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Analysis and Implementation of Gasification Processes in Combined Cycle

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Abstract

Throughout this paper the synthesis of gas from coal as feedstock for combined cycle is explained from different points of view. A complete and detailed explanation of the reactions involving gasification and further implementation of the process into combined cycle is given along the document. In between, an analysis about the state-of-art in which the technology is enclosed at this moment is shown to describe the characteristics of IGCC all around the world.

To continue, an exhaustive breakdown of Puertollano's IGCC power plant is done to clarify concepts into a practical framework. An idea emerges from this power station due to the closure to which has been forced. This premise is to recycle some of the devices concerning gasification that operated at Puertollano in order to hybridize them into another combined cycle, reducing investment and fuel costs. To see if this process is suitable, thermal and economic viability analyses are performed. Finally some possible improvements are stated with the results obtained.



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Glossary

Acronyms

<i>IGCC</i>	Integrated Gasification Combined Cycle
<i>NGCC</i>	Natural Gas Combined Cycle
<i>PC</i>	Pulverized Carbon
<i>USDOE</i>	United States Department of Energy
<i>EPRI</i>	Electric Power Research Institute
<i>ASU</i>	Air Separation Unit
<i>HRS</i>	Heat Recovery Steam Generator
<i>GT</i>	Gas Turbine
<i>VT</i>	Vapour/Steam Turbine
<i>CPIG</i>	Calorically Perfect Ideal Gas
<i>HP</i>	High Pressure
<i>MP</i>	Medium Pressure
<i>LP</i>	Low Pressure
<i>HHV</i>	Higher Heating Value
<i>LHV</i>	Lower Heating Value
<i>CV</i>	Control Volume
<i>FWHC</i>	Feed Water Heater Closed
<i>SEV</i>	Sequential Environmental Combustor
<i>APY</i>	Amortization per Year
<i>IIP</i>	Initial Investment of Puertollano's power plant
<i>IIS4</i>	Initial investment of Soto de Ribera 4
<i>TAY</i>	Total Amortization Years

Symbols

C_v	Air specific heat at constant volume
C_p	Air specific heat at constant pressure
γ	Air specific heat ratio
T'_i	Ideal Temperature of point i
T_i	Real Temperature of point i
P_i	Pressure of point i
π	Pressure ratio
\dot{W}_N	Net Power of combined cycle
\dot{W}_{Nsg}	Net Power of combined cycle with syngas as feedstock
\dot{W}_{Nc}	Net Power of combined cycle with natural gas as feedstock
\dot{W}_{NGT}	Net Power of Gas Turbine
\dot{W}_{NVT}	Net power of Vapour/Steam Turbine
\dot{W}_C	Compressor power consumption
\dot{W}_T	Turbine power generation
\dot{Q}_{in}	Heat transferred to the system
\dot{Q}_{maxsg}	Maximum Heat transferred to the system by syngas combustion
$\Delta\dot{Q}$	Post-combustor added Heat
ΔHr	Enthalpy of reaction
\dot{m}_a	Air mass flow
\dot{m}_c	Natural gas mass flow
\dot{m}_{cpc}	Natural gas post-combustor mass flow
\dot{m}_{esc}	Total exiting mass flow
\dot{m}_w	Water mass flow
\dot{m}_{sg}	Syngas mass flow
η_T	Rankine cycle efficiency
η_B	Brayton cycle efficiency



η_T	Turbine efficiency
η_C	Compressor efficiency
η_{CC}	Combustion Chamber efficiency
η_{Soto4}	Soto 4 combined cycle efficiency
η_P	Pump efficiency
η_{GC}	Gas Cycle efficiency
Li	Lower Heating Value of natural gas
Li _{sg}	Lower Heating value of syngas
y	Steam extraction percentage
z	Natural gas saving percentage
u	Air specific volume
r	Syngas/coal ratio

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1. Introduction

Energy has a vital place in nowadays life style. Lightning, electronic devices or hot water are some of the various applications for which society needs the use of energetic resources. However, for many applications it is necessary the transformation into electric energy before it is used. For this purpose, several types of energies can be used to accomplish the demand. Thermal, mechanical or chemical are some of the examples, but among the years, technologies have made incredible advances regarding electricity generation with thermal power plants. Nonetheless, thermal power plants require the combustion of a fuel with enough heating power in order to operate.

In this sense, there has been an important change regarding the world's point of view, making society more conscientious and committed with environment. As a result, the types of energies known as 'clean' are making impact, not only as a futuristic idea, but also in today's common life. However, fossil fuels are still a step further if statistics are observed conveniently. Looking at the data prepared by BP in July 2015 for 2014 (see figure 1), it can be seen that 86.3% of the energy consumed that year derived from fossil fuels. Making a further breakdown, 30% was carbon, 32.6% petroleum and 23.7% natural gas, what leaves 13.7% for renewable, hydroelectric and nuclear [1]. This poor rating for clean use of energy makes people think about some alternatives while the new clean technologies keep rising.

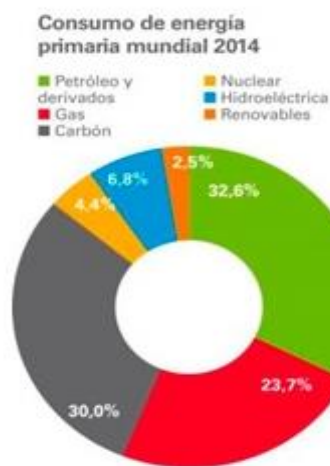


Figure 1. Fuel consumption percentages in 2014 [1].

Despite the apparently moderate use of clean energy nowadays, it is reasonable to say that the great increase they are having lies on two main factors:

1. - Unlimited supply.
2. - Low or inexistent pollutant impact.

Taking advantage of resources such as sun, air or water the security in supply is a matter of fact, as their existence is proved for millions of years becoming. Issues concerning environment deterioration have boosted the use of this kind of technologies. Nonetheless, having positioned fossil fuels in a shaky situation doesn't mean that a clean use of them cannot be made. In fact, natural gas is a low polluting fossil fuel in comparison with petrol or direct combustion of carbon. To this extent, the most common use of natural gas is as feed fuel in combined cycle power plants, which have gained an excellent position in electricity production field.

On the other hand, petroleum and carbon seem to be in the hurricane's eye regarding environment. Nevertheless, they are still the most employed fuels for two main reasons; conventional use and economic affairs. Concerning conventional use it has to be said that they were the first combustibles used under industrial point of view, steam trains and machinery, petrol for cars, etc. Moreover, this made that around carbon and petrol a whole industry was built, including, for good, the investment of huge amounts of money. This led to many political issues that are still present nowadays.

On behalf of carbon, it has to be said that a clean use of this fossil fuel can be done, with coal or any carbonaceous form of it. This technology receives the name of Gasification of Carbon. During this document, studies and detailed explanations on how the technology proposed function will be made. In addition, not only the technology will be explained in a generic way, but also the exhaustive functioning of the Integrated Gasification in Combined cycle (IGCC) power plant located at Puertollano (Ciudad Real, Spain) will serve as an example. Moreover, a comparison between different technologies and integrations will lead to the proposal of a clean plan regarding carbon. Before this occurs, the main objectives that have pushed forward this investigation have to be mentioned.

1.1. Objectives and problem presentation

Throughout this paper some objectives are pursued. The purpose of this investigation is to shed some light over one of the newest technologies in power and electricity generation, studying the advantages and drawbacks it presents for its implementation. However, there are some intermediate goals that need to be achieved before completion, these are:

- **Comprehensive understanding of energy production:** taking a global view of energy production and resources, also a particular one regarding the new technology explained from a technical position.
- **Detailed explanation on how the technology works:** identifying the key stages of which the gasification technology consists, explaining in a brief and adequate way how it works. Also it will be compared to the two main competitors in thermal power plant market.
- **Information research and programmes correct utilization:** in some parts of the paper a deep information research has been done and it is important to identify the reliable sources of information. Regarding the programmes used, one of the goals is to learn to

make use of them as a support tool to solve equations or thermodynamic problems as it will be seen throughout the paper.

Also some ultimate goals are expected to be achieved once the technology is understood and the possible advantages are conveniently explained. These mentioned goals are the following:

- **Insight view of IGCC power plant example:** once the technology is explained, a practical example of its implementation needs to be certified in order to check the influence of variables.
- **Viability study for implementation:** thermal, economic and environmental analysis will be made to try to prove the possibility of recycling some of Puertollano's components and hybridize them into a combined cycle power plant that is currently functioning.
- **Obtain relevant conclusions about the results:** being able to critically analyze the results obtained and is the most important task. In case the results aren't positive, the adequate justifications and proposals for solutions should be made.

Aligned with the objectives, the solution to the next problem is going to be hunted. Once the technology is conveniently explained, the hybridization of some of the devices (gasifier and Air Separation Unit) with a current combined cycle plant is going to be focused from an economic and thermal point of view. Firstly it has to be verified that the plant election is the correct one, justifying the reasons for the election and demonstrating if the operation point that was designed remains unchanged after hybridization. Finally economic evidence has to be given in order to determine if the viability of the process is positive or not. Therefore, and in order to understand the technology proposed some previous knowledge has to be stated. The main use of gasification is focused in small scale to water heating and calefaction. However, some large scale programmes have entered into scope since the late 19s. The connexion between the use of gasification and electricity is the integration of the mentioned process into combined cycles. For this reason it is highly recommendable to start by explaining briefly the way these kinds of cycles operate.

2. Combined cycle

2.1. Introduction

The appearance of combined cycle was fundamentally motivated to approach a method that increased the electric power and the efficiency that were earned from a simple Brayton cycle. As its name states, the combined cycle is formed by the conjunction of a vapour Rankine cycle and the mentioned gas Brayton cycle. During this chapter the basics of this technology will be detailed.

2.2. Brayton cycle

The definition of this cycle can be stated as a turbo-gas group that takes air from the ambient to compress and heat it afterwards. Moreover, the air will be used to spin the paddles of a Gas Turbine (GT) producing mechanical energy that later will enter in an alternator leading to electrical energy [2]. In figure 2, there is a schematic representation of the elements involved in the cycle, as well as graphics that plot the temperature against entropy and pressure against volume, assuming this process as ideal.

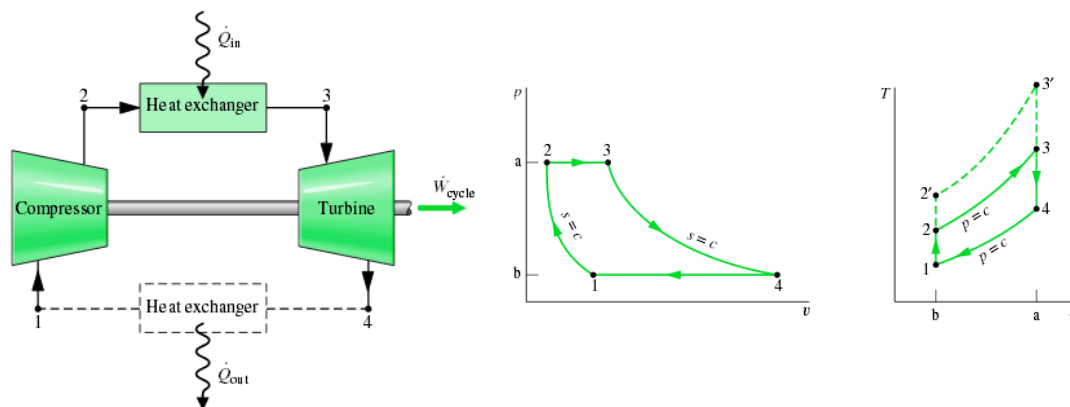


Figure 2. Scheme and diagrams P-V and T-s of an ideal Brayton cycle [2].

As seen above, the cycle consists of 4 steps clearly separated in which 3 of them are mandatory and the other one depends on the nature of the cycle, if it is open or closed.

Step 1-2: Compressor

An adiabatic compression takes place, making the pressure of the working fluid increase in order to make it adequate before entering in the combustion chamber.

Step 2-3: Combustion chamber

Heat is added due to the isobaric combustion of fuel raising air's temperature before going through the GT.

Step 3-4: Gas Turbine

The fluid experiences an adiabatic expansion that generates mechanical power that will be converted into electricity.

Step 4-1: Heat exchanger

This step only takes place in closed cycles, where a heat exchanger is added with a cooler fluid running through it to reduce air's temperature until the ideal is achieved, in order to avoid breaking the compressor's paddles.

It is commonly known that no machine can work with ideal efficiency. For this reason the variations consequent to the real work of the devices cannot be neglected. Mainly these variations are visible in the compression and expansion steps, as figure 3 shows.

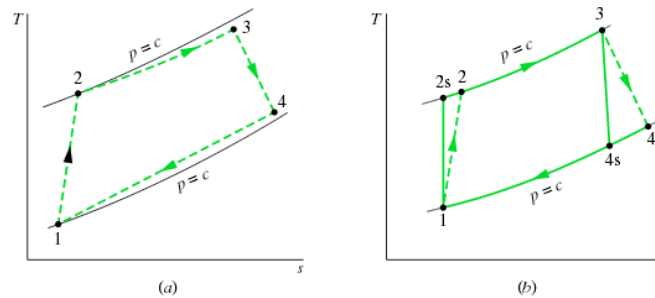


Figure 3. Irreversibility effects in Brayton cycle [2].

The effects are immediately spotted in the compression, where it suffers an enlargement, and in the expansion, where it suffers a shortening. Making a deeper study, the result is that the power needed for the correct functioning of the compressor is higher and therefore, the energetic costs in addition will be augmented. Nonetheless, the power generated at the turbine group will be reduced, which leads to energy losses [2]. Furthermore, the efficiency of both devices can be calculated with the following formulas:

$$\eta_{GT} = \frac{(\dot{W}_{GT}/\dot{m}_a)_{real}}{(\dot{W}_{GT}/\dot{m}_a)_{ideal}} = \frac{T_3 - T_4}{T_3 - T'_4}$$

$$\eta_C = \frac{(\dot{W}_C/\dot{m})_{ideal}}{(\dot{W}_C/\dot{m})_{real}} = \frac{T'_2 - T_1}{T_2 - T_1}$$

Where η stands for efficiency and is function of the power generated or consumed by the device, \dot{W} , and the mass flow of air, \dot{m} . It is sensible to highlight that the ideal and real values for the devices are in the opposite place. The reason is that the compressor requires an

input of power and therefore, the least power it requires to accomplish its task, the better. The turbine generates power and therefore the more it generates the better.

Finally, the efficiency can be calculated with the temperatures, T , of the real process and the ideal process, as shown above. The fundament for this change is that the air that works in the cycle can be considered as a Calorically Perfect Ideal Gas (CPIG). As it will be seen along this document, all the formulae, hypotheses and principles will be taken into profound consideration for the correct study of the cycles.

