássio de uma indústria mineira. Tem também como objetivo perspetivar o uso do calor residual (perdas de calor) resultante do processamento mineral do sistema atual (caldeira a gás natural e eletricidade da rede) no aquecimento das instalações municipais próximas, através de uma rede de calor, a ser aplicado no contexto da indústria mineira de sais de potássio no centro da Catalunha.

Foi desenvolvido um simulador energético, utilizando a ferramenta de simulação *DesignBuilder*, com o objetivo de se fornecer o calor e as necessidades de água quente sanitária através destas perdas de energia. Os resultados mostraram que os 10 % de perdas de calor são uma quantidade suficiente para fornecer o aquecimento proposto para as oito instalações municipais consideradas.

Por outro lado, foi efetuado um levantamento do estado da arte sobre algumas das tecnologias de cogeração, sendo apresentado também a metodologia de modelização de matrizes. Foi implementado em *Matlab* © e usando o Excel uma operação completa dos vários sistemas de cogeração considerados, de maneira a encontrar a melhor topologia, de entre onze sistemas propostos (casos A até K), para a escolha de um sistema de cogeração focando-se em parâmetros económicos e ambientais (custos e emissões de dióxido de carbono).
Os resultados finais mostram que, em termos de análise ambiental, os casos D a J (Caso D: PTC e Sistema solar fotovoltaico; Caso E: LFR e Sistema solar fotovoltaico; Case F: Combustão de biomassa e Sistema solar fotovoltaico, Caso G: PTC e PTC com Turbina de vapor, Caso H: LFR e LFR com Turbina de vapor, Caso I: PTC e Combustão de biomassa com Turbina de vapor e o Caso J: LFR e Combustão de biomassa com Turbina de vapor) são vantajosos porque não apresentam emissões de CO_2. Em termos de análise económica, os casos D e G são os mais favoráveis. O caso D apresenta uma validação positiva para os custos de energia e uma validação intermédia para os custos de investimento, ao passo que o caso G tem validação positiva quer para os custos de energia quer para os custos de investimento. Em termos gerais, numa tentativa de encontrar o melhor sistema de cogeração em termos económicos e ambientais, o caso G parece ser aquele que detém os melhores resultados.
Em suma, a decisão final deve ser realizada pelo *CTM* e, naturalmente, de acordo com os interesses da indústria mineira onde este projeto será aplicado.

Palavras-chave: Sistema de cogeração, indústria mineira de sais de potássio, perdas de calor, rede de calor, metodologia de modelização de matrizes para sistemas de cogeração.

Declaration

I declare that this thesis is original and it was developed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Signature: ____

Contents

Notations

Abbreviations and symbols that occur regularly in this thesis are listed below:

List of Abbreviations

CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
DWH	Domestic Hot Water
HFC	Heliostat Field Collector
HTF	Heat Transfer Fluid
HVAC	Heating, Ventilation and Air Conditioning
IRR	Internal Rate of Return
LFR	Linear Fresnel Reflector
LHV	Lower Heating Value
NPV	Net Present Value
OM	Operation and Maintenance
PDC	Parabolic Dish Collector
PTC	Parabolic Trough Collector
PV	Photovoltaic
SEGS	Solar Electric Generating System
kWh	Kilowatt-hour. It is the amount of electricity used in one hour at a rate of 1 000 watts.
MWh	Megawatt-hour. It is equal to one million watts-hour or one thousand kilowatts-hour.
GWh	Gigawatt-hour. It is equal to one billion watts-hour, one million kilowatts-hour, or one thousand megawatts-hour.
Nm^3	Normal cubic meter. In this context Normal means at standard temperature and pressure conditions.

Output_A refers to the output vector in the base situation (i.e., electricity network and heat from natural gas boiler) for the mining industry.

Input_A refers to the input vector in the base situation (i.e., electricity network and heat from natural gas boiler) for the mining industry.

List of Symbols

η_{th}	Thermal efficiency
η_e	Electrical efficiency
30	indicates a percentage of 30% of humidity
i	Refers to an Input
o	Refers to an Output
(6,1)	The position (line and column) related to the heat generation in the output vector.
(5,1)	The position (line and column) related to the electricity generation in the output vector.

Glossary

Atmospheric clarity index: degree of attenuation of irradiation across the atmosphere and therefore is a sign of the degree of cloudiness and presence of particles in the atmosphere (the more cloudiness or particles are present, the lower is the clarity index).

Biomass: refers to all organic matter of vegetable or animal source, including crops, crop wastes, trees, wood waste, animal waste and materials that result from their natural or artificial transformation.

Brayton cycle: the thermodynamic cycle converting heat and power into heat and power simultaneously using gas turbines.

CO_2 emission factor: indicates the carbon dioxide released per amount of transformed or burned energy. These factors are based on the carbon content of fuels or materials used.

Combined-cycle: combining two or more thermodynamic cycles in improved overall efficiencies. An example is combining a gas and steam turbine.

Combined Heat and Power: simultaneous generation of heat and power in a single process also named cogeneration. The power output is usually electricity, but may include mechanical power. Heat outputs can include steam, hot water or hot air for process heating, space heating or absorption chilling.

Concentrated Solar Power: technology using mirrors to concentrate the sun's light energy (direct irradiation) that convert it into heat and produce steam to drive a turbine that generates electrical power.

Diffuse irradiation: irradiance that has been scattered by atmospheric constituents due to diffraction scattering and reflection of gases and clouds; total irradiation is the sum of direct and diffuse irradiation and also the albedo irradiation that is an irradiation from nearby terrain reflection.

Direct irradiation: irradiance that reaches the earth's surface without being affected by scattering events, maintaining directionality; is of particular interest for concentrated solar power installations.

District heating: heat that is produced centrally and used to yield the hot water that is piped to the buildings.

Irradiation: the incident energy per unit area on a surface, found by integration of irradiance over an hour or a day.

Global irradiation: the total amount of shortwave radiation received from above by a surface horizontal to the ground. This value is of particular interest to photovoltaic installations and includes both direct irradiance and diffuse irradiance.

Energy hubs: The unit that provides the basic features of multiple energy carriers: input and output, conversion and storage, i.e., transmission and distribution systems with distributed energy resources.

Hybrid systems: when referring to systems that combine different sources including multiple forms of energy.

Natural Gas: mixture of light hydrocarbons, primarily methane (CH_4) and that is formed from decayed organic material, as with crude oil.

Non-hybrid systems: when referring to systems that use one source of energy resulting in the simultaneous production of two types of energy: heat and electricity (e.g. CHP systems).

Potash: commonly refers to potassium chloride and when referring to minerals or in geology, all the occurring potassium salts are called potash ores.

Primary energy: the energy that exists in all types of energy resources prior to any treatment.

Rankine cycle: the thermodynamic cycle transforming heat and power into power using steam turbines.

Secondary energy: the energy obtained from the primary energy after appropriate treatment.

Solar PV systems: the technology that captures sun’s energy (global irradiation) using photovoltaic cells that convert the energy into electricity.

Tables and Figures list

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1 Introduction

1.1 Research scope and goals

This master thesis focuses on making a study of the best-suited and most sustainable CHP (Combined Heat and Power) system so as to provide the heat and electricity necessary in the extraction and processing of the potash deposits for a mining industry and the proposal of the waste heat use of the heat losses for the municipal facilities. Important to note that this project is in the initial phase and as such it is necessary to define a concrete methodology because there are not yet enough and concrete data. Thus, the proposed methodology will be implemented from published data and approaches made with information gained from other mining industries equivalent to the mine of the case study. The potash mining industry partner in this project, located in the center of Catalonia, proposed to develop this project by reason of the current and the forecasted situation of the energy cost in Spain and the high electricity and heat consumption in the mining sector. This project has as major objectives the following:

- Definition of the energy demand for the complete potash deposits (from extraction to ore processing) for the mining process: electric power and heat quantification;
- Definition of the energy demand for the close municipal facilities: water systems and heating quantification, for the waste heat use from the heat losses, running therefore the software Design Builder© ;
- Evaluation of the available energy resources, considering fossil and renewable energy resources, that could be used for the proposed CHP system;
- Proposal of the best topology system design using economic and environmental criteria (costs and carbon dioxide emissions) implemented on *Matlab* © and on Excel.

1.2 Company's description

The company's name where this work has been developed is Fundació CTM Centre Tecnològic (from here on referred as CTM) and it's an existing corporation in the city of Manresa, in Spain (Catalonia).

1.2.1 History

The conception of CTM dates the year 1999 and the project came about as a result of the collaboration between a group of *Universitat Politècnica de Catalunya (UPC)* and *Consell Tecnològic del Bages (CTB)*. At the new millennium the new facilities were inaugurated in the center of Manresa campus, integrating all laboratories, research and service spaces. Finally, in December 2004 and respecting the exigency by Spanish legislation, CTM is recognized as a technologic center and in this way it becomes part of the existing system of technology centers in Catalonia.

1.2.2 Mission

CTM has the mission of creating knowledge and transfer technology to other companies and organizations in order to promote research and development for the improvement of competitiveness and for the technological development of such companies.

CTM desires to be a leader in technologies that are developed in the center and to be recognized in the scientific and industrial environment, with qualitative and quantitative dimensions.

1.2.3 Areas of work

CTM’s activity revolves around six areas of work: Materials Technology, which specializes in the research of the relation between the microstructures and the mechanical properties of materials. The area counts with numerous units and is qualified for carrying out many kinds of tests.

Another area is the Environmental Technology that works with the objective of improving the environmental quality and contributing to a more sustainable industrial and social development.

The area of Support to Innovation develops its activity in different fields that are considered crucial for those companies which wish to take a step forward and get ahead their competitors in what concerns innovation, environment and technical advice in management and training.

It is also worth mentioning the area of Simulation and Innovative Design that is specialized in numerical Simulation, both in engineering and in research.

The area of Processes is the one specialized in the development and research of industrial processes; the area of Processes works on the optimization of industrial processes and also with the objective of obtaining materials with improved characteristics.

Another area of work, and the last one of that list, is the Area of Energy of CTM that aims proposing and developing projects which should have the mission of improving the competitiveness of companies through the transfer of technology and knowledge in the field of energetic efficiency and renewable energies, this way making a record of their needs.

1.3 Work contribution

This project involves the Area of Energy in *CTM* and a mining industry company. In this project the development of a CHP system in order to be applied in the potash mining sector in Catalonia appears as a pioneer aspect in this type of industry; moreover, this project will be innovative in the proposal of using residual low temperature heat fluxes from the mining process in the close municipal facilities. The outcome of this work intends to bring an additional contribution to the existing general information in order to amplify the knowledge of the institution in processes of mining extraction and development and implementation of renewable energies. Moreover, the proposal of a methodology design for the mining sector related to the dimensioning and selection of the best suited cogeneration system will be essential for the knowledge in *CTM*.

1.4 Thesis outline

To perform the research objectives previously presented, a strategy was developed which comprises several research stages addressed in different chapters along this thesis, as described herein:

- Chapter 2: In order to present more detailed intrinsic information about the current project, it was created a chapter to present the Case Study. It is intended to give a quantified perspective of what the potash mining sector means to Spain today, including details of these minerals and where they are produced. It also contains the concrete scenario in the mining process, or either, the definition of the complete mining process from the extraction of the ore until its processing, and also the inputs and outputs of energy flows, including the heat demand characterization (for the analysis about the district heating for the close municipal facilities using *Designbuilder*). In this chapter it is also presented an evaluation about the availability and costs of the energy resources (fossil resources and renewable resources).

- Chapter 3: Based on a bibliographic review, this section is a State of the art that contains the description of some of the possible technologies that may be applied to provide the heat and electricity demands, including the description of the availability and costs of these technologies; it is also included the carbon dioxide (CO_2) emission factors for each case, and the data required to propose a CHP system. It is also presented the matrix model methodology for each technology considered.

- Chapter 4: In this chapter an overview is given about the topology design in order to evidence the methodology applied to obtain the best CHP system, presenting some possible energy systems to be implemented in the mining industry. Then the system modeling for the proposed approaches is shown, the operation being performed in *Matlab © software* and Excel; after that comes the economic and environmental analysis and then the main results obtained. Finally it's provided a critical analysis of the results in the section of the discussion and evaluation of the results.

- Chapter 5: The main conclusions reached during the thesis are presented, by summarizing and discussing the most important achievements.

- Chapter 6: After the work produced there is a short chapter where an appreciation of the work done is made, the limitations and suggestion for possible future work and it is presented a final appreciation about the work produced in this master thesis.

This thesis also contains five appendixes, which are meant to present in some detail the study and revision carried out about the Simulation and Design for the District Heating (Appendix I), the concepts of solar irradiation (Appendix II), the *Matlab* © code for the heat generation and electricity generation (Appendix III), the investment project concepts (NPV, IRR and Payback period) (Appendix IV) and the Carbon Dioxide emissions calculation (Appendix V).

2 Presentation of the Case Study

2.1 Potash and salt deposits in the mining industry in Spain

Firstly, it should be noted that potash and salt deposits consist in a combination of several minerals that were shaped by the evaporation of seawater and their composition is often affected by secondary changes in the primary mineral deposits. Nowadays, more than forty salt minerals are known, which contain some or all of the small number of cations like sodium (Na^{+}); potassium (K^{+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}); the anions chloride (Cl^{-}), and sulphate (SO_4^{2-}); and sporadically iron (Fe^{2+}) and borate (BO_3^{3-}), as well. Under these circumstances the most important salt minerals are halite, anhydrite, sylvite, carnallite, kieserite, polyhalite, langbeinite, kainite and gypsum that occur at the edges of salt deposits and in the overlying strata (Ullmann, 1931).

The Spain mining industry is known to be an industrial activity that, like others, involves the selective extraction by applying mining techniques and making use of explosive substances and minerals in the crust of the earth, in order to be economically profitable. In general, the term includes extracting, in addition to surface and underground operations, which occur in the processing of minerals extracted. Potash deposits in mining industry are a significant sector of exploitation, development and production in Spain; in *Table 2.1* can be seen the production evolution of these components for the period 2007 - 2011.

***Table 2.1**: Salt and potash production in Spain (units in tons). Source: adapted from (Instituto Geológico y Minero de España, 2011).*

Years	2007	2008	2009	2010	2011
Salt Mining (t)	2,454,345	2,490,638	2,102,207	2,343,952	2,480,990
Potash Mining (t)	225,493	419,269	660,874	771,988	615,393
Total (Rock Salt) (t)	2,709,545	2,910,267	2,763,081	3,115,940	3,096,383
Marine Salt (t)	1,332,360	1,290,672	1,338,789	1,242,178	1,314,529
Spring Salt (t)	102,524	102,149	99,853	91,644	92,860
Total (t)	4,144,429	4,303,088	4,201,723	4,451,302	4,503,772

Salt production endured an increase in the transition of 2007 to 2008, however in 2009 it was noted a decrease in its production and after increased again in 2010. The production of potash grew up constantly until 2010 but in 2011 it was observed a decrease in more than 150 tons. In overall terms, the salt and potash experienced increases and decreases along the recent years while in 2010 there was the peak of production with an output of 3,115,940 tons.

Potash salt discovery in deposits in Catalonia, northeast corner of Spain, appeared in print in 1913 with the publication of the first of two reports on the subject by engineers of the *Instituto Geológico de España*. There had been much discussion about the salt deposits of the region, which had long attracted attention due to the very remarkable features; the potash associated with these salt deposits was recognized in 1912 and only by accident as a result of development to enlarge the production of salt (Gale, 1921). The beginning of the potash mining industry in Spain was in Catalonia, in the 20th century with the establishment of underground workings firstly in Súria in 1920, 1931 in Cardona, 1932 in Sallent and in 1948 in Balsareny (all in the province of Barcelona). Later it was also undertaken work in Navarra: 1960 in Beriaín and 1986 in Olaz-Subiza in old fields Eocene-Oligocene depression located in Pamplona, without production since many years ago (Instituto Geológico y Minero de España, 2011; Colom, 2008). This industry provides many of the essential raw materials in our modern society, so the difficulties in providing basic raw minerals may affect the operation of the industrial activity. Recently, as a result of the strong global economic growth, the demand for mineral raw materials increased significantly enhancing the strategic importance of mining activity (Ministerio de industria, Energía y Turismo, 2011).

Nowadays, the only Spanish potash field lies in the north to northwest of Barcelona, in an area extending approximately from east to west between the towns of Vic and Balaguer. The area thus defined is about 120 km long, and the claims or concessions, though of irregular shape, form a practically continuous belt with a maximum width between Manresa and Cardona of about 24 to 29 km (International mining, 2012; Gale, 1921).

Concretely, the mining sector has significant economic, environmental, and social implications in the countries where it’s practiced, as well as globally, and despite of the intense restructuring process caused mostly by the economic crisis that began in 2008, the mining sector in 2011 had an income of 6,000 million euros and it was responsible for 4.4% of the gross value added of the industry in Spain. On the year 2006, the energy consumed amounted to 4,539 MWh of electric power in own production; 207,831 MWh of electric power acquired, 49,144 liters of diesel oil, 880 tons of fuel-oil, 117,399 MWh of natural gas and 149,868 euros in other outlets, e.g. gasoline (Sánchez, C. V., 2011). All these consumptions are represented in the *Table 2.2*.

Table 2.2: *Energy resources consumption in 2006 for the mining sector in Catalonia. Source: adapted from* (Sánchez, C. V., 2011).

Years	Energy products	Industrial minerals	Ornamental rocks	Quarry products	Total
Production power (MWh)	0	780	0	3,759	4,539
Acquired power (MWh)	7,723	100,601	3,040	96,467	207,831
Diesel oil (L)	2,676	3,431	2,862	40,175	49,144
Fuel-oil (t)	0	0	0	880	880
Natural gas (MWh)	148	117,251	0	0	117,399
Other consumption (€)	12,657	109,660	2,417	25,134	149,868

2.2 Complete mining industry process in Súria

Subsequently it will be presented concepts relating to the mining exploration (mineral extraction to mineral processing), which is located at Súria (Catalonia) consisting of Cabanasses mine as shown in *Figure 2.1*.

Figure 2.1: *The territory comprising Geological and Mining park of central Catalonia where is situated Súria. Source: adapted from (Climent et al., 2011).*

The current Cabanasses mine began the operations in 1960 (International mining, 2012) and the mined deposits is a sylvinite ore: essentially a mixture of sylvite (KCl), halite (NaCl) with inclusion of insoluble matter and minor compounds which occur together in the mine. Knowing that industry mining in Súria contains more than 27% of KCl (International mining, 2012) and according to the observed data searched in the economic assessment report for a potash industry mining in the Afar State, in Ethiopia; the sylvinite mineralized material contains an average mineralogical composition as, approximately, by 31% of sylvite, 52% of halite, and 17% of minor compounds and insoluble matter (12% of minor compounds and 5% of insolubles); so it will be followed the same percentages for this study.

In the Suria's mine KCl is the unique element tapped and it is employed as a fertilizer for plants. NaCl is not used yet in the market of human consumption because it does not contain satisfactory purity levels in order to be applied but the impure sodium salt from the flotation rejects is sold to the chlor-alkali industry as well as for road de-icing (International mining, 2012).

2.2.1 Mineral extraction and handling

The extraction of industrial minerals is the first stage and employs both surface and underground mining techniques and the method selected depends of a variety of factors, including the nature and location of the deposit and the size, depth and grade of the deposit. The mining method used in Súria is the Conventional Underground Mining and it's the most common mining method for the extraction of potash ore (United Nations Environment Programme, 2001), it requires more energy than surface mining due to greater requirements for hauling, ventilation, and other operations (BCS Incorporated, 2007; Hartman & Mutmansky, 2002).

The mine in Súria has at least two shafts as shown in *Figure 2.2*: a service shaft that transports workers and materials and a production shaft for hoisting potash ore, the latter being a shaft with a 30 tons skip, running at up to 16 meters per second, allowing a potential production rate of 10,000 tons per day (International mining, 2012).

Figure 2.2*: Shafts of the extraction process followed in Súria. Source: (Colom, 2008).*

Data of 2012 shows that Cabanasses extraction averages 6,000 – 6,500 tons per day of silvinite but new development underground, together with an advanced continuous mining system, will allow this figure to increase to over 7,000 tons per day in the coming years. Potash is mined using massive mining machines that weigh approximately 200 tons and cutting at high rates. These machines produce material suitable for transport by conveyor belt, enabling continuous extraction in 30 – 60 meters sections. Also, two or three drum shearers and these machines are enable daily outputs between 1,500 and 4,000 tons to be achieved.
The fleet at Súria is formed of 30 tons trucks that include 8 Atlas Copco Minetruck MT436Bs as well as additional six GHH Fahrzeuge trucks, both of which are loaded by a fleet of seven Sandvik electric roadheaders – four newer machines delivered as MR520s and three older machines with the previous AM85 model name. Both the truck models have ejector bodies for more efficient unloading (International mining, 2012).

The main hoist level is at 680 meters from surface with the main production level at 800 m and the main workshop at 834 meters, with the main development level at 900 meters. The production areas are located just above the main ramps in the potash rich zones; with the development area in the salt below. The underground 30 tones trucks empty potash ore into vertical ore passes that feed temporary stockpiles known as under which are located chain conveyors similar to those used in the coal industry. The ore is conveyed a short distance to a feeder breaker that feeds a suspended conveyor positioned perpendicular to it. There are two main conveyors that go directly to the hoist and skip via two main ramps connecting the production and hoisting levels. One of these carries intake air and the other return air and the two ramp areas are separated by ventilation doors (International mining, 2012). Important to note these machinery works mainly with the use of diesel and gasoline fossil resources.

The mined ore is sent to the conveyor and it belts carry ore to underground bins, where is stored until being transported to the loading pocket of the shaft hoist. Then, the mined ore is brought to the surface to be milled (PotashCorp, 2013).

2.2.2 Mineral processing

The main objective of the downstream process is to physically liberate the potash and salt compounds. Once ore is extracted, the Súria mining fundamentally follows the next milling process at the surface as described below.

2.2.2.1 Crushing and grinding

First of all, before the minerals can be separated and the useful components recovered, the ore must be sufficiently reduced in size so that individual components are accessible to the processing method to be used. Thus, sylvinite ore hoisted from the mine is crushed into small pieces (150 mm), which release the crystals of potash and salt in the ore, and are transported to large sylvinite covered storage areas. Clay particles are separated from the crystals using agitation machines. The clay particles are much smaller than the potash and salt crystals and are removed using size separators. Before flotation it undergoes secondary crushing to 10 mm and then are ground to 1.5 mm and treated to remove waste clays (PotashCorp, 2013); (International mining, 2012). Crushing and grinding plants are powered by electric motors.

2.2.2.2 Flotation

Flotation is the most widely used technique after crushing, relying on the difference in surface properties between minerals to selectively float the desired one (United Nations Environment Programme, 2001). Then, using conventional flotation and constant oversaturation of the water with the mineral salts, the potash is separated from the salt, i.e., achieving the potash buoyancy does not require xanthate as it is not a sulphide, and is instead achieved by adding pine oil or guar gum, which makes the potash hydrophobic. These reagents enable potash to attach to fine air bubbles that are introduced into the bottom of flotation machines. The potash particles adhere to the air bubbles and rise to the surface for collection while the salt remains on the bottom, where it is discarded (PotashCorp, 2013); (International mining, 2012). It is important to refer that this step has very low electricity consumption when compared to the other processes involved in the production of potash, so it was despised the energy involved in the flotation.

2.2.2.3 Drying and Sizing

Drying is an extremely energy intensive operation where potash particles and brine are transferred to centrifuges (similar to a washing machine spin cycle), which separates potash from the brine. The potash is moved to the dryer and the temperature of gases supplied to the dryer may vary gradually from about 170 ºC to 260 ˚C (Lizarraga & Aguado, 1995), resulting in an average of 215 ºC. The foam is dried using natural gas fuelled fluid bed dryer (*Figure 2.3*) where is included a cylindrical vessel with an air distribution plate in its lower portion to form a plenum below the plate and bed zones above the plate. Hot air from a heater passes through the plate and enters the bed and wet feed is added through the side of the vessel at the top of the bed or through the top of the unit.

Dry product either overflows from the top of the bed or is discharged through an underflow at the level of the distribution plate. The dryer exhaust gases temperature is 120 ºC (Department of Energy & Climate Change, 2000) and it contains entrained fines as it passes through the expanded freeboard zone, which is followed by a cyclone and baghouse for particulate material removal (Mular et al., 2002). Thus, the final product is 95% KCl and 99% of its production is directed to the manufacture of potassium fertilizer (Colom, 2008).

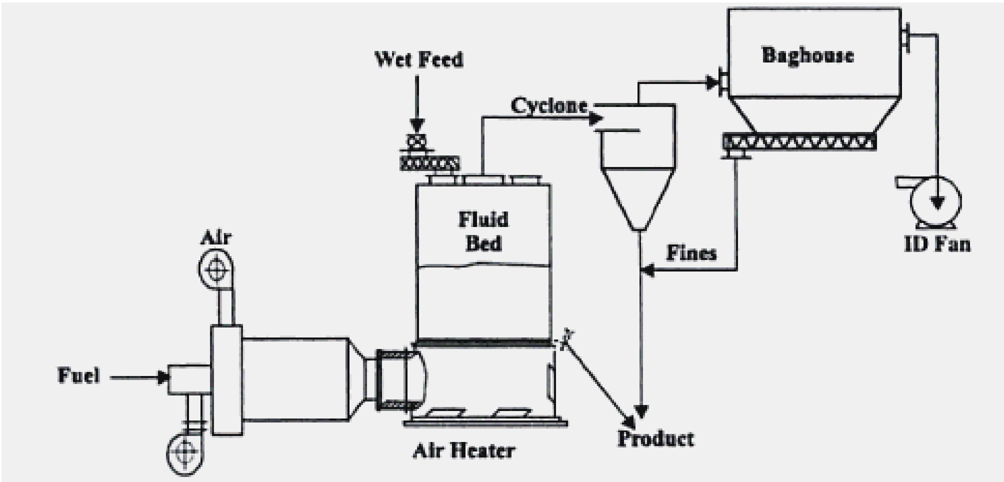


Figure 2.3: *Fluid bed dryer system. Source: (Mular et al., 2002).*

The resulting dry mixture contains various sizes that are separated by huge mesh screens into the standard potash that has a grain size of 0 - 1.5 mm and granular potash 2 - 4 mm (PotashCorp, 2013); (International mining, 2012). It is important to note that heat losses from dryer body are typically 5-10% but can be greater if the dryer is poorly insulated or of small capacity when it exists a higher surface-to-volume ratio (Tsotsas & Mujumdar, 2012).

2.3 Energy flows

Energy requirements in the mining industry are dictated by the concern to excavate, break down, transfer and sort materials. Some of the mass flows in a mine site are continuous and others are batch processed. In a mine site it is necessary to increase an effective understanding of the overall mining energy use. The energy flows will depend of the type of mining operations that are conducted at the site while the quantity of material that must be extracted, transported, processed, and disposed is the key factor impacting energy consumption for each commodity. It is also necessary to know how much energy is being used, wasted or lost and where this occurs, whether the systems and equipment are operating according to design and work schedules, as well as energy use variability and its underlying causes, if useable waste heat is being produced or processes could be alternatively powered and the efficiency of energy-using processes within the business. Energy use in mining operations is influenced by a number of factors, many of which also affect productivity (Department of Resources, Energy and Tourism, 2010).

2.3.1 Energy consumption by potash deposits: extraction and production

Firstly it is noted that the processing plant at Súria has a capacity of 580,000 tons/y of KCl (International mining, 2012). In terms of total electricity consumption, for the period 2003-2012, the mining industry in Súria presents the data range from as low as 128.0 kWh/ton to as high as 224.0 kWh/ton, resulting an average of 168.0 kWh/ton, as shown in *Figure 2.4*.

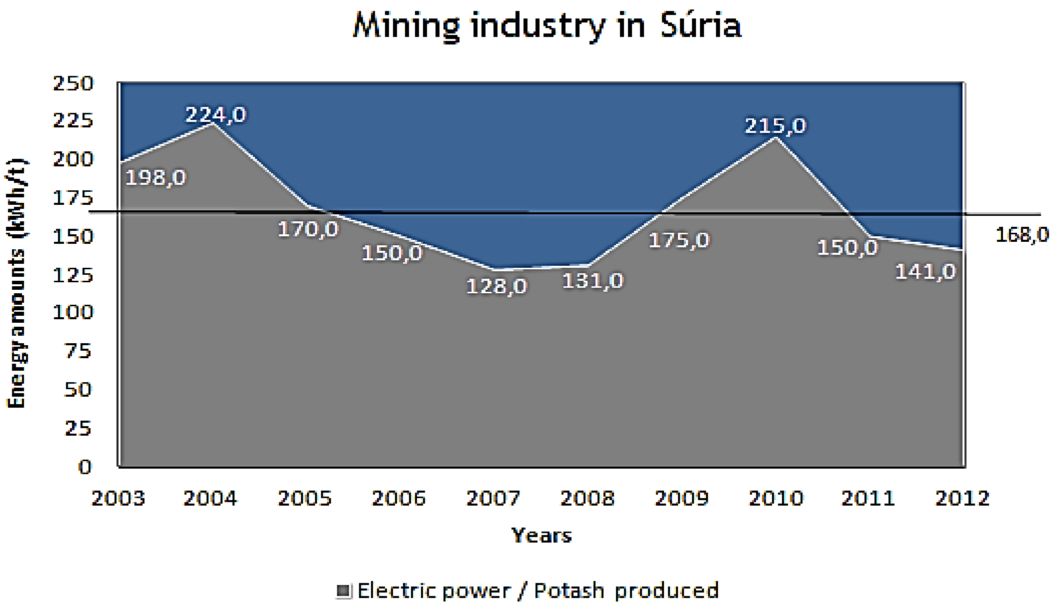


***Figure 2.4**: Consumed energy per ton (kWh/t) of potash produced in mining industry in Súria for the period 2003-2012. Source: adapted from (Iberpotash comunicació, 2013).*

On the other hand the mine in Súria not only consumes electricity but also hydrocarbon fuels (natural gas, diesel and gasoline) and then became necessary to obtain these data, since it was not provided. Thus, then an approximation was made from data obtained from Canadian potash operations for the years 2000 and 2001. The report was made counting eleven potash production facilities in Canada and of the eleven potash mines, nine are conventional underground mining operations, as the mining industry in Súria, which means that there is underground equipment and personnel. Important to note once it comes to processing the ore from the nine conventional mines, eight of the operations were using a conventional mechanical/flotation process and the other one was using a thermal leaching process, which is more energy intensive. So, the total natural gas, diesel and gasoline consumption for the eight conventional potash Canadian mines resulted in an average of 364 kWh/t. Of this amount, 120.0 kWh/t corresponds to total electricity consumption, 242.0 kWh/t to total natural gas consumption and 2 kWh/t to diesel and gasoline. It appears that 32.97% is the percentage of electricity consumption in the overall energy income, 66.48% is the percentage of natural gas and 0.55% is for diesel and gasoline. Therefore, with these data it was estimated the inputs for the mining industry in Súria. Providing that 32.97 % would be the slice to the total corresponding to electricity consumption, and knowing that average electricity supplied corresponds to 168 kWh/t (Figure 2.4), then it is promptly established that the total energy consumption amounted to 509.55 kWh/t. Now, with the aid total energy consumption it was obtained the total natural gas consumption (in a percentage of 66.48 %) and the total diesel/gasoline consumption (in a percentage of 0.55%), resulting in 338.8 kWh/t and 2.8 kWh/t, respectively. In *Figure 2.5* it is provided an overview of the energy consumption with energy use by type.