2.3. Rankine

On the other hand, the main difference that can be stated regarding the preceding cycle is the employment of water as the working fluid that will be expanded in a Vapour Turbine (VT) in order to obtain electric power. Similarly to Brayton cycle, the fluid will suffer a compression and heating up process before entering the turbine for a higher achievement in electric power. It is recommendable to highlight that the calculus held for this new cycle will diverge because of the substantial differences between vapour and air. Regardless of the simplicity of the cycle, power plants consisting in Rankine cycle span a bigger surface due to the inclusion of a refrigeration tower (see figure 4) so that the flow of water can be cooled.

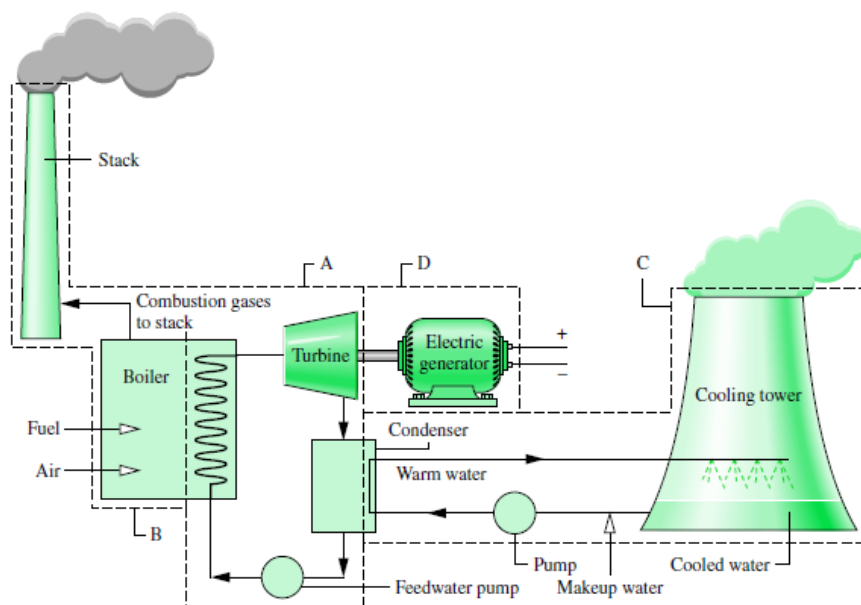


Figure 4. Components of a simple vapour power plant [2].

A simplified scheme of the cycle can be seen in figure 5. In it, it is appreciated the power and heat exchanges that take place in the system. Additionally, the devices of which it consists of are significantly different to the ones seen in the Brayton cycle that was explained before. In this case the compression is done by a pumping group whereas the combustion chamber is substituted by a boiler and the expansion will happen in a VT.

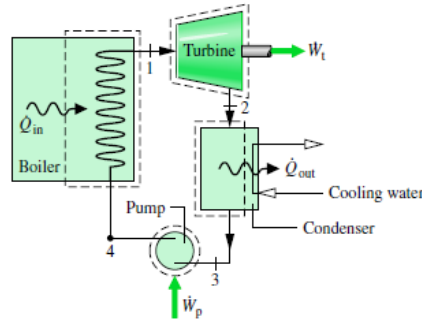


Figure 5. Simplified scheme of Rankine cycle [2].

Similarly to Brayton cycle, the process consists of four steps [2]:

Step 1-2: Turbine

The steam generated by heating water in the boiler passes through the paddles of the turbine making them spin and producing power and reducing pressure.

Step 2-3: Cooler

After expansion, the vapour enters in the cooler where a heat exchange will reduce its temperature by means of cold water that flows inside separated pipes coming from the refrigeration tower. In this way both flows don't get mixed and the steam recovers its initial liquid phase before being pumped. This process happens under isobaric conditions.

Step 3-4: Pump

At this point the vapour is transformed into saturated water with low pressure due to the preceding expansion and moreover the pump will increase it making it suitable for the boiling process.

Step 4-1: Boiler

Pressurized liquid and pressurized water enters in the boiler, where the combustion of a fuel will make it earn enough temperature to evaporate it to steam.

In this case irreversibility is also present as turbines, pumps and even boilers don't operate in isentropically on common basis. The procedure to calculate the efficiency is quite similar to the ones shown for Brayton cycle. The main difference is that now, enthalpies are involved instead of temperatures. The reason is that water or steam can't be seen as a CPIG.

$$\eta_{VT} = \frac{(\dot{W}_{VT}/\dot{m}_w)_{real}}{(\dot{W}_{VT}/\dot{m}_w)_{ideal}} = \frac{h_1 - h_2}{h_1 - h'_2}$$

$$\eta_P = \frac{(\dot{W}_P/\dot{m}_w)_{ideal}}{(\dot{W}_P/\dot{m}_w)_{real}} = \frac{h'_4 - h_3}{h_4 - h_3}$$

2.4. Combined cycle

To squeeze at the maximum point the calorific power of the fuels used in Brayton cycle, made its appearance combined cycles. The combination of a vapour system and a gas system led to a high improvement in the production of electricity because of the sum of two turbines operating simultaneously.

In figure 6, all the devices that form a simple combined cycle are represented with the order in which the steps take place during the operation.

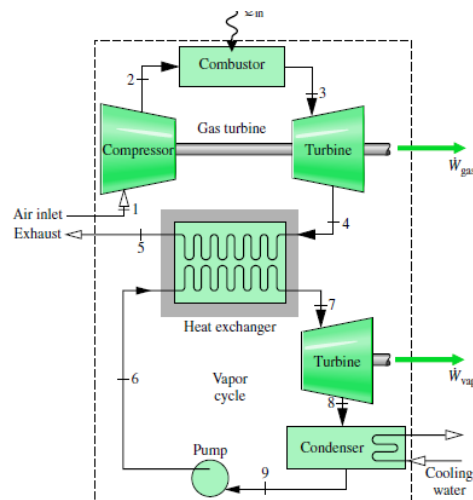


Figure 6. Representation of the devices of a simple combined cycle in operating position [2].

2.4.1- Operation

The gas cycle will happen in the first place since the high temperature of air at the end of the turbine step is used to heat up and evaporate the water that runs in the Rankine cycle. The mentioned heat exchange occurs in a new device named Heat Recovery Steam Generator (HRSG) [2]. Moreover, it is displayed the functioning of a HRSG developed by Horizon (see figure 7) in which it is seen the hot air inlet (gas flow) and water pipes where the heating up takes place. In addition to them, the outlets are distributed as a function of the pressure suffered by the fluid; distinguishing high pressure (H.P. Steam outlet) and low pressure (L.P. Superheated outlet)

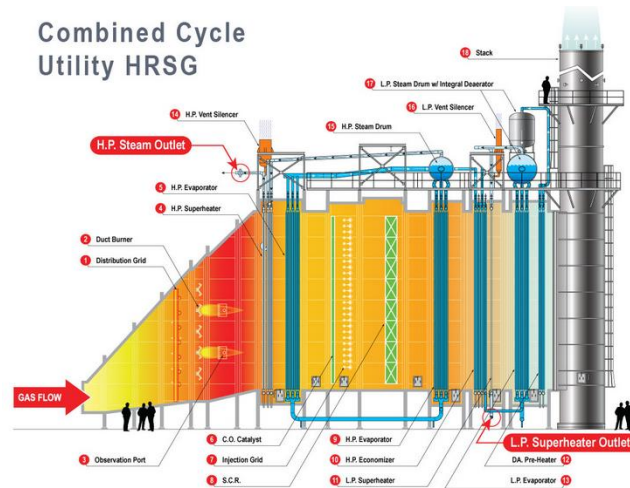


Figure 7. Utility HRSG developed by Horizon. Source: VictorEnergy online website.

Once the operation has been explained, the advantages of this kind of combined distribution offers over both cycles separately will be briefly justified.

- Fuel saving
- Reduces energy losses
- Higher overall efficiency
- Higher energetic production

To this end, fuel savings are a fact to take into serious consideration as the only step of the process where fuel is required is in the combustion chamber of gas cycle, using the same amount employed in Brayton cycle but feeding both processes with heat. In the same way, the effect subsequent makes the energy losses due to the consumption of fuel for the vapour cycle null, as well as the losses according to air cooling in the gas cycle. Regarding efficiency, theoretical proof will be given of the increase experienced when both cycles operate combined rather than separately.

2.4.2- Brayton

The thermal performance of any system can be expressed as the total net power developed divided by the total input heat needed to produce it. As a result, in Brayton cycle the next extend is reached:

$$\eta_B = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

Where net power can be defined as the power generated by the impulsion devices minus the power consumed by the compression groups. Moreover the input heat to the system will be the one consumed in the combustion chamber when fuel is burned.

$$\eta_B = \frac{\dot{W}_{TG} - \dot{W}_C}{\dot{Q}_{CC}}$$

2.4.3- Rankine

A homologous study can be made for the efficiency in Rankine cycle, with the difference of changing the devices of the gas cycle for the ones concerning vapour cycles. Hence:

$$\eta_R = \frac{\dot{W}_{VT} - \dot{W}_P}{\dot{Q}_C}$$

2.4.4- Combined Cycle

Applying the same methodology, the efficiency in a combined cycle can be stated as the net power divided by the input heat following the same steps as before:

$$\eta_{CCycle} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

Just as it was done before, net power and input heat have the same definition and therefore, net power will be calculated as the result of the difference between the power generated by the impulsion groups and the power consumed by the compression groups.

$$\dot{W}_N = \dot{W}_{GT} + \dot{W}_{VT} - \dot{W}_C - \dot{W}_P$$

It is highly remarkable that the system will only have one heat input place, the combustion chamber. The inclusion of the HRSG enables heat transfer without supplementary heat inputs. Finally:

$$\eta_{CC} = \frac{\dot{W}_{GT} + \dot{W}_{VT} - \dot{W}_C - \dot{W}_P}{\dot{Q}_{CC}}$$

Having the same denominator as Brayton cycles, it is sensible to say that the efficiency increases as the net power for the gas cycle and the steam cycle are positives and therefore, the sum of both makes the efficiency grow. In other words, the advantage earned for joining both systems is clearly justified.

In fact, when talking about numbers, the range of efficiency regarding a simple Rankine cycle oscillates around 35-37% that can be raised to 42-45% potentially in supercritical power plants. In counterpart, the investment needed to achieve those values is considerably high. With respect to Brayton cycle the efficiency is quite similar despite the fact they operate at higher temperatures. The value reaches between 35-38%. Finally, not only combined cycles have a range of efficiencies that surpasses widely these values, but also has plenty of advantages regarding environment and economic matters. The table below supports these statements (see table 1).

Advantages	Combined Cycle Power Plants	Simple water/steam Power Plants
Net efficiency	55-57%	35-40%
CO ₂ emissions	350g/kWh	850g/kWh
Water consumption for refrigeration	435m ³ /h (400 MW power plant)	875m ³ /h (400 MW power plant)
Initial investment	400-600 €/kW	>1000 €/kW
Building time	2 years	3-4 years
Span	100.000 m ² (400 MW power plant)	260.000 m ² (400 MW power plant)

Table 1. Comparison between Combined cycle and simple water/steam cycle [3].

Summing all up, it is demonstrated that the combination of gas and steam cycles is a way of improving the efficiency and reducing the costs sharply. Natural gas and fuel-oil are commonly used to feed this kind of cycles, favoured by their high heating values. However, there are other kinds of combustibles that can be used to supply the combustion chamber. Furthermore, this document is going to now focus in gasification as a preceding process for feeding combined cycles.

3. Gasification technology

3.1. Introduction

Gasification is a process that can be easily defined as the manufacture of combustible gases from solid fuels [4]. Nevertheless, the scope can be reduced. The term encloses the transformation of any carbonaceous fuel to a gaseous product with a usable heating value. Explaining the process roughly, the gas obtained (otherwise known as syngas) is created by applying heat to the fuel in a reduced oxygen atmosphere.

At a start, the definition given may resemble to a common combustion process however, there are vital differences between them. Firstly, combustion implies a rich oxygen atmosphere for burning the fuel, whereas gasification processes avoid flames reducing oxygen. Next, a crucial fact that proves differentiation between them is the resulting gas. In combustion the resulting flue gas has no residual heating value while the objective of syngas is being used as fuel in an industrial process. Once the difference is stated, the exclusion of combustion as a gasification process is a fact.

Regarding the actual technologies, long ago there was a heavy dependence on pyrolysis (i.e. application of heat in absence of oxygen), but the dominant technology nowadays is based in partial oxidation. The gas consequential of partial oxidation has a high concentration of hydrogen (H_2) and carbon monoxide (CO), as well as other compounds that vary as a function of the fuel from which they come from. In order to make the process happen, the partial oxidation needs an oxidant agent (so-known gasifying agent) that can be pure oxygen, air or steam. On the other hand, pyrolysis still plays an important role as intermediate step in most of the gasification processes [4].

Finally, the syngas consists of several gases that have to be taken into consideration such as CO, CO_2 , H_2 , CH_4 , C_2H_6 , CH_3OH , SH_2 , NH_3 y N_2 [3]. The mixture has a high heating value when further burning takes place, but some of the compounds may be potentially noxious for environment. In this sense, the appropriate measures should be taken into account to reduce potential damage.

3.2. Gasification reactions

The order of the reactions may be subjected to the type of gasifier the system has. Next, the main reactions will be described in order to have a deeper knowledge of gasification processes. In figure 8 a schematic vision of the process can be seen.

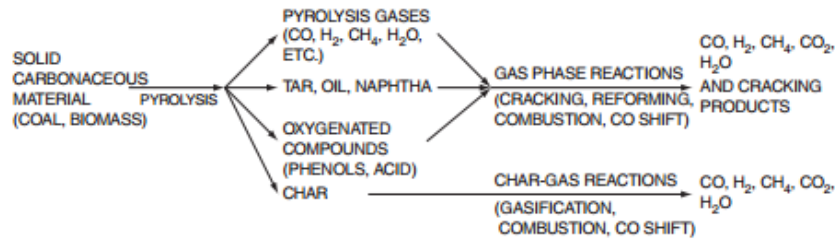


Figure 8. Reaction sequence for gasification of coal or biomass [4].

3.2.1- Drying and water evaporation

Regardless of the type of gasifier, the first step in any process concerning gasification will be the treatment of the fuels that will be exploited. Temperature is raised up to 100°C leading to evaporation and deleting the water contained inside the fuel. In case of neglecting this task, the oxygen particles contained in water could produce spontaneous combustion when further heat is applied. On the other hand, by evaporating the mentioned water, the flow of oxygen is fully controlled from the outside [5].

3.2.2- Pyrolysis

During this process, heat and pressure are applied to the fuel dissociating the chemical bonds in it and producing chemical reactions [6]. As a consequence, part of the fuel goes from solid phase into gas phase. For this purpose the temperature keeps raising from 230°C to 600°C, where it reaches its optimal point. In the image above (see figure 8), it can also be seen the three products obtained after pyrolysis.

Gas phase:

A primary form of the final syngas is observed, having as principal compounds hydrogen and carbon.

Liquid phase:

Tar, oils, naphtha and oxygen compounds are by-products originated due to the heating process.

Solid phase:

The residue obtained, so-called char, will be necessary later in the future reactions.

It is sensible to say that both, liquid and solid compounds can be synthesized for developing products for future sale and generate some benefit. Products such as vegetal carbon, fertilizers or bio-fuels are some of them, in contrast char has to wait until the complete gasification process is done and ashes are removed.

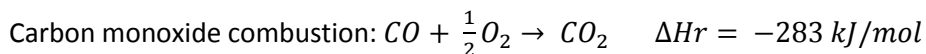
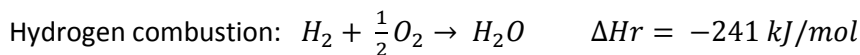
When pyrolysis ends, a new step can be done to ensure the complete thermal decomposition of the fuel. This step is known as 'pyrolysis flash' due to the sharp and sudden increase in temperature up to 1000°C.

3.2.3- Combustion

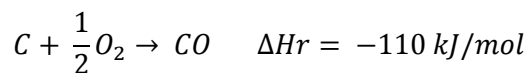
Temperature continues rising after pyrolysis has finished, so that the pertinent reactions that will end up producing the final syngas take place. It can be done in various ways:

- Combustion of the gases produced after pyrolysis.
- Extra external heat.

In order to reduce costs, it is advisable to say that the first option doesn't need more external equipments and therefore, is a way of recycling the gases obtained to produce heat. In this way, two main reactions will happen [3]:



Beside these exothermic reactions, the oxygen that is still present inside the gasifier reacts with char until the oxygen runs out. Moreover, the heat turned out from these reactions will keep increasing temperature and, also, will favour the next step, gasification reactions [3].



3.2.4- Gasification

Once the suitable temperature for chemically breaking fuel's bonds is reached, gasification reactions start. Multiple reactions happen, though the organic nature of the fuel and the complexity of the compounds make the reactions quantification an unworthy task. In this sense the most important reactions will be the ones detailed in this document.

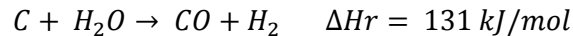
In addition oxygen is introduced in a very small fraction (around 1/5 of the oxygen necessary in combustion) and due to the high temperature endothermic (absorbs energy) and exothermic (releases energy) reactions appear:

Endothermic reactions:

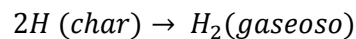
Boudard's reaction is produced by carbon dioxide obtained in combustion reacting with the carbonaceous residue, char (C).



Also a reaction vapour-carbon takes place. Vapour is a by-product of combustion and will also react with char generating big carbon monoxide and hydrogen quantities. Both of them will be the dominant compounds in the final syngas.

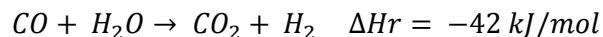


Finally, there is a process of hydrogen liberation from char that will increase the heating value of syngas. As it can be seen, the major compound released to gaseous phase is hydrogen and CO.

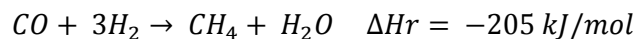


Exothermic reactions

A spontaneous reaction between carbon monoxide and water, originated in the combustion process, appears to liberate energy, hydrogen and carbon dioxide. This process is contrary to the interest of syngas as it steals some carbon monoxide of the final syngas. The loss isn't very significant though.



The next process that will appear is known as methanation. These types of reactions are favoured at low temperatures and high pressures; however, in this case they will not be dominant. Despite the fact of not being so relevant, they have to be taken into consideration because of the energy they liberate.



Due to the complexity of the fuel exploited, these will not be the only compounds of the final syngas. There will be a series of pollutant elements which have to be treated.

Sulphurous compounds:

Coal is an organic compound with high levels of sulphur in its structure, which react with hydrogen and carbon monoxide generating de H₂S and COS. It is interesting to see that both compounds are, by far, less pollutant than SO₂, which is generated by the direct combustion of coal. Following the same path, both compounds also have an easier treatment process to delete them [7].

Nitrates:

Favoured by high temperatures, the major part of nitrogen compounds that turn into gas transform into pure nitrogen N₂. The benefits that implies are considerable as it can be sell directly as by-product or, like is usual, used in the cycle for multiple issues, as it will be seen in

this document. As the temperature decreases in the process, ammonia and hyponitrous acid (HNO) generation increases. More benefits can be earned with ammonia sales [7].

One of the reasons for considering gasification as a clean energy lies on the fact that the noxious elements can be easily cleaned with low cost procedures such as water washing process or absorption solvent process [3].

3.3. Gasifying agents

According to the gasifying agent employed, there will be some variations in the efficiency of the process and in the final composition of the gas. Because of economic reasons the dominant technology nowadays is the one that uses air as gasifying agent. The efficiency suffers a small decrease but air is abundant, free and everywhere.

If high efficiency is required, the agent that should be employed is vapour or pure oxygen as it is sharply increased obtaining syngas with a heating value that almost doubles the one obtained with air (4-7 MJ/m³ to 10-18 MJ/m³) [8]. On the other hand, oxygen implies an added cost.

The last of the common gasifying agents is hydrogen. The heating value of the gas produced is outstanding, reaching values near 30 MJ/m³ [5]. Consequently, the use of gas with hydrogen as gasifying agent can be used as a suitable alternative to natural gas. Nonetheless, the exceptional combustion conditions hydrogen offers makes it less appropriate for gasification as for combustion. Besides, the cost of hydrogen has its influence in the election for other technologies.

3.4. Gasification processes

Due to the numerous variables that influence gasification, there is a wide range of gasifiers that are mainly enclosed in three major groups: entrained-flow gasifiers, fluid-bed gasifiers and moving-bed gasifiers, which differences and similarities are shown in table 2 below [4].

Category	Moving-bed		Fluid-bed		Entrained-flow
Ash conditions	Dry bottom	Slagging	Dry ash	Agglomerating	Slagging
Feed characteristics					
Size	6-50mm	6-50mm	6-10mm	6-10mm	$\leq 100\mu\text{m}$
Acceptability of fines	Limited	Injection through tuyères	Good	Better	Unlimited
Acceptability of caking coal	Yes	Yes	Possibly	Yes	Yes
Preferred coal rank	Any	High	Low	Any	Any
Operating characteristics					
Outlet gas T	Low (425-650°C)	Low (425-650°C)	Moderate (900-1050°C)	Moderate (900-1050°C)	High (1250-1600°C)
Oxidant demand	Low	Low	Moderate	Moderate	High
Steam demand	High	Low	Moderate	Moderate	Low
Other characteristics	Hydrocarbons in gas	Hydrocarbons in gas	Lower carbon conversion	Lower carbon conversion	Pure gas, high carbon conversion

Table 2. Characteristics of the different gasifier groups [4].

3.4.1- Entrained-flow

Carbon is pulverized ($\leq 100\mu\text{m}$) before entering in the gasifier, making it have gaseous behaviour. For this reason the reactions that take place are sudden and the time for accomplishing gasification is really short. In addition it is sensible to highlight that the fact of pulverizing carbon needs a high temperature to make the conversion successful in a short time [4].

The ashes are extracted from the inferior part of the gasifier whereas the generated syngas from the top. Due to the gaseous behaviour of the fuel special measures are needed to filter syngas and waste. If these measures are neglected, the gasifier will start to malfunction after a certain period of time.

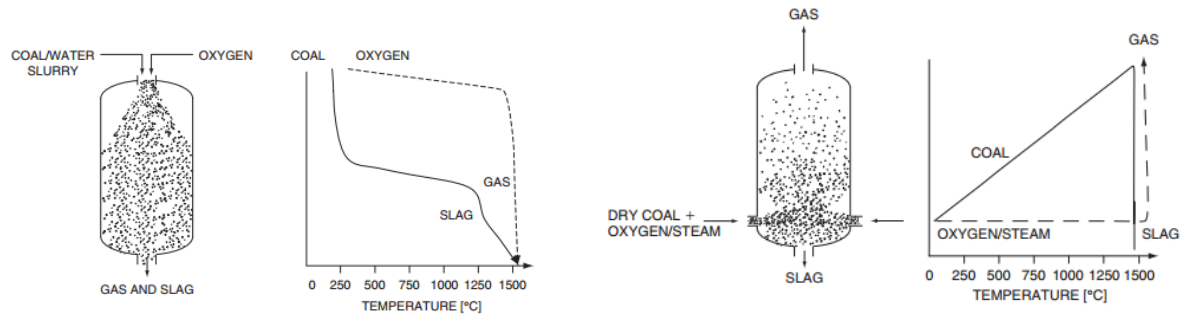


Figure 9. Examples of entrained-flow gasifier [4].

The images above (figure 9) show examples of entrained-flow gasifiers. The first one reflects the functioning of a top-fired gasifier, where gas and slag exit in the same place and will be separated afterwards. Moreover, the second image shows a side-fire gasifier where slag and gas take opposite directions and are separated by physical means. Lastly, due to the temperature conditions the efficiency is lower than in other procedures, but pollutant agents are considerably lower as well.

3.4.2- Fluidized-bed

Precedent technologies placed some unsolved issues regarding fuel. This technology appeared as a possible solution to them, specifically for the deposit draft force. The functioning is quite simple; the gasifying agent will support an additional inert element before the coal is introduced. Then, the chamber is heated up to a temperature that doesn't reach the fusion point of either, the additional element nor carbon. Once this temperature is achieved, coal is added (850-1050°C) [7]. These gasifiers enable an outstanding mixing between the elements, offering homogenized conditions [4].

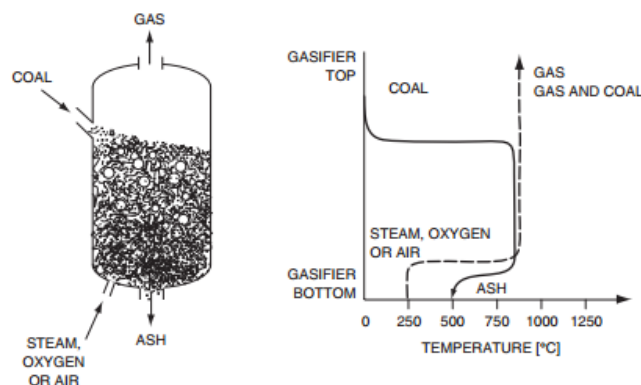


Figure 10. Example of fluid-bed gasifier [4].

One of the main characteristics of this technology is the control given over the feed, as can be seen in figure 10. In contrast, it presents some drawbacks such as higher tar generation rate in comparison to others. Other of the advantages that this process offers is a higher efficiency in syngas production and a low residence time. Finally, depending on the fluidization speed there are three groups (see figure 11); stationary fluid-bed, circulating fluid-bed and transport reactor.

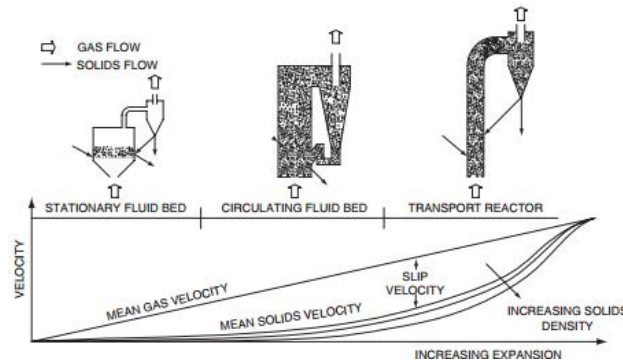


Figure 11. Fluid-bed gasifiers [4].

3.4.3- Moving-bed

The most common and old of the technologies is moving-bed. It is characterized by the slow movement of the coal downwards the gasifier, while the blast of gasifying agent forces it to react. If the blast interacts with the coal in counter-current, the syngas produced is used to pre-heat the coal (drying process) and pyrolyse it. For this reason sometimes the by-products formed are present in the final syngas [4]. Depending on the direction the blast takes there are two main groups:

Updraft

Among the years, this kind of gasifier has lost their preferential place in the market due to their impossibility to generate a continuous and homogeneous gas. On the other hand, the syngas extracted has excellent properties and an outstanding low temperature process. The process explained is showed in the next image (see figure 12).

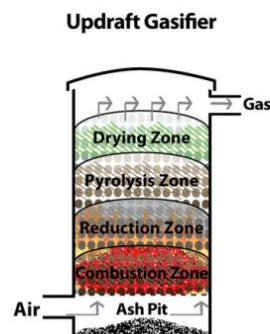


Figure 12. Updraft gasifier. Source: GEK gasifiers online website.

Downdraft

In this case both, blast and coal, travel in the same direction inside the gasifier increasing the time of residence. As a result, tar production increases but syngas production is continuous and homogeneous in counterpart. According to temperature, procedures to lower the value of the syngas are needed in order to make it suitable for the next processes. The temperature has this value as a result of the reduced combustion zone that enables to concentrate heat (see figure 13).

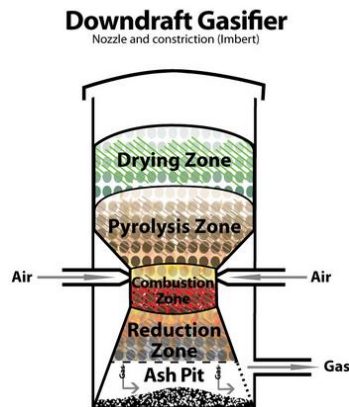


Figure 13. Downdraft gasifier. Source: GEK gasifiers online website.

As it is noticed, there hasn't been a specification about the fuel elections when talking about gasification, only a high composition in carbon has been mentioned. In this sense, the next chapter is oriented to the fuels that are suitable for gasification. Moreover, the convenient justifications are given in order to support the best option.

4. Organic Fuels

The fuels used must be seriously studied if a successful process it is wanted to be achieved. Firstly, the fuel should be organic-based, in other words it must held a carbonic structure. The importance of it is that the synthesis gas obtained after gasification must have a high calorific power for the leading process of combustion in the combined cycle.