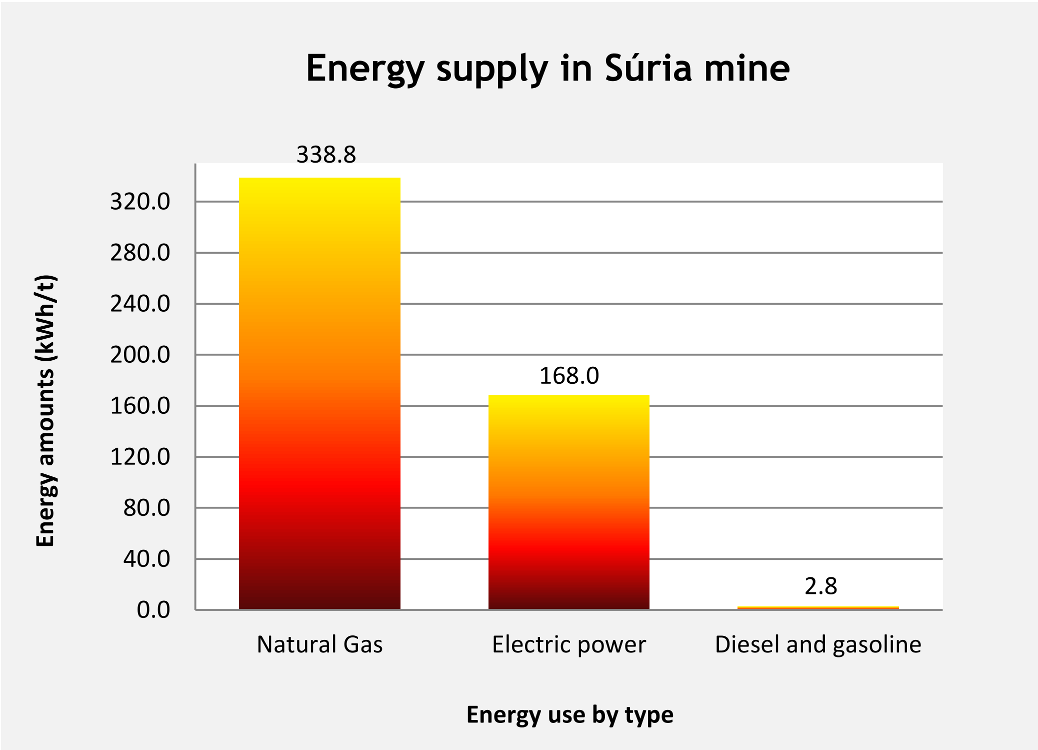


Figure 2.5: *Energy consumption in the mining industry in Súria by type of energy.*

The data obtained provide an overview of the state of energy intensity for the mining and mineral process in Súria; it may be noted that though the analogy made between the mines in Canada and the mine in Súria it's possible to mention that there are some factors that control the energy intensity of each operation that haven't been taken into account, and no correction was done about following issues: age of plant and equipment types or equipment design within each operation requires for the dewatering underground, distance to activate mining specific operational requirements (i.e., placing mine tailings underground) and about the level of production (i.e., no provisions were made for shutdowns or production cutbacks).

It is essential to recognize which energy is used in the process and characterize the waste energy able to use in the municipal facilities near the mining industry. In that way, with the values of natural gas, electric power and gasoline and diesel consumption, it is possible to obtain the energy and power values. Due to the absence of data it was considered that the capacity of potassium as the annual production resulting in 580,000 tons per year of KCl, which also corresponds to the maximum energy consumption at the plant. Moreover, the operations were developed taking as hypothesis a continuous mining process (i.e., 24 hours per day and 365 days per year). At this point, a presentation of the energy and power values is described in *Table 2.3* in order to elucidate the consumption by type of energy in the mining industry under study.

Table 2.3: *Energy and power values of consumption by type of energy.*

Type of energy	Energy values			Power values
	kWh/y	GJ/y	GJ/h	MW
Electricity	97,440,000	350,784	40	11.1
Natural Gas	196,504,000	707,414	81	22.4
Diesel and gasoline	1,624,000	5,846	0.7	0.18

In the previous table it can be observed that the natural gas exemplifies the major energy and power values which exceed, by more than the double, the values of electricity; on the other hand the diesel and gasoline consumptions are tiny when compared to those obtained for the natural gas and electricity.

Thus, to identify and analyze the impacts of factors in the energy consumption and how these factors interact, a schematic diagram releasing the inputs and outputs is presented below (Figure 2.6). As a first step, it is advisable to map out the mining operations so as to identify the key factors that will impact on energy use. This mapping is a brainstorming process that helps to identify how operational factors, external influences and site characteristics interact and contribute to energy use. Mapping these influences will establish which data need to be collected and may indicate which energy-using systems at the site have the strongest interactions. Having mapped out the various factors that influence energy use, it was assumed that high losses arise from flue gas in the dryer and it was considered the worst scenario of 10 % of heat losses (CTM, 2013) resulting in 70,741 gigajoules per year of heat energy losses.

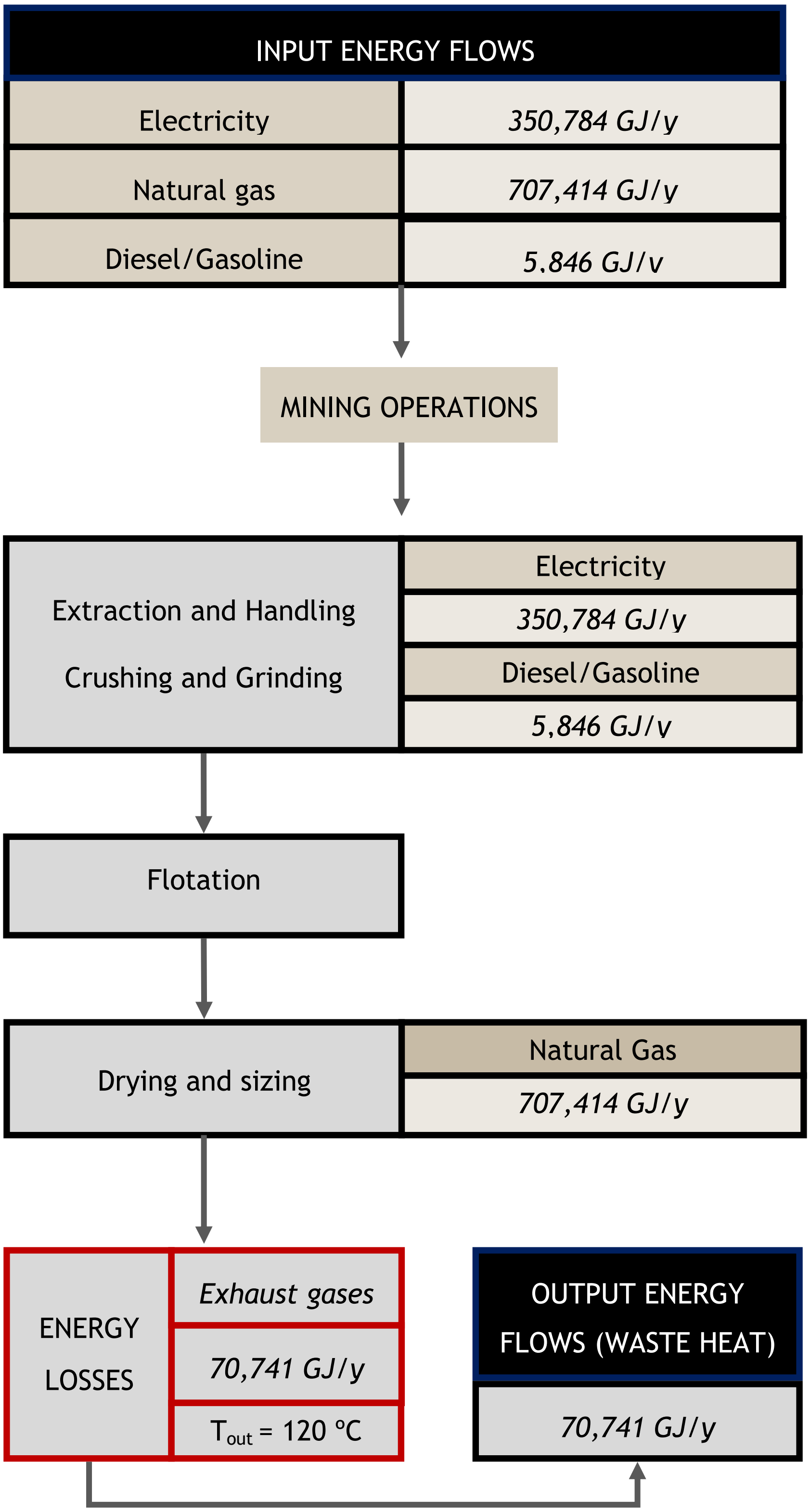


Figure 2.6: *Map of energy flow with input and outputs of energy consumption for potash mining industry in Súria.*

In this diagram (*Figure 2.6*) is realized that the inputs energy flows in the mining industry for potash are electricity, natural gas and diesel/gasoline and the obtained outputs are waste heat fluxes mainly exhaust gases from the dryer. The electricity and diesel/gasoline inputs are measured only for mining operations of extraction, handling, crushing and grinding because it characterizes the high consumption operations of this inputs. The input natural gas only has been considered in the mining operation of drying and sizing since the dryer has the highest demand in order to dry the potash brine. Finally, the energy losses shown result from exhaust gases from the dryer.

2.4 Municipal facilities: Demand characterization

This project also aims to evaluate the thermal energy for heating and DWH (Domestic Hot Water) in order to apply in the surrounding municipal facilities so as to achieve improvements in the energy utilization, reducing their energy input by the use of residual low temperature heat fluxes (from the mining process). At this point, with the heat losses quantified in the previous section it was thought that it would be required to make a study of the energy necessary to supply the demands of heat and DWH through a District Heating (DH). The DH means the heat that is produced centrally and the hot water that is piped to the buildings. It results in the potential to improve the efficiency of energy use, particularly where heat production involves CHP systems or waste heat from existing power stations. It also has the flexibility to accommodate heat from a diversity of sources, such as biomass. The use of the heat losses can be accomplished through a reuse cycle in which heat from exhausted gases is recovered by a device where the fluid is heated and then through an evaporator, a heat exchanger is located in the system and hence the exhausted gases from flowing into the device and deliver heat to the fluid to be heated. Typically a DH network consists in three elements:

a) Local networks: consisting of heat mains in each street, probably buried beneath the road surface in most streets together with connecting pipes into each building;
b) District networks: which link the supply points of the local mains and which may also serve larger buildings only;
c) Transmission networks: which link the district networks to a more remote energy source and frequently operate at higher pressures and temperatures.

DH is one of several heat technologies that may supply heat to domestic and commercial buildings. The heat distribution network consists of a pair of pipes, one carrying the flowing water at temperatures of 90 ºC-120 ºC and one the return water after the heat has been extracted at temperatures of 40 ºC-70 ºC. The heat is transferred to conventional heating systems within the buildings either directly or indirectly through a heat exchanger which provides a separation of the two water based systems; these heat exchanger substations may be at an individual dwelling level or a block of street level or an area level. The development of the pipe systems for this market normally includes an internal carrier pipe of steel, cross-linked polyethylene or polybutylene, an insulation of polyurethane foam or foamed polyethylene and an external casing of high density polyethylene (Davies & Woods, 2009). So, here is presented a study that pretends to model and simulate the heat energy consumption for the municipal facilities that could be provided by a DH system using the simulation tool *DesignBuilder* associated to the *EnergyPlus* software. *DesignBuilder* is a graphical interface for the simulation *EnergyPlus*, making this software easier to use and enabling to simulate various alternatives of improvement about energy in existing buildings without any intervention in the buildings. This methodology has been gaining strength since there are scanning tools, that allow the simulation of real situations and obtaining respective study data with great approximation; moreover, it allows for 3D modeling, with no limitations on the complex geometries. *Designbuilder* has pre-defined libraries that allow a simple way to choose a weather database by simply selecting a region, type of construction materials and further activities and use systems. It is important to note that the profiles are developed based on the building occupancy defined according to the active schedule of each building. The software also has the functionality to create templates on the issues discussed previously in order to extrapolate them to other situations that have similar functions (Cúmano, 2009).

The municipal facilities measured are composed by eight buildings as shown in *Table 2.4*.

Table 2.4: *Municipal facilities with their surface area and use of each.*

Building	Name	Surface area (m^2)	Use
A	Col.legi Dominiques	1,768.3	Primary school of a religious congregation
B	C.E.Súria	299.8	Sportive center to play football
C	C.E.I.P Francesc Macià	518.6	Public primary school
D	Casal d'Avis	384.2	Care home to old people
E	Llar d'infants	638.4	Children garden
F	Ajuntament	1,116.3	Town hall
G	Escola de Música	998.2	School music
H	Centre d'Atenció Primària	1,672.2	Medical Center

Next is outlined the map of the close municipal facilities considered in this case study and where the action may be applied (*Figure 2.7*). Note that a DH has a maximum distance from the heat generation point to the heat receiving areas; according to the consulted bibliography (Institut Català de d'Energia, 2010) the radius recommended for the DH zone is 500 meters in order to have a comfortable zone to develop the heat distribution in terms of economical and heat losses. However, this current study focused in the 650 meters distance as the study zone and one of the eight municipal facilities is located close to that distance. Note that for distances equal or higher than 500 meters have been leading for a higher demand power system because of the stability with heat losses that could occur.

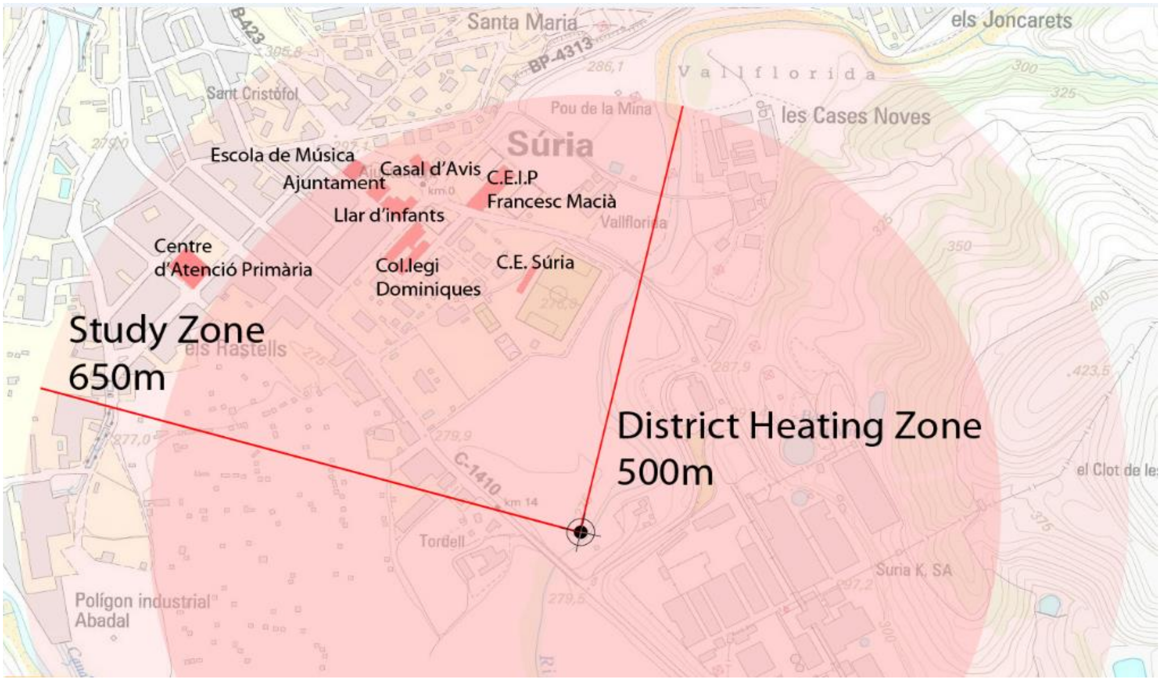


***Figure 2.7**: Municipal facilities around the mining industry in Súria with the study zone (650 meters) and district heating zone (500 m).*

In order to carry out this research, several steps had to be taken to come up with valid results on the influence that the district heating (heating and water systems) has on the overall energy demand for each building. The first step of modeling was a physical description of the building system when it was discovered the dimensions of each one with the support of *Google maps*; after, with the support of *DesignBuilder,* it was made the layout for each municipal facility giving that Barcelona Airport was the geographical location chosen to estimate the heat fluxes based in typical meteorological conditions since there are not enough data for Súria region. Then it has been set up the tab related to the activity zone where the software assumed data predefined for each type of activity. By defining the activity template the software presented a wide range of data, being the most relevant for this study the occupancy in terms of people density, the DHW (Domestic Hot Water) consumption rate and heating set point temperatures.

After appears the construction tab related to the dimensions of the doors and windows of the building. The tab of lighting defines the luminaire type used and the energy lighting but these two tabs were not sufficiently taken into account for this study. After in the tab of HVAC (Heating, Ventilation and Air Conditioning) is presented an extended list of parameters for this study but were analyzed the most important ones from heating section where it was defined the HVAC template, the mechanical ventilation with the suitable schedule, definition of fuel (waste heat) and heating system COP (Coefficient of Performance) with the definition of schedule and also the DWH template with the water temperatures about delivery temperature (60 ºC) and mains supply temperature (12 ºC) also with condition the adequate schedule of this operation.

Finally, it was performed an annual building utility performance summary for each building and the output results are attached in Appendix I with an example of one of the buildings in graphical and tabular data schedules of outside temperatures, energy flows through engaging and consumption and energy in order to elucidate which steps were used and present a comprehensive range of simulation in annual intervals. The main results in terms of kWh of energy consumption per year have been presented on *Table 2.5* concerning only the district heating as principal heating source based on energy usage by waste heat.

Table 2.5: *Total energy consumption broken down by fuel and end uses in terms of kWh/year for the municipal facilities.*

Building	Heating (kWh/year)	Water systems (kWh/year)	Total end uses (kWh/year)
A	7,616	4,258	11,874
B	20,476	2,614	23,090
C	2,900	1,631	4,531
D	9,051	1,732	10,783
E	7,347	1,674	9,021
F	3,335	2,230	5,566
G	3,099	2,193	5,292
H	20,111	4,848	24,959
Total end uses of all buildings (kWh/year)			**95,115**

As indicated in the table above, the building with the highest energy demand is building H that relates to a medical center while the building with the lowest energy demand corresponds to building C, that is a public primary school. One should note that in all cases the heating is the parameter with higher values of energy demand comparatively to water systems.

The total energy demand for heating and water systems in the municipality of Súria is 26,146,030.96 kWh/ year (this value includes municipal facilities and private/residential areas) (Ferrer & Sant, 2012). In that way, the total end uses of these eight buildings in terms of district heating corresponds to 95,115 kWh/year that means 0.36 % of the total energy demand for heating and water systems in the municipality of Súria. Finally, it comes out that the 10% of heating losses in the potash mining industry in Súria (*Figure 2.6*) are sufficient to supply the proposed district heating because the heating losses of 70,741 GJ/y mentioned previously correspond to 1,965,027 kWh/year against of 95,115 kWh/year for the proposed district heating.

2.5 Analysis of energy resources

In this section, an analysis of the possible fossil and renewable energy resources is made in order to be applied in the technologies for the proposed CHP systems.

2.5.1 Availability and costs of primary energy

2.5.1.1 Fossil resources: Natural Gas and Diesel/Gasoline

Natural gas is a fossil resource available to be used in mining facilities, as in the mining industry in Súria, since it is also considered to the 'cleanest' burning fossil fuel because few byproducts are emitted into the atmosphere as pollutant source; moreover, because when selecting natural gas one eliminates the need for an underground storage tank eliminating the threat of oil spills, soil contamination and costly environmental clean-up or, if the oil tank is above ground, switching to natural gas eliminates worry about spills or corrosion of the tank. It is important to refer that the amount of natural gas available is equal to its actual consumption, but it can be increased if it's necessary. The price applied to large consumers of natural gas in Catalonia is 0.06 €/kWh, according to information exchanged between *CTM* and large consumers. This price already includes the taxes. Diesel/Gasoline are resources that are used in the machinery related to extraction and transport of the mining ore but taking into account that the consumption amount of this resource is very low (compared with the use of other energy resources), and knowing that it is not a goal of this project, then no connection with the managing of diesel/gasoline study will be conducted.

2.5.1.2 Renewable resources: Solar and Biomass

Solar and biomass are the renewable resources that are more appellative for this project and are the available resources prompt to be implemented in the mine facilities since these are requirements of the mining industry in Súria.

a) Solar resource

Firstly, it is significant to note that the cost for solar energy is null because the solar irradiation received does not have any cost, however the equipment costs are considerable and will be shown later. The solar resource is determined by the solar radiation received at a particular site in units of kWh/m^2 and the principal feature of solar radiation is the strong seasonal dependence with a minimum in winter and maximum in summer. Solar radiation consists of direct and diffuse components (Cooper, 1974).

The development and results of the tasks related to solar resource assessment in Súria will be shown here. In this way, about the estimation of solar energy availability in Súria (41°50 '5.52" N and 1º45'11.79" W), it is known that is located in areas with high radiation according to the *Atlas Solar de Catalunya* by the *Institut Català de l'Energia* and *Universitat Politècnica de Catalunya* in 2000 (Institut Català de l'energia, 2001). Approximately maximum daily total radiation in Catalonia lies between the regions of *Segrià*, *Pla d'Urgell* and *Les Garrigues* and is 10% higher than the area of Bages where is Súria.

According to the study made the regions of the area of *Lleida* manifest the minimum and maximum daily total radiation of Catalonia; therefore it is the most oscillation territory in terms of solar radiation fluxes. This oscillation decreases as we approach the coast, though it is still important in the central depression (central Catalonia). Thus, even if Súria is not a region of high radiation (*Lleida* area), if faces high enough values but with greater stability (*Figure 2.8*).

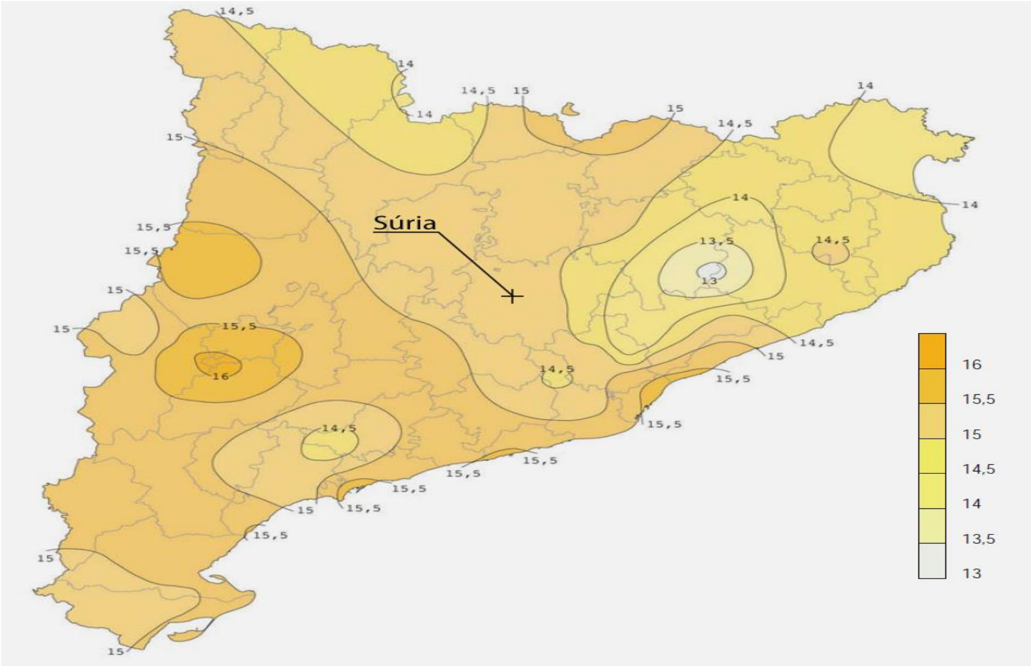


Figure 2.8*: Global medium radiation map of Catalonia (units: MJ/m*^{2}*). Source: (Institut Català de l'energia, 2001).*

The comparison of Súria with the rest of the peninsula is reflected in *Figure 2.9* from the Solar Atlas of Spain by the *Agencia Española de Meteorología (AEMET)* (Avila et al., 2012). In this figure it is possible to observe how, despite being in the northern part of the peninsula, Súria area presents similar values as some areas in the middle of the peninsula. It is worth mentioning that in the *Guadalquivir-costa de Cadiz* and *Costa de Almería* where approximately the maximum radiation is observed, there has been an annual average radiation about 18% higher than in Súria area. Once analyzed Súria in the map of Iberian radiation, the evaluation of any plant using solar thermal technology requires knowledge of the radiation available at the chosen location. For this project it was required knowledge about direct irradiation available in Súria along time.

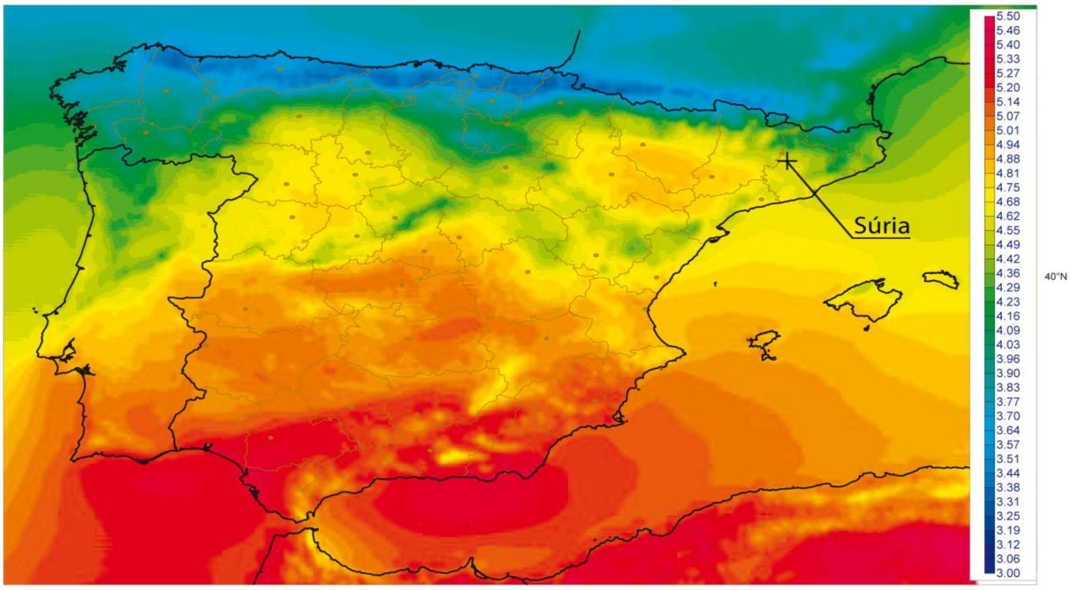


Figure 2.9: *Global medium radiation map of the Iberian Peninsula (units: MJ/m^2). Source: (Avila, Martín, Alonso , Escuin, Cadalso , & Bartolomé, 2012).*

After a search of possible sources to provide a record of radiation at Súria area, it was determined that the closest weather station with capacity for radiation measurement was located in *Castellnou de Bages* (6.5 km from Súria). The registration of radiation from that meteorological station was obtained by contact of *Servei Català de Meteorologia (SCM)*, which is the owner and manager of this station. Finally, this data center provided total daily global radiation on a horizontal surface, in a daily basis, along 14 years (1998-2011). Thus, it was suggested the creation of a typical meteorological year that means a set of hourly data of solar irradiation and weather for a period of one year. It consists of months selected from different years and joined to form a full year. This data set represents typical values from a set of a longer period, in this case fourteen years. Typical meteorological year is widely used for the simulation of renewable energy plants and buildings and is considered a standard that allows comparison of performances of these facilities. One should keep in mind that it represents an approximate average and therefore does not cover the worse possible cases (National Renewable Energy Laboratory (NREL), 1995). At this point were available daily medium values for radiation and after it was made a daily radiation distribution along the daylight hours of the day from the correlations found in the literature (Duffie & Beckman, 2006). A distribution of the irradiation between the daylight hours is shown in *Figure 2.10* where it's possible to verify that the radiation is maximum at 13h. It should be noted that applying the correlations found for daily radiation distribution between daytime hours of the day, it is being attenuated the transient occurrences of radiation that would oscillate often sharply, as would be the passage of clouds above the ground.

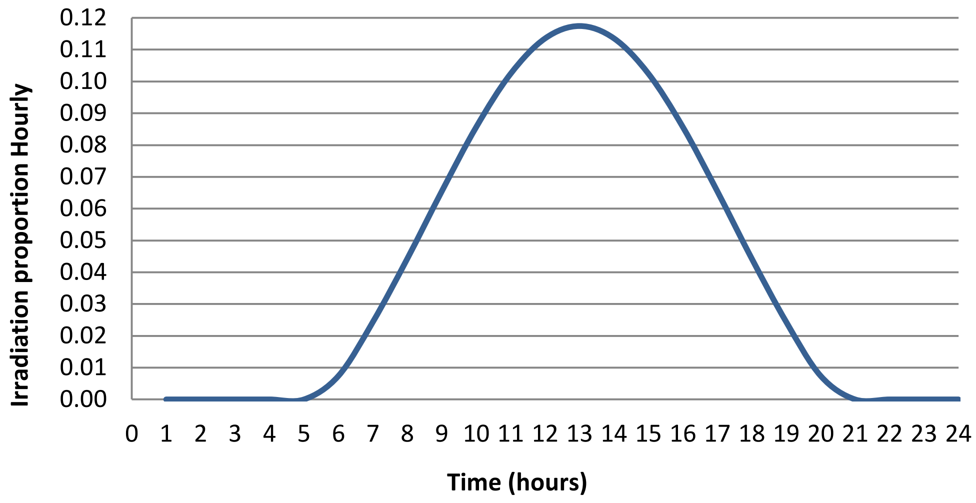


***Figure 2.10:** Distribution of irradiation along each hour of the 21st of June.*

Now is required to obtain hourly direct irradiation. Therefore it has been applied correlations proposed by *(Duffie & Beckman, 2006)* which indicates the proportion in one of diffuse radiation to total radiation from a specific schedule of atmospheric clarity index. This index is calculated by dividing the total irradiation measured at the surface and extraterrestrial radiation that comes to the upper layers of the atmosphere. After, using another expression established in *(Duffie & Beckman, 2006)*, it has been estimated hourly extraterrestrial irradiation (only depends on the time and latitude), are then it was obtained clarity index and with it, the hourly direct and diffuse irradiation. Reflecting the distribution below (*Figure 2.11*) shows the distribution of direct and diffuse irradiation for a day.

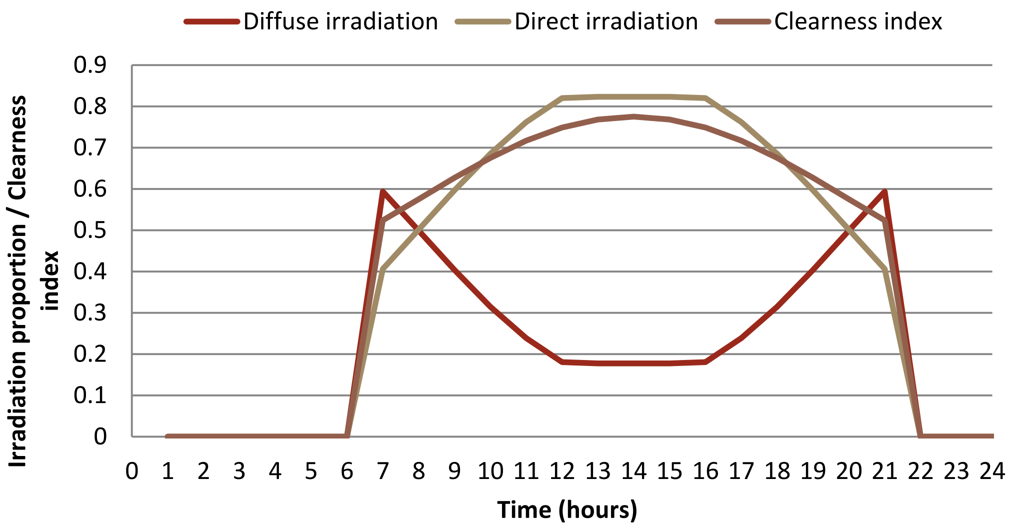


***Figure 2.11:** Distribution of direct and diffuse irradiation plus the clearness index for 21st of June.*

As noted in *Figure 2.11* the proportion of diffuse irradiation is more significant in the first and last hours of the day because irradiation is less perpendicular to the earth's surface (lower clearness index); more air mass travels in the atmosphere, increasing the dispersion of the irradiation and also absorption. Note that the profiles shown correspond to a profile of a clear day, without nebulosity. Once the hourly direct irradiation was obtained, a summary of the values contained on the typical meteorological year are given below. Four points were chosen along one year which are particularly interesting with respect to radiation (*Table 2.6*). The solstices mark the minimum and maximum annual irradiation (when the sun reaches the maximum and minimum altitude), whereas the equinoxes mark the days when the hours of daylight and night are equal. Consequently, these days create an average daily total radiation that is chosen in most cases to carry out the sizing of plants (Winter et al., 1991).