4.1. Coal

According to its definition, coal is a compact form of biomass developed amongst the years due to pressure and temperature, which have a very significant impact in the type of coal formed. Moisture, minerals and ash are its principal components; however the composition may suffer relevant changes depending on the type of coal studied [9]. According formation time, it is so high that coal is considered to be a fossil fuel. Nevertheless, coal reserves are much higher in comparison to most of the other fossil fuels and its dispersion is much more equal. This fact mustn't be neglected, as transcendental political issues may appear as consequence of the sell and purchase of fuels. The reason for this equity is quite simple. Millions of years ago forests were very prolific all around the world. Then, the decomposition and consequent transformation into sediments formed layers underneath the ground distributed the coal. In the next figure the process is shown.

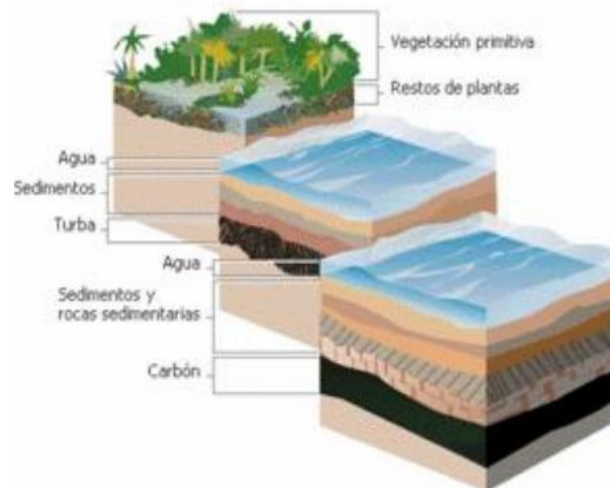


Figure 14. Coal formation process [10]

Regarding extraction procedures, the level of difficulty increases proportional to the deepness of the coal thus, depending on the variety that is targeted, the investments in specialized machinery has to be considered. Nowadays there are four important kinds of coals; each of them can be subdivided according to their content in carbon.

4.1.1. Peat

Being the most recent type of carbon, it is sensible to state that is also the one that has the least percentage of it. As a result, it has a low calorific value that can be aggravated by the significant moisture levels that presents. Concerning to how it looks like, peat has a spongy texture, brown colour and lots of similarities to common ground (see figure 15). Finally, peat has a distinguished use as fertilizer [10].



Figure 15. Peat. Source: NordTorf online website.

4.1.2. Lignite

The next variety of coal is lignite that is deeper in ground; however, its location doesn't bring many problems as the extraction can be done in open-air mines. The carbonization process is visible at naked eye, making lignite resemble burned wood (see figure 16).



Figure 16. Lignite. Source: image taken by Javier Mena Bayón.

Due to the higher content in carbon, it suffers an increase in its thermal properties and therefore is commonly used in industrial processes of low impact. Alternatively, moisture is considerable, making lignite less appropriate for gasification [10].

4.1.3. Bituminous Coal

Advancing towards The Earth's centre, pressure and temperature sharply increase and force biomass to be converted into bituminous first and anthracite in lower layers. It should be mentioned that at this point the extraction has a certain complexity level whereas before the extraction can be considered practically costless. In contrast, the substantial raise in the properties of this element make the effort worthy. As shown in figure 17, the layers above bituminous coal make the pressure on it so high that the change of properties can be held in only 5 meters.

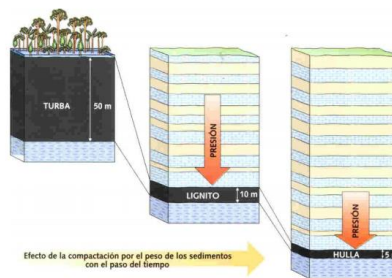


Figure 17. Coal varieties location [5].

Nevertheless, combustion of carbon is contraindicated due to environmental issues. Some of the internal components, such as sulphur or nitrates, may derivate in potential polluting gases when direct burning takes place. In this sense, gasification approaches a huge advantage considering that the process will allow the extraction and purification of the synthesis gas separating the noxious compounds and processing them for future sell. In this way, the potential calorific power of the bituminous coal can be widely used, saving money and being respectful with environment.

Up to 60-86% of the structure can be made out of carbon; the rest is composed by a rich mixture of minerals that make it perfect for the metallurgic industry [4]. Finally, and as it can be seen in the image below (see figure 18), bituminous coal has a rocky, shiny black aspect.



Figure 18. Bituminous coal. Source: Emaze online website.

4.1.4. Anthracite

Anthracitic coals are the richest in carbon, achieving levels over 90% most of them and 98% the purest ones, meta-anthracite [4]. Its thermal properties are outstanding due to the extreme pressure and temperature conditions in which is born. It is interesting to see the laminar shape (see figure 19) it earns because of the sudden transformation that it suffers. The conditions are so extreme for its formation that slim layers are found at a very deep location.



Figure 19. Anthracite. Source: Lexicoon online website.

The purity of this variety makes it an ideal compound for combustion as the potential pollution is very reduced in comparison to the rest of coals. In contraposition, the huge display of resources needed for its extraction is only justifiable for uses of optimum requirements.

4.2. Biomass

Even though biomass is not a commonly renamed fuel, it supplies between 15-20% of the total fuel use in the world, for this purpose it shouldn't be neglected [4]. Moreover, if a definition has to be given for this term it has to be mentioned that the huge scope that it broads makes it difficult to specify. Along this document, biomass is going to be understood as the raw material obtained from recently living organisms. This definition resembles the one given to fossil fuels; however the difference is that fossil fuels need millions of years to be formed, whereas biomass is much more recent. In table 3, some of biomass properties, such as Higher Heating Value (HHV), moisture, ash, sulphur and chlorine percentages can be seen.

Biomass	HHV (MJ/kg)	Moisture (Wt %)	Ash (Wt %)	Sulphur (Wt %)	Chlorine (Wt %)
Wood	10 - 20	10 - 60	0.25 - 1.7	0.01	0.01
Coconut shell	18 - 19	8 - 10	1 - 4	-	-
Coffee husks	16	10	0.6	-	-
Palm oil residues	15	15	-	-	-
Cotton residue	14	9	12	-	-
Sawdust	11	35	2	-	-
Maize (stalk)	13 - 15	10 - 20	3 - 7	0.05	1.48

Table 3. Properties for different biomasses [4].

Regarding some the advantages biomass offers with respect to the common fossil fuels, it is remarkable that the emissions of CO₂ clearly diminish. In addition, ash properties relating to coal ones have a lower melting point due to its mineral nature, some of them can be observed in table 4 [4].

Mineral nature	Straw (Wt %)	Miscanthus (Wt %)	Wood (Wt %)
CaO	6.5	7.5	37.3
MgO	3	2.5	8.5
Na ₂ O	1.3	0.2	3
K ₂ O	23.7	12.8	8.6

Table 4. Ash components of straw, miscanthus and wood [4].

Finally, it is advisable to highlight that, not only vegetable residues can be used as biomass fuel, but also animal biomass has to be taken into consideration as their HHV can reach values between 13 and 28 MJ/kg.

4.3. Waste

The last of the fuels that are considered in this document is waste. To establish a suitable difference between what is waste and what is biomass is an unworthy task. On the other hand, in this document waste is going to be understood as the residue produced by still living things. It can be liquid or solid and one of the biggest differences with biomass is that most of the materials included in waste have a high moisture percentage. For this reasons the levels of oxygen included in them are noticeable.

One of the main drawbacks regarding wastes is the characteristic heterogeneity it has, so it is issuable to obtain a continuous and homogeneous syngas. As a result, the gasifiers have to be built to support big bunches of waste, to make the conditions more homogeneous. On the other hand, it is a way to get a thermal benefit of residues destined to dumps and decomposition. It is sensible to say that the heating value of waste isn't very different to the ones obtained with biomass.

4.4. Fuel election

After analyzing the possible fuels, neglecting other possible ones such as oils, the most suitable fuel is coal. In fact, the majority of stations that have embrace IGCC technology use coal. However, coal by its self is not as powerful as the mixture formed with petroleum coke.

Taking as an example Puertollano's power plant, petcoke and coal are inserted in the gasifier in a 50-50 mixture ensuring the complete conversion of carbon, as the temperature has to be increased to favour petcoke's decomposition and liquid slag, which is easier to extract. Not every IGCC power plants have the same fuel running their systems, but coal is the principal fuel.

In order to back-up the election, the reasons for it are going to be detailed. Firstly, the location of coal mines all around the world makes this fuel a suitable election worldwide, so the technology can be globalized and therefore the advances made in one part of the world can be easily exported to another. In this sense figure 20 shows coal's distribution all around the world. Taking this premise to Spain, in Puertollano the dependence of Argelia's natural gas supply is considerably abated.

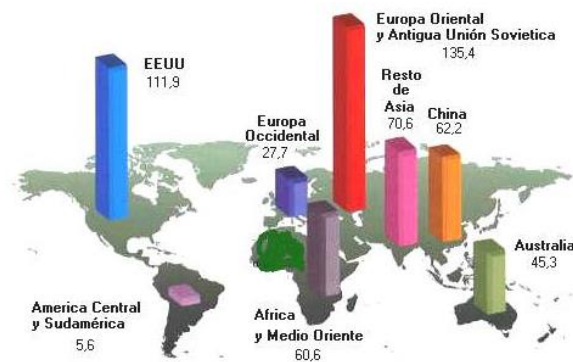


Figure 20. Coal reserves in 1×10^{12} tons. Source: Wordpress.com

Secondly, concerning the heating values it can be seen in the table below that any kind of coal has a potential heating value that overcomes the other fuels considered (see table 5). Analyzing the table, where all the kinds of coals are compared with the higher heating values and the energy density (energy related with the volume occupied by one gram of fuel) it can be seen that coal isn't the most energetic fuel. Crude oil, natural gas or gasoline have almost double higher heating value, however the principal drawback of these technologies is the

noxious gases generated when they are used. In addition, when talking about energy density it can be stated that coal has significant advantages to most of the other fuels. The reason for it lies on the solid composition of coal, so the energy in one m³ of it rises sharply with respect to the other non-solid compounds. Gas fuels have to be compressed in order to achieve a suitable energy density.

FUEL	HHV (MJ/kg)	Energy density (MJ/m ³)
Crude oil	45.543	35.8
Bituminous Coal	27.267	21
Natural gas (80 bar)	52.225	2.9
Biomass (average)	18.123	3.7
Bio-oil	17.571	20
Gasoline	46.536	35
Methanol	22.884	19

Table 5. HHV and Energy density comparison for various fuels [4].

Summing all up, coal is the election made due to its gasifying suitability, that makes it less pollutant by far to the common fuels, to its higher HHV with respect to other possible gasifying fuels and to its worldwide distribution.

Having these all in mind, it is reasonable to start to have a deeper look on to the integration of the mentioned technology nowadays, explaining in depth the functioning of the process and some of the most relevant examples. Afterwards, a more detailed breakdown of Puertollano's power plant will be done in order to clarify the most important aspects and devices.

5. IGCC technology

5.1. Introduction

The emergence of this new technology isn't matter of casualty, as the first approach that has to be made is achieving the highest efficiency with the smallest impact possible within the resources available. In this sense the optimization of coal is one of the fundamental matters concerning IGCC technology. Despite the eye-catching nature of this technology, there is a minor sector in the energy field that still aren't completely convinced of the advantages of the integration of gasification technologies. During this chapter, the operating properties and the study of advantages and drawbacks will be made in order to shed some light over IGCC systems.

Firstly, coal is an abundant energy reserve all around the world, but the way it is usually exploited isn't the most appropriate for environment preservation. Typically, the use of coal as fuel is associated to pulverized coal (PC) fired boilers. The fact of using it for direct combustion generates noxious gases present in the flue gas that contribute to deteriorate environment. For example, nearly 63% of sulphur emissions and 19% of nitrogen emissions in the U.S. are derived from PC- fired power plants [6]. However the problem doesn't ends here, as coal-based power plants also have inherent particulate emissions that risk population's health and the treatments needed for reducing or eliminating them aren't effective or enough.

In this matter, gasification has an important role. The syngas produced at the first stages has contaminant components but the removal of them is much easier and effective than in flue gas. In fact, sulphur impurities can be removed in excess with efficiencies near 95%. In addition, gasification offers the advantage of exploiting industrial and domestic surplus such as wastes, bio-material or by-products from refineries as feedstock, which contains fewer toxic components [6].

Moreover, not only from an environmental standpoint, but also from an energetic one, one of the main components of syngas is hydrogen. It is sensible to say that is the cleanest and highest efficient burning fuel, however it is expensive. With gasification it is favoured the production of H₂ without extra expenses is favoured, what makes gasification interesting from an economic point of view. Retaking the pollutant impurities subject, their removal of can be up to 99% efficient and further synthesis can be made to convert them into commercial products [6]. Additionally, syngas is a rich source of chemicals that isn't only suitable for combustion, but also can be derived into liquid fuels or petrochemicals that can be used as feedstock for refineries. Moreover, carbon dioxide is a dominant issue when talking about combustion. It has to be mentioned that the production of CO₂ during gasification process is a fact to take into consideration. The main difference with the traditional coal-based power plants is that inside gasifiers the CO₂ exits in a concentrated stream instead of being

completely diluted in flue gas like in combustion. This isn't a trivial detail as the capture of CO₂ is much more efficient and can be used for commercial purposes.

Approaching a thermodynamic standpoint, gasification of coal also offers a better electricity conversion. The reason for it is quite simple due to the explanation about efficiencies regarding Rankine and combined cycles. Typically, coal-based plants that burn the fuel directly only work in steam cycles, which efficiencies range is held around 35%. On the other hand, and as it was explained before, gasification is integrated in combined cycles that boost the efficiency up to 55% and can potentially reach 60% with technological advancements [6]. It has to be highlighted that the possibility of integrating direct combustion of coal into a combined cycle is not possible due to the complexity of combustion chambers. The reason is that the slag produced will collapse the exits of the chamber forcing it to malfunction in a short period of time.

Summing up the differences between conventional uses of coal for electricity generation, some of the advantages are detailed below:

- Secure supply due to the high coal reserves all around the world
- Possibility of taking benefit of different kind of industrial, nature and human surplus as feedstock.
- Concerned with environment with lower CO₂ emissions and the almost complete removal of pollutant agents.
- Thermodynamic, economic and environmental superiority with respect to conventional PC-fired power plants.
- Economic benefits derived of the by-products synthesis from gasification.
- Higher electricity conversion.

5.2. Examples of some IGCC power plants

Due to the number of plants that have been based in IGCC cycles, it is sensible to say that this technology is no longer an idea but a reality. However the implementation hasn't been worldwide yet, economies such as China, Japan or EEUU are pioneer in this new technology with different conclusions.