Table 2.6: *Diary radiation of typical year developed for Súria.*

Time of year	Total irradiation (kWh/m^2)	Direct irradiation (kWh/m^2)	Difuse irradiation (kWh/m^2)
Winter Solstice (21st of December)	2.22	1.41	0.81
March Equinox (20th of March)	2.77	0.36	2.41
Summer Solstice (21st of June)	8.30	6.24	2.06
September Equinox (22nd of September)	5.24	3.80	1.44
Annual diary average	4.41	2.60	1.81

To better match the goals of solar implementation it was made an analysis of the possible areas to implement solar energy technologies resulting in two surfaces available. The criteria for selecting these areas were related to its proximity for potash mining industry and the fact that are empty areas favorable to solar. The surfaces selected (*Figure 2.12*) are named *Campt de la Bota* and *Pla dels Horts* with the total surface area available of 172,297 m^2, each with 58,575 m^2 and 113,722 m^2, respectively. Applying an annual average of direct irradiation of 949 kWh/m^2/year and 1,608 kWh/m^2/year for global irradiation, an average of the last ten years (CTM, 2013), results in 163 509 853 kWh/year (163.5 GWh/year) for direct irradiation and 277,053,576 kWh/year (277.0 GWh/year) for global irradiation. Of course, solar occupancy factors have to be taken into account has described in the chapter 3 of this thesis.

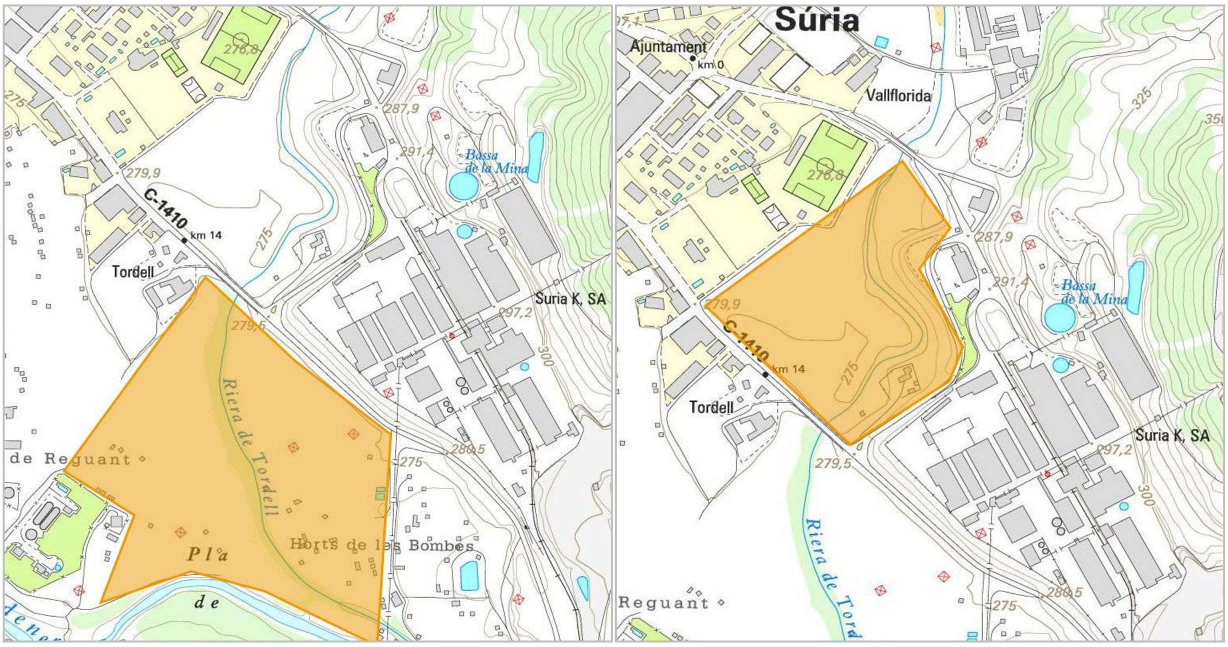


Figure 2.12: *Enlarged map of Súria with the possible areas to implement solar energy: a) Campt de la Bota and b) Pla dels Horts.*

b) Biomass resource

Another possible renewable energy to use in the mining industry in Súria comes from biomass resources. In addition, it's known that *Concell Comarcal del Bages*, where is located Súria, promotes the use of forest biomass for energy purposes in order to improve forest management and fire prevention, mitigation of climate change, promote the use of renewable local energy and reducing foreign energy dependence and also to promote the local economy and generate jobs. In order to achieve these objectives, the *Concell Comarcal del Bages* is promoting the installation of biomass boilers for heating and hot water production, especially in public buildings. Furthermore, in the current context is a solution to generate less dependence on foreign energy and more sustainable energy promoting biomass contest (Ferrer & Sant, 2012).

Below is presented a map of the different habitats in Bages (*Figure 2.13*) in order to find out where it can emerge biomass near Súria. According to the characterization of habitats of Bages made in a plan for environmental and landscape protection of Bages, almost half of the regional territory is occupied by forests (45%). The forests of the region have high biomass densities of medium-low quality, because in general there is no forest management and, where there have been forestry, those trees have higher quality.

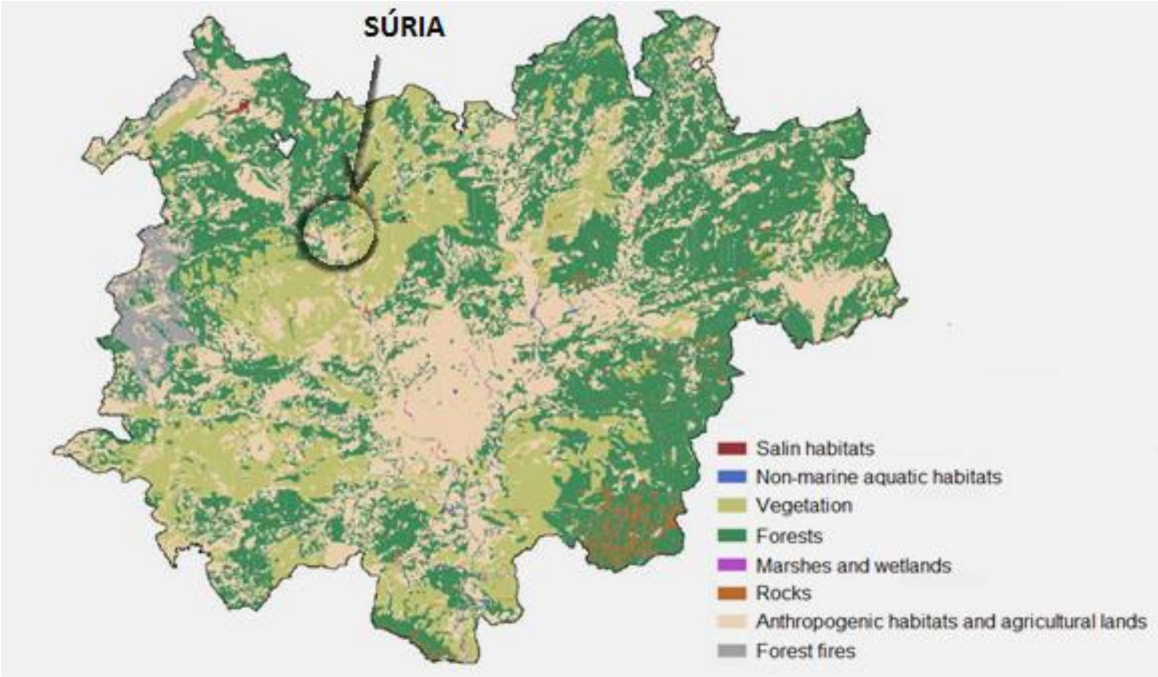


***Figure 2.13**: Distribution of groups of habitats in the territory of Bages. Source: adapted from (Fosas & Sant, 2012).*

The current natural vegetation of that region has its origin in the propagation of plants that remained in the few patches of vegetation of agriculture in the XIX century. For this reason, in conjunction with the several fires which have occurred over the last 20 years in the region, most of the forests are in various stages of ecological succession, although very few mature forests exist there. In this regard, 20% of the territory is occupied by shrubs and herbs (vegetation) that corresponds to large areas burned by fires in previous years, which were gradually regenerating. Then 2% of the surface corresponds directly to recent fires and burned areas that have not yet regenerated. All this is what could be called forest land. Furthermore, cultures and artificial habitats in urban areas are also included and occupy about 30% of the territory. These first two percentages determine the mosaic features of the region, forests interspersed with fields. The remaining habitats are represented by a percentage less than 1% of the regional territory, the case of non-marine aquatic habitats, marshes, wetlands and rocks. The presence of saline habitats, with an area of about 64 hectares, which corresponds to 0.05% of Bages area, is directly related to the presence of salt in the farm area.

It is important to identify the quantity of biomass to estimate the amount of wood that accumulates in the forests of the region of Bages each year and to set the limit to its maximum extraction in order to be considered a sustainable use. In that way, it is precisely the production of forest fragments that can actually give greater access to the market of biomass. The table below (*Table 2.7*) summarizes the results obtained for the situation of potential exploitable biomass for the region of Bages.

Table 2.7: *Summary of the annual potential biomass usable in Bages. Source: adapted from (Fosas & Sant, 2012).*

Types of biomass	Biomass potential (t_{30}^{*}/year)
Primary forest biomass (maximum)	30,664
Primary forest biomass (minimum)	2,273
Wood	5,144
Industries of first transformation	175,050
Wood cultures	740.91
Energy cultures	1,884
Total Bages (maximum)	213,453
Total Bages (medium)	30,664
Total Bages (minimum)	2,273

** t_{30} indicates 30% of humidity*

According to the results of *Table 2.7*, it is possible to conclude that at least it could be considered the value of 2,273 t_{30}/year to the fragment forest. However, in a more realistic scenario, it should be noted that in what concerns the total primary forest biomass that can be used in *Bages*, a fraction of 30,634 t_{30}/year could be applied for heating uses. It should be noted that it could also be used with relative ease some of the industry's top waste processing, and woody crops could be also considered a realistic scenario adopted intermediate biomass for thermal applications resulting in 30,634 t_{30}/year. If concerns about the potential exploitable of biomass then displays the value of 213,453 t_{30}/year of available biomass for thermal applications, considering all the available wood in the forests of the region and from primary processing industries that are destined to fragment forest, ignoring existing markets. Undoubtedly, this is an improbable scenario.

Finally, it's essential to refer a recent study (Fosas & Sant, 2012) about restrictive criteria of accessibility according to purely economic reasons for potential biomass such as slopes less than or equal to 60% and 50 meters on both sides of roads and agricultural fields. About the access of the roads, it may be noted that the lack of roads can cause increased costs or even may represent an obstacle for the use of biomass and increase drag distance, which can lead to further damage of the soil. *Bages* has an extensive system of roads that provide access to remarkable forests. The application of the accessibility criteria mentioned before allows ascertaining that the distribution of the resulting surface ends up giving 71% of accessibility to dense forests woodland (Ferrer & Sant, 2012).

In an attempt to consider the availability of forest biomass for the regions around Bages, a research was made resulting in the values shown in *Table 2.8*.

Table 2.8: *Residual forest biomass for regions surrounding Bages. Source: adapted from (CTM, 2012)* .

Region	Biomass potential (t_{30}/year)
Anoia	6,055
Baix Llobregat	9,574
Berguedà	24,271
Osona	31,016
Solsonès	14,738
Vallès Occidental	10,529
Vallès Oriental	23,059
Total in these regions	119,242
Total including Bages	149,906

Although the total amount of biomass is 149,906 tons (considering a realistic scenario for Bages assuming the intermediate biomass for thermal applications of 30,634 t_{30}/year), according to contacts established by *CTM* and biomass associations producers in the central part of Catalonia it could be estimated an approximate current and realistic availability of 100,000 tons per year of biomass at a price of 75 euros per ton. Other important information is about the LHV (Lower Heating Value) of the biomass in Bages. The value corresponds to the weighted average of calorific values of the different tree species in the region according to the availability of each type of biomass offered with 30% of humidity. The following value was obtained: 3,391 kWh per ton of biomass (Innobiomassa, 2010) that corresponds to 0.02 €/kWh.

2.5.2 Availability and costs of secondary energy

2.5.2.1 Electricity

The generation of electricity differs from the others resources analyzed because this is a secondary source of energy, meaning that this source is generated from other primary sources. It also means that electricity cannot be classified as a renewable or nonrenewable form of energy. Although the energy source we use to make electricity may be renewable or nonrenewable, the electricity is neither. It should be noted that the availability of power and energy of this feature is the same as the mining industry plant in Súria is currently consuming. According to *Instituto Catalán de Energía* and analyzing data from free-market traders it was possible to obtain the cost of electricity to the period of october 2012 to september 2013. Adding 50% to taxes applicable to electrical energy consumption it was obtained the final value of 0.11 €/kWh.

2.5.3 Summary of the available resources

Table 2.9 summarises the most important parameters of all resources, which are the maximum availability and price of generated energy including the CO_2 emissions factors, affected by each energy resource.

Table 2.9: *Availability of energy resources with energy costs and CO_2 emission factor.*

Type		Maximum availability (per year)		Energy costs	CO_2 Emission Factor
Primary energy	Natural gas	707,414 GJ	196,504,000 kWh	0.06 €/kWh	2.15 kg CO_2/Nm^3
	Biomass	100,000 t	339,100,000 kWh	0.02 €/kWh	0
	Direct Solar	949 kWh/m^2	163,509,853 kWh	0 €/kWh	0
	Global Solar	1,608 kWh/m^2	275,675,200 kWh	0 €/kWh	0
Secondary energy	Electricity	350,784 GJ	97,440,000 kWh	0.11 €/kWh	0.30 kg CO_2/kWh

The CO_2 emission factors mentioned in the previous table relate to the year of 2012 and were obtained from *CTM* data. The balance of CO_2 emissions caused by biomass can be considered neutral if we take into account the emissions produced by the combustion are counteract by the absorption of these emissions by the trees, or either, the CO_2 emissions from burning of wood are not a greenhouse gas problem like burning of fossil fuel because the energy from wood is simply renewable solar energy which has been stored in the wood for a few decades, and the release of CO_2 is part of a natural cycle which will occur anyway. About solar resource (direct and global irradiation), the emission factor of CO_2 is also zero because this technology when operational does not produce CO_2.

In that way, in this study the analysis of the CO_2 emissions only make sense for natural gas and electricity. The CO_2 emission factor caused by natural gas is provided by a combustion factor that indicates the CO_2 emissions from the volume of fuel resulting in a CO_2 emission factor of 2.15 kg CO_2/Nm^3. In the case of the electricity, to calculate the associated CO_2 emissions one need to apply a factor of CO_2 attributable to electricity also called electric mix (g CO_2/kWh), which represents the emissions associated with electricity generation. In Catalonia, the electricity consumed and self-generated comes from the mainland grid, thus being unable to distinguish exactly what plant has been generating electricity. Therefore, the data used to calculate the electricity mix are those corresponding to the mainland grid resulting in 0.30 kg CO_2/kWh. (Oficina Catalana de Canvi Climàtic, 2013).

3 State of the Art

The theoretical principles related to the technologies evaluation (efficiency, availability and costs) and the matrix modeling methodology is given in this chapter; both the theory and literature review here presented are essential for the modeling and operation described in chapter 4.

3.1 Energy systems: CHP technologies

Combined Heat and Power also called cogeneration or distributed generation, is the simultaneous production of two types of energy: heat and electricity from one source (non-hybrid systems). Because of the high efficiency of the system, CHP systems provide considerable energy, environmental and economic benefits. CHP systems reduce the demand on the utility grid, increase energy efficiency, reduce air pollution, lower greenhouse gas emissions and protect the property against power outages, while significantly lowering the utility costs of building operations.

These systems can also be hybrid. The term hybrid energy system refers to those applications in which multiple energy conversion technologies are used together to supply energy demand. These systems are often used in isolated applications and normally include at least one renewable energy source in the configuration. Hybrid energy systems are used as an alternative to conventional systems, which typically are based on a single fuel source. Hybrid energy systems may also be used as part of a distributed generation application in conventional electricity grids (Mesquita, 2010). Thus, the hybrid energy systems such as the hybrid CHP technologies are becoming popular for remote area power generation applications due to the advances in renewable energy technologies and subsequent rise in prices of petroleum products; its popularity has also been motivated by the fact that the conversion of primary fossil fuels, such as gas, to electricity is a relatively inefficient process. Even the most modern combined cycle plants can only achieve efficiencies of between 50-60%. Most of the energy wasted in this conversion process is released to the environment as waste heat power (Institution of Engineering and Technology, 2008; Deshmukh & Deshmukh, 2006).

A system using a combination of different resources and renewable energies has the advantage of balance and stability, providing stable outputs from sources, minimizing the dependence of the output upon seasonal changes and, furthermore, optimizing the utilization of the different renewable resources of energy available (Ding & Buckeridge, Design considerations for a sustainable hybrid energy system, 2000).

Economic aspects of the hybrid CHP technologies are sufficiently promising to include them in power generation capacity for developing countries. Research and development efforts in solar, biomass, and other renewable energy technologies are required to improve their performance, establish techniques for accurately predicting their output and reliably integrate them with other conventional generating sources.

The basic argument in favor of the hybrid CHP technologies use is the possibility to obtain electric and thermal energy *in situ*, improving the power generation efficiency and reducing the losses usually related to the energy distribution. The very best CHP schemes can achieve fuel conversion efficiencies of the order of 90%, taking into account electricity and heat produced. Notably among the existing CHP technologies, only a few exceptions are based on the exploitation of different fuels from natural gas, *i.e.*, small-scale power plants based on biomass derived fuel exploitation, like wood or biogas. Most of the literature indicates that a CHP plant needs to be fully utilized providing heat and power for a minimum duty of 4 500 hours per annum to attain its breakeven point. When designing renewable energy-based CHP technologies, in a distributed generation concept, one of the key factors is the capability of tracking the time-dependent end-user load. Given the unpredictability of weather conditions, renewable energy systems often rely on energy backup systems to assure that the load demands are met by the overall system (Borello, 2013). In conclusion, a hybrid CHP system (*Figure 3.1*) combines multiple sources to deliver non-intermittent electric power and heat and the utilization of these systems has lately become attractive as a promising way to reduce fossil fuel consumption and consequently diminish CO_2 emissions.

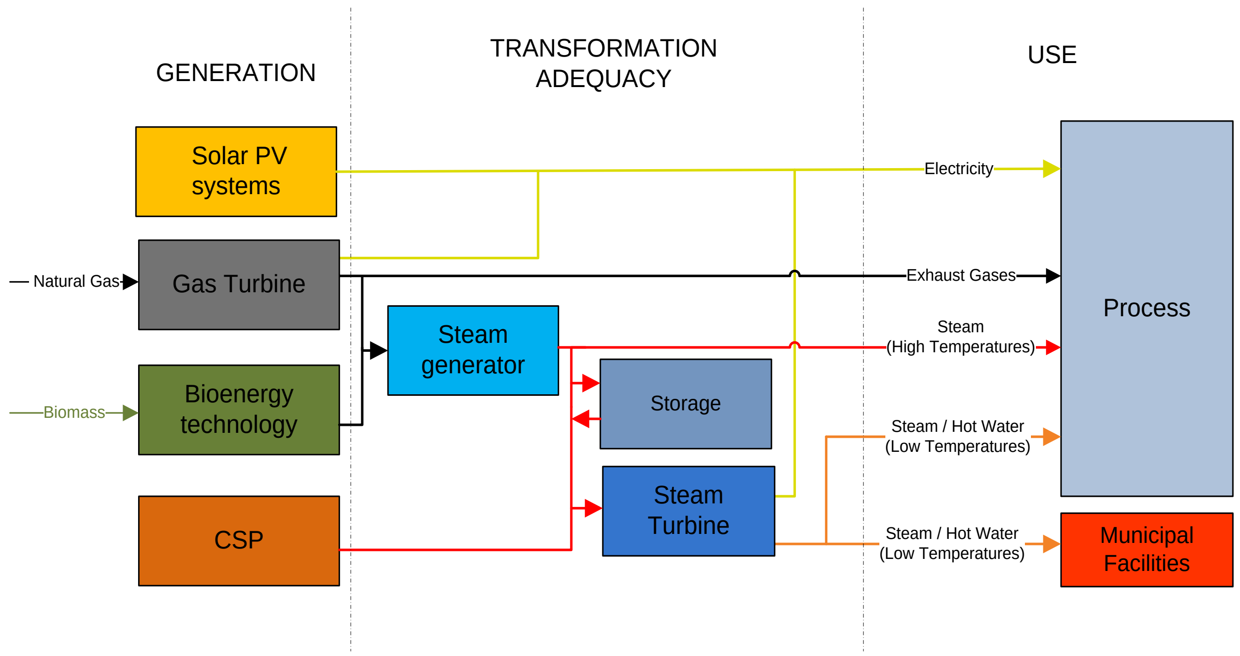


Figure 3.1*: Diagram of a potential hybrid CHP system. Source: (CTM, 2013).*

3.1.1 Thermodynamic power cycles: Brayton and Rankine

3.1.1.1 Brayton cycle

The Brayton cycle is a thermodynamic system that is applied to gas turbines. This is an ideal cycle for a simple gas turbine and is also called the Joule cycle. Gas turbine power plants may operate on either an open (*Figure 3.2 (a)*) or closed basis (*Figure 3.2 (b)*), although the open mode is more common. This technology is based in an engine in which atmospheric air is continuously drawn into the compressor where it is compressed to a higher pressure. The air then enters a combustion chamber, or combustor, where it is mixed with the fuel and combustion then occurs, resulting in combustion products at an elevated temperature. The combustion products expand through the turbine (also called the expander) and are subsequently discharged to the surroundings. Part of the turbine work developed is used to drive the compressor and the remainder is available to generate heat and electricity. The system visualized in *Figure 3.2 (b)* receives an energy input for the working fluid from an external source and the gas leaving the turbine is passed through a heat exchanger to be cooled prior to returning to the compressor.

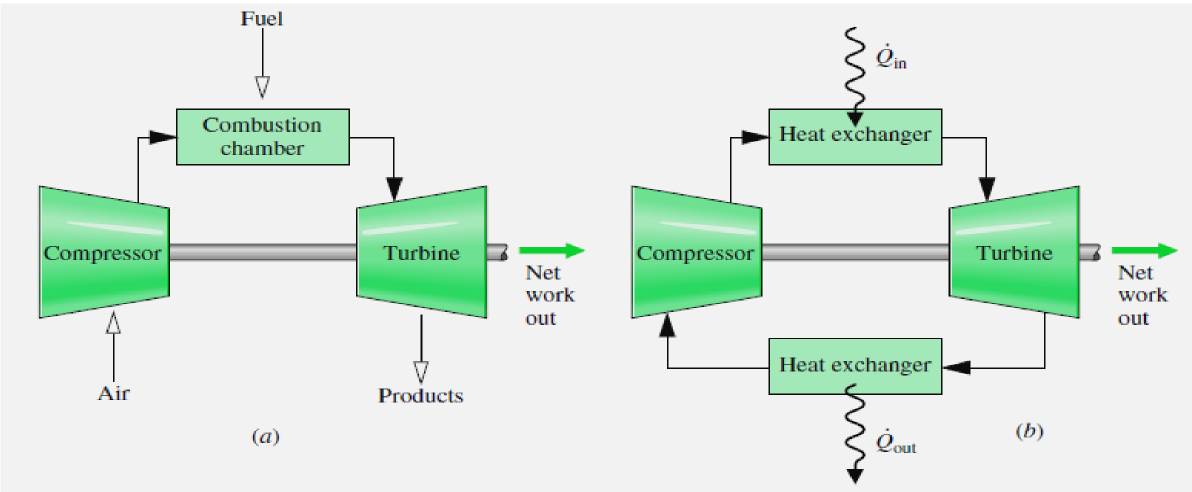


Figure 3.2: *Gas turbine open to atmosphere (a) and closed (b). Source: (Moran & Shapiro, 2006).*

Most of the applications of gas turbines are done through the use of fossil fuels; natural gas is the most widely used. There are several variations of the Brayton cycle in use today. Fuel consumption may be decreased by preheating the compressed air with heat from the turbine exhaust using a regenerator; the compressor work may be reduced and net power increased by using intercooling or precooling; and the exhaust may be used to raise steam in a boiler and to generate additional power in a combined cycle. The primary components of a simple cycle gas turbine are shown in *Figure 3.3*.

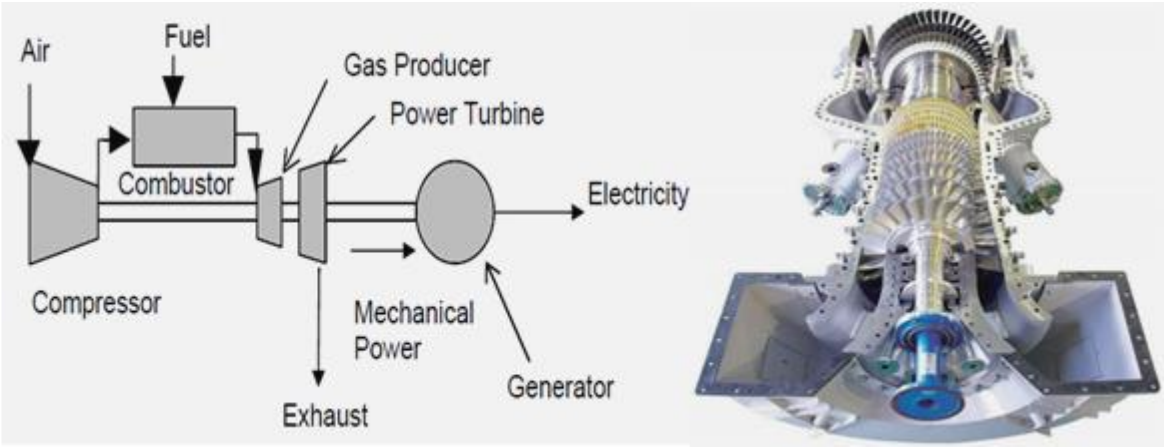


Figure 3.3: Components of a typical simplified cycle gas turbine and image of one prototype. Sources: adapted from (Energy and Environmental Analysis (an ICF international company), 2008) and (Institut Català de d'Energia, 2010).

The prototype of a gas turbine is composed, shown from down to up in *Figure 3.3*, by the compressor, the combustion chambers (two are shown), the three-stage turbine and the exhaust system. The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the device. Consequently, it is advantageous to operate the expansion turbine at the highest practical temperature consistent with economic materials and internal blade cooling technology and to operate the compressor with inlet air flow at as low a temperature as possible. As technology advances permit to use higher turbine inlet temperatures, the optimum pressure ratio also increases. Higher temperature and pressure ratios result in higher efficiency and specific power. Thus, the general trend in gas turbine advancement has been towards a combination of higher temperatures and pressures. While such advancements increase the manufacturing cost of the machine, the higher value, in terms of greater power output and higher efficiency, provides net economic benefits. Thus, the industrial gas turbine is a balance between performances and costs that results in the most economic machine for both the user and manufacturer.

The development in engineering has resulted in the advance of gas turbines in the early of 1900s, and turbines began to be applied for stationary electric power generation in the late 1930s. Such turbine used to have representative simple cycle efficiencies of about 17% due to low compressor and turbine efficiencies and low turbine inlet temperatures for material stress and thermal limitations. Efforts to improve these efficiencies have specifically or concurrently concentrated in three areas: modifying the working cycle, increasing turbine inlet temperature, and enhancing the performance of cycle components. Recently, developments in material science allow using turbine inlet temperatures up to 1,500°C. Gas turbines are available in power ranging from 500 kilowatts (kW) to 250 megawatts (MW) and can be used in power-only generation or in CHP systems. Simple-cycle gas turbines for power-only generation are available with efficiencies approaching 40 percent. This technology has long been used by utilities for peaking capacity. However, with changes in the power industry and advancements in the technology, the gas turbine is now being increasingly used for base-load power. This technology produces high-quality exhaust heat that can be used in CHP configurations to reach overall system efficiencies (electricity and useful thermal energy) of 70 % to 80 %. By the early 1980s, the efficiency and reliability of smaller gas turbines (1 to 40 MW) had progressed sufficiently to be an attractive choice for industrial and large institutional users for CHP applications (Energy and Environmental Analysis (an ICF international company), 2008; Al-Sood et al., 2013).

3.1.1.2 Rankine cycle

The Rankine cycle is more versatile than the Brayton one, once it can be used by several heat sources. This thermodynamic cycle operates in steam turbines that are a heat engine used to generate mechanical work the steam enthalpy containing energy implemented in the form of pressure and temperature. When high energy fluid passes through series of rotor blades, it absorbs energy from fluid and starts rotating, thus it transforms thermal energy in fluid to mechanical energy. Steam turbines operate in closed loop using water as the working fluid and the basic steps of that thermodynamic cycle are the next ones, as exemplified in *Figure 3.4*:

1) Isentropic expansion (Steam turbine): Feedwater is pumped at high pressure into a boiler which is heated by the boiler. The water is heated and evaporated at high pressure, becoming steam. The steam is further heated to become superheated. So, the boiler supplies the energy required to perform vapor phase change. This is an isentropic process, in which the entropy of working fluid remains constant.

2) Isobaric heat rejection (Condenser): The steam expands through the turbine to produce work and then is discharged to the condenser. Heat transfer occurs in the condenser from the vapor to cooling water flowing in a separate stream. The vapor condenses and the temperature of the cooling water increases. This is an isobaric process, in which the pressure of working fluid remains constant.

3) Isentropic compression (Pump): The liquid condensate, leaving the condenser at steam 3, is pumped from the condenser into the higher pressure boiler. At this stage, during the isentropic compression process, external work is done on the working fluid by means of pumping operation.

4) Isobaric heat supply (Boiler): During this process, the heat from the high temperature source is added to the working fluid to convert it into superheated steam. This steam (which may be wet or not depending on the cases) is prepared to start the cycle again (Wu & Wang, 2006).

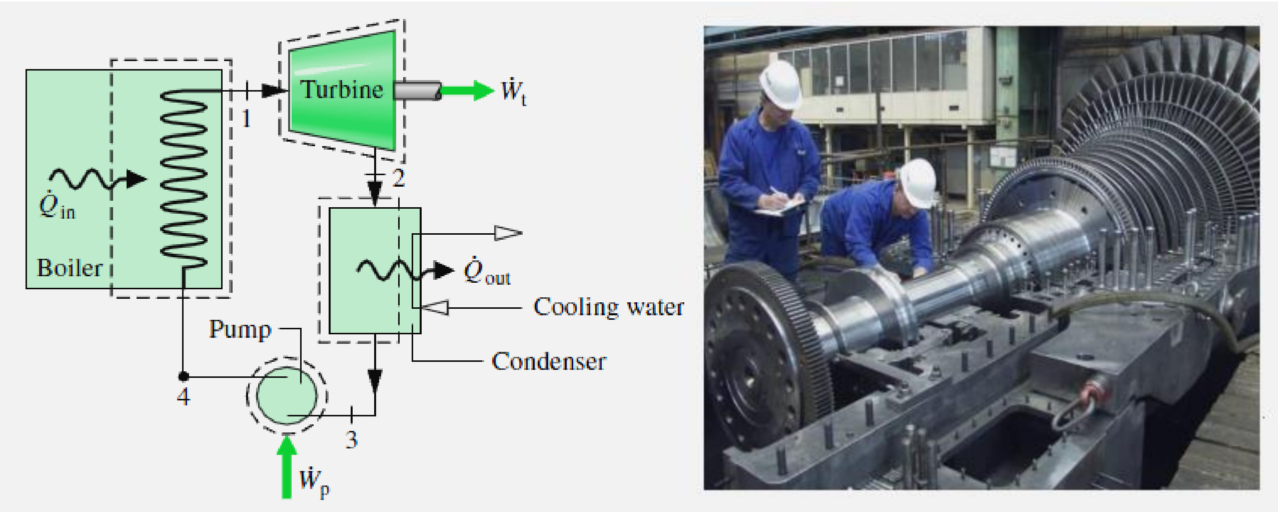


Figure 3.4: *Diagram of a system consisting of a steam turbine (Rankine cycle) and image of one prototype. Source: adapted from (Moran & Shapiro, 2006) and (Institut Català de d'Energia, 2010).*

One of the oldest principal mover technologies still in general production used to drive a generator or mechanical machinery are the steam turbines. Already has more than a century that power generation has been using steam turbines, when they replaced reciprocating steam engines due to their higher efficiencies and lower costs. The capacity of steam turbines can range from 50 kW to several hundred MW for large utility power plants. Steam turbines are widely used for CHP applications around the world.