5.2.1. United States

Starting with U.S. as an example isn't trivial, as they can be considered as fathers of this technology. Around the 1960s the U.S. Government started to give financial support for determining if coal was feasible as gas turbine fuel [11]. The result was that combusting coal directly or mixed with other liquid fuels was a waste of time and money. In this sense, the U.S. Government was really determined in reaching a suitable solution to make coal an economic

fuel. After further researches and tests, they found in gasification the key they were looking for.

Approximately ten years after, in the 1970s, the U.S. Department of Energy (USDOE or DOE) assisted in technology development and demonstration since then, showing the compromise they had with this new system. The conclusion was that large-scale plants (above 200MWe) were much more suitable according to commercial standards than small-scale ones [6]. To this end, some of the IGCC-based power plants are mentioned below.

- Tampa Electric IGCC Project, Florida [12].
- Wabash River Coal Gasification Repowering Project [13].
- Duke Energy Edwardsport IGCC Project [14].
- Kemper County IGCC Project [14].

5.2.2. Asia

The use of this kind of technology in Asia is a today's issue. However, the production of energy derived from IGCC is exponentially growing since the first demonstrations proved the utility of it. Regarding the economic emergence of many countries, makes suitable the appearance of new IGCC power plants or substitution of previous highly pollutant power plants. For this reason, it is sensible to express the most important examples of the pioneer plants in Asia.

- Nakoso IGCC demonstration, Japan [12]
- GreenGen Project, China [15]

5.3. Comparing technologies

5.3.1. Economical comparison

Economical standards aren't the only thing to take into account when talking about costs. Unfortunately, society is focused on the impact investment will have in people's wallets without thinking in environmental impact or even in social repercussion. In this sense, the next lines will make an analysis that doesn't stop in the cost per kWh of electricity produced.

- Fixed costs: these costs are the simplest ones as they correspond to the initial inversion and the costs derived of maintenance and operation. Usually, they are the easiest to calculate and establish, therefore no further surprises are expected.
- Variable costs: Supplies needed is the core of variable costs. It is commonly known that the demand of supplies isn't determined in normal basis; it is subjected to the reserves and the operation efficiency.

- Social costs: Due to the large space power plants span, there is an indubitable impact in society, environment and fauna surrounding. Obviously some of these costs may be positives, such as the employment created.

The order in which the costs are written above isn't trivial, as the first two are the ones with mayor impact when the decision of constructing a new power plant is taken. However, neglecting the derived impacts suffered by the surroundings only favours the firm's economic wealth, forgetting people's one. On the other hand, to achieve a tangible value for these kinds of costs carries lots of time and study.

During this chapter, the comparison between IGCC, PC-fired and NGCC will be recurrent. The advantages and disadvantages of choosing one or other technology will be justified from different points of view.

Fixed costs

Despite having several advantages because of being a relatively new technology, the initial investments are rather high, as the common optimization developments are still in process. On top of that, IGCC has an economic drawback with respect to its strongest competitors, as the calculation of an approximate initial investment has too many variables. In contrast, it is reasonable to think that once the commercialization of IGCC continues it will be easier to establish more solid values instead of approximations [3].

Since the first IGCC power station started to operate, initial investment costs as well as the operation and maintenance ones have decreased considerably matching the predictions done in 2000 by the US DOE (see table 6).

Year	Capital costs (€/kW)	Efficiency rate (%)
1997	1,285	39.6
2000	1,110	42
2010	885	52
2015	750	60

Table 6. Initial costs prediction of IGCC technology [11].

On one hand there has been a certain decrease in the initial costs, on the other, time has demonstrated that the predictions where far too positive. Something similar happens with the efficiency rates. For instance, the current values estimate that initial costs are around 1000€/kW and efficiency rate under 50%. Nevertheless, as far it is known, if the technology continues in the development line in which is improving, significant advances will be made.

Once the most striking values for IGCC are given, let's make a comparison with the two main competitors. It is fair to say that in the matter concerned both, PC and NGCC, have significant advantages given by the optimization processes since they first appeared in the

market. However, bearing this in mind, these technologies have no further advance in cost reduction matters [16]. Moreover, PC has a crucial drawback when talking about emissions. In order to take under control the noxious gases produced, an extra investment has to be made in specialized equipment, therefore the initial investment increases.

Variable costs

Placing the scope in fuel as vital variable cost, many aspects should be treated. Firstly, it has to be highlighted that the main advantage that IGCC has among its competitors is concerning the combustible used. Compared to natural gas, the thermal properties aren't so powerful; regardless the difference isn't that significant, whereas the economic aspect really makes the difference. However, there are many variables that can influence in fuel's prize. Some of them are location and national reserves, purchase and transport of fuel or the cycle's efficiency.

Justifying the previous statement, the price of coal for IGCC power plant is usually given in €/ton instead of €/Nm³, so conversion has to be made in order to make the economic comparison. In figure 21, the costs for petroleum, natural gas and coal is done under USD/Tonnes equivalent of oil (Toe).

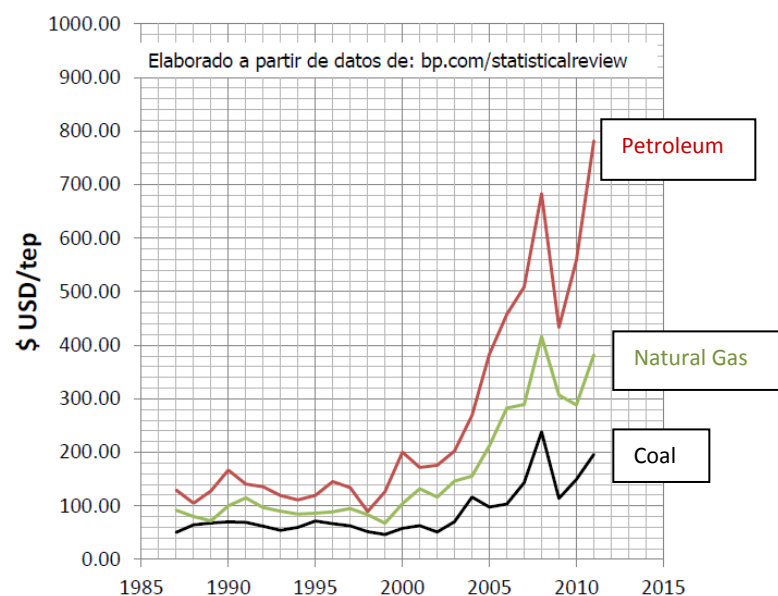


Figure 21. Year by year fluctuations in fuel costs. Source: OCW Universidad Carlos III de Madrid. Fuentes de energía.

In this sense, it can be highlighted that natural gas almost doubles coal when talking about costs. Furthermore, it is sensible to mention that these values have been collected for EU market, where petroleum and natural gas are scarce. This makes the cost rise due to the special utilities needed for transporting natural gas. At the end of the day, handling natural gas implies higher costs than handling carbon.

Social costs

Prior to the construction of any plant, many drawbacks and regrets are considered by the nearby villages, until they realise the economic advantages from which they will benefit. Contrary to this, it is known that the visual impact derived from the power plants building can still bring several retractors.

Taking as an example IGCC plants, there are various notable social advantages with respect to NGCC and PC-fired plants. Firstly, PC-fired plants need more time for their building-up, making annoyance persist in time. On the other hand, the expensive cost for transporting natural gas leads to optimization of the pipeline. For this reason, some places can be found non-suitable for NGCC technology, yet as a consequence further disturbs could be occasioned.

Economic conclusion

Summing up the facts given in the previous lines, several comparisons are made between technologies. Firstly, fuel is a crucial issue due to the continued employment to which is subjected. In this field, it has been made clear that depending on the place where the plant is located careful study has to be carried out in order to reach a resolution. However, concerning EU market in particular and the world in general, coal can be described as a much more diversified fuel than natural gas or petroleum. As a result, it can be stated that the mean prize for coal is more affordable than those for natural gas or petroleum.

Regarding the facilities needed for the generation of electricity, it was said that PC-fired technology is only appropriate for Rankine cycle plants whereas NGCC and IGCC are developed in combined cycle plants. As a consequence, not only the efficiency is lower, but also the construction time and costs are much higher. For this reason, PC continues to have important drawbacks compared with IGCC for the same fuel. In addition, PC plants produce higher quantities of noxious pollutants, which lead to further costs derived from pollutant palliation.

Finally, it has to be mentioned that the initial investment for IGCC is the principal disadvantage regarding costs. The reason is quite simple, as it was said before is a relatively new technology and the corresponding optimizations haven't been processed yet. To shed some light over the facts proposed, table 7 reflects the comparison done between three different plants of 500MW. It has to be mentioned that the values are approximate and based in data from the DOE and the Electric Power Research Institute (EPRI) [17].

	IGCC	PC	NGCC
Efficiency (%)	41	35	50
Initial investment (cent €/kWh)	2.02	2.4	0.96
O&M (cent €/kWh)	0.71	0.68	0.32
Fuel (cent €/kWh)	1.14	1.33	2.57
Total cost (cent €/kWh)	3.87	4.41	3.85

Table 7. Cost comparison between IGCC, PC and NGCC 500 MW power plants [11] [17].

Rate	Value
IGCC/NGCC	1.0005
IGCC/PC	0.877

Table 8. Cost comparison rates.

The table above (see table 8) shows that IGCC is a suitable competitor for NGCC power plants regarding costs whereas PC plants should get out of schedule. Embracing pragmatism, the suitable idea for new power plants should be NGCC technology, but further study needs to be made as money isn't the only thing to take into consideration.

5.3-2 Environmental Comparison

Attending to environmental issues, IGCC has gained substantial relevance nowadays. One of the most important threats today concerns environment and the abusive behaviour men have taken over it. For this reason, society has gained the courage to face equally economic and environmental approaches when new power stations are going to be built. Moreover, detailed explanation will be given stating the need for changing the old fashioned carbon based plants into modern IGCC, NGCC or renewable plants. In order to obtain the maximum benefit out of carbon, being this fossil fuel abundant, facts will be given as justification for the change.

The problematic mainly focuses on the emissions of CO₂, which favours greenhouse effect, SO₂ and NO_x, principal producers of acid rain, and solid particles [3]. Several studies carried out, since IGCC as clean use of carbon started to emerge, reflect the considerable reduction, which this technology can produce when talking about emissions. In this sense, the environmental impact is really limited when comparing it with the traditional carbon-based technologies such as PC plants. Additionally, what makes even more attractive IGCC against PC plants is that the limitation is due to the nature of the consequent products that can be easily

separated before combusting syngas and prepared for commercial use, giving not only environmental benefits, but also economic ones.

Next, each of the concerning compounds of the emissions will be detailed giving some numerical facts as mere comparison between the different technologies that have been treated.

Carbon dioxide, CO₂

Without question, CO₂ has given society lots of headaches since the damage of the ozone layer started to be a fact. Many treatments and councils have been agreed in order to end the abusive emissions of this compound to the atmosphere. However, many of the conventional carbon-based plants are still open and functioning.

As it was said before, with the employment of gasification, the CO₂ produced stays in a concentrated stream instead of being completely diluted in the complexity of flue gas after combustion [6]. This favours what is known as CO₂ capture, cleaning syngas before combustion and reducing the emissions in more than a 20%, matching the fundamentals of all the global official documents [3]. Also, the extraction before combustion is highly advisable from an economic point of view, whereas the extraction from flue gas requires more time and money.

According to natural gas, the emissions of CO₂ are considerably lower than the ones derived from direct combustion of coal. Bearing this in mind, the Spanish Government has elaborated a comparison that states that the use of natural gas implies a reduction of almost 50% in CO₂ emissions. To this extent, it is sensible to say that with IGCC the differences are narrower, but natural gas still produces less CO₂.

SO₂ and NO_x

The transcendence of these compounds lies on the production of acid rain that leads to the burning of surroundings, causing environmental and social damage. For this reason they can't be neglected. In the case of SO₂, it has been proved that IGCC accomplishes an excellent job in sulphur recovery, reaching values near 99%. Furthermore, this makes the atmosphere receive less concentrations of sulphur and the recovered part can be synthesized and sold, as it appears mainly as H₂S instead of SO₂. This process is possible due to the extraction before burning, a process that is not feasible neither in NGCC nor PC technologies.

Concerning NO_x, huge advances have been made because of gasification. The pressurized characteristics in which the process is done makes the nitrates present in the final compound appear in ammonia form instead of NO_x, which can be easily cleaned with water treatment [6]. Nevertheless, when combustion takes place, pure nitrogen is added to control the free radicals that could be contained in it, avoiding the formation of thermal NO_x [3].

Solid particles

It is universally known that one of the vital problems regarding conventional carbon-based power plants lies on the emission of tiny solid particles that can cause respiration malfunction after a long exposure. To this end, it is obvious that a wide range of filters are used in order to try to cope with it, but is quite inefficient. On the other hand both, natural gas and syngas are almost free of particles due to their gas phase, what makes the emission negligible. However it is advisable to use filters at the stack, hence some slag could be dragged along the process.

Environmental conclusion

After the comparison of various pollutant compounds regarding the three technologies studied, it is recommended to propose some values that will corroborate the statements written above.

	Syngas/Biogas (GT)	Natural Gas (GT)	Combustion Coal (Boiler)
NO _x (g/GJ)	39	205.55	638.88
SO ₂ (g/GJ)	24.44	150	694.44
CH ₄ (g/GJ)	1.12	4	0.60
CO (g/GJ)	100	10	14
N ₂ O (g/GJ)	1.80	1.30	0.80
CO ₂ (g/GJ)	61	56	93.70
Solid Particles (g/GJ)	29.10	2.10	536

Table 9. Emissions approximations [18].

Attending to the data of table, it can be seen that the use of syngas as fuel for a combined cycle reduces considerably the emissions to the atmosphere. On the other hand, it is advisable to say that the quantity of different compounds is subjected to the starting carbonaceous solid gasified. In this sense, there are some processes that can produce higher emissions than the ones above mentioned [18].

Undoubtedly, syngas will always offer a much cleaner output than the direct combustion of coal, which values are way up higher than those for syngas. For this reason is sensible to say that it is urgent to change the conventional carbon-based plants into modern IGCC technologies for both, environmental and economic issues.



In addition, it is remarkable the fact that many documents push forward the theory of 'zero emissions' regarding CO₂. To explain this fact they state that the gas combusted will never generate further CO₂ than the one the starting carbonaceous solid has gained along its life, what makes the balance between CO₂ earned and released zero. However this fact is true for biomass, in the case of bituminous coal a small amount of CO₂ is released. Regardless of this event, the truth is very clear; IGCC is a clean technology which reflects keen commitment with the world, employing an abundant fuel.