Unlike gas turbine and reciprocating engine CHP systems where heat is a byproduct of power generation, steam turbines typically generate electricity as a byproduct of heat (steam) generation. A steam turbine is captive to a separate heat source and does not directly convert fuel to electric energy. The energy is transferred from the boiler to the turbine through high pressure steam that in turn powers the turbine and generator. This separation of functions enables steam turbines to operate with an enormous variety of fuels, varying from clean natural gas to solid waste, including all types of coal, wood, wood waste, and agricultural byproducts. In CHP applications, steam at lower pressure is extracted from the steam turbine and used directly in a process or for district heating, or it can be converted to other forms of thermal energy including hot or chilled water. Steam turbine-based CHP systems are primarily used in industrial processes where solid or waste fuels are readily available for boiler use. The turbine may drive an electric generator or equipment such as boiler feed water pumps, process pumps, air compressors and refrigeration chillers. Turbines as industrial drivers are almost always a single casing machine, either single stage or multistage, condensing or non-condensing depending on steam conditions and the value of the steam. Steam turbines can operate at a single speed to drive an electric generator or operate over a speed range to drive a refrigeration compressor. For non-condensing applications, steam is exhausted from the turbine at a pressure and temperature sufficient for the CHP heating application (Energy and Environmental Analysis (an ICF International Company), 2008).

3.1.2 Bioenergy technology

The bioenergy technologies have as source the biomass. This renewable resource can generate various types of energy such as heat, where heat is usually produced in combustion systems; biomass use also allows producing mechanical energy, by generating heat and power, as steam engines or internal combustion engines. So, the processes for the conversion of biomass into energy forms may be classified into three categories:

a) Biochemical processes: relates to the decomposition of organic wastes in an oxygen-deficient atmosphere with the production of methane (anaerobic digestion), or to the controlled fermentation for production of alcohols (ethanol and methanol);
b) Direct combustion: refers to the burning of biomass to produce heat for space heating of for the production of electricity through a steam turbine. Anything from solid wastes to crop residues or wood can serve as feedstock for this process;
c) Pyrolysis: related to the thermal decomposition of wastes into a gas or liquid (with a relatively low heating value) under high temperatures (500 º to 900 ºC) in a low-oxygen atmosphere (Hinrichs & Kleinbach, 2013).

Direct combustion of biomass is still the most convenient and economical way to utilize biomass energy. It is responsible for over 97% of the world's bio-energy production. The development of biomass combustion technologies is principally focused on understanding the characteristics of biomass as a fuel and using it to design combustion facilities. Though having great advantage in environmental performance, biomass fuels have a wide range of different physical and chemical properties, particularly when compared with traditional fossil fuels (Dermibas, 2004).

The diagram below illustrates a typical example of a biomass boiler package where sufficient air is supplied to the burning fuel to ensure complete combustion (*Figure 3.5*).

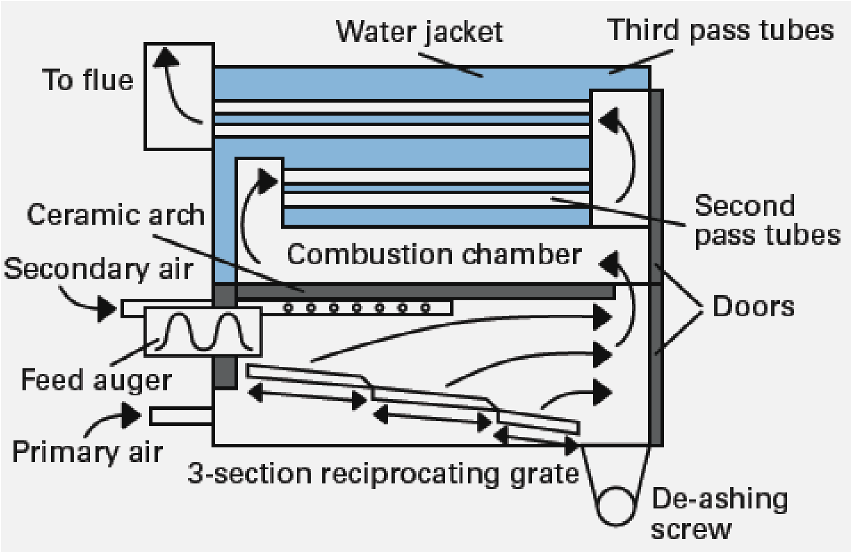


Figure 3.5*: Typical biomass boiler package. Source: (Enhanced Capital Allowances).*

In normal environmental conditions the biomass is not self-inflammable, so the extraction of energy goes through a complex process of thermo chemical conversion. It is also worth noting that using biomass does not contribute as much to the greenhouse effect, since the amount of carbon dioxide produced is offset somewhat by the amount taken in during growth.. Biomass combustion supplies about 11% of the world's total primary energy and biomass combustion systems are available in the power range from a few kW up to more than 100 MW. The efficiency for heat production is considerably high and heat from biomass is economically feasible; commercial power production is based on steam cycles as Rankine cycle (Overend; Nussbaumer, 2003).

Depending on the origin, the biomass source can be classified into biomass energy crops whose function is the storage of solar energy irradiation in the form of biomass, such as sunflower and maize; forest and agricultural waste generated by farming or forestry activities; organic byproducts, where the processing of biomass for the creation of other products leads to an additional group of byproducts such as organic waste, effluents from agricultural and industrial waste and organic waste, including household waste and sludge of domestic and industrial effluents.

CHP technologies related to biomass combustion have been recently developed and plants have been successfully implemented in many European countries. Moreover, several medium and large scale applications are available on the market and have demonstrated their technology maturity. The electricity generation from biomass increased by a factor of 4.7 between 1990-2005 with an average rate of about 11% annually and the major share of this increase is attributable to CHP plants based on biomass combustion (Obernberger I. , 2010) (Obernberger & Thek, 2008).

Various technologies are available for the electricity production based on biomass combustion. For large-scale applications, or either more than 2,000 kW_{el} (kilo-watt electric), the steam turbine (Rankine cycle) has been applied for many years because is economically and technically feasible, so this is a technology that was further developed and optimized during the past ten years and can now be considered as a market-proven technology (Obernberger I. , 2010; Obernberger & Thek, 2008).

Finally, it's important to mention that this technology (biomass combustion) is one of the cleanest means of generating electricity, with emissions of nitrogen oxides (NO_x) from some large turbines in the single-digit parts per million (ppm) ranges, either with catalytic exhaust cleanup or lean pre-mixed combustion. Because of their relatively high efficiency and reliance on natural gas as the primary fuel, gas turbines emit substantially less carbon dioxide (CO_2) per kilowatt-hour (kWh) generated than any other fossil technology in general commercial use.

3.1.3 Concentrated Solar Power (CSP)

CSP technologies have been under exploration for several decades and are based on a simple general proposal: using mirrors, sunlight can be redirected, focused and collected as heat, which can in turn be used to power a turbine or a heat engine to generate electricity. The concentration of radiation can only be performed on direct irradiation, since concentration systems (heliostats, parabolic troughs, parabolic dishes etc.) are designed to reflect radiation with a specific directionality in the receiver. Despite being relatively uncomplicated, this method involves several steps that can each be implemented in a plethora of different ways. The chosen execution method of every stage in solar thermal power production must be optimally matched to various technical, economic and environmental factors that may favor one approach over another. Extensive explorations of various solar collector types, materials and structures have been carried out, and a multitude of heat transport, storage and electricity conversion systems has been tested. The progress made in every aspect of CSP, particularly in the last decade, was geared towards increasing the efficiency of solar-to-electric power production, while making it affordable in comparison with near-future fossil fuel derived power (Barlev et al., 2011).

A solar energy collector is a heat-exchanging device that transforms solar radiation into thermal energy than can be used for power generation. The basic function of a solar collector is to absorb incident solar irradiation and convert it into heat, which is then carried away by a heat transfer fluid that links the solar collectors to the power generation system, carrying thermal energy from each collector to a central steam generator or thermal storage system as it circulates.

A CSP plant mainly consists of four subsystems: a focusing System that captures and concentrates the radiation on the receiver; a reception system that absorbs and transforms solar irradiation into thermal energy, heating the carrier fluid and in the case of water, also generating steam; a storage system that allows thermal energy storage for subsequent use; an auxiliary energy supply system which is an auxiliary power supply: system using other energy not from sunlight (natural gas, biomass, etc.); and a power system that allows the generation of electricity, thermal system (thermodynamic cycle) and electrical system (generator, transformer, etc.). The definition of these subsystems allows the classification of the different CSP technologies in the combination chosen for concentration and receiving systems. Then, the four main types of concentrating solar collectors are: Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Parabolic Dish Collector (PDC) and Heliostat Field Collector (HFC) (*Figure 3.6*).

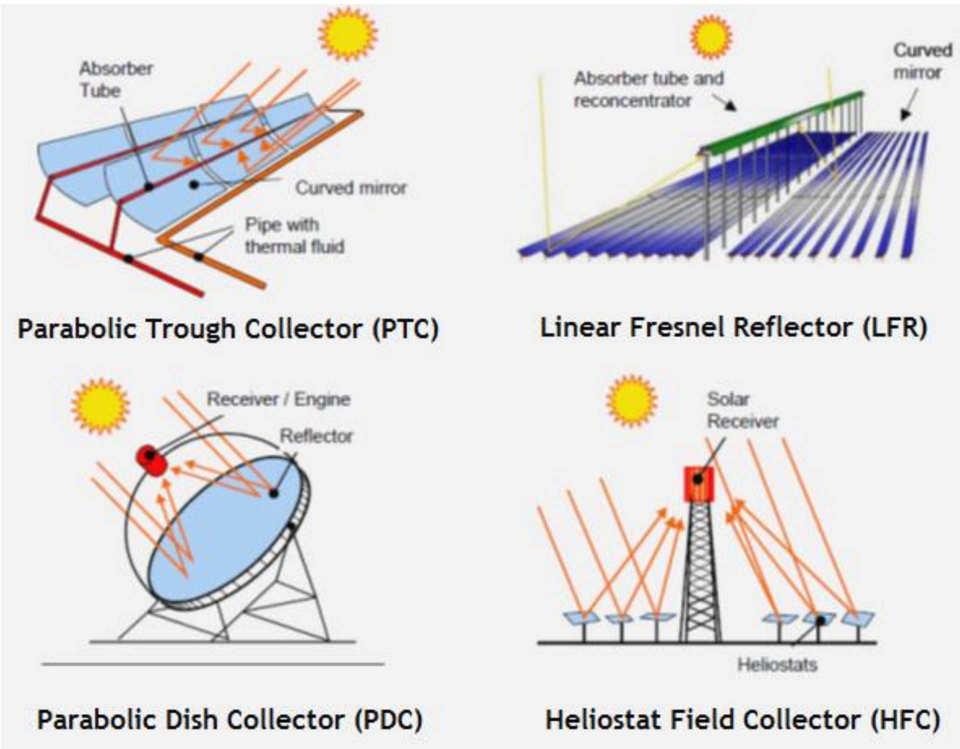


Figure 3.6*: Schematic diagrams of the each CSP technologies. Source: adapted from* (Mendes & Horta, 2010).

The CSP technologies can achieve different concentration ratios and thus operate at various temperatures. From a theoretical standpoint, the efficiency of power producing heat processes is both proportional and strictly dependent on the operation temperature. In practice, however, the materials chosen for light concentration and absorption, heat transfer and storage, as well as the power conversion cycles used are the true deciding factors (Segal & Epstein, 2003). On *Table 3.1* is presented the description of the four main CSP technologies.

Table 3.1: *Technical features of the four main CSP technologies. Source: (Barlev, Vidu, & Strover, 2011).*

Collector Type	Operating temperature range (°C)	Relative cost	Concentration ratio (sun)	Technology maturity
PTC	50-400	Low	15-45	Very mature
LFR	50-300	Very low	10-40	Mature
HFC	300-2,000	High	150-1,500	Most recent
PDC	150-1,500	Very high	100-1,000	Recent

Observing the previous table is possible to note that PTC and LFR are the lowest-cost technologies and the most mature. PDC and HFC are recent technologies and with the higher costs. Thus, according to studies conducted in the company *CTM* the PDC and HFC technologies are not economically viable and so it will not be given much significance in this chapter to these two technologies.

The following text will describe the PTC and LFR technologies in more detail and a succinct explanation about PDC and HFC technologies.

3.1.3.1 Parabolic Trough Collector (PTC)

This technology consists in a PTC to concentrate sunlight into the black reception line (linear receiver) located at the focus of the parabola. Since the collector aperture area is bigger than the outer surface of the receiver tube, the direct solar radiation is concentrated. The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar irradiation into thermal energy in the form of sensible heat of the fluid. This fluid can be efficiently heated up to 400ºC (Zarza, 2003).

The tube has a selective coating, which combines high absorption to solar irradiation and low thermal emissivity, and is usually placed inside a glass tube, to reduce losses. In that way, mobile receivers collect more radiation energy than corresponding fixed receivers. Next, the tube absorbs fluid which circulates heated (*Figure 3.7*). This will be pumped to the power system (usually evaporator and turbine), which generate electricity through a Rankine cycle, or to the storage system.

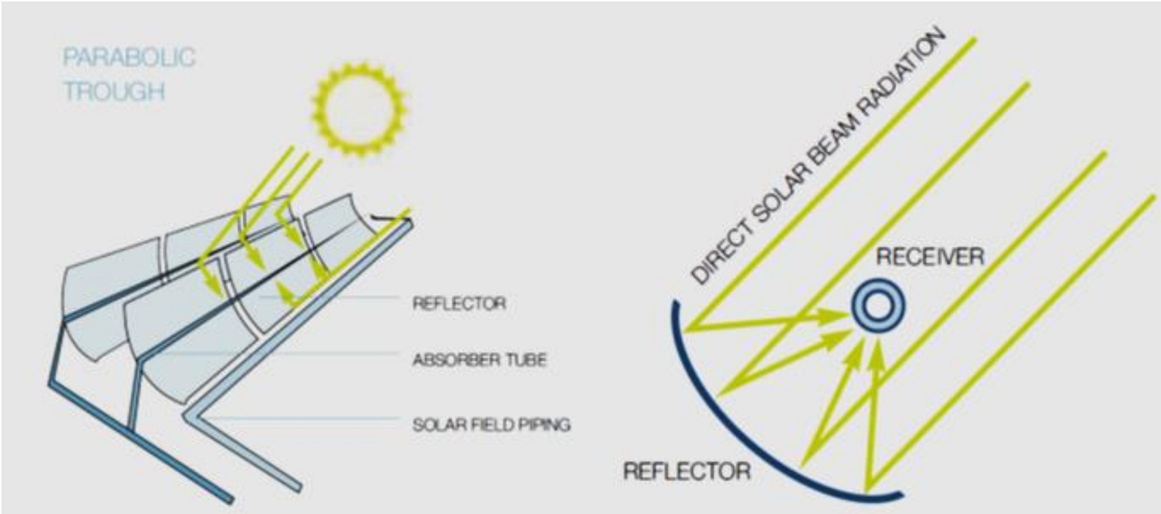


Figure 3.7: *Exemplification of the operation of PTC technology. Source: (Greenpeace, 2009).*

Since a PTC is an optical concentrator it has to be positioned at every moment in accordance with the sun position so that the incoming direct solar irradiation is reflected onto the receiver tube (Zarza, 2003).

About technology development and the current situation of PTC, it is known that the plant DCS (Distributed Collector System, 1981) at the *Plataforma Solar de Almería* (Spain) was pioneering, and has high technical and commercial maturity. This is due to the valuable experience provided by the solar plants SEGS (Solar Electric Generating System) of California. These nine plants were built since 1984 till 1991 and are located in the Mojave Desert using synthetic oil as heat transfer fluid. They represent a total of 354 MW electric networked, distributed in power plants of 14 to 80 MW, without thermal storage systems and with natural gas auxiliary boilers. The cost of current production is 0.12-0.14€/kWh (2008) (López-Cózar, 2008). After the building of SEGS the construction of these plants paralyzed due to cuts in aid and stabilization and falling oil prices in the 1990s. The arrival of the new century reactivated the construction of such plants primarily in Spain due to the appearance of a favorable regulatory framework through premiums. This was reflected in the construction, in the recent years, of 30 plants of this type, compared to 4 plants built in the United States. Currently it exceeds the number of plants, installed capacity and production as compared to other solar technologies. In the following table (*Table 3.2*) is reflected the current situation about the PTC technology.

***Table 3.2**: Power scenario for PTC technology in Spain, in the USA and in the rest of the world. Source: adapted from (NREL - National Renewable Energy Laboratory, 2010).*

	Spain		USA		Rest of the World		Total
Power	MW	% of total	MW	% of total	MW	% of total	MW
Installed	1,450	67.7	515.8	24.1	175	8.2	2,140.8
Construction	672.5	36.0	1,080	57.9	114	6.1	1,866.5
Development	50	14.3	300	85.7	0	0	350

The predictions made by the CIEMAT (Centre for Energy Environment and Technology) and the DLR (German Aerospace Center) on the assumption of a realistic optimist scenario for 2050, predict that PTC technology will get a share of 40 % of total installed thermal power plants and the power will range between 200 and 400 MW, powered by direct steam generation, and storage of 16 hours with different phase materials (Viebahn et al., 2010).

Finally, it's important to mention that PTC has the value of 30% as occupancy factor for the available surface area to implement that technology. This occupancy factor is relating the usage of the total PTC installed in the available surface area (CTM, 2013).

3.1.3.2 Linear Fresnel Reflector (LFR)

The LFR technology is a solar concentrator system that incorporates long arrays of flat mirrors that rotate about independent parallel axes to reflect light into a fixed elevated receptor through which the heat transfer fluid is flowing. This is subsequently heated and the transfers the heat to the evaporator of the power cycle (*Figure 3.8*). For the generation of electricity is also used the Rankine cycle in this technology. The only heat transfer fluid used for this technology has been water resulting in Systems of Direct Steam Generation.

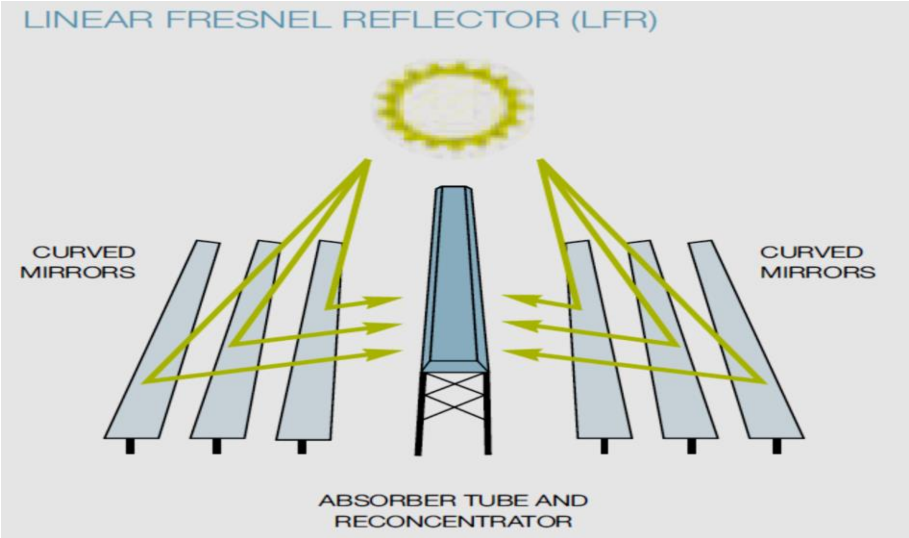


***Figure 3.8**: Scheme of LFR technology. Source: (Greenpeace, 2009).*

The main advantage of this technology, because of its structure and lightweight design, is the specific low utilization of material. Furthermore, despite having the lowest efficiency of all CSP technologies, for the same production and power output uses 50% less area than the PTC technology (European Academies Science Advisory Council , 2011).

This technology was initially proposed as an alternative to systems with heliostats. Although the comparison with heliostats was unfavorable, more recently it was proposed as an alternative to concentrating systems using PTC because the temperatures achieved and thermal losses are similar. Therefore, the LFR systems are considered natural competitors of PTC, presenting as the main advantage a smaller manufacturing cost and lower maintenance (European Academies Science Advisory Council , 2011)

The biggest innovation in the design of these plants was proposed by Mills and Morrison from the University of Sydney, Australia (European Academies Science Advisory Council , 2011). They proposed the Compact Linear Fresnel reflector (CLFR) that uses multiple receivers with the purpose of compact the distribution of the reflectors, including avoiding shadows and better exploiting the incident radiation field.

Recently, several prototypes have been built in Australia (Mills, D. R. et al, 2004), Belgium (Häberle, A.) and at the *Plataforma Solar de Almería*. In the commercial perspective, it is worth stressing that in the California it was built in 2008 a 5 MW plant named Kimberlina Solar Thermal Energy Plant; the German company *Novatec* built in 2009 the plant *Puerto Errado 1* of 1.4 MW in Spain and after it was installed the *Puerto Errado II* of 30 MW. This power values are presented in the following table (*Table 3.3*) that shows the power installed, in construction and in development of LFR technologies in Spain, in the USA and in the rest of the world.

***Table 3.3**: Power scenario for LFR technology in Spain, USA and in the rest of the world. Source: adapted from (NREL - National Renewable Energy Laboratory, 2010).*

	Spain		USA		Rest of the World		Total
Power	MW	% of total	MW	% of total	MW	% of total	MW
Installed	31.4	85.7	5	13.6	0.25	0.68	36.65
Construction	0	0	0	0	0	6.1	0
Development	0	0	0	0	12	100	12

It is expected that in the long term (2025-2050) this technology should be dominant because of its simple design and material consumption and lower surfaces requirements. Although FLR systems are reaching a lower efficiency of 11.9% (two-third of the efficiency of PTC), compared with installing a PTC and taking into account the low efficiency for the same electricity, this technology saves 50% of space. It is estimated that the installed power using this technology will be 400 MW around 2025-2050.

Finally, it's important to mention that LFR has the value of 50% as occupancy factor for the available surface area to implement that technology, i.e. this percentage means the usage of the total LFR that could be installed in the available surface area (CTM, 2013).

3.1.3.3 Parabolic Dish Collector (PDC) and Heliostat Field Collector (HFC)

PDC technology uses a reflector with parabolic disc-shaped to focus the radiation at the focus of the disc. The discs must track the sun on two axes for maintaining the convergence of the radiation at the same point. The receiver is mounted on the focus of the parabola; two general schemes exist for power generation: the less implemented solution is based on the use of a heat transfer fluid which connects the various discs receptors carrying the heat to the power system (this system presents difficulties because it requires a system of pipes, pumps and causes more heat losses); the most used is based on an engine mounted near the focal point for each disc. These engines absorb heat energy from the receiver and use it to produce mechanical work which is converted into electricity by an alternator work adjacent to the engine.

HFC technology is based on a circular distribution of heliostats (mirrors with ability to follow the movement of the sun on two axes), each with an area of between 50 and 150 m^2. Each heliostat focuses individually to reflect the incident irradiation directly to the receiver. In the first, heliostats completely surround the receiver tower, and the receiver, which is cylindrical, has an exterior heat-transfer surface. In the second, the heliostats are located north of the receiver tower (in the northern hemisphere), and the receiver has an enclosed heat-transfer surface. In the third, the heliostats are located north of the receiver tower, and the receiver, which is a vertical plane, has a north-facing heat-transfer surface. In the final analysis, however, it is the selection of the heat-transfer fluid, thermal-storage medium, and power- conversion cycle that defines a central-receiver plant. The heat-transfer fluid may either be water/steam, liquid sodium, or molten nitrate salt (sodium nitrate/potassium nitrate), whereas the thermal-storage medium may be oil mixed with crushed rock, molten nitrate salt, or liquid sodium (Kalogirou, 2004). As in the case of PTC technology, the thermodynamic cycle chosen is the Rankine one.

3.1.4 Solar Photovoltaic (PV) systems

The energy that comes from the sun is delivered in two main forms: heat and light. There are two main types of solar power systems, namely solar thermal systems that trap heat to warm up water and solar PV systems, the technology that will be presented here, that converts sunlight directly into electricity. This technology makes use of global irradiation and is based on photovoltaic cells that are electrically connected to produce higher voltages and/or currents. These cells were first developed in the late 1950s to provide power to earth-orbiting satellites. As the technology improved and costs became more reasonable, PV were used in terrestrial applications to power a number of remote, off-grid critical electrical requirements such as railway signals, telecommunications repeaters and lighting. In the 1980s, PV cells became a popular power source for consumer electronic devices, including calculators, watches, radios and other small battery charging applications (Singh , 2006). As manufacturing levels for PV continued to grow throughout the 1980s, PV systems were used for a variety of off-grid applications, including water pumping, rural residential and transportation safety systems. Today, a major international market for PV technology is for providing power to the billions of people throughout the world who live without electrical service, for applications such as health care facilities, community centers, water delivery and purification systems, and rural residences. In industrialized nations, grid-connected PV system applications are now being deployed in great numbers, for residential, commercial and utility grid-support applications.

The photovoltaic generation of energy is based on the principle of irradiation separating positively and negatively charged carries in an absorbing material. In an electric field these charges can produce a current for use in an external circuit. In junction devices, or either, photovoltaic cells, it is the current that is produced by the radiation and not the voltage (Ding & Buckeridge, Design considerations for a sustainable hybrid energy system, 2000).

The solar PV process converts the sun's energy directly in electricity, so the solar irradiation can be converted into useful energy directly by the use of different technologies. It can be absorbed in solar collectors to heat water and can also be converted directly into electrical energy using PV solar cells. Unlike conventional generation systems, fuel of the solar PV energy is available at no cost and the interest in solar PV energy is growing worldwide. It's important to mention that solar PV systems have the value of 43.4% as occupancy factor for the available surface area to implement that technology (CTM, 2013).

The classification of solar PV systems is based in the end-use application of the technology, classifying them as stand-alone and grid connected systems. The main difference between both systems is that in the stand-alone system the generated energy is matched with the load while the grid-connected system is connected with the existent electrical utility grid. Since PV modules produce power only when illuminated, PV systems often make use of energy storage mechanisms such as batteries. In this manner, the energy yielded by the modules may be made available at a later time. On the other hand, using storage batteries provides other advantages as system voltage regulation or a source of current that can exceed the PV configuration capacities. Thus, using battery storage it is common to employ a charge controller, thus it can prevent reaching possible battery levels of overcharged or over discharged. An inverter may also be needed in case of serving alternating current (AC) loads. The functions of an inverter will be converting direct current (DC) power from the solar modules into AC. Another possible configuration for the PV systems is to be connected to a utility grid. Such systems may operate in bidirectional mode, delivering excess PV energy to the grid or using it as a backup system when lacking PV generation (*Figure 3.9*). It is possible to note that the basic structure of PV systems consists of arrays of PV modules, energy storage batteries, backup generators, battery charge controllers and inverter but it is possible to vary certain components and designs depending on each particular system (Lobera, 2010).

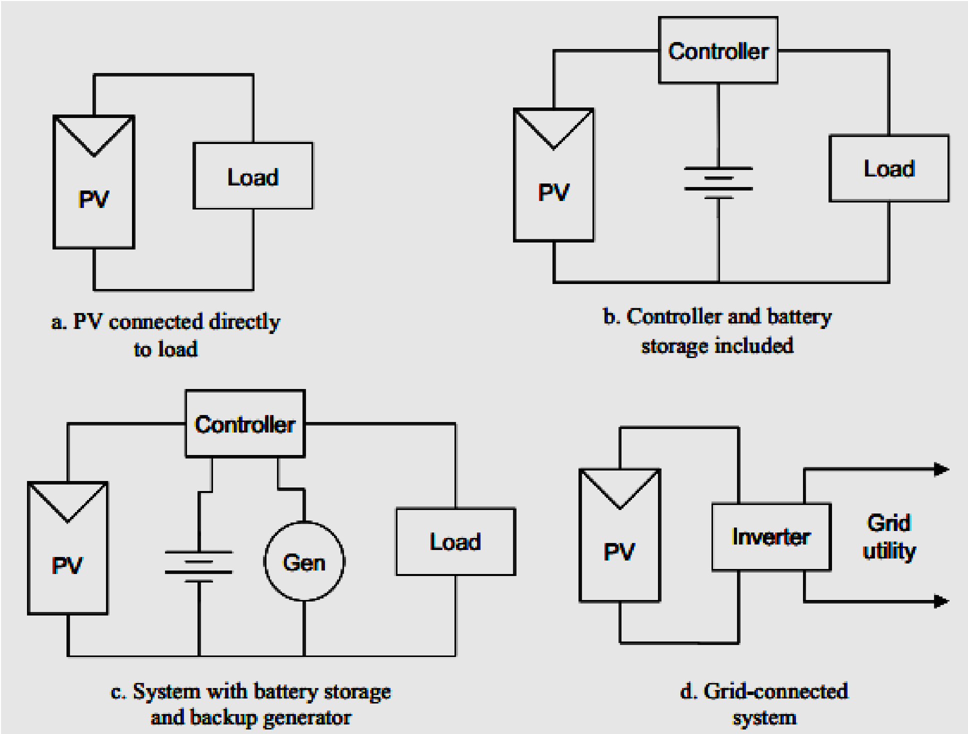


Figure 3.9*: Some examples of PV systems. Source: (Lobera, 2010).*

Several aspects, such as continual lowering of costs and prices in most PV system components, institutional economic support, versatility and modularity and minimum maintenance cost, have led to a situation such that installed PV power in Spain was estimated to rise to 3,000 MW by the end of 2009, with more than 14,000 grid-connected systems. The Spanish autonomous region of *Castilla y León* was, in August 2008, the second autonomous region in Spain in terms of PV energy with 215 MW of installed power, second only to *Castilla La Mancha*, with 402 MW. This amount occurs because large plains with high levels of solar insolation, very few cloudy days and moderate ambient temperatures favor this region to the construction of 'solar farms' to exploit solar energy (Díez-Mediavilla et al., 2010). At *Figure 3.10* is presented an aerial photograph of a PV system.

Figure 3.10: *PV system located in Astudillo (Palencia) at the centre of the autonomous region of Castilla y León in Spain. Source: (Díez-Mediavilla et al., 2010).*

3.1.5 Summary of all technologies

After making an analysis for each technology, it's conceivable to classify them according to their capacity to generate heat and electricity. Thus, these technologies can be divided into:

a) Heat generation technologies: comprise all the technologies that turn some form of energy only into generation of heat;

b) Electricity generation technologies: include the technologies that turn some form of energy into useful electric energy.

c) Electricity and heat generation technologies: the technologies that produce at the same instance electricity and heat;

In *Figure 3.11* is depicted a scheme that shows which technologies are included in each of the sections presented above.