6. IGCC of Puertollano: ELCOGAS

6.1. Introduction

In April 1992 Puertollano's IGCC power plant was officially opened. With the approval of the Ministerio de Industria the mentioned power plant was designed to back-up the Spanish electric energy network (REE) by using Integrated Gasification Combined Cycle. The enterprise in charge of the process was ELCOGAS S.A., a firm that was formed by the conjunction of a series of powerful external partners in the energy field, such as Siemens, Endesa, Enel or Iberdrola (see figure 22).

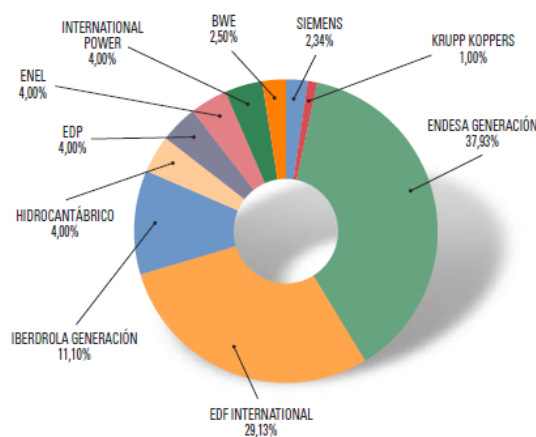


Figure 22. Owners and percentage of participation of ELCOGAS S.A. [3].

Several considerations were taken into account when the location was decided. It is sensible to say that the proximity to the source of the fuel that is employed for the cycle was a crucial factor to tip the scale in favour of Puertollano. It is important to mention that the fuel is a mixture of coal extracted from the nearby mines and the surplus petroleum coke from the Repsol's refinery also located in Puertollano [3]. This mixture is done joining the same amount of each component. The heating value for the mixture will be the mean for both components, as the mixture is done in 50% weight. However, the cycle can function with either natural gas or syngas, and therefore it is positive to mention that natural gas feed is also nearby. The use of natural gas is necessary for the first years, until the plant guarantees full capacity work with syngas; afterwards it continues to be used in supporting activities, reducing consumption to minimum levels.

Setting the installations so close to the source has a positive impact on the economy of the plant, as the costs due to transport are sharply reduced. On the other hand, the water necessary to run the vapour cycle can be easily obtained from the nearby streams, so the cycle can be accomplished without delay. All of these facts make the entire supply chain reliable, cheap and quick.

During this chapter, the mentioned power plant is going to offer some of the main characteristics that IGCC power plant have, giving a clearer and more detailed view on how this technology works. In this sense, factors such as gasification and cycle equipments, operation characteristic values or reasons for closing up will be seen in depth. Before that, the initial designed operation data are shown in table 10, sourced for ELCOGAS online website:

FUEL				
Lower Heating Value (GJ/t)	Subituminous coal and petcoke			
	Subituminous coal	Petcoke	Mixture	
	13.37	31.90	22.64	
Electric power generated	GT (MW)	VT (MW)	Gross Power (MW)	Net Power(MW)
	Designed In place	200 182.3	135 135.4	335 317.7
EFFICIENCY				
Thermal efficiency Electric consumption	Gross Efficiency		Net Efficiency	
	47.12%		42.2%	
	7.647 kJ/kWh		8.538 kJ/kWh	
EMISSIONS				
	g/kWh		mg/Nm ³	
SO ₂	0.07		25	
NO _x	0.40		150	
Solid Particles	0.02		7.5	

Table 10. Designed values before operation of ELCOGAS power plant. [3].

Taking into careful consideration the values in the table it can be seen that:

- The LHV of the mixture is substantially lower than the value of natural gas (around 50 GJ/t) [18].
- Due to the differences between theory and experimental results, the values for the electric power generated are usually lower than the estimated on paper. It has to be highlighted that VT has an unusual higher production when tested in place.
- The consumption to make the cycle operative grows due to the decrease of efficiency, which is below the standards.

6.2. Plant's contents and description

To make a further approximation on the way in which this new technology operates, during this section some of the most relevant parts Puertollano's plant will be described. Moreover, the size of thermal power plants makes it tremendously difficult to reach an exhaustive breakdown of all the equipment and devices. Therefore only the most interesting and relevant ones will be thrown into the spotlight. To begin, it is sensible to say that many of

the IGCC plants constructed consist of three core structures; Gasification Island, Combined Cycle Power Generator and Air Separation Unit (also known as ASU). Other devices concerning natural gas piping and treatment may be also taken into consideration; however in this document the structures named above are the ones which drag more attention.

As far as integration is concerned, it is vital to say that the process will fail whenever any of those structures stops working, as any of them needs to be back-upped by the other two. In order to offer some clarification, the piping and connection system between the devices of Puertollano's power plant (see figure 23).

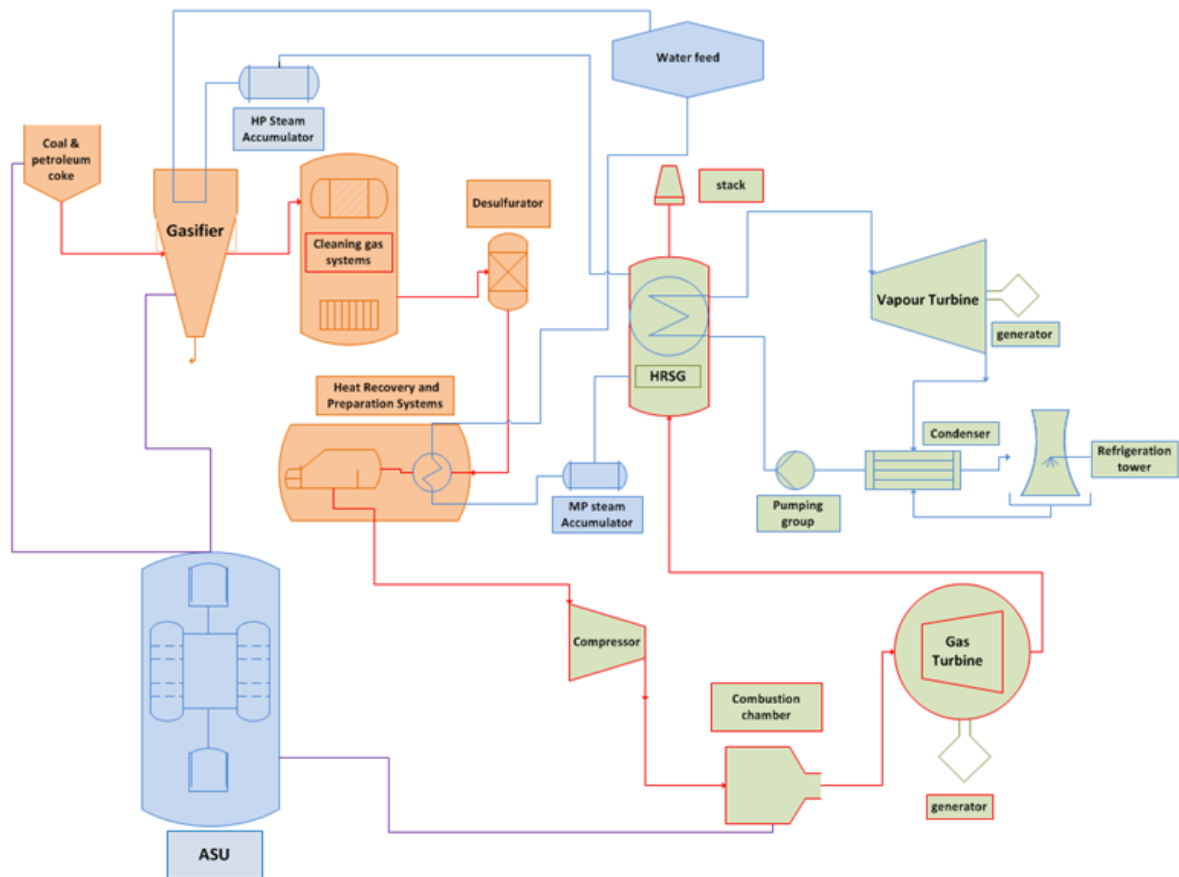


Figure 23. Connection and flows directions in Puertollano's power plant designed in Microsoft Visio.

To avoid confusion regarding the way in which the process is going to be explained, from this point onwards, the process starts with raw material storage and reception, ending with production of electric energy.

6.2.1. Gasification Island

Since fuel reception until clean syngas is delivered, the main operations are held inside what is known as Gasification Island. During the process, many parts function simultaneously to achieve the desired final product. Over each step, the adequate systems have to be correctly positioned and some of them are [3]:

- Coal storage yard and fuel conditioning systems
- Feed systems and gasification chamber
- Slag extraction systems
- Heat recovery systems
- Cleaning gas and preparation systems

Before further details, it cannot be mistaken the type of gasifier employed by the power plant. In this sense, a complete study of possibilities was done before arising with a solution. Finally, entrained-flow technology was the most suitable according to the process designed for Puertollano's power plant. Next, the various parts of which the gasification island consists of will be briefly explained.

Coal storage yard and fuel conditioning

During this first stage, the coal and petcoke transported are positioned in a huge depot that can hold over 100,000 tonnes, or what is the same, 40 days of duty. In the image below (figure 24) the mentioned yard is shown. It can also be seen the way in which coal is handled, by means of large cranes that advance back and forward on a transport belt.



Figure 24. ELCOGAS power plant's coal storage yard [3].

It is sensible to mention that the entire fuel isn't useful, as moisture, mineral compounds or ash percentages play an important role (see table 11). To this extend, the ash percentage concerning coal is way too high in comparison to the rest of components. As a result, the LHV is considerably reduced and therefore mixing it with petc oke is advisable.

Percentage in weight	Coal	Petcoke	Mixture
Ash	41.10	0.26	20.68
Carbon	36.27	82.21	59.21
Moisture	11.80	7.00	9.40
Oxygen	6.62	0.02	3.32
Hydrogen	2.48	3.11	2.80
Sulphur	0.93	5.50	3.21
Nitrogen	0.81	1.90	1.36
LHV (MJ/kg)	13.37	31.90	22.64

Table 11. Composition of fuels used in ELCOGAS power plant [3].

Feed systems and gasification chamber

The next step is to pulverize the mixture and make it pass through cyclonic filters to get rid of the bigger particles. Afterwards, is pressurized and introduced into tanks. Then, it is fed into the gasifier, keeping it as dry as possible to increase efficiency and protect the gasifier from erosion. Inside the gasification chamber 85% pure oxygen, steam and pure nitrogen are added and gasification takes place due to the temperature increase. Data relevant to design values for the gasification chamber are stated below (see table 12).

Pressure	25 bar
Temperature	1,200-1,600 °C
Capacity	2,600 t/day
Gas production capacity	180,000 Nm ³ /h
Rate of carbon conversion	98-99%

Table 12. Design data for gasification chamber [3].

As in a simple combined cycle fed with natural gas, the pressure of the syngas has to be fixed from this point onwards, due to compatibility issues with the GT. Something similar happens with temperature, if the appropriate temperature isn't, achieved the slag remaining will not melt completely and the extraction isn't successful.

Slag extraction systems

The melted slag exits the gasifier and enters in a water bath were is converted into vitreous solid form due to the high decrease in temperature. In this way it is suitable to be sold for future utilities such as vegetal carbon. Slag is mainly formed by ashes and some moisture.

Heat recovery systems

Continuing with the path travelled by the gas produced; at the exit of the gasifier the temperature is considerably high. This fact makes syngas incompatible with the cleaning procedures that lead this step, and therefore, it is necessary to cool it down. For this purpose, water cools down gas pipes and the steam generated is exported to the combined cycle. The process works in the next way:

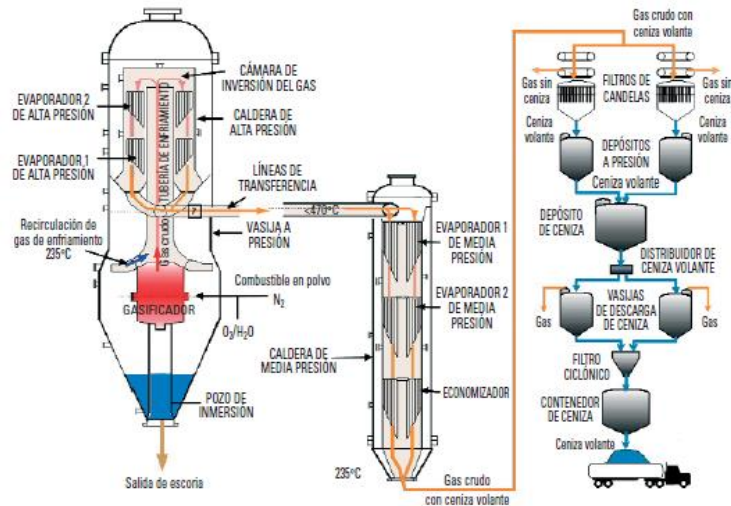


Figure 25. Heat recovery scheme [3].

Syngas enters the heat recovery system (see figure 25) at a temperature near 1,550°C, exiting at 235°C and steam is generated with two different pressures [3].

Cleaning gas and preparation systems

The last step in the process concerns the adequacy of the produced gas for combustion, generating the least possible emissions and guaranteeing the maximum efficiency. To this extent several systems are involved in the extraction of unnecessary compounds:

- Volatile ash filtration with ceramic filters
- Acid gases washing (extraction of HCl, HF, NH₃, HCN)
- Desulfurization transforming COS into H₂S and capturing it
- Sulphur recovery by means of Claus system that transforms H₂S into S₂, NH₃ and HCN into N₂
- Effluent treatment, for further water conditioning after the process.

Some of the data concerning the mentioned cleaning processes is observed in table 13:

Removed volatile ashes	3,0 t/h	
Solid particles after filtration	< 3mg/Nm ³	
LHV after Acid gas removal	10,429 kJ/ Nm ³	
Syngas composition after desulfurization	CO	60.51%
	H ₂	22.08%
	N ₂	12.46%
	CO ₂	3.87%
	Ar	1.03%
LHV after desulfurization	10,029 kJ/ Nm ³	
Removed S (removal rate)	3,1 t/h (99.84%)	

Table 13. Cleaning process relevant data [3].

From these data many things have to be explained. For instance, it has to be noticed the decent in the value for LHV, as compounds are extracted from the gas produced. On the other hand, loosing this energy means achieving a higher commitment with environment, which tips the balance in favour for the cleaning process. Also, it has to be mentioned the final composition of syngas, where CO and H₂ are clearly the major compounds. The fact of generating pure H₂ isn't trivial as it has the highest heating value of all the elements known as well as the cleanest combustion.

Finally gas is mixed with pure nitrogen and forced to its saturation point by means of water. After these two steps, the emissions regarding nitrates are substantially decreased. Nonetheless this processes have a prize, LHV is also decreased below half of its value. The final conditions for syngas are stated in table 14 [3].

Pressure	19.4 bar
Temperature	302.0°C
Mass flow	120.2 kg/s
LHV	4,242 kJ/ kg

Table 14. Clean syngas properties [3].

6.2.2. Combined Cycle

This second part is going to be in charge of producing energy by means of two different cycles that are connected by means of the HRSG system, as it was explained in previous chapters. Due to the previous explanations, it is sensible to skip the functioning and focus on

the values predicted for this combined cycle in particular. In order to accomplish this job, the different devices of which the cycle consists are stated below:

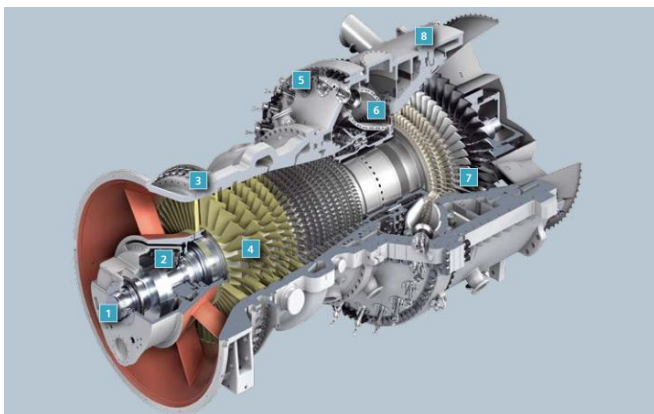
- Gas cycle:
 - Compressor
 - Combustion chamber
 - Turbine

- HRSG

- Vapour cycle:
 - Vapour turbine
 - Condenser
 - Pump

Gas cycle

As one of the participants, Siemens was in charge of supplying the devices needed to build a complete combined cycle circuit. Regarding the gas cycle, which is the first step to produce electricity, a SGT5 4000F, formerly known as V94.3 GT, was installed. Moreover, the mentioned GT is going to be broken-down into its devices. In the CAD design (figure 26) of the GT its different parts are shown:



Key [19]:

1. Feed generator coupling
2. Rotor bearings
3. Compressor
4. Variable inlet guide vanes
5. Fuel nozzle
6. Combustion chamber
7. Turbine rotating blades
8. Turbine casing

Figure 26.SGT5 4000F design and distribution [19].

Compressor

The role this device plays varies depending on the gas introduced into the combustion chamber because during the process fed with syngas, some of the air compressed is going to be reoriented into the ASU. The compression is done by means of 17 stages, making air suitable for the process and enabling maximum efficiency in partial load processes.

Combustion chamber

Here is where fuel is introduced for further burning. It is a silo-type combustor separated into two different zones with eight combustors. It has different configurations available to enable introducing various fuels. For this reason is suitable for syngas, natural gas or both at the same time. Air at the exit is highly uniform, benefiting the leading expansion stage [19].

Turbine

Power is going to be generated by the expansion in four stages of which consists the turbine designed by Siemens. The blades are made of a nickel-based material and consist of conventional cooling to control the exiting air, protecting the device from mbreaking in the first stages, where temperatures are critical [19]. Then, the power generated is transformed into electricity.

In the image (figure 27), GT in its operating position can be seen along with table 15, where the design values for the gas process are stated and obtained from ELCOGAS S.A.



Figure 27. GT operating position [3].

Siemens SGT5 4000F (V93.4)	
Air mass flow	537.0 kg/s
Compression stages	17
Compression ratio	15:1
Combustion T	1,250°C
Expansion inlet T	1,120°C
Expansion stages	4
Outlet T	539°C
Thermal efficiency	34.6%

Table 15. Design values for GT developed by Siemens [3].

HRSB

Heat Recovery Steam Generators are devices that operate as heat exchangers between gas cycles and steam cycles. They use the heat form exiting gases of the GT to evaporate water and generate steam for the VT. In Puertollano's particular case, the exchange surface is approximately 300,000 m² distributed in 10 modules mentioned below. The steam generated to reduce syngas' temperature before cleaning in the Gasification Island is now incorporated into the HRSB and afterwards into the VT. In order to incorporate the mentioned steam streams, the HRSB consists of various devices separated by pressures:

- Low pressure (LP)
 - Preheater
 - Evaporator
 - Superheater

- Medium pressure (MP)
 - Economizer
 - Evaporator
 - Overheating

- High pressure (HP)
 - Economizer
 - Evaporator
 - Superheater

Steam cycle

As the HRSG system makes useless a boiler, the steam cycle is going to have only three main devices; turbine, condenser and pump. Just like in the gas cycle explained above, this cycle is also property of Siemens, who developed a K30-16-1 with three pressure levels. This turbine has a minor contribution to electricity generation but it can be considered as 'free energy' as no fuel is consumed to produce it. The efficiency will rise with steam extractions.

Condenser

It is used to condense the steam that comes out of the turbine under almost vacuum conditions. For refrigeration, a tower is implemented and water will complete a closed circuit through stainless steel pipes.

Pumps

Two pumps will complete the system being in charge of keeping the fluid moving towards the HRSG for the next cycle. It is vital that the pumps keep water moving to avoid stagnation of the system, producing a continuous electricity output.

Once the complete cycle is described it is sensible to state the most relevant values obtained from the cycle's operation. It is remarkable that, though natural gas and syngas have a very different value regarding LHV, the values obtained for power generation are quite similar (see table 16).

	Syngas	Natural gas
Lower Heating Value (kJ/kg)	4,242	49,220
Power developed in GT (MW)	182.3	195.1
Power developed in VT (MW)	135.4	85.6
Gross total electrical power (MW)	317.7	280.7
Gross Combined Cycle efficiency	52.4%	53.1%
Emissions (mg/Nm ³)	SO ₂	25
	NO _x	150
	Solid Particles	7,5

Table 16. Design values for combined cycle in Puertollano's power plant [3].

6.2.3. ASU

Last but not least, the Air Separation Unit (figure 28) has two main objectives; supply the oxygen necessary to accomplish gasification and produce nitrogen for creating inert conditions for fuel transport (99.99% pure N₂) and mixing it with syngas for NO_x reduction after gas combustion (98% pure N₂).

The air that enters this separation unit is obtained from the compressor in the gas cycle. This fact has its relevance, as it has better conditions for separation and further use as both, transport and combustion, are processes that require pressure for optimum result. However, the air has to be conditioned before separation is done. For this purpose cooling and purification devices are employed.

Cooling and purifying

Various heat exchanger groups are involved in the cooling process. The first one uses water from the refrigeration tower and residual nitrogen (98% pure) to cool the air from 400°C to 125°C [3]. Afterwards, the air is introduced in the next group of heat exchangers, lowering its temperature down to 14°C, the appropriate one. Next, water and CO₂ are captured to purify and avoid stagnation. When this process comes to an end, air is ready for its separation.

Distillation towers

Here is where the separation takes place and, for this purpose, special pressure and temperature conditions are prepared. The idea is to separate oxygen and nitrogen due to their differences in weight and volatility. As a result, nitrogen will be extracted at the top of the distillation tower and oxygen at the bottom after previous heating, which forces the separation.

Finally, both gases are pressurized and stored for further use. The main drawback for ASU systems is the complexity it adds to the complete cycle; however it is a low prize if the advantages it brings are taken into consideration. For instance, oxygen and nitrogen supplies are no longer a cost to take into consideration, as they are freely produced for the system (see table 17). In the image below Puertollano's ASU is observed as well as the values for it (see figure 28). In it, the systems mentioned above are visible.

	Oxygen	MP Nitrogen	LP Nitrogen	Residual Nitrogen
Flow rate(Nm ³ /h)	70,000	22,100	8,150	188,000
Purity	85%	99.99%	99.99%	98%
Pressure (bar)	31	49	4	18
Destination	Gasifier	Transport and cleaning systems	Coal preparation systems	GT, reduction of NO _x formation

Table 17. Design values for ASU in Puertollano's power plant. Source [3].



Figure 28. From left to right; refrigeration tower, storage units, distillation tower and heat exchangers [3].



At this point of the document, all parts concerning this technology have been explained in several ways. First, introduction to combined cycles operation system was made in order to gain some knowledge about the power generating method that is going to be employed. Secondly, a deep view into gasification processes and reactions is suggested to understand the functioning of this technology, with a summary of the possible gasification fuels. Moreover, the integration of the technology into combined cycles for energy production, known as IGCC, is explained, as it is going to be the fundament of the leading parts of the document. To emphasis the bases of the studied technology, a detailed example is proposed, being this one the unique example in Spain and one of the pioneers of this technology.

Once the state-of-art and the theoretical knowledge are completed, it is time to present the problem and calculations for a particular case. As it was mentioned at the beginning of the document, the implementation of Puertollano's gasifier and ASU is going to be hunted from thermal and economical points of view. This idea emerges from the recent failure of ELCOGAS power plant due to economic affairs, after the outstanding operation results. Therefore, to take advantage of the expensive devices, recycling them into an existing combined cycle seems a suitable solution to be studied.

7. Thermal study of Soto de Ribera combined cycle

After 15 years of operation with syngas, Puertollano's gasification power plant was forced to closure. The reasons for it weren't based in malfunctioning or failure of the calculations regarding an energetic point of view. The incomplete promises regarding economic affairs led ELCOGAS to battle against the Spanish Government for almost three years and, even though they manage to obtain a payment guarantee, the amount was insufficient. On the other hand the forming partners of ELCOGAS refused any idea which made them continue spending more money. At the end of the day, the project failed economically before it could stand by itself.

One of the main issues was the high investment done initially, over 600 million of €. In figure 29, it is detailed the investment breakdown during the period between April 1993 and December 1997. The final amount invested was 601,287,389 €, amount that was expected to be covered in more than the 15 years of operation of the plant [3].

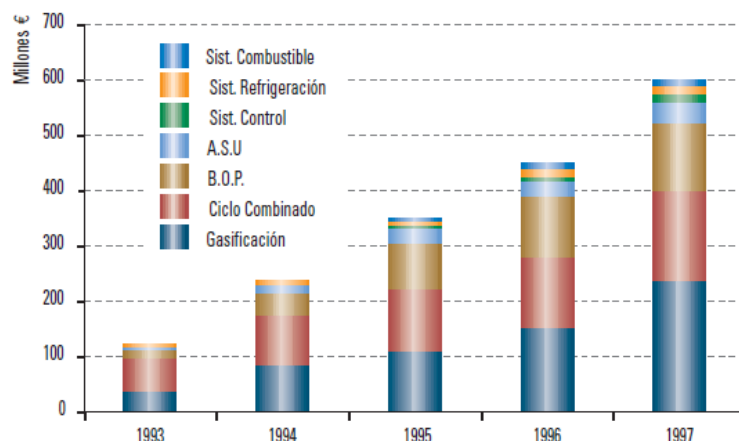


Figure 29. Initial investment breakdown [3].

Having in mind the enormous effort that has to be made in order to build and operate a power plant, it is reasonable to say that seeing fail a technology that has demonstrate that not only the theoretical advantages were taken into the practice, but also that Spain could manage to handle the fuel supply instead of keep buying expensive foreign combustibles.

As a result, in the leading chapters a viability analysis will be made in order to try to hybridize some of the expensive components used in Puertollano, such as the gasifier or the ASU, with a common combined cycle that operates nowadays in Spanish territory. The idea is to demonstrate that, avoiding the sharply high values of initial investment, the substitution of syngas for natural gas as main fuel for the cycle could bring, not only economic benefits, but

also environmental advantages. For this purpose, Soto de Ribera's combined cycle power plant has been elected to carry out the study and the cycle will be comprehensively calculated in order to obtain thermal and economic approaches to compare both technologies.

7.1. Soto de Ribera

This power plant, located at Asturias, has been giving service to the Spanish electric grid for more than 40 years. Since then, five different groups have been used to produce electricity. The first three (Soto 1, Soto 2 and Soto 3) are based in PC-fired technology with direct combustion of bituminous coal from nearby coal mines adjacent to Caudal, Aller and Nalón rivers [20]. However, in 2007 the Ministerio de Industria brought up a closure process for Soto 1 after more than 191,000 hours of operation.

In order to cover the electric power lost due to the closure of the PC-fired power plant Soto 1, it has opened the fourth power plant known as Soto 4. This new combined cycle plant offered since then 426 MW of cleaner energy, which was added to the 254 and 361 MW generated by Soto 2 and Soto 3 respectively. Three years later the second combined cycle, Soto 5, was installed and operating, adding 428 MW more. In the image below, nowadays disposition can be seen (see figure 30).



Figure 30. Soto de Ribera thermal power plant seen from above.

As it can be seen above, refrigeration process is in charge of a cooling tower, a wet cooling tower of induced drafted more precisely [20]. This makes the mass flow absorbed from Nalón River almost negligible, as most of it is again released to the river after the adequate cleaning processes.

Regarding fuel, both combined cycles are fed by natural gas. The pipe line is 1.8 km away from the plant; therefore transport of natural liquid gas is necessary. It is sensible to say that natural liquid gas is both, expensive and dangerous. In addition, Soto 4 is equipped with additional diesel pipelines for continuous operation in case gas natural supply has further issues.

During this chapter of analysis, Soto 4 is going to be the group about which all the calculations and viability analysis are going to be done. Mainly because the additional supply option is necessary in case syngas needs any kind of support. Once the location has been set out, the calculations and analysis of the combined cycle that operates at Soto 4 are going to be carried out.

7.2. Operation analysis

As it was explained in the second chapter, combined cycles operate with the conjunction of gas and steam cycles in order to take advantage of the same combustible feed. In Soto 4's case, the complete cycle is distributed by Alstom Power operating with a KA26 combined cycle as shown in figure 31. Deepening inside the devices, it can be said that the gas turbine, named as GT 26, is a modern device that has 22 compression stages, a sequential environmental combustor (SEV) and a turbine that can stand temperatures up to 1500°C. Regarding steam cycle, the turbine counts with three different levels of pressure [21] [22]. It has to be said that what makes this power plant suitable for the hybridizing analysis is that the SEV allows a wide range of fuels, including synthetic gas obtained from gasification processes.



Figure 31. CAD design of Alstom KA26 [21].

Now the cycle is going to be described and the variables may also be stated. The architecture of Soto 4, as almost all of them, is confidential and only some of the components may be found in official documents and internet. Therefore, the analysis has been done based on the structure most of combined cycles present, as it can be seen below (see figure 32). The fact of not being for sure the real architecture isn't completely relevant, as the comparison between the power plant before and after hybridizing the gasification process will be analogous.