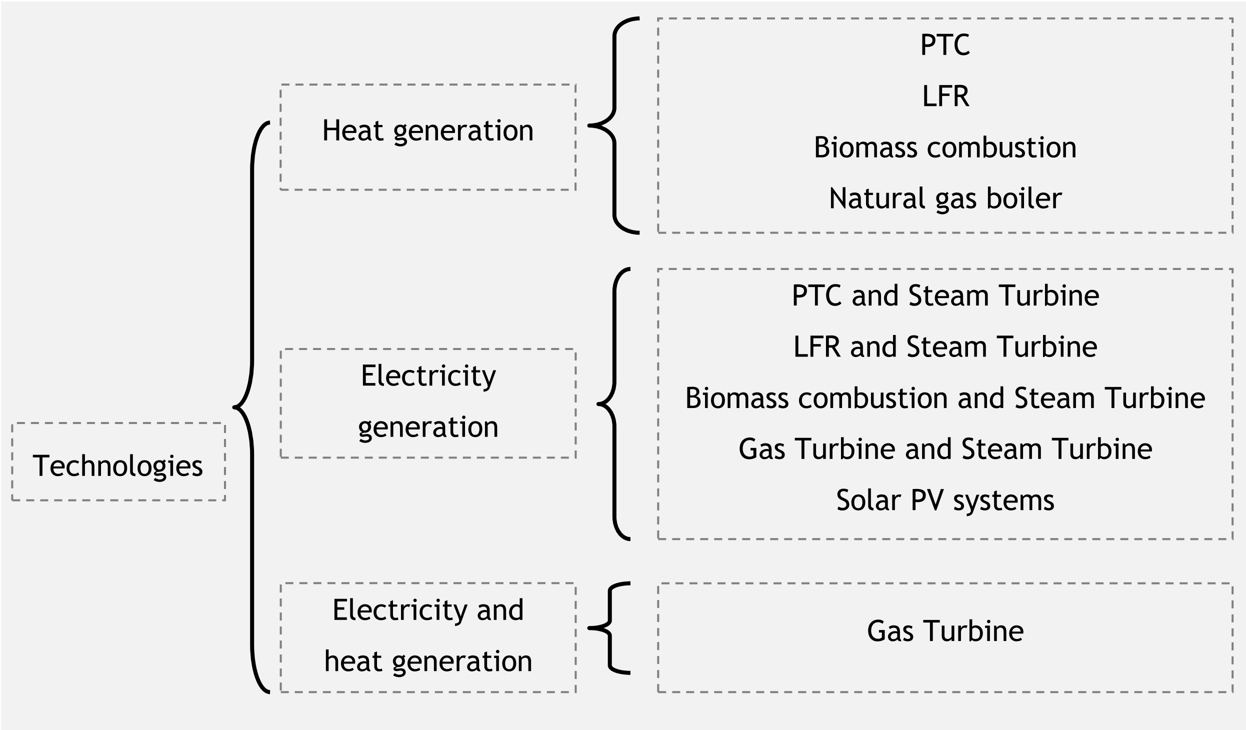


Figure 3.11: *Representative scheme of the different technologies considered according to their capacity to generate heat and/or electricity.*

One relevant information is that Biomass combustion, PTC and LFR are technologies that generate only heat, then it's necessary to make use of thermodynamic cycles (such as the Brayton and Rankine cycles in Gas Turbine and Steam Turbine, respectively) in order to also generate electricity. Natural gas boiler represents the actual technology implemented in mining industry in Súria. On the other hand, PV systems technology does not need to make use of thermodynamic cycles because generate electricity in its operation.

The most important parameters of the technologies mentioned above are described in *Table 3.4*. In addition to the investment costs mentioned it is also necessary to consider the project costs, or either, the EPC (Engineering, Procurement and Construction) costs, which corresponds to 17% of the total costs of equipment throughout the systems. The function that appears in *Table 3.4* concerns the heat generation technology of Biomass combustion and as the following form:

$$y\ [€/kW_{th}] = -258.5 log_e(x\ [kW_{th}]) + 3{,}380.7$$

where the *y* represents the investment costs in euros per kilowatt-thermal and *x* stands for the thermal power in kilowatt-thermal, therefore the investment cost appears as a function of thermal power (CTM, 2013).

Table 3.4: *Costs and technological parameters of considered heat generation and electricity technologies. Source: adapted from* (CTM, 2013).

	Investment costs			OM costs	Technological parameters				
Heat Generation	**(€)**	**(€/m^2)**	**(€/kW$_{th}$)**	**(€/kWh)**	**$\eta_{thermal}$**		**HTF**	**Steam Temp. (°C)**	**Pressure (bar)**
PTC	3.8×10^5	320.1	1,350.2	0.036	0.47		Oil	400	---
LFR	---	187.7	1,782.2	0.036	0.35		Steam	270	55
Biomass combustion	---	---	$258.5log_e(x)$+3,380.7	0.005	0.90		Steam	400	100
Natural gas boiler	---	---	---	0.003	0.90		Steam	215	120
Electricity Generation	**(€)**	**(€/m^2)**	**(€/kW$_e$)**	**(€/kWh)**	**$\eta_{electrical}$**		**HTF**	**Steam Temp. (°C)**	**Pressure (bar)**
PTC and Steam Turbine	3.8×10^5	320.1	700.0	0.041	0.16		Oil	400	---
							Steam	400	100
LFR and Steam Turbine	---	87.7		0.041	0.10		Steam	270	55
Biomass combustion and Steam Turbine	---	---		0.009	0.24		Steam	400	100
Gas Turbine and Steam Turbine	---	---	3,072.4	0.009	0.45		Exhaust gases	500	---
							Steam	565	127
Solar PV systems	---	80.3	2,200	0.002	0.15		---	---	---
Electricity and Heat Generation	**(€/kW$_e$)**			**(€/kWh)**	**$\eta_{electrical}$**	**$\eta_{thermal}$**	**HTF**	**Steam Temp. (°C)**	**Pressure (bar)**
Gas Turbine	975.9			0.004	0.28	0.72	Exhaust gases	500	---

3.2 Energy system modeling methodology

3.2.1 Energy hubs

Energy-services supply systems, so-called energy hubs, are related to the transmission and distribution systems with distributed energy resources, and from a system point of view mean the interfaces between energy producers, consumers, and the transportation infrastructure. An energy hub can be represented as a unit that provides the basic features of multiple energy carriers: input and output, conversion and storage. In *Figure 3.12* it's possible to note that a energy hub contains typical elements: electrical transformer, gas turbine, heat exchanger, battery storage, hot water storage, absorption chiller (Geidl, 2007).

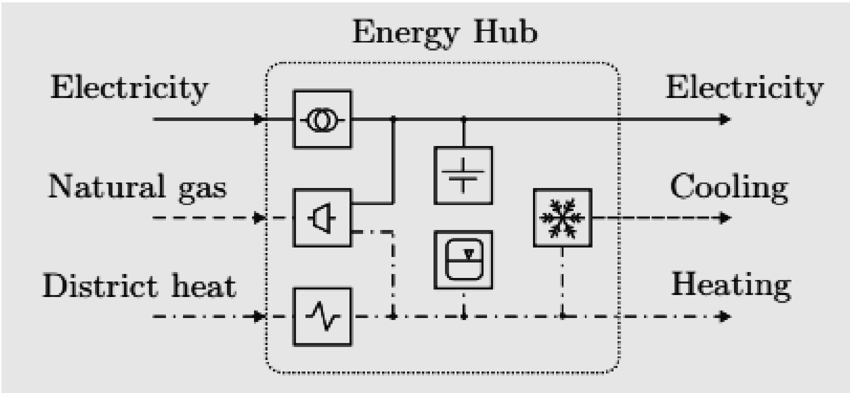


Figure 3.12: *Example of a energy hub.*

The energy hub exchanges energy with the surrounding systems via hybrid ports. A hybrid port is established by a bundle of single carrier ports. *Figure 3.12* outlines this concept where it's possible to detect two hybrid ports. At the input port, electricity, natural gas and district heat are demanded from the corresponding infrastructures. The output port provides transformed electricity, heating and cooling. The energy hubs comprise three basic elements: direct connections, converters and storage. Direct connections are implemented to deliver an input carrier to the output without converting it into another form or considerably changing its quality as electric voltage or hydraulic pressure. Then, the converter elements are used to convert power into others forms or qualities, for example in steam and gas turbines, reciprocating internal combustion engines. Finally, the energy storage can also be stored in the network itself, or either, in the pipelines by increasing the pressure in the system. An example is the electricity that can be stored directly in superconducting devices or indirectly, for example, in batteries (Geidl, 2007).

Besides that, there are real facilities that can be modeled as energy hubs, including power plants (cogeneration and trigeneration) and industrial plants (steel works and refineries).

3.2.2 Matrix modeling methodology of cogeneration systems

This section introduces a comprehensive energy hubs input-output matrix approach aimed at modeling cogeneration equipment taking into account the interactions among plant components and external energy networks in a steady-state modeling approached adapted from the work of Geild (Geidl, 2007).

Then, the entries of the matrix representing the links between inputs and outputs are given. Some optimizations can be developed by resorting to linear programming techniques, for instance to assess the impact of the change of a given input typology on the outputs. So, this approach defines input-output relations among the plant components where the different inputs considered are characterized by their availability and efficiency in order to obtain the best topology designs considering the costs and related emissions of carbon dioxide.

The matrix representation introduced here considers E energy entries and constructs the extended input array $v_1 = [v_{i1}, \dots, v_{iM}]^T$ and the extended output array $v_0 = [v_{01}, \dots, v_{0M}]^T$. The symbol T means transportation. The representation with E ordered entries is used for both the individual cogeneration plant components and the whole plant. The energy vectors involved are biomass (input B_i), natural gas (input N_i), solar (input G_i to global irradiation and input D_i to direct irradiation), electricity (input from the electricity distribution systems, P_i), and output to the load and/or to the electricity distribution systems and heat (demand output, H_0), thus the extended input and output arrays can be formed as $v_1 = [B_i, N_i, S_i, P_i, H_i]^T$ and $v_0 = [B_0, N_0, S_0, P_0, H_0]^T$.

The link between output and input in the whole cogeneration plant is given by the $E \times E$ overall efficiency matrix A in the form of $v_0 = A \,.\, v_i$. Considering a given set X of plant components, the efficiency matrix of an individual component $X \in X$ is denoted as A^X (with dimensions $E \times E$), and the corresponding output-to-input relationship is written in analogy to $v_0 = A \,.\, v_i$ as $v_0^X = A^X . v_i^X$.

The entries of A^X are identified by using a two-letter subscript, where the first subscript refers to the output energy vector and the second one to the input energy vector, resulting in the following general modeling matrix representation:

$$\begin{pmatrix} B_0^X \\ N_0^X \\ G_0^X \\ D_0^X \\ P_0^X \\ H_0^X \end{pmatrix} = \begin{pmatrix} \eta_{BB}^X & \eta_{BN}^X & \eta_{BG}^X & \eta_{BD}^X & \eta_{BP}^X & \eta_{BH}^X \\ \eta_{NB}^X & \eta_{NN}^X & \eta_{NG}^X & \eta_{ND}^X & \eta_{NP}^X & \eta_{NH}^X \\ \eta_{GB}^X & \eta_{GN}^X & \eta_{GG}^X & \eta_{GD}^X & \eta_{GP}^X & \eta_{GH}^X \\ \eta_{DB}^X & \eta_{DN}^X & \eta_{DG}^X & \eta_{DD}^X & \eta_{DP}^X & \eta_{DH}^X \\ \eta_{PB}^X & \eta_{PN}^X & \eta_{PG}^X & \eta_{PD}^X & \eta_{PP}^X & \eta_{PH}^X \\ \eta_{HB}^X & \eta_{HN}^X & \eta_{HG}^X & \eta_{HD}^X & \eta_{HP}^X & \eta_{HH}^X \end{pmatrix} \begin{pmatrix} B_i^X \\ N_i^X \\ G_i^X \\ D_i^X \\ P_i^X \\ H_i^X \end{pmatrix}$$

A more extensive application of this approach is presented below for all matrices representations of the technologies considered previously.

3.2.2.1 Matrix representation of heat generation technologies

The performance of the heat generation technologies is indicated by the thermal efficiency (η_{th}). Thus, the matrix representation of the PTC technology is presented below:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ H_0^{PTC} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_{th} & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ D_i^{PTC} \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{PTC} = A^{PTC}.v_i^{PTC}$$

The representation of the performance of the LFR technology is given by:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ H_0^{LFR} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_{th} & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ D_i^{LFR} \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{LFR} = A^{LFR}.v_i^{LFR}$$

The matrix representation of the performance of the Biomass combustion technology (from now on referred simply as Bio) is presented below:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ H_0^{Bio} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \eta_{th} & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} B_i^{Bio} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{Bio} = A^{Bio}.v_i^{Bio}$$

For the current situation in the mining industry, it has been applied the Natural gas boiler (from now on referred as NGB), as mentioned before to produce heat to dry the ore. Its matrix representation is presented below.

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ H_0^{NGB} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_{th} & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ N_i^{NGB} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{NGB} = A^{NGB}.v_i^{NGB}$$

3.2.2.2 Matrix representation of electricity generation technologies

The performance of the electricity generation technologies is indicated by the electrical efficiency (η_e).

The representative matrix connected to the PTC and Steam turbine (PTC_ST) technology is shown below:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{PTC\_ST} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_e & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ D_i^{PTC\_ST} \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{PTC\_ST} = A^{PTC\_ST}.v_i^{PTC\_ST}$$

Now, for the LFR and Steam turbine (LFR_ST) technology the matrix can be extracted as:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{LFR\_ST} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \eta_e & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ D_i^{LFR\_ST} \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{LFR\_ST} = A^{LFR\_ST}.v_i^{LFR\_ST}$$

Biomass combustion and Steam turbine (Bio_ST) technology is represented by the following matrix:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{Bio\_ST} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \eta_e & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} B_i^{Bio\_ST} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{Bio\_ST} = A^{Bio\_ST}.v_i^{Bio\_ST}$$

The combined-cycle (Gas and Steam Turbine (G_ST)) is represented as follows:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{G\_ST} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_e & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ N_i^{G\_ST} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{G\_ST} = A^{G\_ST}.v_i^{G\_ST}$$

Finally, the matrix representation of the Solar PV systems (PV) technology can be established as:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{PV} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_e & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ G_i^{PV} \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{PV} = A^{PV}.v_i^{PV}$$

For the current situation in the mining industry it has also been applied the electricity, as mentioned before, to produce power. Its matrix is presented below and the efficiency represents the energy transport. Thus, the losses are nearly nonexistent and its efficiency is considered equal to unity.

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{E} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \eta_e & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{E} \\ 0 \end{pmatrix} \Leftrightarrow v_0^{E} = A^{E}.v_i^{E}$$

3.2.2.3 Matrix representation of electricity and heat generation technologies

The performance of the electricity or heat generation technologies is also indicated by thermal efficiency (η_{th}) and electrical efficiency (η_e).

The Gas turbine (GT) is characterized by the matrix shown below:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{GT} \\ H_0^{GT} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \eta_e & 0 & 0 & 0 & 0 \\ 0 & \eta_{th} & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ N_i^{GT} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{GT} = A^{GT}.v_i^{GT}$$

4 Topology design

Computer modeling permits an easy and efficient analysis of the different engineering and economic parameters that have to be used as inputs in order to plan, design and create an energy system. In particular, computer simulations can be used to perform a feasibility study on any new system. Thus, this chapter mainly pretends to assess which is the best topology design related to a CHP system focusing on economic and environmental criteria (analysis costs and carbon dioxide emissions) to compare the different technologies mentioned before; a model will be elaborated using *MatLab © software and* Excel.

4.1 Methodology applied

This section pretends to evidence the methodology applied to found out the best CHP system (*Figure 4.1*). Firstly, some possible energy systems to be implemented in the mining industry are presented, then the system modeling for the proposed systems is shown, implemented in *MatLab© software* and Excel; after that comes the economic and environmental analysis and then the results obtained. Finally, it's provided a critical analysis of the results in the discussion and evaluation of the results section.

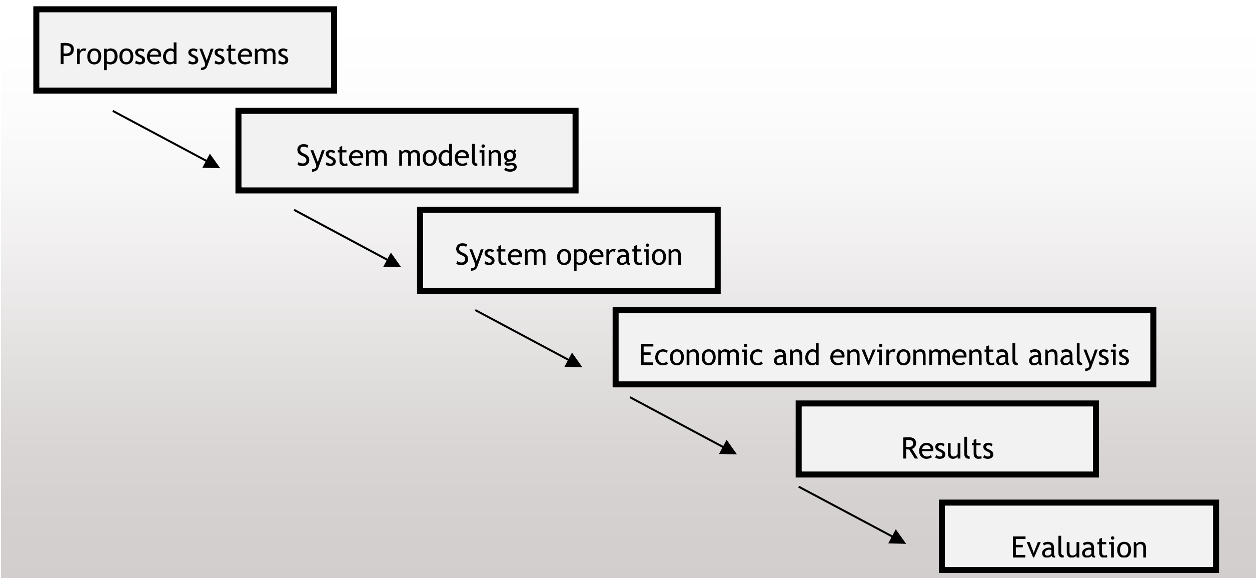


Figure 4.1*: Sequential scheme of the methodology applied.*

4.2 Proposed systems

From the current situation existing in the mining industry, where the electricity network and heat from natural gas boiler are used, herein are proposed new systems that should provide the energy requirements for the mining industry under study. Therefore, at this stage the proposed systems are defined; these systems will be hybrid and non-hybrid with the aim of evaluating the results from both and compare them.

Some of the possible variants to the current system are the following ones shown in *Table 4.1*. There are eleven different cases (Case A to K) that will be analyzed in this project.

Table 4.1: *Proposed systems for the CHP system in the mining industry.*

Case	Combination	
	Heat generation	Electricity generation
A:	Gas Turbine following heat demand	
B:	Gas Turbine following electricity demand	
C:	Natural Gas boiler	Solar PV system*
D:	PTC**	Solar PV system
E:	LFR***	Solar PV system
F:	Biomass combustion	Solar PV system
G:	PTC	PTC + Steam turbine
H:	LFR	LFR + Steam turbine
I:	PTC	Biomass combustion + Steam turbine
J:	LFR	Biomass combustion + Steam turbine
K:	Biomass combustion	Gas and Steam turbine

**Solar PV system: Solar Photovoltaic system; **PTC: Parabolic Trough Collector; ***LFR: Linear Fresnel Reflector*

The cases that integrate the goal of this study, mentioned in the previous table, were chosen based on interests of *CTM*. The cases A and B are important to ascertain what benefit is provided for the process by the use of a single technology for the simultaneous production of heat and electricity; cases C to F intend to demonstrate the versatility of solar PV systems, testing them simultaneously with the heat generation, namely with currently used situation in the mining industry (Case C). Case C is also proposed in order to be able to reuse the existing structure in the mining industry (i.e., natural gas boiler). Solar PV systems will be also tested with the other solar technologies (Cases D and E), as well as with the technology of combustion of biomass (Case F). The cases G and H have been tested to evidence the versatility of solar technologies, PTC and LFR, in the production of heat and, on the other hand, the electricity production by association with a steam turbine. Cases I and J also intend to investigate the performance of PTC and LFR with the technology of biomass combustion associated with a steam turbine. At last, the case K tries to analyze the system using biomass combustion and the combination of a gas and steam turbine in order to examine if there are benefits about this combination of technologies.

4.3 System modeling

The process begins by applying the concepts of energy hubs in order to apply in the implementation of the technologies matrix representation, which was already elaborated previously on sections 3.2.2.1 to 3.2.2.4. Thus, it was proposed the systems based on the sum of the matrix representation of a heat generation technology and another one of electricity generation, except for the gas turbine that features a single technology with heat and electricity simultaneous generation. Here is presented an example of a system modeling for a proposed system (Case C) that considers the heat generation technology of natural gas boiler and the electricity generation technology of solar PV systems, resulting in the following matrix representation:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ P_0^{PV} \\ H_0^{NGB} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \eta_e & 0 & 0 & 0 \\ 0 & \eta_{th} & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ N_i^{NGB} \\ G_i^{PV} \\ 0 \\ 0 \\ 0 \end{pmatrix} \Leftrightarrow v_0^{NGB\_PV} = A^{NGB\_PV} . v_i^{NGB\_PV}$$

As previously mentioned, the vector on the left side of each representation is the energy hub output, while on the right side one has the energy hub input that results from multiplying the matrix representation of each proposed system. Note that the output vector is always referring to heat (H_0^X) and electricity (P_0^X).

4.4 System operation

The matrix modeling methodology referred before has been implemented based in several simulations by a logical order with the purpose of developing a model of heat and electricity generation for the mining industry. Firstly it was implemented a priority of resources, then it was selected the type of the case (heat generation, electricity generation, heat and electricity generation) and finally it was designed the system operation implemented in *MatLab* © and Excel. In relation to the priority of the resources, that priority was created in order to benefit the use of renewable resources followed by the associated costs and only then must appear the non-renewable resources.

The resources priorities for the heat generation are started by giving advantage to solar (direct irradiation), followed by biomass with natural gas in the last place. On the other hand, for the electricity generation the resources priorities are implemented by giving priority to solar (first global irradiation then direct irradiation), followed by biomass, then by natural gas and electricity in the last position.

If not mentioned otherwise, the system operation is based on the following assumptions and simplifications: the system is considered to be in steady-state, which is reached after all transients or fluctuating conditions have damped out, and all quantities remain essentially constant, or oscillate uniformly; the loads at the energy hub outputs are inelastic because they consume constant power within the considered time period; penalties, such as cost, related to the individual energy carriers and/or system components are independent and separable from each other and storage are not included in this process.

The simulation parameters are defined with a fixed time step of 1 hour (60 minutes) for one year, i.e. 8,760 time periods are used.

The model for the system operation of heat generation, described in *Figure 4.2*, starts by presenting the matrix representation of the base situation in the mining industry. In that way, expressing the known values of the energy hub input for heat and electricity and the heat and electricity efficiencies matrix it is obtained the output of the base situation. This output has been compared to the output of each resource of each proposed system and the goal is that the proposed system achieves the values required by the output of the base situation. For that three conditions were tested in order to discover the maximum output for each proposed system: it was tested the condition when the output of the base situation has a higher value than the output in test, when the output of the base situation is equal to output of the proposed system and when the output of the base situation is smaller than the output of the proposed system. In this last condition is discovered the reached value of the input of the proposed system in order to know the difference between this value and the value of the base situation (referred as matrix operation). For the model of system operation for the electricity generation (*Figure 4.3* and *Figure 4.4*) the previous concepts are followed as well.

It is noteworthy that whenever the heat and electricity required production is not supplied, the consumption is made by prevailing resources in the current situation (i.e., electricity network and heat from natural gas boiler).

The required values of the output in terms of heat generation and electricity generation are 176.60 GWh/year and 97.24 GWh/year, respectively.

Besides that, in the schemes (*Figure 4.2* to *Figure 4.4*) when going from the input to output there is a multiplication by an efficiency matrix, however, it was omitted in order to not become so dense in the schemes.

Subsequently are shown the schemes for the heat generation (*Figure 4.2*), electricity generation (*Figures 4.3* and *4.4*) and finally for the heat and electricity simultaneous generation (*Figure 4.5*).

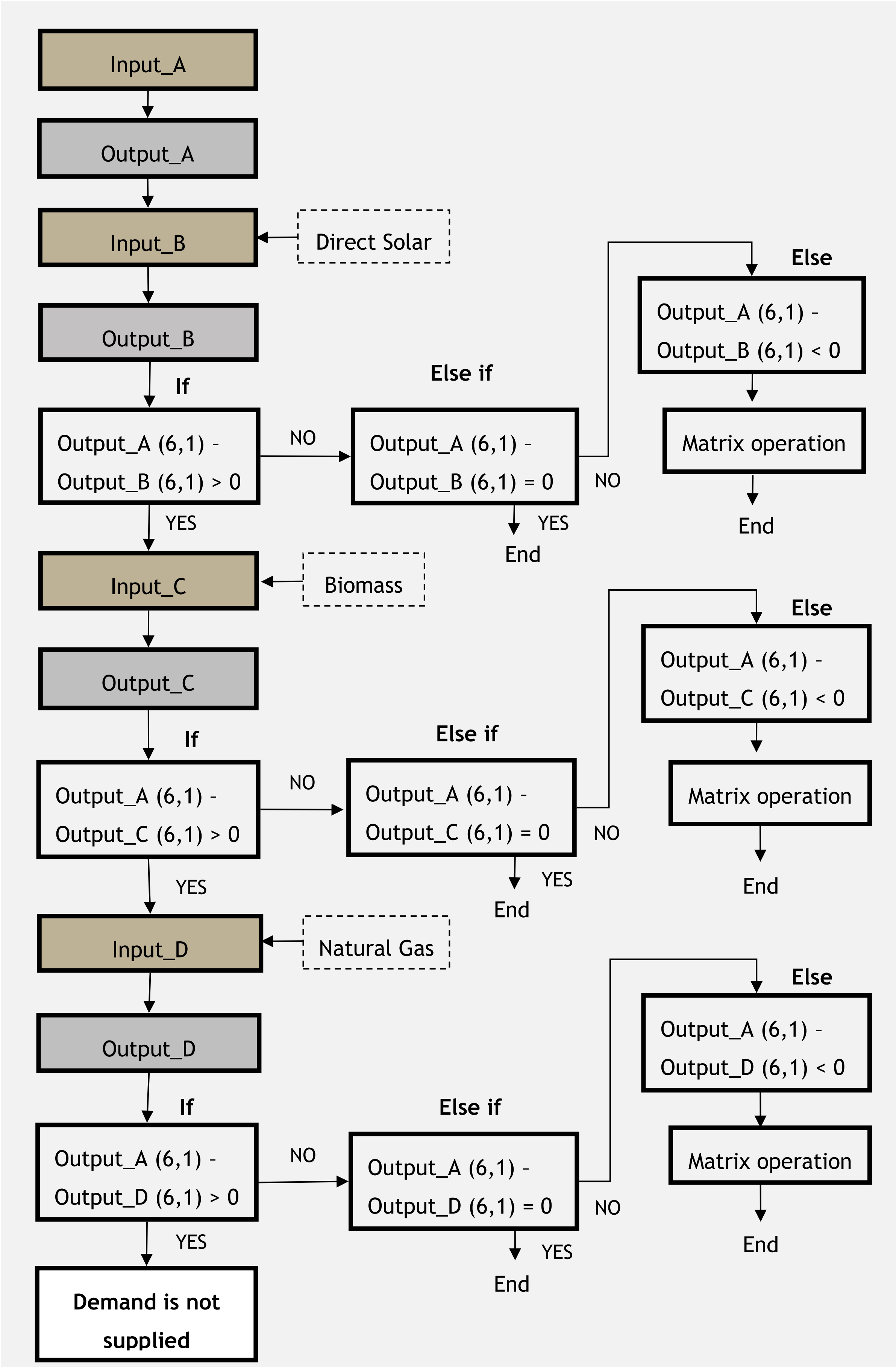


Figure 4.2: *System operation for heat generation.*

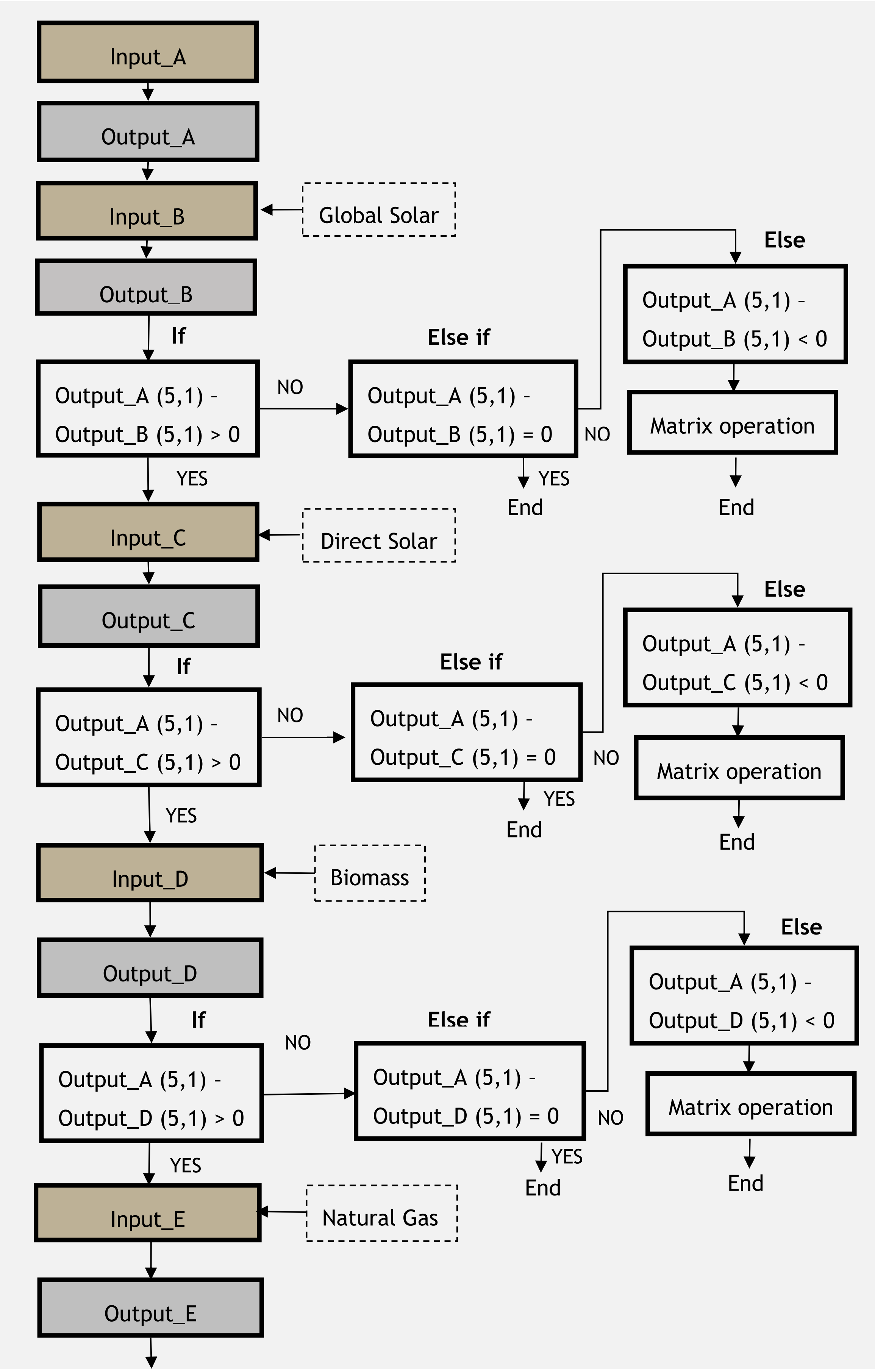


Figure 4.3: *System operation for electricity generation (Part I).*

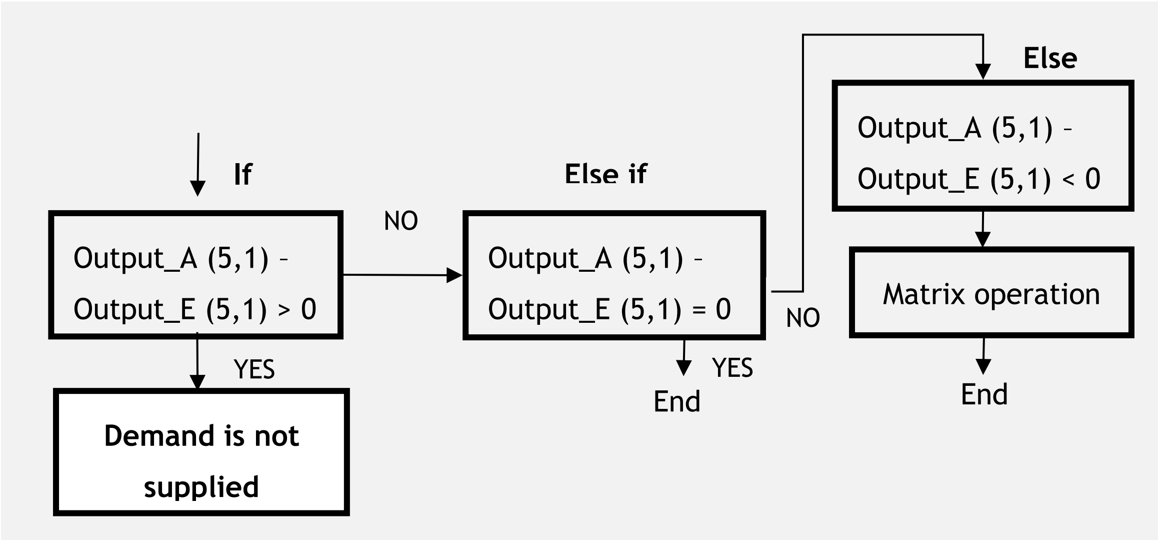


Figure 4.4: *System operation for electricity generation (Part II).*

For the systems of simultaneous generation of heat and electricity (cases A and B) the system operation was done by forcing these systems to provide the desired outputs of heat and electricity; since the demands are constant, it was used the Excel instead of MatLab ©. In Figure 4.5 is shown the system operation for the case A. In the case B the logical is similar, the difference is that this one is following electricity demand.

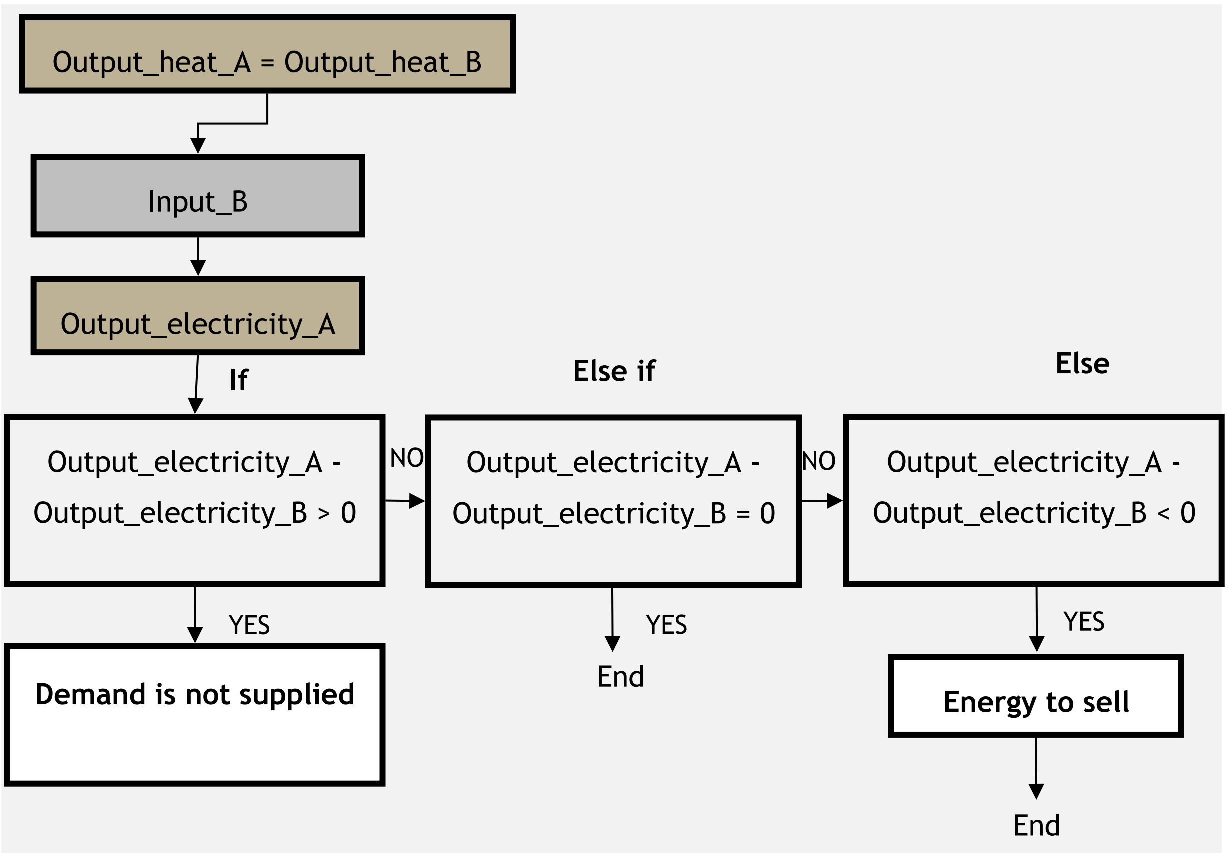


Figure 4.5: *System operation for heat and electricity generation for the case A.*

4.5 Economic and environmental project analysis

The economic and environmental analysis concepts define the most eco-financially attractive investment project. It involves decisions that are part of a process, which also includes generation and evaluation of alternatives to assist the technical specifications in a project. After the choice of technically viable alternatives are made, the most economical and environmental attractive ones are identified. In the process of establishing the economical and environmental viability of a project several parameters should be considered. In this tense, some of the factors that have been considered for the economic analysis (including investment project) and environmental analysis are presented below.

4.5.1 Economic factors

The scope of economic analysis of projects should be, broadly speaking, understood how to answer to a series of questions relating to project design, and to bring together the information required to make a decision whether to proceed with the project or not.

The economic factors considered for this project were the annual costs (energy costs, operation and maintenance – O&M – costs and Investment costs) and in terms of project analysis it was considered the NPV (Net Present Value), the IRR (Internal Rate of Return) and the Payback period. The NPV, IRR and Payback period offer three different perspectives into the economic value of projects. Since each technique has strengths and weaknesses, projects should be evaluated with respect to all three to obtain a better understanding of potential value (see Appendix IV).

4.5.2 Environmental factors

Global warming has been attributed to increased concentrations of greenhouse gases (GHG) and it is one of the main problems facing the planet today. Industrial activities are a major source of greenhouse gas emissions in production processes. The current study is focusing only in energy-related CO_2 emissions, not for any other greenhouse gases. The main part of the emissions are direct CO_2 emissions resulting from combustion processes for direct heating, and indirect emissions related to steam and electricity consumption. In this thesis, options are evaluated for the emissions caused by the natural gas resource (direct CO_2 emissions) (see Appendix V). Moreover, it is important to note that in this study, when talking about greenhouse gases (GHG), one refers only to CO_2 and not to CO_2 equivalent, the last taking into account the six greenhouse gases contained in the Kyoto protocol, that are CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC's), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

4.6 Results obtained

After testing the various proposed CHP systems (Cases A to K) the results obtained are described below in *Tables 4.2* to *4.4*. In *Table 4.2* are mentioned the results about the output and input values in each case; Table 4.3 presents the results about the investment analysis and finally, in *Table 4.4* are observed the results related to CO_2 emissions.

***Table 4.2**: Final results in terms of the output and input for each case analyzed.*

Case	Deviation of the OUTPUT required		Value reached from the OUTPUT required (%)		INPUTS			
					Resource		Energy (GWh/y)	
	Heat generation (GWh/y)	Electricity generation (GWh/y)	Heat	Electricity	Heat	Electricity	Heat	Electricity
A	0.00	-28.6	100%	70.6%	Natural Gas		245.3	
B	73.4	0.00	142%	100%	Natural Gas		347.3	
C	0.00	-79.2	100%	18.5%	Natural Gas	Solar	196.5	120.2
D	-66.9	-79.2	62.1%	18.5%	Solar		283.7	
E	-81.0	-79.2	54.1%	18.5%	Solar		283.7	
F	0.00	-79.2	100%	18.5%	Biomass	Solar	196.2	120.2
G	-66.9	-48.1	62.1%	50.5%	Solar		327.0	
H	-81.0	-54.9	54.1%	43.5%	Solar		327.0	
I	-66.9	0.00	62.1%	100%	Solar	Biomass	163.5	196.2
J	-81.0	0.00	54.1%	100%	Solar	Biomass	163.5	196.2
K	0.00	-8.90	100%	90.8%	Biomass	Natural Gas	196.2	196.5

***Table 4.3**: Final results about the investment analysis for all cases analyzed.*

Investment analysis									
	Annual costs (M€ *)			Investment costs					
	Energy	O&M		Installed power					
Case		Heat generation	Electricity generation	Thermal (MW)	Electrical (MW)	Costs (M€)	NPV (M€)	Payback period (years)	IRR (%)
A	14.7	0.71	0.27	20.1	7.84	7.65	31.2	2.10	47.6
B	20.8	1.00	0.39	28.5	11.1	10.8	-7.83	38.6	-3.09
C	11.8	0.53	0.10	20.1	10.3	22.7	-9.43	18.3	2.56
D	0.00	3.95	0.10	7.97	10.3	33.4	21.6	6.48	15.0
E	0.00	3.44	0.10	25.8	10.3	68.6	-18.1	14.5	4.72
F	3.90	0.88	0.10	20.1	10.3	39.1	54.4	4.47	22.2
G	0.00	3.95	1.98	7.97	7.06	15.7	56.8	2.31	43.2
H	0.00	3.44	1.73	25,8	7.36	51.0	11.4	8.73	10.5
I	3.90	3.95	0.39	7.97	11.1	15.7	88.3	1.61	61.9
J	3.90	3.44	0.39	25.8	11.1	39.9	59.5	4.29	23.2
K	3.90	0.88	0.79	20.1	10.8	16.5	96.6	1.56	64.3

M€ means million euros.*

In this table the NPV (Net Present Value), the IRR (Internal Rate of Return) and the Payback Return were calculated based on some assumptions: the discount rate considered (project cost of capital) was 8 % (not considering the inflation) and for a time of depreciation of 25 years. These values were indicated by *CTM* as acceptable for the type of project in question.

Table 4.4: *Final results related to CO_2 emissions for all cases analyzed.*

Case	INPUTS				CO_2 Emission Factor (kg CO_2/Nm^3)	CO_2 Conversion Factor (kWh/Nm^3)	CO_2 emissions (tons CO_2/year)
	Resource		Energy (GWh/y)				
	Heat	Electricity	Heat	Electricity			
A	Natural Gas		245.3		2.15	10.70	49,285
B	Natural Gas		347.3		2.15	10.70	69,779
C	Natural Gas	Solar	196.5	120.2	2.15	10.70	39,484
D	Solar		283.7		0	0	0
E	Solar		283.7		0	0	0
F	Biomass	Solar	196.2	120.2	0	0	0
G	Solar		327.0		0	0	0
H	Solar		327.0		0	0	0
I	Solar	Biomass	163.5	196.2	0	0	0
J	Solar	Biomass	163.5	196.2	0	0	0
K	Biomass	Natural Gas	196.2	196.5	2.15	10.70	39,484

4.6.1 Case A: Gas turbine following heat demand

The operation of this non-hybrid case was performed in order to generate the heat supply for the system, therefore the demand for the heat is automatically satisfied, but the electricity generated is 70.6% of that required for the system (*Table 4.2*). However, the rest 29.4% of the electricity loads may be directly supplied from the network.

4.6.2 Case B: Gas turbine following electricity demand

In this non-hybrid case the demand is validated for both heat and electricity supplies. The operation is conducted in order to produce the electricity demand and the heat generated is reaching the heat supply by the system and still providing 42% of overproduction (*Table 4.2*).

4.6.3 Case C: Natural gas boiler and Solar PV system

For this proposed hybrid system the electrical demand is not supplied because the Solar PV systems cannot generate the required electricity demand, providing only 18.5% of the required output (Table 4.2). Being a technology that uses solar irradiation, concretely global irradiation, it cannot always be constant, thus it becomes important to ascertain its behavior for the time of analysis. In that way, by creating a plot for the output obtained by solar PV systems during one year, it becomes evident that in some peak hours the coverage reached for achieving the desired electricity output is more than 100%, but only in 11 hours of the year. Considering 90% of the coverage reached the number rises to 128 hours and for 80% of the coverage reached the number rises to 356 hours. The highest coverage reached is 104.9% at hour 4,765, i.e., during the summer time, as shown in Figure 4.6.

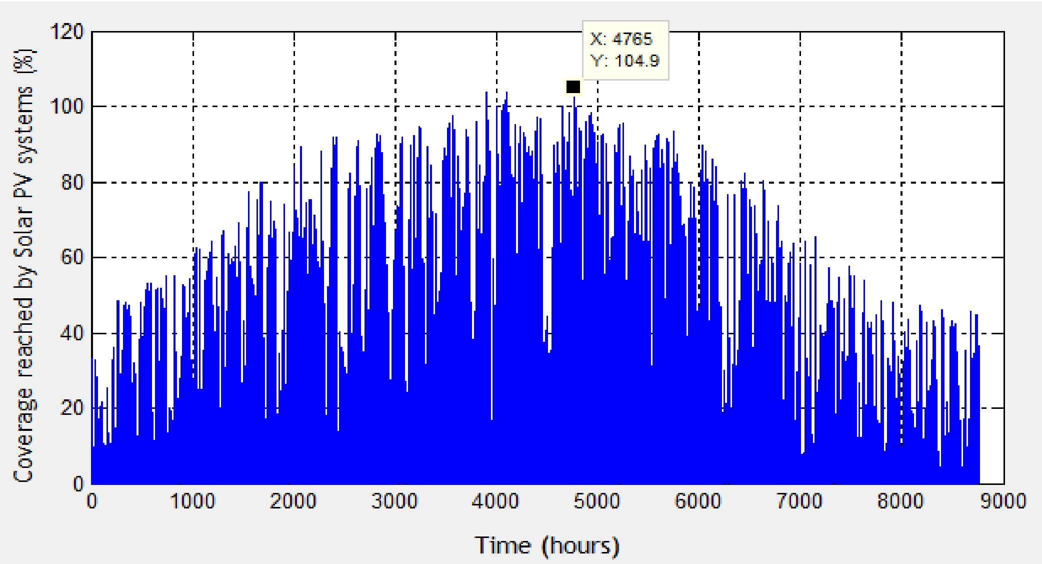


Figure 4.6: *Coverage reached by Solar PV systems hourly for a simulation time of 8,760 hours.*

So, it would be crucial to redefine the areas of implementation to use solar power in order to increase its area, and thus satisfy the demands required by the system.

Naturally, for the Cases D to F the demand of electricity it not supplied as well.

4.6.4 Case D: PTC and Solar PV system

In this non-hybrid case the demand is not validated, neither for heat nor for electricity. For heat generation the technological solution tested supplies 62.1% of the amount required and for electricity demand the amount supplied, as in Case C, is only 18.5% (*Table 4.2*). The highest coverage reached by PTC for heat generation is 102.9% at hour 4,765, i.e., during the summer time, as shown in *Figure 4.7*.

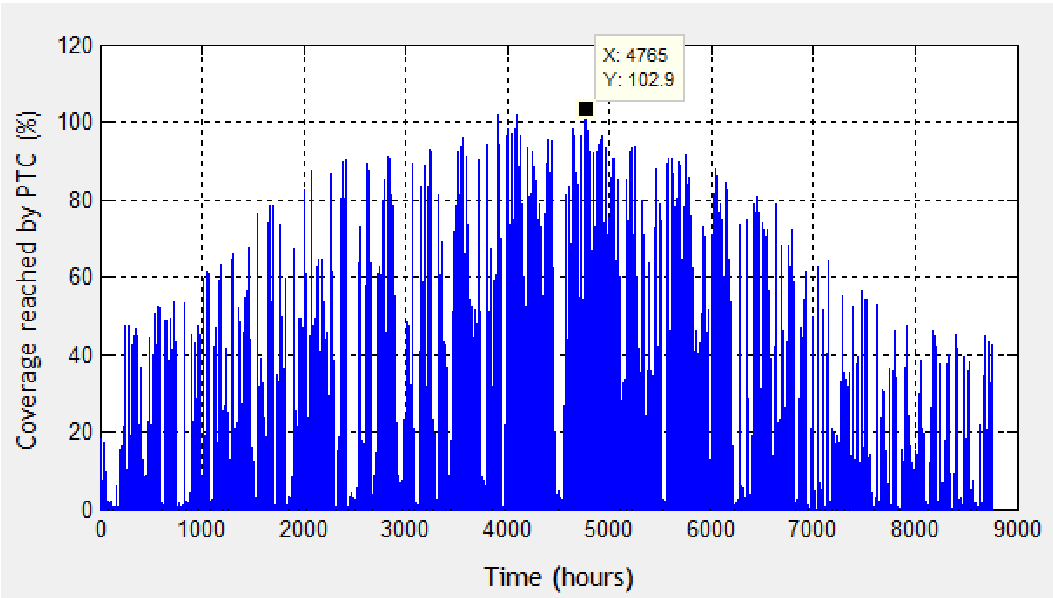


Figure 4.7: *Coverage reached by PTC hourly for a simulation time of 8760 hours.*

4.6.5 Case E: LFR and Solar PV system

The simulation for this non-hybrid case is very similar to the previous one because the heat generation is supplied by the same resource and for electricity generation uses Solar PV systems. So, the demand results obtained are nearly the same.

4.6.6 Case F: Biomass combustion and Solar PV system

For this hybrid system case the requirement of heat generation is totally supplied (100% of coverage reached – *Table 4.2*) and, as in other previous cases, the demand of electricity is not supplied by Solar PV systems. The requirement by biomass combustion for the heat generation is totally supplied because the biomass resources are sufficient to supply the required demands in each hour of the process.

4.6.7 Case G: PTC and PTC with Steam turbine

In the operation of this non-hybrid system the demand of heat and electricity are both not supplied. For heat generation the system supplies 62.1% of the amount required and for electricity demand the amount supplied is 50.5% of the one required.

4.6.8 Case H: LFR and LFR with Steam turbine

For this non-hybrid system the demand of heat and electricity are both not supplied. For heat generation the technological solution supplies 54.1% of the amount required and for electricity demand the amount supplied is 43.5% of the amount required.

4.6.9 Case I: PTC and Biomass combustion with Steam turbine

For this proposed hybrid system the heat demand is not supplied but the electricity demand is supplied. The values reached from the output required were 62.1% and 100%, respectively.

4.6.10 Case J: LFR and Biomass combustion with Steam turbine

In this hybrid case the demand is validated for electricity supplies but not for the heat supplies. For the heat generation the system supplies 54.1% of the amount required and for electricity demand the amount supplied is 100%.

4.6.11 Case K: Biomass combustion and Gas turbine with Steam turbine

For tis hybrid system the demand of heat is supplied. The demand of electricity is not satisfied (90.8% is supplied) but it could be supplied if the natural gas infrastructure was increased. Thus, the 9.2% of electricity that is missing could be provided with electricity from the grid.

4.7 Evaluation of the results

In this section an analysis of the results will be done. For simple understanding of the different obtained results in the different cases presented, main results will be shown in some graphs.

In *Figure 4.8* it is possible to see the energy consumed (input) by each proposed system (Cases A to K) analyzed for heat and electricity supplies. It is important to note that in some cases we have three columns which indicate that it has two different resources for the generation of the heat and electricity. The third column indicates the total input energy for those cases. The cases in the referred situation are the hybrid proposed systems: the cases C, F, I, J and K. The others have the same resource for the generation of heat and electricity (the non-hybrid proposed systems). For these cases the values of the input energy was summed.

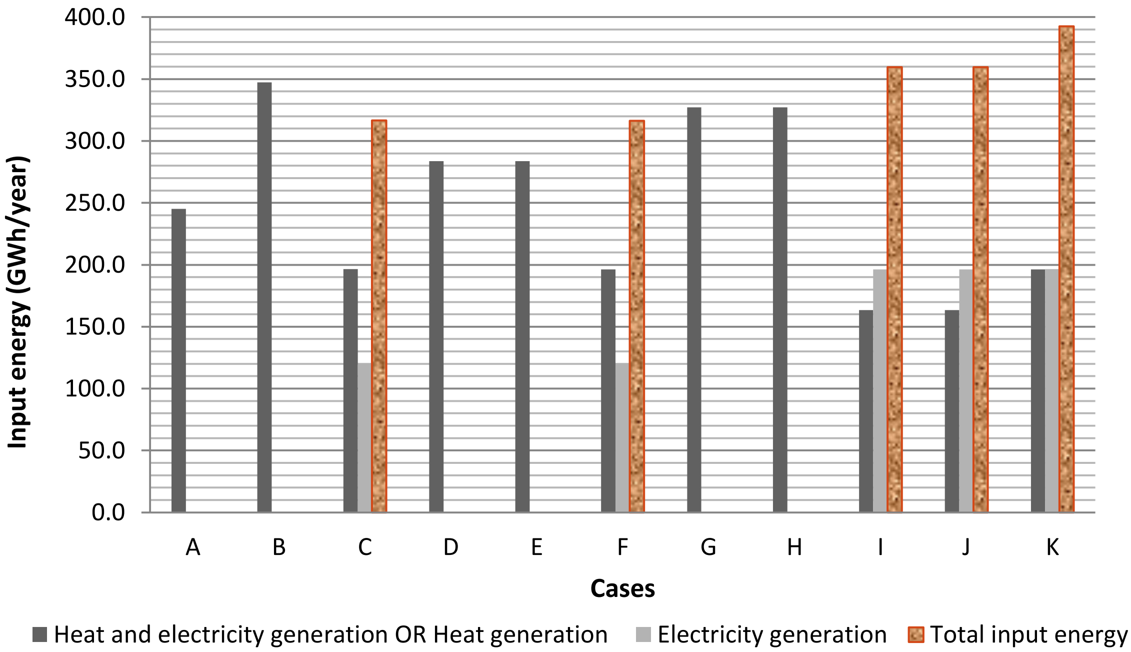


Figure 4.8: *Input energy (i.e., energy consumed) for all analyzed cases.*

Analyzing the previous graph (*Figure 4.8*) we can see that among the non-hybrid cases, case B (Gas turbine following electricity demand) is the one that has higher values of energy consumed (347.3 GWh/year) and the case A (Gas turbine following heat demand) is the one with less energy consumed (245.3 GWh/year). For the case D (PTC and Solar PV systems) and case E (LFR and Solar PV systems) the energy consumed are the same (283.7 GWh/year) because the solar resource is the same in these proposed systems.

Among the hybrid systems, in terms of the heat generation, the case F (Biomass combustion and Solar PV systems) and case K (Biomass combustion and Gas and Steam Turbine) are the proposed systems with higher values of energy consumed (196.2 GWh/year), while the case I (PTC and Biomass combustion with Steam turbine) and case J (LFR and Biomass combustion with Steam turbine) have lower energy consumed (163.5 GWh/year). In terms of the electricity generation for the hybrid proposed systems, the case K (Biomass combustion and Gas and Steam turbine) is the case with higher values of energy consumed (196.5 GWh/year for electricity generation, although very similar to cases I and J) and the cases C (Natural Gas boiler and Solar PV systems) and F have the smallest values of energy consumed (120.2 GWh/year). Globally, the case K is the proposed system with higher values of input energy.

Important to note that in the cases D and E (non-hybrid proposed systems) the energy consumed is exactly the same because in these cases the resource for heat and electricity generation is the same (solar resource). The same situation occurs in the case G (PTC and PTC with Steam turbine) and case H (LFR and LFR with Steam turbine) and also in the cases I and J (hybrid proposed systems) because the resources for heat generation and for electricity are the same (in this case Solar and Biomass resources).

In *Figure 4.9* is shown the relation between the input energy (i.e., energy consumed) and the energy costs by every single case. It is possible to note that the Case B is the most expensive proposed system (20.8 M€/year) and, as seen previously, is also the case with higher values of energy consumed. Obviously the systems with just solar energy as input are the cheapest (and with null cost in terms of energy consumed – Cases D, E G and H).

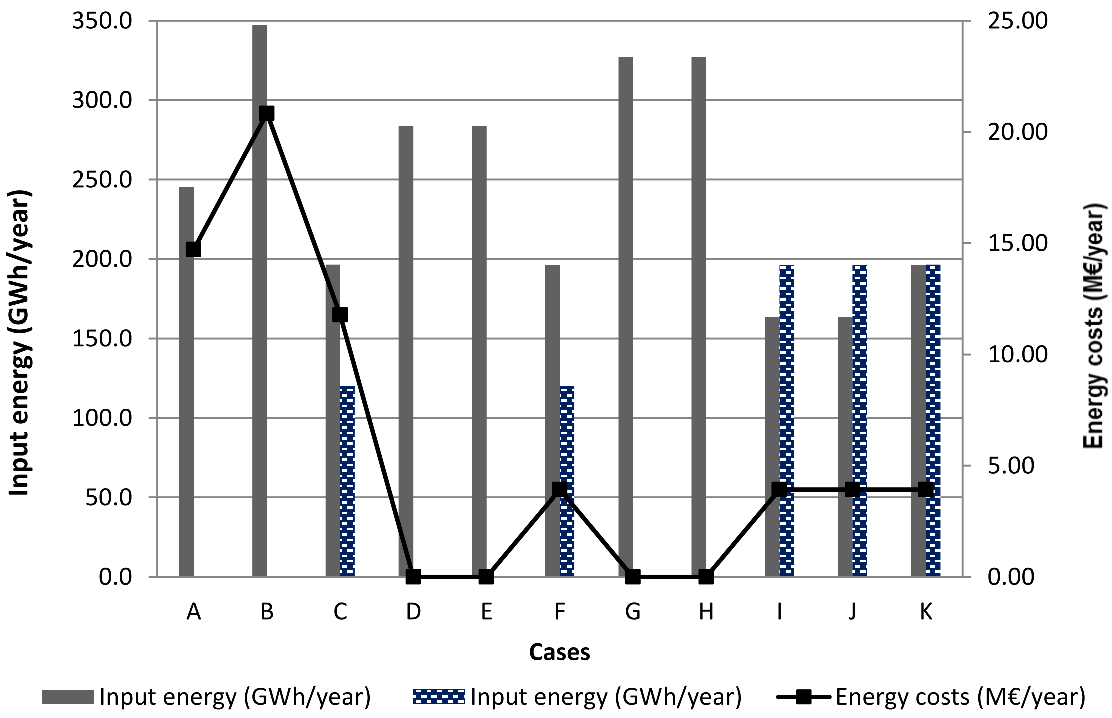


Figure 4.9*: The input energy and the energy costs for all cases analyzed.*

In this previous figure, it is also observed that the Cases F, I, J and K have the same energy costs (3.90 M€/year) related to the biomass combustion.

Figure 4.10 presents an overview of the O&M (Operation & Maintenance) costs and the Investment costs for all cases.

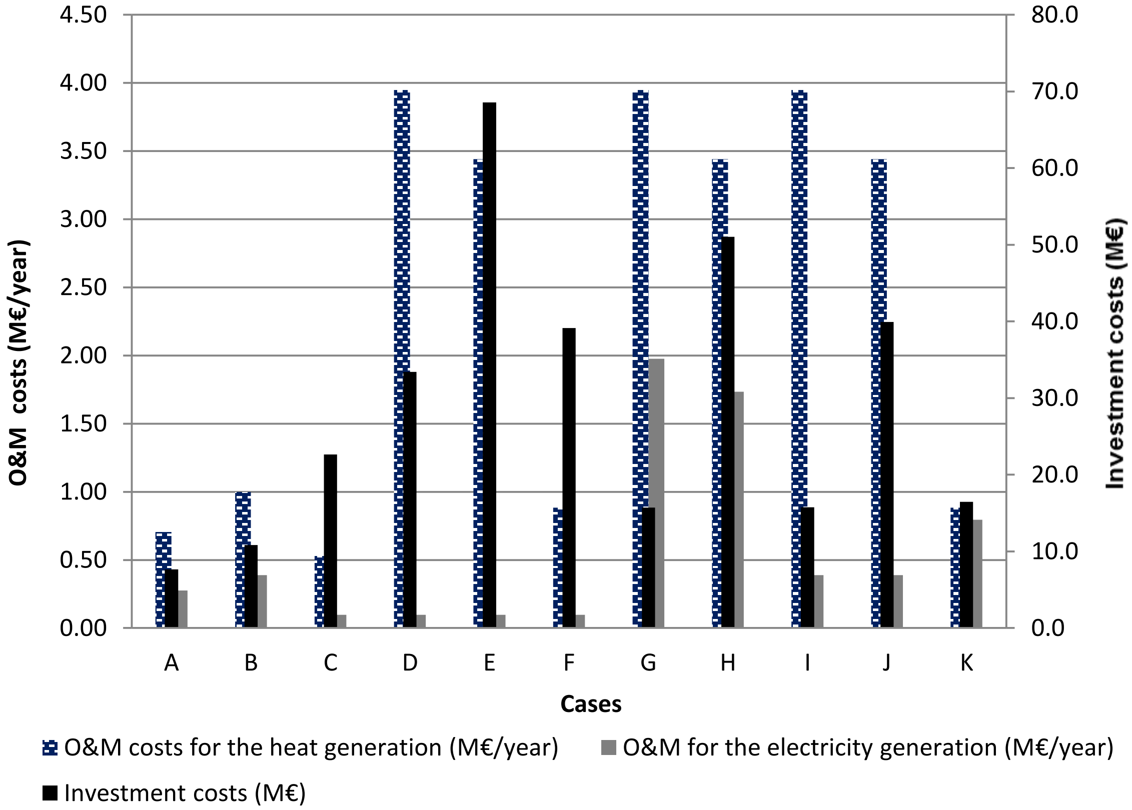


Figure 4.10: *O&M costs and the Investment costs for the proposed systems (Cases A to K).*

According to the results indicated in this figure, in terms of the O&M costs for the heat generation, the cases D, E, G, H and I represent the higher values (nearly 4.0 million euros per year). The case C has the lowest O&M costs for the heat generation (nearly 0.5 million euros per year). On the other hand, the results about the O&M costs for the electricity generation show that the case G is the most expensive one (nearly 2.0 million euros per year) and the cases C to F are the less expensive (0.10 million euros per year). In that way, it is possible to note that in terms of O&M costs for the heat generation the cases integrating the CSP technologies (PTC and LFR) are the most expensive and the technologies using gas turbines are the cheapest. In terms of the O&M for the electricity generation, the proposed systems that are integrating Solar PV systems are the cheapest and the cases that are integrating steam turbines are the most expensive.

About the Investment costs, it is possible to note that the case E (LFR and Solar PV systems) is the system with higher investment costs (68.6 M€/year) and the case A is the cheaper in terms of the investment costs (7.7 M€/year).

Looking at the cases where it is considered the Solar PV systems (Cases C to F), it is clear that the case C is the proposed system with the lowest costs. This can, at least partially, be explained because this case is considering the Natural gas boiler for the heat generation, from the current situation existing at the mining industry. In that way, the costs are lower because the infrastructure is already in the mine.

In terms of the investment project analysis it was considered the parameters of the NPV (Net Present Value), the IRR (Internal Rate of Return) and the Payback period. The final results shown in Figure 4.11 shown that there are large differences among the different proposed systems and this variability can be confirmed by the NPV, IRR and Payback period results that spread out between 96.6 M€ and -18.1 M€ for NPV; 64.3% and -3.09% for IRR and 38.6 years to 1.56 years for the Payback period.

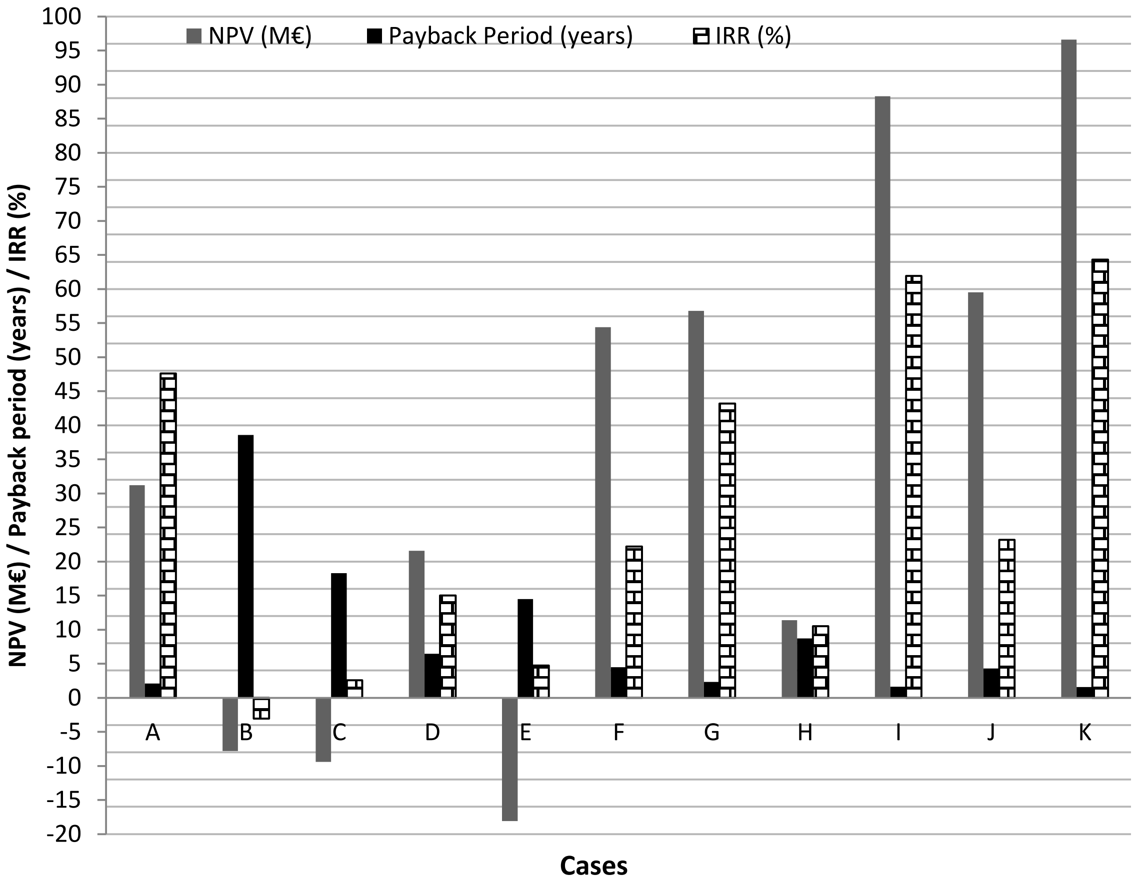


Figure 4.11: *NPV, Payback periods and IRR for all analyzed cases.*

According to the final results in terms of NPV, the proposed systems that have acceptable values of NVP (NPV > 0) are all cases except the cases B, C and E.
When comparing several exclusive investment projects, the projects with the highest positive NPV should be accepted. So, the case K was the proposed system with the highest value of NPV.
In terms of the IRR parameter, the case K was the proposed system with higher value. Finally, about the Payback period, the Case B has the highest payback return (38.6 years) and the Case K has the smaller value (1.56 years).

In *Figure 4.12* are outlined the results about the annual CO_2 emissions and the energy costs.

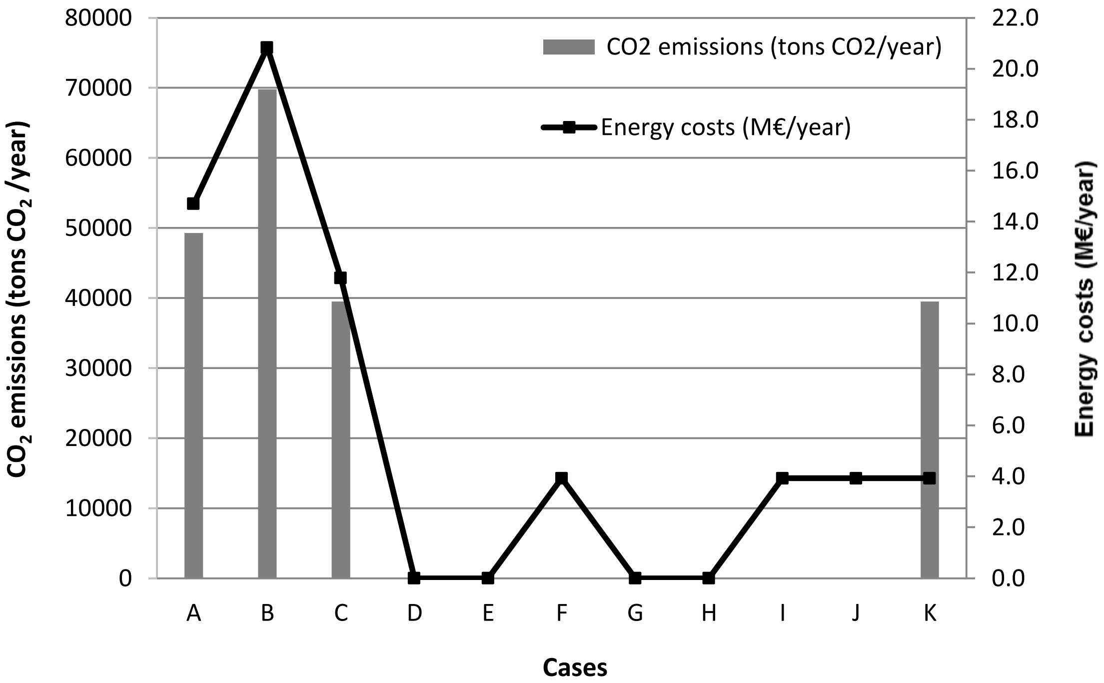


Figure 4.12: Annual CO_2 emissions and energy costs for the different cases.

Analyzing the graphic above (*Figure 4.12*) it appears that the scenarios where CO_2 is generated correspond to the cases A, B, C, and K. It is important to refer that all in these cases the CO_2 emissions are generated by the natural gas resource. Case B has the highest CO_2 emissions; moreover, case K is the one that produces less CO_2 emissions (among the possibilities that make use of NG). In terms of the annual energy costs it appears that Case B requires higher costs (Cases D, E, G and H have no energy costs because are the cases with solar energy).

In the cases D to J the CO_2 emissions are zero because these proposed systems are using biomass and/or solar resources to produce the heat and electricity and that do not produce CO_2 emissions.

Now taking into account the various parameters analyzed economically and environmentally, it was made a final table (*Table 4.5*) in order to clarify the results by assigning a positive, intermediate or negative validation analysis for each value of the parameters. It should be noted here that in this table although the various parameters analyzed are identified, according to the interests of *CTM* the parameters of the energy costs, investment costs and CO_2 emissions should have a higher consideration for the final decision of the most sustainable CHP system so as to provide the heat and electricity necessary in the extraction and in the processing of the potash deposits.

Thus, the Case B is the proposed cogeneration system with more negative validations (five in a total of eight validations), including bad validations for the energy costs and for the CO_2 emissions, which suggests that this proposed cogeneration system should not be chosen.

The Cases C and E have both four negative validations and for the case C two of these bad validations are about the CO_2 emissions and energy costs; case E has a positive validation in terms of the energy costs.

Besides that, the cases D, E, G and H are the proposed systems with more positive validations for the most relevant parameters. In this way, the cases D and E have positive validations for the parameters of the energy costs and CO_2 emissions and in terms of the investment costs the case D has intermediate values and the case E has bad values. The case G has positive validations in the three more relevant parameters and the case H has positive validation for the energy costs and for the CO_2 emissions.

The case F has intermediate validation for the energy costs and investment costs but has a satisfactory validation for the CO_2 emissions.

The cases I and J have an intermediate validation for the parameter of the energy costs and a satisfactory validation about the investment costs and CO_2 emissions.

The case K has an intermediate validation for the energy costs but about the investment costs has a satisfactory validation and a bad validation for the CO_2 emissions.

In terms of environmental analysis of the proposed systems the cases D to J are all advantageous because they have no CO_2 emissions. In terms of economic analysis the cases D and G are the most advantageous cases because the case D has positive validation for energy costs and intermediate validation for the investment costs and the case G has positive validation for the energy and investment costs both.

Overall an attempt to find the best system in economic and environmental terms the case G seems to be the one that has the best results.

__Table 4.5__: Validation of the final results for all proposed cogeneration systems.

Case	Energy costs (M€/year)	O&M (M€/year) Heat generation	O&M (M€/year) Electricity generation	Investment costs (M€)	NPV (M€)	IRR (%)	Payback period (years)	CO_2 emissions (tons CO_2/year)
A	↓	↑	↑	↑	↑	↑	↑	↓
B	↓	↔	↑	↑	↓	↓	↓	↓
C	↓	↑	↑	↔	↓	↔	↓	↓
D	↑	↓	↑	↔	↑	↔	↑	↑
E	↑	↓	↑	↓	↓	↔	↓	↑
F	↔	↑	↑	↔	↑	↑	↑	↑
G	↑	↓	↔	↑	↑	↑	↑	↑
H	↑	↓	↔	↓	↑	↔	↑	↑
I	↔	↓	↑	↑	↑	↑	↑	↑
J	↔	↓	↑	↔	↑	↑	↑	↑
K	↔	↑	↑	↑	↑	↑	↑	↓
↓	$\Omega \geq 4.00$	$\Omega \geq 3.00$	$\Omega \geq 3.00$	$\Omega \geq 40.00$	$\Omega > 0.00$	$\Omega > 0.00$	$\Omega \geq 20.0$	$\Omega \geq 10.000$
↔	$2.00 \leq \Omega < 4.00$	$1.00 \leq \Omega < 3.00$	$1.00 \leq \Omega < 3.00$	$20.0 \leq \Omega < 40.00$	---	---	$0.00 \leq \Omega < 20.0$	$0.00 < \Omega < 10.000$
↑	$0.00 < \Omega < 2.00$	$0.00 < \Omega < 1.00$	$0.00 < \Omega < 1.00$	$0.00 < \Omega < 20.0$	$\Omega \leq 0.00$	$\Omega \leq 0.00$	$\Omega < 0.00$	$\Omega = 0$

Legend:

Ω means the value of the parameter evaluated; ↑ *means that the evaluated parameter for the current proposed system has satisfactory values;* ↔ *means that the evaluated parameter for the current proposed system has intermediate values;* ↓ *means that the evaluated parameter for the current proposed system has unsatisfactory values.*

5 Conclusions

An analysis of the complete mining process for a potash mining industry in Catalonia (Súria) was done to understand its energy demand conditions and the energy losses. An energy simulation approach was developed, using the simulation tool *DesignBuilder*, to be able to supply the heat and domestic hot water demands, by those energy losses, for the near eight municipal facilities (referred as buildings A to H). The first conclusion that can be withdrawn from this work is that the total end uses of the municipal facilities corresponds to 95,115 kWh/year, which means 0.36 % of the total energy demand for heating and water systems in the municipality of Súria. Thus, it comes out that the 10% of heating losses resulting from the drying and sizing the mineral in the potash mining industry in Súria are sufficient to supply the proposed district heating, because the heating losses of 70,741 GJ/year correspond to 1,965,027 kWh/year against 95,115 kWh/year for the proposed district heating.

On the other hand, a state of the art related to the technologies evaluation was made, and the matrix modeling methodology is presented. A comprehensive system operation was implemented in *MatLab*© and using Excel, and was carried out to develop a general model in order to obtain the best topology design between the eleven proposed systems (refereed as Cases A to K) on the selection of a CHP system focusing on economic and environmental parameters. The economic parameters were the energy costs, O&M (Operation and Maintenance) costs, investment costs, the NPV (Net Present Value), IRR (Intern Rate of Return) and payback period, while the environmental parameter was the carbon dioxide emissions. The matrix modeling methodology was demonstrated for all the proposed systems examples showing its characteristics and usefulness. Once developed the general model, all proposed systems were simulated and the evaluation of the results was done.

Analysis over the final results shows different performances for the proposed cogeneration systems and concretely shows that, in terms of environmental analysis, the cases D (PTC and Solar PV systems), E (LFR and Solar PV systems), F (Biomass combustion and Solar PV systems), G (PTC and PTC with Steam turbine), H (LFR and LFR with steam turbine), I (PTC and Biomass combustion with Steam turbine) and J (LFR and Biomass combustion with steam turbine) are all advantageous because they have no CO_2 emissions. In terms of economic analysis the case D and the case G are the most advantageous. The case D has positive validation for energy costs and intermediate validation for the investment costs and the case G has positive validation for both the energy and investment costs.

Overall an attempt to find best cogeneration system in economic and environmental terms, the case G seems to be the one that has the best results, because it defines the best optimization of economic and environmental benefits in the heat and electricity generation process (zero energy costs and zero carbon dioxide emissions).

In summary, the final decision should be taken by *CTM* and naturally taking into account the interests of the mining industry where this project will be applied.

6 Appreciation of work produced

6.1 Objectives accomplished

The main objectives for this project were effectively reached, namely:

- Definition of the energy demand for the complete potash deposits (from extraction to ore processing) for the mining process: electric power and heat quantification;
- Definition of the energy demand for the near municipal facilities: water systems and heating quantification, for the waste heat use from the heat losses, running for this purpose the software *Design Builder* © ;
- Evaluation of the available energy resources, considering fossil and renewable energy resources, that could be used for the proposed CHP system;
- Proposal of the best topology system design using economic and environmental criteria (costs and carbon dioxide emissions) implemented on *Matlab* © and on Excel.

6.2 Limitations and future work

Analyzing all the work that was done in this master thesis and in order to improve it, the following aspects can be mentioned to be addressed in the future:

From the sustainability perspective it would be interesting to conduct a study about the application of the environmental tool decision named LCA (Life Cycle Assessment) in order to develop a compilation and evaluation of the inputs, outputs and the potential environmental impacts of potash and salt related to the potash and salt deposits in the mining industry in Súria.

Besides that, it should be continued the definition of the energy demand of the complete salt deposits for the mining process under study: electric power and heat quantification (energy flux and temperature).

Since the heating losses in the mining industry can satisfy the needs of the proposed district heating and still gets a lot of energy, it would be interesting to expand the district heating not only for municipal facilities but also for residential facilities so as to be able to use as much energy as possible from these heating losses.

It is important to note that the analysis about the investment project was done based on a simplified financial analysis. However, this simplistic analysis can detect previously what occurs in each analyzed case (Case A to Case K) and subsequently, from this analysis, it can be performed a more detailed analysis in future works.

It would also be grateful to make a review of energy policies implemented by European Union countries related to self-generation and self-consumption in the industry sector in order to assess which technologies will create more benefits in economic terms. These policies assess the benefits of investment in order to determine which policies are most favorable for each technology so that later CTM can create partnerships in these countries.

6.3 Final appreciation

The project developed during this master thesis allowed observing more realistically the implementation and the rationalization of the energy strategies, in terms of heat and electricity, and their resources.

The propose of a district heating for the near municipal facilities, using *Designbuilder,* was very interesting as well as to notice the energy demand about domestic hot water and heating for a building, allowing a better sensibility to this theme.

The modeling of cogeneration systems, using *Matlab* ©, was very important to analyze the various technologies that can be applied for these systems and to observe the different results obtained for each proposed cogeneration systems.

Finally, this project can help *CTM* on its further projects between this mining industry in Súria or with projects related to cogeneration systems.

7 References

Al-Sood, M. M., Matrawy, K. M., & Abdel-Rahim, Y. M. (2013). *Optimum parametric performance characterization of an irreversible gas turbine Brayton cycle* (Vol. 4, pp. 1-13). International Journal of Energy and Environmental Engineering.

Avila, J. M., Martín, J. R., Alonso , C. R., Escuin, M. C., Cadalso , J. M., & Bartolomé, M. L. (2012). *Atlas de Radiación Solar en España utilizando datos del SAF de Clima de EUMETSAT* (pp. 29-101). Gobierno de España: Agencia Estatal de Meteorología.

Barlev, D., Vidu, R., & Strover, P. (2011). *Innovation in Concentrated Solar Power.* (Vol. 95, pp. 2704-2716). Solar Energy Materials & Solar Cells. Elsevier.

BCS Incorporated. (2007). *Mining Industry Energy Bandwidth Study* (pp. 4-29). U.S Department of Energy - Industrial Technologies program.

Borello, D. (2013). *A Co-Powered Biomass and Concentrated Solar Power Rankine Cycle Concept for Small Size Combined Heat and Power Generation* (Vol. 6, pp. 1478-1496). Roma: Energies.

Climent , F. C., Perelló , J. M., Poch, J., Gual, G., Duocastella, D. P., & Abella, M. P. (2011). Datos relativos al parque geológico y minero de la Catalunya Central. *XII Congreso Internacional de Patrimonio Geológico y Minero, XVI Sesión Científica de la SEDPGYM*, (pp. 89-94). Manresa.

Colom, A. Y. (2008). *Anàlisi dels moviments superficials de l'àrea de Súria per mitjà d'Interferometria Diferencial SAR (DINSAR)* (pp. 53-58). Universitat Politècnica de Catalunya.

Cooper, P. I. (1974). *Design philosophy and operating experience for Australian solar stills* (pp. 1-8). Solar Energy. Elsevier.

CTM. (2012, october). *Estudio, construcción y operación de una planta de generación/cogeneración de energía eléctrica, utilizando como combustible biomasa.*

CTM. (2013). Centre Tecnologic de Manresa .

Cúmano, G. N. (2009). *Análise técnico-económica de diferentes estratégias passivas de eficiência energética em edificios* (pp. 14-40). Lisboa: Instituto Superior Técnico .

Davies, G., & Woods, P. (2009). *The potential and costs of disctrict heating networks.* Oxford: Pöyry Energy (Oxford) Ltd.

Department of Energy & Climate Change. (2000). Retrieved October 1st, 2013, from Appendix 3: Example 3 - Determination of Useful Heat Output by Direct Use of Gas Turbine (or Engine) Exhaust Gases : http://chpqa.decc.gov.uk/guidance-notes/

Department of Resources, Energy and Tourism. (2010). *Energy efficiency opportunities.* Retrieved from http://www.ret.gov.au/energy/Documents/energyefficiencyopps/EMB%20Mining.pdf

Dermibas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science* (pp. 219-230).

Deshmukh, M. K., & Deshmukh, S. S. (2006). *Modeling of hybrid renewable energy systems* (Vol. 12, pp. 235-249). Renewable and Sustainable Energy Review. Elsevier.

Díez-Mediavilla , M., Alonso-Tristán , C., Rodríguez-Amigo, M. C., & García-Calderón , T. (2010). *Implementation of PV plants in Spain: A case study* (Vol. 14, pp. 1342-1346). Renewable and Sustainable Energy Review. Elsevier.

Ding, J. J., & Buckeridge, J. S. (2000). *Design considerations for a sustainable hybrid energy system* (Vol. 27, pp. 1-5). IPENZ Transactions.

Duffie, J. A., & Beckman, W. A. (2006). *Solar Engineering of Thermal Processes* (3rd ed.). Hoboken, New Jersey: Wiley.

Energy and Environmental Analysis (an ICF International Company). (2008). *Technology Characterization: Steam Turbines* (pp. 2-14). Arlington, Virginia : Energy and Environmental Analysis .

Energy and Environmental Analysis (an ICF International Company). (2008, december). *Technology Characterization: Gas Turbines.* Arlington, Virginia : Energy and Environmental Analysis .

Enhanced Capital Allowances. (n.d.). *Biomass boilers and room heaters.* Retrieved novemer 2, 2013, from https://etl.decc.gov.uk/etl/site/resources.html

European Academies Science Advisory Council . (2011). *Concentrating solar power: its potential contribution to a sustainable energy future* (pp. 7-11). UK: The Clyvedon Press Ltd.

Ferrer, N. F., & Sant, J. M. (2012, Maio). Àrea de Territori i Medi Ambient - Consell Comarcal del Bages i Federació ADF Bages. *Estudi de disponibilitat de Biomassa al Bages.* Manresa, Generalitat de Catalunya.

Fosas, N. F., & Sant, J. M. (2012, Maio). Àrea de Territori i Medi Ambient - Consell Comarcal del Bages i Federació ADF Bages. *Estudi de disponibilitat de Biomassa al Bages*. Manresa, Generalitat de Catalunya.

Gale, H. S. (1921). *Potash Deposits in Spain* (pp. 3-16). Contributions to Economic Geology.

Geidl, M. (2007). *Integrated Modeling and Optimization of Multi-Carrier Energy Systems* (pp. 7-35). Austria : ETH Zurich .

Greenpeace. (2009). *Concentrating Solar Power: Global Outlook 09* (pp. 7-60). Amsterdam : Greenpeace International .

Häberle, A. (n.d.). *The Solarmundo line focussing Fresnel collector.Optical and thermal performance and cost calculations*. Retrieved november 3, 2013, from http://solarpaces-csp.org/CSP_Technology/docs/solarpaces_fresnel_9_2002.pdf

Hartman, H. L., & Mutmansky, J. M. (2002). *Introductory mining engineering* (2nd ed., pp. 327-331). John Wiley and sons, inc.

Hinrichs, R. A., & Kleinbach, M. (2013). In *Energy its Use and the Environment* (5th ed., pp. 528-532). Canada: International Edition.

Innobiomassa. (2010). *Estudi de Disponibilitat de Biomassa i Demanda Energètica a la Comarca de l'Anoia*. Catalunya : Servei d'Ocupació de Catalunya .

Institut Català de d'Energia. (2010). In *Guia de Desenvolupament de Projectes de Xarxes de Disctricte de Calor i de Fred* (pp. 7-31). Barcelona: Institut Català d'Energia.

Institut Català de l'energia. (2001). *Universitat Politècnica de Catalunya*. Retrieved november 2, 2013, from Atlas Solar de Catalunya: http://www20.gencat.cat/portal/site/icaen

Institution of Engineering and Technology. (2008). C*ombined Heat and Power (CHP)*. The Institution of Engineering and Technology.

Instituto Geológico y Minero de España. (2011). Retrieved September 23, 2013, from Panorama Minero: http://www.igme.es/internet/PanoramaMinero/PMLin.htm

International mining. (2012). *Potash from Iberia* (pp. 14-16). InfoMine.

Kalogirou, S. A. (2004). *Solar thermal collectors and applications* (Vol. 30, pp. 247-251). Progress in Energy and Combustion Science. Elsevier.

Kindlein , M. A. (2007). *Identification of Profitable Projects: A Survey among Firms in IT and Telecommunications Industry* (pp. 14-16). Sweden : Blekinge Institute of Technology.

Kopp, J. R. (2009). *Towards a Multi-Dimensional Framework for Assessing the Value of Software Projects* (pp. 49-53). Pace University .

Lizarraga, J. M., & Aguado, A. V. (1995). *Cogeneration with gas turbines for dryers and hot water boilers* (Vol. 15, pp. 319-325). Heat recovery Systems and CHP. Spain: Elsevier Science Ltd.

Lobera, D. T. (2010). *Measuring actual operations conditions of a photovoltaic power generator* (pp. 4-10). Master of Science Thesis. Tampere University of Technology .

López-Cózar, J. M. (2008). *Energía Solar Térmica*. Retrieved november 3, 2013, from Instituto para la Diversificación y Ahorro de la Energía: http://www.iea-shc.org/publications/statistics/IEA-SHC_Solar_Heat_Worldwide-2008.pdf

Lund, H. (1995). *The Design Reference Year Users Manual*. Technical University of Denmark : Thermal Insulation Laboratory .

Manser, J. (2011). *Feed-in Tariffs and Economic Profit of Small Hydropower Plants in Switzerland* (pp. 52-54). Zurich: Centre for Energy Policy and Economics (CEPE).

Mendes, J. F., & Horta, P. (2010). A produço de electricidade por via termosolar em centrais de concentração. *Renováveis magazine - Revista técnico-profissional de Energias Renováveis*, 30-35.

Mesquita, F. G. (2010). *Design Optimization of Stand-Alone Hybrid Energy Systems* (pp. 5-7). FEUP. Porto.

Mills, D. R., Le Lievre, P., & Morrison, G. R. (2004). *First Results from Compact Linear Fresnel Reflector* (pp. 1-6). Sydney.

Ministerio de industria, Energía y Turismo. (2011). *Minería y Explosivos*. Retrieved September 24, 2013, from http://www.minetur.gob.es/energia/mineria/Paginas/Index.aspx

Moran, M. J., & Shapiro, H. N. (2006). *Fundamentals of Engineering Thermodynamics* (pp. 388-424). England: John Wiley & Sons, Inc.

Mular, A. L., Halbe, D. N., & Barratt, D. J. (2002). *Mineral processing plant design, practice, and control :proceedings* (Vol. 1, pp. 1371-1400). USA: Littleton : Society for Mining, metallurgy and exploration.

National Energy Education Development Project. (2012). *School Energy Survey - Student Guide*. Retrieved october 24, 2013, from http://www.need.org/needpdf/EnergySurveyStudent.pdf

National Renewable Energy Laboratory (NREL). (1995, June). *User's Manual for TMY2s-Typical Meteorological Years*. Retrieved november 2, 2013, from http://rredc.nrel.gov/solar/pubs/tmy2/PDFs/tmy2man.pdf

Natural Resources Canada. (n.d.). *Boilers*. Retrieved Septiembre 14, 2012, from http://oee.nrcan.gc.ca/industrial/equipment/boilers/10852

Neumann, A. M. (2001, february). *Characterizing Industrial Crystallizers of Different Scale and Type*. Retrieved ocotber 15, 2013, from http://www.dart-europe.eu/full.php?id=531192

Norgate, T., & Haque, N. (2009). *Energy and greenhouse gas impacts of mining and mineral processing operations*. Retrieved Setembro 26, 2013, from http://www.sciencedirect.com/science/article/pii/S0959652609003199

NREL - National Renewable Energy Laboratory. (2010). Retrieved november 2013, from http://www.nrel.gov/csp/

Nussbaumer, T. (2003). *Combustion and Co-combustion of Biomass:Fundamentals, Technologies, and Primary Measures for Emission Reduction* (Vol. 17, pp. 1510-1521). Energy & Fuels. Zurich.

Obernberger, I. (2010). *Trends and opportunities of micro-CHP technologies based on Biomass combustion* (pp. 1-7). Austria: Proceedings of the 18th European Biomass Conference .

Obernberger, I., & Thek, G. (2008). *Combustion and gasificatiion of solid biomass for heat and power production in Europe - State-of-the-art and relevant future developments* (pp. 4-20). Austria : Proc. of the 8th European Conference on Industrial Furnaces and Boilers .

Oficina Catalana de Canvi Climàtic. (2013). *Guia pràctica per al càlcul d'emissions de Gasos amb Efecte d'Hivernable (GEH)*. Catalunia.

Overend, R. P. (n.d.). Direct Combustion of Biomass. In R. P. Overend , *Renewable energy sources charhed with energy from the sun and originated form earth-moon interaction* (Vol. 1, pp. 74-100). Moscow : Encyclopedia of Life Support Systems .

PotashCorp. (2013, august). *The Potash Journey* (pp. 1-4). Potash Corp.

Prokesch, M. E., & Ciccarelli, S. A. (2011). *Method for drying potash*. United States : FLSMIDTH A/S.

Sánchez, C. V. (2011). Tesis doctoral. S*istemas de gestión en explotaciones mineras de Cataluña: Situación, factores determinantes de implantación y posibilidades futuras* (pp. 5-12). Manresa: Universitat Politècnica de Catalunya.

Segal, A., & Epstein, M. (2003). *Optimized working temperatures of a solar central* (pp. 503-510) *Solar Energy*.

Separations Product Group. (n.d.). *APV Dryer Handbook*. Retrieved october 10, 2013, from http://userpages.umbc.edu/~dfrey1/ench445/apv_dryer.pdf

Singh , V. (2006). *Introduction to Photovoltaic Systems* (Vol. 5, pp. 22-25). Institute of Technology and Management.

Tsotsas, E., & Mujumdar, A. S. (2012). *Modern Drying Technology* (First ed., Vol. 4, pp. 5-8). Wiley-VCH.

U.S Manufacturing and Mining (2004). Retrieved October 8, 2013, from http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/energy_use_loss_opportunities_analysis.pdf

Ullmann, F. (1931). Enciclopedia de Química Industrial. *Metalurgia. Minería. Cerámica. Electroquímica. Explosivos.* (Vol. 8, pp. 117-121). Gustavo Gili.

United Nations Environment Programme. (2001). *Environmental Aspects of Phosphate and Potash Mining* (1st ed., pp. 10-14). UNEP.

Viebahn, P., Lechon, Y., & Trieb, F. (2010). *The potential role of concentrated solar power (CSP) in Africa and Europe—A dynamic assessment of technology development, cost development and life cycle inventories until 2050* (Vol. 39, pp. 4420-4430). Energy Policy. Elsevier.

Winter, C. J., Van-Hull, L. L., & Sizmann, R. L. (1991). *Solar Power Plant: fundamentals, technology, systems, economics* (pp. 25-90). New York: Springer-Verlag.

Wu, D. W., & Wang, R. Z. (2006). *Combining cooling, heating and power: A review* (pp. 459-495). Progress in Energy and Combustion Science. Elvesier .

Zarza, E. (2003). *Solar Energy Conversion and Photoenergy Systems* (Vol. 1, pp. 341-351). Encyclopedia of Life Support Systems.

8 Appendix I: Simulation and Design for the District heating

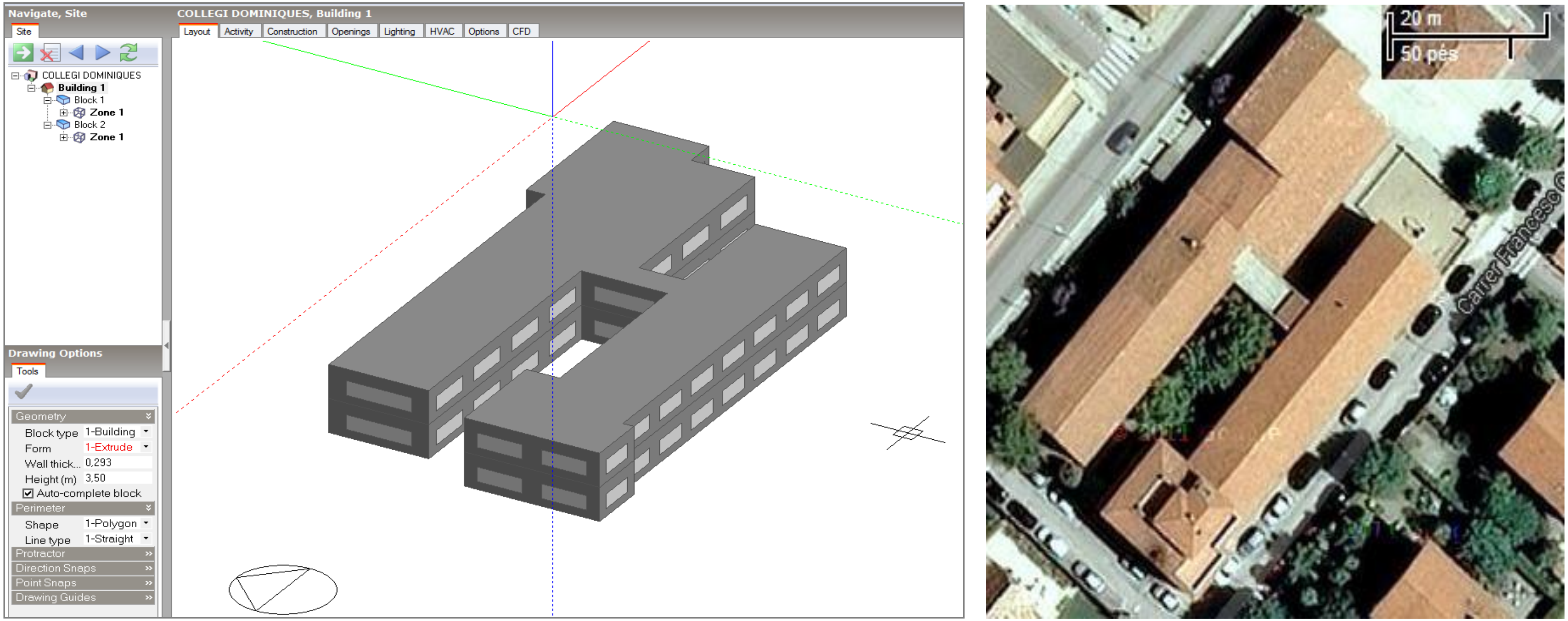


Figure 8.1: *General overview of the building A designed on DesignBuilder (on the left) and the respectively overview on Google maps (on the right).*

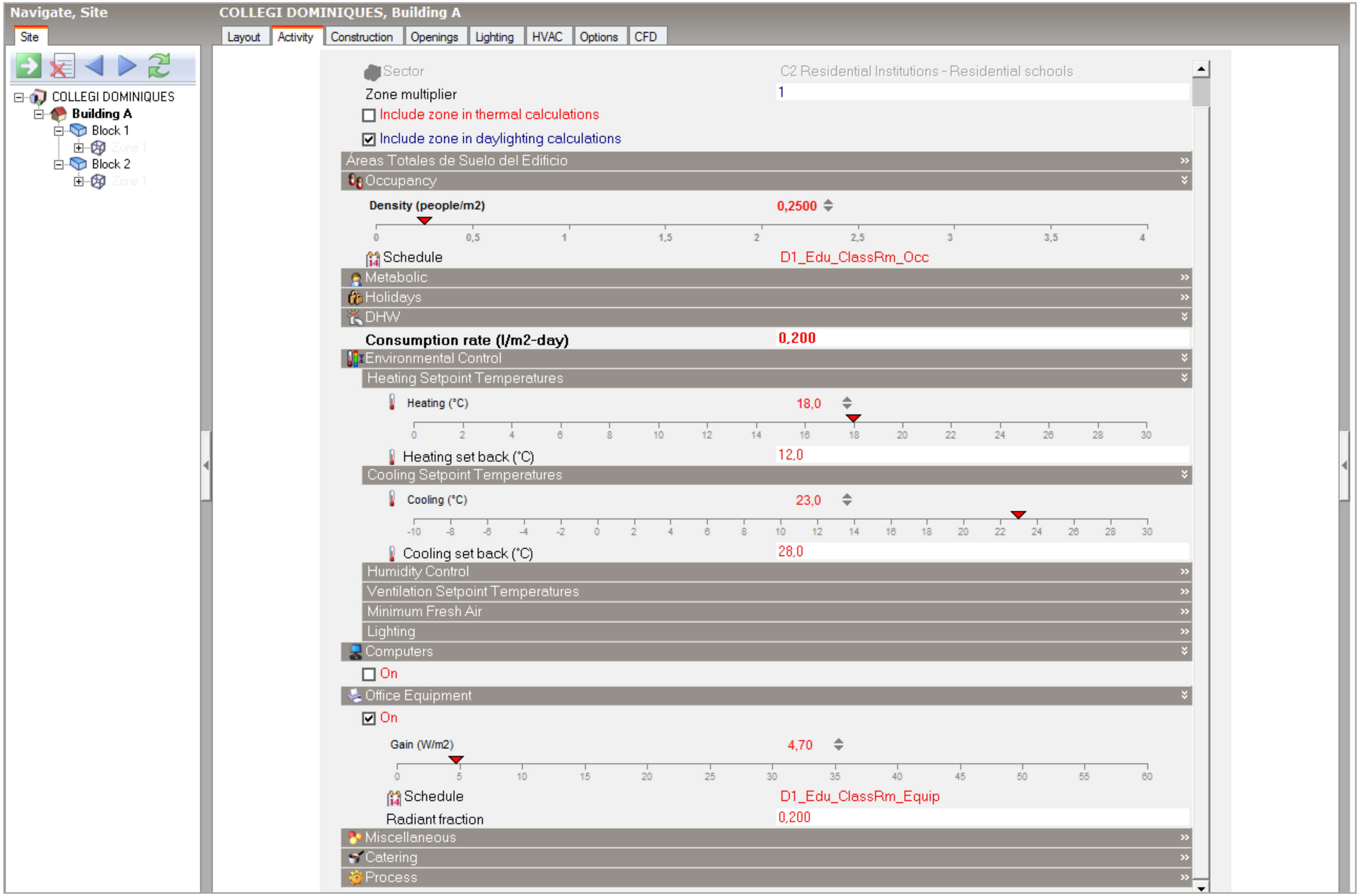


Figure 8.2: *Detailed analysis of the activity performed in the building A with the incorporation of data on Designbuilder.*

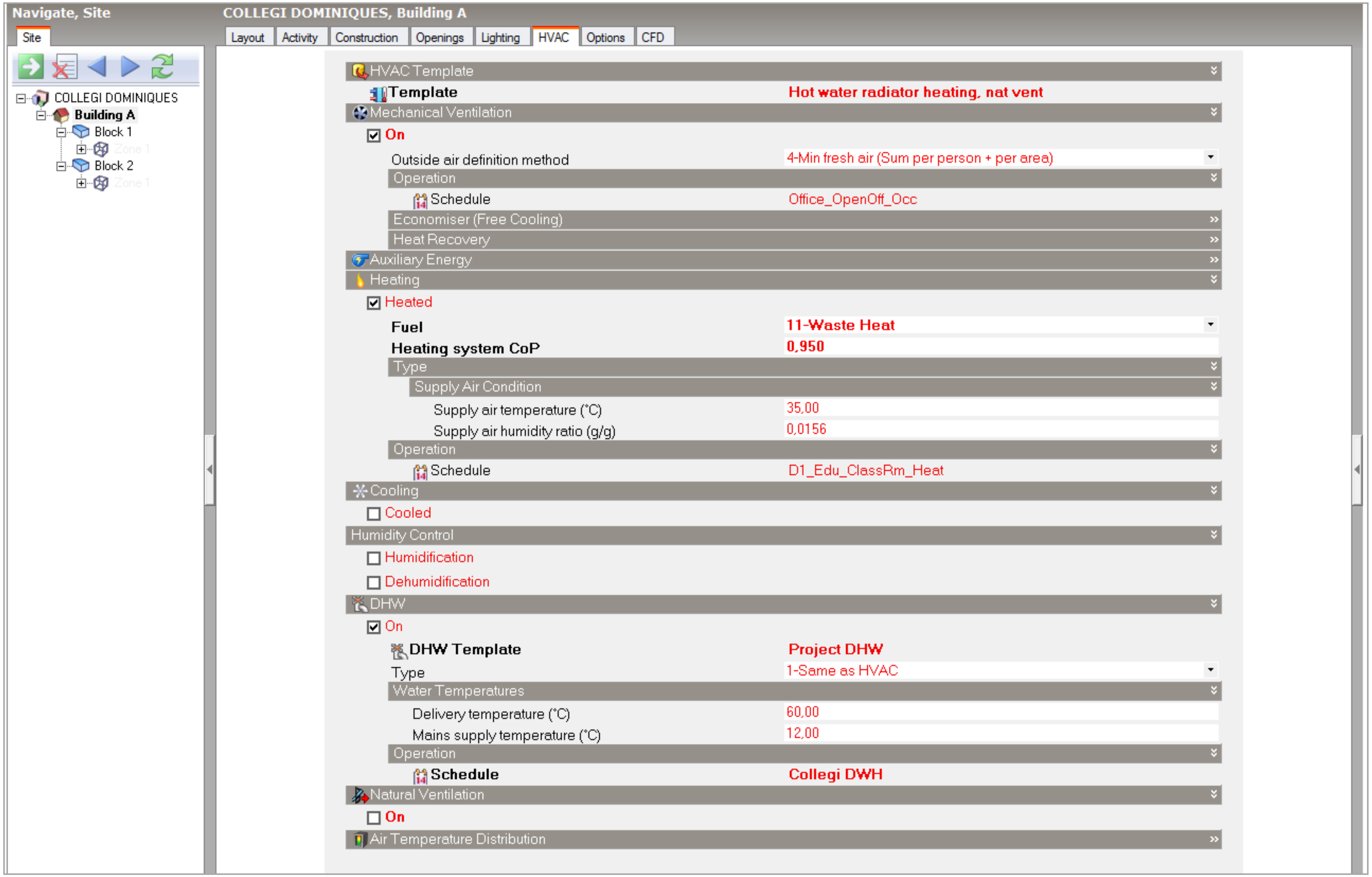


***Figure 8.3**: Detailed analysis about HVAC (Heating, Ventilation and Air conditioning) for the building A on Designbuilder.*

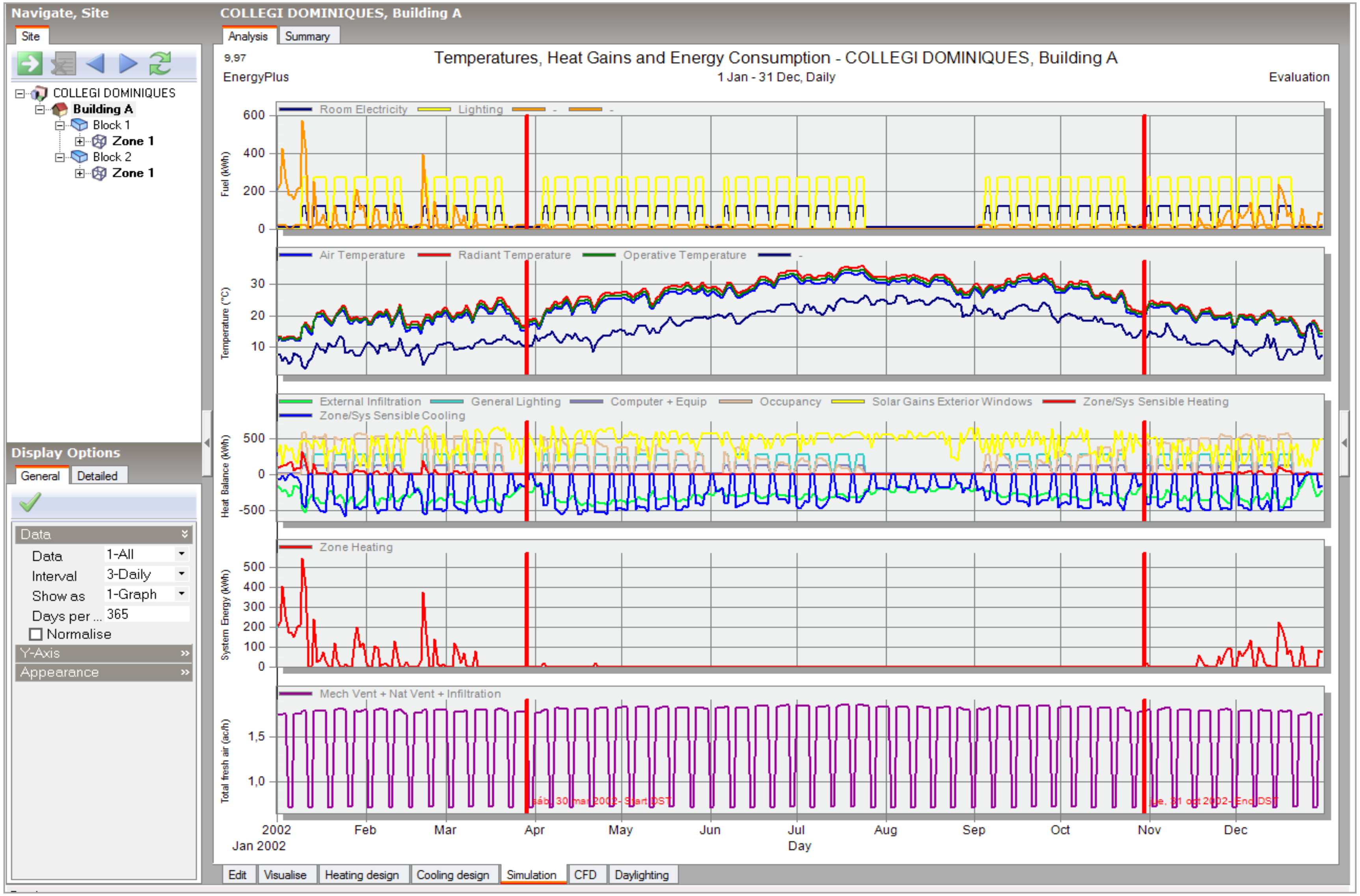
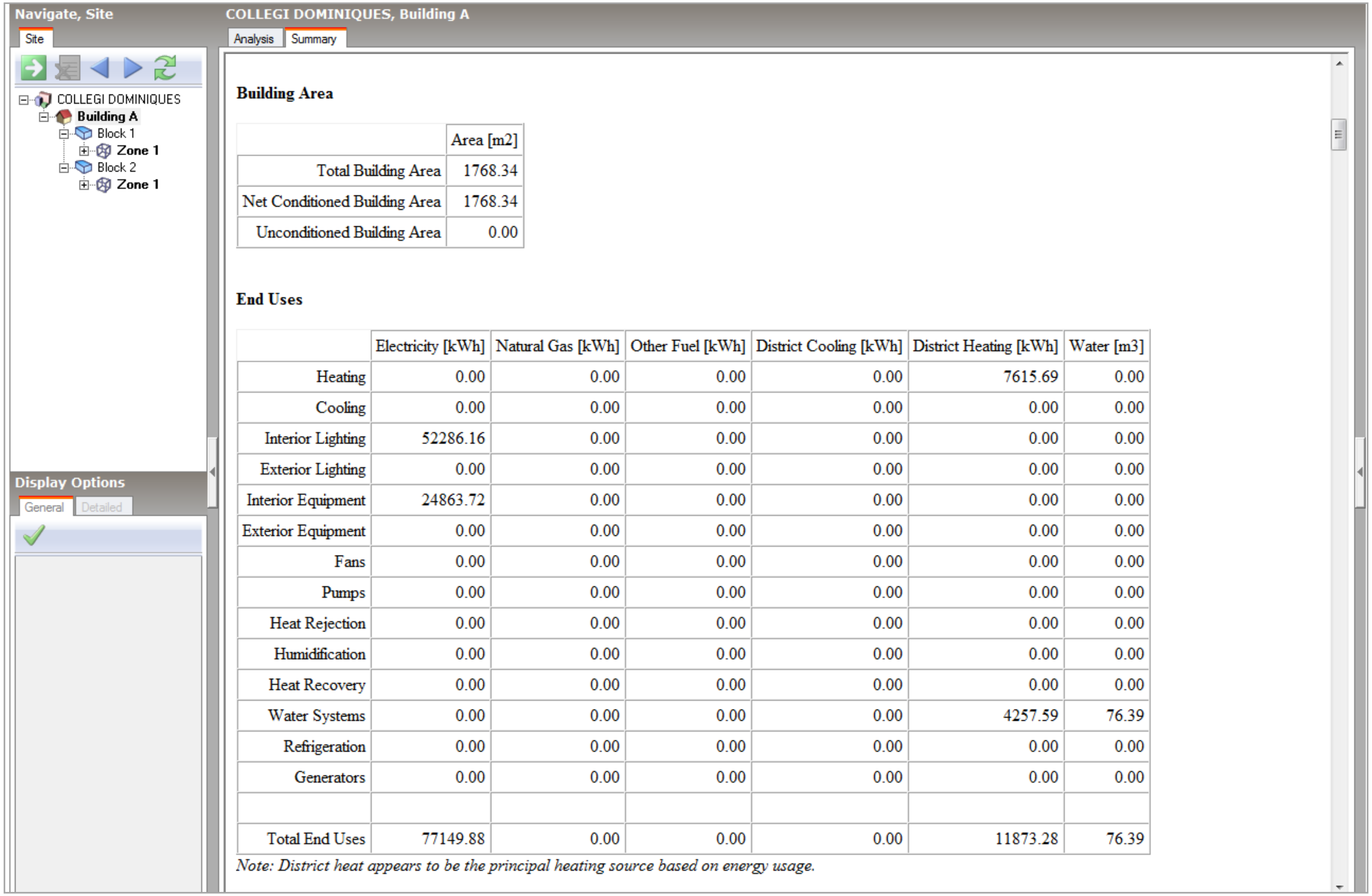


Figure 8.4: *Graphic results about temperatures, heat gains and energy consumption obtained for the building A on Designbuilder.*



Building Area

	Area [m2]
Total Building Area	1768.34
Net Conditioned Building Area	1768.34
Unconditioned Building Area	0.00

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Other Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	7615.69	0.00
Cooling	0.00	0.00	0.00	0.00	0.00	0.00
Interior Lighting	52286.16	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	24863.72	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	4257.59	76.39
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	77149.88	0.00	0.00	0.00	11873.28	76.39

Note: District heat appears to be the principal heating source based on energy usage.

Figure 8.5: *Main results about District Heating for the building A obtained on Designbuilder.*

9 Appendix II: Concepts of solar irradiation

It is known that solar energy comes from the sun where happens the fusion reaction between two hydrogen atoms, resulting in a helium atom, and releasing large amounts of energy which is emitted as electromagnetic radiation. Approximately, the radiation emitted at the solar surface is 63 MW/m^2. However, the solar energy that reaches the earth (prior to the atmosphere) is a small part of which is emitted by the sun due to the distance between earth and the sun, on average arriving 1,366.1 W/m^2 (Lund, 1995) located in a surface perpendicular to the solar radiation outside the atmosphere. This value is known as "solar constant" (*Figure 9.1)*.

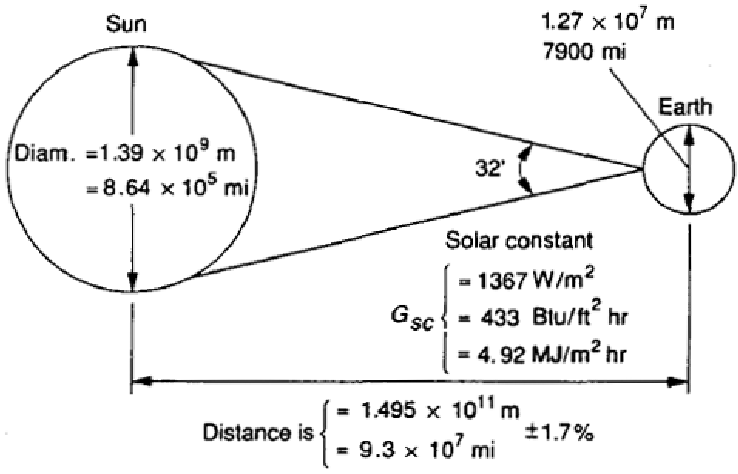


***Figure 9.1**: Relations obtainable between sun and earth. Source: (Duffie & Beckman, 2006).*

Then the radiation is partially reflected back into the space and attenuated by the earth's atmosphere, mainly by two major procedures: dispersion (loss of directionality) and absorption (loss of energy) *(Figure 9.2)*.

At last, the radiation that reaches the earth's surface is mostly dispersed and the average values are recorded as solar irradiation on a horizontal surface, of the order of 900-1,000 W/m^2. In this context, the concentration of radiation is a prerequisite for the technical and economic feasibility of solar plants.

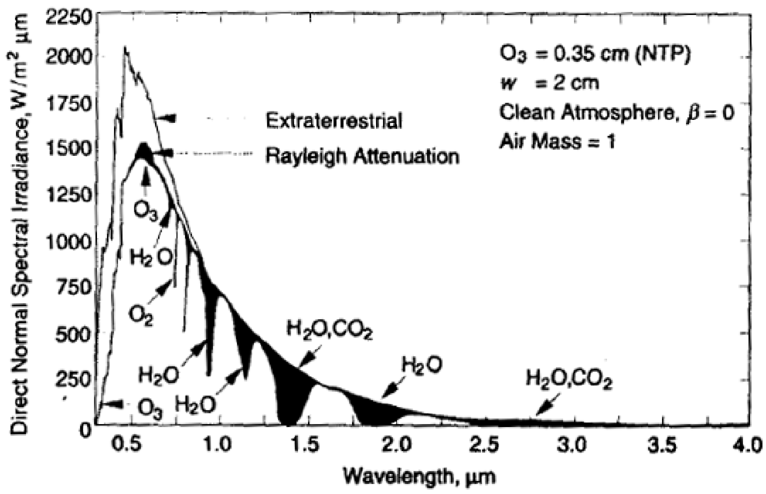


***Figure 9.2**: Atmospheric dispersion and absorption of the radiation. Source: (Duffie & Beckman, 2006).*

At this point, it is necessary to identify the concepts of the solar radiation that could be exploited in the earth's surface: it is the extraterrestrial irradiation, the direct irradiation and diffuse radiation as shown in Figure 9.3.

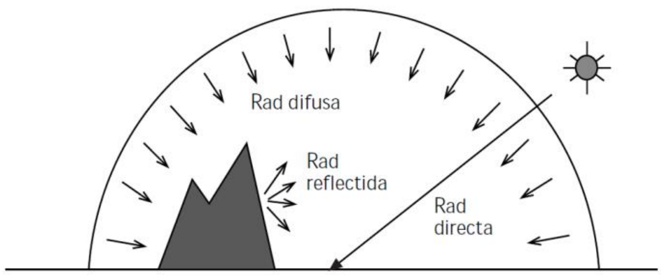


***Figure 9.3**: Different types of radiation (diffuse, reflected and direct). Source: (Institut Català de l'energia, 2001).*

10 Appendix III: *Matlab©* code for the heat generation and electricity generation

10.1 Heat generation: Example for the Case C

```
% CASE C FOR HEAT GENERATION

% Case of the current situation: Electricity and heat generation: Natural Gas Boiler and Electricity (NGB_E)

% Matrix_A1 refers to Electricity

Matrix_A1 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 1 0; 0 0 0 0 0 0];

% Matrix_A2 refers to Heat

Matrix_A2 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0;0 0.90 0 0 0 0];

Matrix_A = Matrix_A1 + Matrix_A2;

Input_A = [0 22400 0 0 11100 0]';

Output_A = Matrix_A*Input_A;

% Case of Evaluation:
% First step: Only Solar

Matrix_B1 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0.90 0 0 0 0];

Matrix_B2 = Matrix_A1;

Matrix_CaseB = Matrix_B1 + Matrix_B2;

Matrix_Eval=Matrix_CaseB;

Input_total=[0 0 0 0 0 0]'; % Accumulated value


Output_total=[0 0 0 0 0 0]';


for i=1:8760
```

```
Input_B = [0 0 0 D(i,1) 0 0]';

Output_B = Matrix_Eval*Input_B;

if (Output_A(6,1) - Output_B(6,1) > 0)

    Demand(i)=0;

    Step=1;

    % Second step: Solar + Biomass

    Input_C = [B(i,1) 0 0 D(i,1) 0 0]';

    Output_C = Matrix_Eval*Input_C;

    if (Output_A(6,1) - Output_C(6,1) > 0)

        Demand(i)=0;

        Step=2;

        % Third step: Solar + Biomass + Natural Gas

        Input_D = [B(i,1) N(i,1) 0 D(i,1) 0 0]';

        Output_D = Matrix_Eval*Input_D;

        if (Output_A(6,1) - Output_D(6,1) > 0)

        Demand(i)=0;

        Step=3;

        elseif (Output_A(6,1) - Output_D(6,1) == 0)

        Demand(i)=1;

        Step=3.1;

        else

            Input_D(2,1) = (Output_D(6,1) -
Matrix_Eval(6,1)*Input_C(1,1)-
Matrix_Eval(6,4)*Input_B(4,1))/Matrix_Eval(6,2);

            Step=3.2;
        end
```

```
    elseif (Output_A(6,1) - Output_C(6,1) == 0)

    Demand (i)=1;

    Step=2.1;

    else
        Input_C(1,1)= (Output_C(6,1)-
Matrix_Eval(6,4)*Input_B(4,1))/Matrix_Eval(6,1);

        Step=2.2;
    end

elseif (Output_A(6,1) - Output_B(6,1) == 0)

Demand (i)=1;

Step=1.1;

Input_total= Input_total + Input_B;

else
    Input_B(4,1)= (Output_B(6,1)/Matrix_Eval(6,4));

    Step=1.2;

    Input_total = Input_total + Input_B;
end

end
```

10.2 Electricity generation: Example for the Case C

```
% CASE C: FOR ELECTRICITY GENERATION - Solar PV Systems (Global Solar)

% Case of the current situation: Electricity and heat generation:
Natural Gas Boiler and Electricity (NGB_E)

% Matrix_A1 refers to Electricity

Matrix_A1 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0
0 1 0; 0 0 0 0 0 0];

% Matrix_A2 refers to Heat

Matrix_A2 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0
0 0 0; 0 0.90 0 0 0 0];
```

```
Matrix_A = Matrix_A1 + Matrix_A2;

Input_A = [0 22400 0 0 11100 0]';

% Output_A means the required demand

Output_A = Matrix_A*Input_A;


% First step: Only Global Solar

Matrix_B1 = [0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0 0 0 0 0; 0 0
0.15 0 0 0; 0 0 0 0 0 0];

Matrix_B2 = Matrix_A2;

Matrix_CaseC = Matrix_B1 + Matrix_B2;

Matrix_Eval=Matrix_CaseC; % Matrix Evaluation

% Definition of the vector of the Input_total

Input_total=[0 0 0 0 0 0]'; % It will accumulate the values

% Definition of the vector of the Input_total

Output_total=[0 0 0 0 0 0]'; % It will accumulate the values

%A=172297; % A means the Area available for Solar

%G=G*172297; % The Global Irradiation for solar is multiplied by the
Area available to obtain the values in kWh/year

%D=D*172297;


for i=1:8760

    %G(i,1)=G(i,1)*172297;

Input_B = [0 0 G(i,1) 0 0 0]';

Output_B = Matrix_Eval*Input_B;

if (Output_A(5,1) - Output_B(5,1) > 0)
```

```
    Demand(i)=0; % When the condition mentioned before it is not
validated the Demand shows the zero value for each hour

    Step=1;

    Input_total= Input_total + Input_B;

    Output_total= Output_total + Output_B;

    CoveragePVsolar(i)= (Output_B(5,1)/Output_A(5,1))*100;

    Output_hour(i)= Output_B(5,1);

    % Second step: Global Solar + Direct Solar

    Input_C = [0 0 G(i,1) D(i,1) 0 0]';

    Output_C = Matrix_Eval*Input_C;

    if (Output_A(5,1) - Output_C(5,1) > 0)

        Demand(i)=0; % When the condition mentioned before it is
validated the Demand shows the unit value each hour

        Step=2;

        Input_total(4,1)= Input_total(4,1) + Input_C(4,1);

        Output_total= Output_total + Output_C;

    % Third step: Global Solar + Direct Solar + Biomass

    Input_D = [B(i,1) 0 G(i,1) D(i,1) 0 0]';

    Output_D = Matrix_Eval*Input_D;

        if (Output_A(5,1) - Output_D(5,1) > 0)

        Demand(i)=0;

        Step=3;

        Input_total(1,1)= Input_total(1,1) + Input_D (1,1);

        Output_total= Output_total + Output_D;


        % Fourth step: Global Solar + Direct Solar + Biomass + Natural
Gas
```

```
        Input_E = [B(i,1) N(i,1) G(i,1) D(i,1) 0 0]';

        Output_E = Matrix_Eval*Input_E;

            if (Output_A(5,1) - Output_E(5,1) > 0)

            Demand(i)=0;

            Step=4;

            Input_total(2,1)= Input_total(2,1) + Input_E (2,1);

            Output_total= Output_total + Output_E;

            elseif (Output_A(5,1) - Output_E(5,1) == 0)

            Demand (i)=1;

            Step=4.1;

            % Input_total makes the sum of the Inputs each hour

            Input_total(2,1)= Input_total(2,1)+ Input_E (2,1);

            % Output_total makes the sum of the Outputs each hour

            Output_total= Output_total + Output_E;

            else

            Input_E(2,1)= (Output_E(5,1)-
Matrix_Eval(5,3)*Input_B(3,1) - Matrix_Eval(5,4)*Input_C(4,1) -
Matrix_Eval(5,1)*Input_D(1,1))/Matrix_Eval(5,2);

            Step=4.2;

            Input_total(2,1)= Input_total(2,1) + Input_E(2,1);

            Output_total= Output_total + Output_E;

            end

        elseif (Output_A(5,1) - Output_D(5,1) == 0)

        Demand (i)=1;

        Step=3.1;
```

```
        Input_total(1,1)= Input_total(1,1) + Input_D(1,1);

        Output_total= Output_total + Output_D;

        else

        Input_D(1,1)= (Output_D(5,1) - Matrix_Eval(5,3)*Input_B(3,1) -
Matrix_Eval(5,4)*Input_C(4,1))/Matrix_Eval(5,1);

        Step=3.2;

        Input_total(1,1)= Input_total(1,1) + Input_D (1,1);

        Output_total= Output_total + Output_D;


        end

    elseif (Output_A(5,1) - Output_C(5,1) == 0)

    Demand (i)=1;

    Step=2.1;

    Input_total(4,1)= Input_total(4,1) + Input_C(4,1);

    Output_total= Output_total + Output_C;

    else

    Input_C(1,1)= (Output_C(5,1) - Matrix_Eval(5,3)*Input_B(3,1))/
Matrix_Eval(5,4);

    Step=2.2;

    Input_total(4,1)= Input_total(4,1) + Input_C(4,1);

    Output_total= Output_total + Output_C;

    end

elseif (Output_A(5,1) - Output_B(5,1) == 0)

Demand (i)=1;

Step=1.1;
```

```
Input_total= Input_total + Input_B;

Output_total= Output_total + Output_B;

else

Input_B(3,1)= (Output_B(5,1)/Matrix_Eval(5,3));

Step=1.2;

Input_total = Input_total + Input_B;

Output_total= Output_total + Output_B;

end

end

disp('end');
```

11 Appendix IV: Investment project concepts

11.1 Net Present Value (NPV)

The NPV is a decision tool for assessment of project's financial costs and benefits and represents the economic value expected to be generated by the project at the time of measurement.

The NPV of an investment project is determined by calculating the present values of the future cash flows generated by this investment, summing them up and finally subtracting from this the initial outlay for the investment. In this way, the calculation of NPV consists of three essential elements. These elements are time of the cash flow, discount rate and the net cash flow. The method of calculation is as follows:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - I$$

t= period of the cash flow

T= the total time (years) of the project

r= the discount rate (project cost of capital)

C_t=the net cash flow at time t

I = the single (initial) investment outlay

If the NPV is positive, it means a company could get profits after investing. On the other hand, the investment should be dropped while the net present value is negative. Furthermore, when the net present value is zero, the company may neither get nor lose money from the investment and this project may not be invested in (Manser, 2011).

11.2 IRR (Internal Rate of Return)

The IRR evaluates an investment in terms of an interest rate. The IRR is the discount rate i^* for which the present value of the net cash flows NCF_t is equal to the corresponding initial investments *I*. The IRR can be obtained by solving the following equation for i^* iteratively (Manser, 2011):

$$\sum_{t=1}^{n} \frac{NCF_t}{(1+i^*)^t} = I$$

It is important to note that we should invest in a project with the higher IRR.

11.3 Payback period

The payback period is defined as the length of time required by an investment project to equal the initial investment outlay with the expected future cash flows. The shorter the payback period of an investment project, the better for the project to be accepted.

Firms may specify payback requirements as accept-reject decision rules for investment projects, thereby limiting the length of time in which an investment project shall have earned the initial cash outlay. Intuitively, this can be stated as the investment will pay for itself in *x* number of years (Kindlein , 2007).

12 Appendix V: CO_2 emissions calculation

Here is presented an example (Case A: Gas turbine following heat demand) for the calculation of the CO_2 emissions caused by the natural gas resource (direct CO_2 emissions).

The first term refers to the CO_2 emission factor, the second to the CO_2 conversion factor, the third refers to the energy input resulting in CO_2 emissions in tons of CO_2 per year. To implement this approach, we proceed as follows:

$$2.15\ \frac{kg\ CO_2}{Nm^3} \times \frac{1}{1.07 \times 10^{-5}} \frac{Nm^3}{GWh} \times 245.3 \frac{GWh}{y} \approx 4.9 \times 10^7 \frac{kg\ CO_2}{y} \approx 4.9 \times 10^4 \frac{tons\ CO_2}{y}$$

In that way, for the Case A we have 4.9×10^4 $(49{,}000)$ tons of carbon dioxide per year.