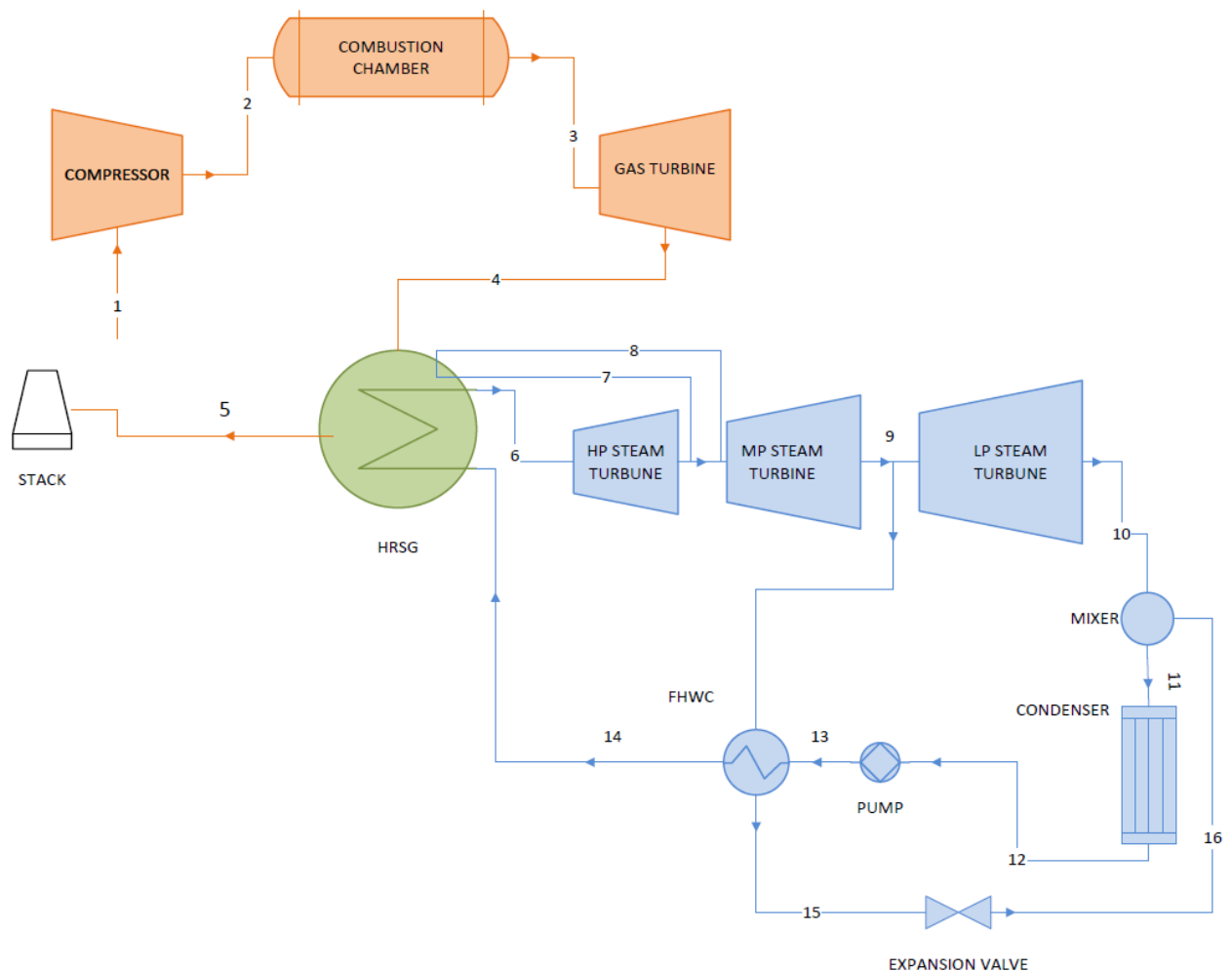


Figure 32. Soto 4 hypothetical structure designed in Microsoft Visio.

In the scheme attached, all the points that are going to be studied are shown (from 1 to 16) in the same order as the process takes place. It has to be remarked that the orange lines and devices belong to gas cycle and the blue ones to the steam cycle. All the devices are named in the scheme as they are going to be name in the leading pages.

7.2.1. Gas Cycle

Before showing the calculations, some explanation has to be done. In this part of the cycle no improvements have been performed, therefore its functioning is the same as in chapter 2. The working fluid is air, considered as perfect ideal gas (CPIG), which properties will be stated moreover.

Starting data:

Air

$$Cv = 0.718 \frac{kJ}{kgK} (300 K)$$

$$\gamma = Cp/Cv = 1.400 (300 K)$$

$$Cp = 1.005 \frac{kJ}{kgK} (300 K)$$

$$Cv = 0.929 \frac{kJ}{kgK} (1500 K)$$

$$\gamma = Cp/Cv = 1.309 (1500 K)$$

$$Cp = 1.216 \frac{kJ}{kgK} (1500 K)$$

Due to the high temperature differences involving the cycle, air suffers substantial changes that may affect the cycle's calculations. In this sense, the value for Cp , Cv and γ will be different for each point in the cycle. The value for γ will be calculated for each point with respect to the information given by Table A-20 Moran-Shapiro [2] and ohio.edu [23]. On the other hand, and to add simplicity over the whole calculation process, Cp will take a constant value based on the mean value between the higher and the lowest values seen above.

$$Cp = \frac{Cp_{high} + Cp_{low}}{2} = \frac{1.216 + 1.005}{2} = 1.1105 \frac{kJ}{kg}$$

The reason for doing this is that results don't suffer significant changes, whereas the variations on γ do, as it is involved in exponential operations.

Temperature and Pressure

According to EDP Spain online website, the temperature at which the gas exits the GT is fixed for achieving the correct heat transfer inside the HRSG. In this sense, the information they give, corresponding to step 4 in the cycle, is [20]:

$$T'_4 = 615.5^{\circ}C = 888.5 K$$

$$T_1 = 13.65^{\circ}C = 286.65 K$$

The temperature at the entrance of the compressor is assumed as the mean atmospheric temperature in the location [26]. With respect to T'_4 , the temperature given is theoretical and therefore should be considered as ideal. Regarding pressures, gas cycles only operate at two different pressures. High pressure (Points 2 and 3) and low pressure (Points 1, 4 and 5). Often gas cycles depend on a parameter that relates both pressures, compression

ratio. Alstom GT 26 is able to operate at compression ratios over 30:1, which is a sharply high value that will make the turbine generate lot of power. However, these values are reserved for aeroderivative uses. Commonly, industrial GT operate up to 18:1 ratios to avoid critical temperatures at the entrance of the turbine, which would deteriorate most of the materials [22].

$$P_2 = P_3 = 14 \text{ bar} \quad P_1 = P_4 = 1 \text{ bar} \quad \pi = \frac{P_2}{P_1} = 14$$

Accomplishing the adjustment mentioned before, 14:1 has been assumed as a suitable hypothetical operation ratio for Soto 4. Low pressure is fixed in 1 bar as air enters the cycle under atmospheric conditions.

Net power, irreversibility and mass flow.

Some other information relevant to the calculation of the cycle has to be stated before calculations can be done. Firstly, the total net power given by the complete cycle was given when introducing this chapter, but the input of each part hasn't been detailed. Also, as in most of the GT that can be purchased in the market, the mass flow of exiting gases is given.

$$\dot{W}_N = \dot{W}_{NGT} + \dot{W}_{NVT} = 426 \text{ MW} \quad \dot{m}_{esc} = \dot{m}_a + \dot{m}_c = 641.4 \frac{\text{kg}}{\text{s}}$$

Nonetheless, devices aren't perfect and their performance is subjected to irreversibilities. As it was explained in chapter 2, the way to obtain their values is quite simple. On the other hand, attending to Alstom Power data, the values for turbine efficiency can be estimated around 90-95% for theoretical purposes, in the practice the value could be improved. Regarding to the compressor, as there are more stages, the efficiency drops. Finally the combustion chamber usually offers lower values than the turbine. Assuming the worst conditions, the estimated values are as follows:

$$\eta_T = 0.93 \quad \eta_c = 0.88 \quad \eta_{CC} = 0.85$$

As part of the data, the global efficiency of the cycle is given as [20]:

$$\eta_{Soto4} = \frac{\dot{W}_N}{\dot{Q}_{in}} = 0.587$$

Objectives

By performing the study of the cycle it is wished to obtain all the temperatures, air and combustible mass flows, heat consumption in the combustion chamber and individual efficiency for the gas cycle:

$$T_2, T_3, \dot{m}_a, \dot{m}_c, \dot{Q}_{in}, \eta_{GT}, \dot{W}_{NGT}$$

With these data, the calculations can start. During the process, some other data could be added, with their corresponding justification. The first value that is wished to be obtained concerns the mass flow of air and combustible input. To this extend, the starting point will involve the equation relating the exiting gases, air and combustible mass flows and the energy balance involving the combustion chamber.

Energy Balance in control volume (CV)

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_1^{in} \dot{m}_{in} \cdot h_{in} - \sum_1^{out} \dot{m}_{out} \cdot h_{out} \quad (1)$$

The following assumptions are made:

- Stationary process $\frac{dE_{CV}}{dt} = 0$
- Mass conservation law $\sum_1^{in} \dot{m}_{in} = \sum_1^{out} \dot{m}_{out}$
- Air is assumed as ideal gas, and thermodynamic laws referring to CPIG state that $\Delta h = Cp\Delta T$

The equation ends up as follows:

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}_a \cdot Cp \cdot \Delta T_{CV} \quad (2)$$

Regarding the isobaric process between points 2 and 3, the combustion chamber has an energy balance that involves the specific heat at that point, temperatures 2 and 3 and air mass flow. Equating those terms with the mentioned mass flow conservation law, the result is a two equation system with \dot{m}_a , \dot{m}_c , T_2 and T_3 as unknowns:

$$\dot{m}_{esc} = \dot{m}_a + \dot{m}_c = 641.4 \frac{kg}{s} \quad (3)$$

$$0 = \frac{\dot{Q}_{2-3}}{\dot{m}_a} - \frac{\dot{W}_{2-3}}{\dot{m}_a} + Cp \cdot \Delta T_{2-3} \quad (4)$$

During the combustion process no work is obtained or released, therefore $\dot{W}_{2-3} = 0$. Moreover, rearranging the terms for equation (4):

$$\dot{Q}_{2-3} = \dot{m}_a \cdot Cp \cdot (T_3 - T_2)$$

Finally, the heat input into the system depends directly on the efficiency of the combustion chamber, the heating value of the fuel and combustible mass flow. The heating value considering natural gas as fuel is the same as the one seen for Puertollano's power plant, 49.220 MJ/kg [3]:

$$\dot{Q}_{2-3} = \dot{m}_a \cdot Cp \cdot (T_3 - T_2) = \dot{m}_c \cdot Li \cdot \eta_{CC} \quad (5)$$

Within equation (5), there are many variables that need to be computed before calculating the mass flows. The first step is to identify the value for $\dot{Q}_{2-3} = \dot{Q}_{in}$. For this purpose a new equation is involved:

$$\eta_{Soto4} = \frac{\dot{W}_N}{\dot{Q}_{in}} = 0.587 \quad (6)$$

Rearranging for \dot{Q}_{in} and introducing the values for \dot{W}_N and η_{Soto4} :

$$\dot{Q}_{in} = \frac{\dot{W}_N}{\eta_{Soto4}} = \frac{426 \text{ MW}}{0.587} = 725.72 \text{ MW}$$

With this value and rescuing equation (5) the value for the fuel mass flow, \dot{m}_c , can be obtained after the corresponding rearrangement.

$$\dot{m}_c = \frac{\dot{Q}_{in}}{L_i \cdot \eta_{CC}} = \frac{725.72 \cdot 10^6}{49.220 \cdot 10^6 \cdot 0.85} = 17.35 \frac{\text{kg}}{\text{s}}$$

Introducing this value in equation (4) and isolating \dot{m}_a :

$$\dot{m}_a = \dot{m}_{esc} - \dot{m}_c = 641.4 - 17.35 = 624.05 \frac{\text{kg}}{\text{s}}$$

$$\dot{m}_c = 17.35 \frac{\text{kg}}{\text{s}} \quad ; \quad \dot{m}_a = 624.05 \frac{\text{kg}}{\text{s}}$$

However, to calculate the power released and consumed by the turbine and the compressor groups respectively, the computation of T_3 and T_2 needs to be done. To do so, one of the main characteristics involving thermodynamic laws for CPG processes is going to be used [24] [25].

$$\frac{T_{in}}{T_{out}} = \left(\frac{P_{in}}{P_{out}} \right)^{\frac{\gamma-1}{\gamma}} = (\pi)^{\frac{\gamma-1}{\gamma}} \quad (7)$$

Then, introducing the corresponding points and the data known, it is possible to obtain T'_2 , being this the value for the ideal temperature exiting the compressor stage. T_3 isn't calculated the same way as to do so it is required the ideal temperature of point 4. Nevertheless, there is a different method to acquire it, which will be seen moreover.

$$\frac{T'_2}{T_1} = (\pi)^{\frac{\gamma-1}{\gamma-2}} \quad ; \quad T'_2 = 286.65 \cdot (14)^{\frac{0.388}{1.388}} = 599.43 \text{ K}$$

Now, the real value has to be computed. As it was said in chapter 2, the efficiency of compressors and turbines relate ideal and real temperatures depending on the device studied. To this extent it can be stated that:

Compressor stage:

$$\eta_c = 0.88 = \frac{T'_2 - T_1}{T_2 - T_1} \quad ; \quad T_2 = T_1 + \frac{(T'_2 - T_1)}{0.88} = 286.65 + \frac{(599.43 - 286.65)}{0.88}$$

$$T_2 = 642.08 \text{ K}$$

It can be seen that the compressor outlet temperature has increased, what makes necessary an increment in the power introduced to the system and, therefore, a loss. This fact makes sense because the compressor is consuming power, when less power is consumed, the more ideal the process becomes.

Once this temperature is computed, all of the information regarding equation (5) is obtained except for T_3 . Thus, it is sensible to rearrange the equation and calculate the value for that temperature:

$$T_3 = T_2 + \frac{\dot{Q}_{in}}{\dot{m}_a \cdot Cp} = 642.08 + \frac{725.72 \cdot 10^6}{624.05 \cdot 1.1105 \cdot 10^3} = 1689.29 \text{ K}$$

$$T_3 = 1689.29 \text{ K} = 1416.29^\circ\text{C} < 1500^\circ\text{C}$$

Knowing the temperature at the inlet of the turbine and the efficiency of the device, now it is possible to find the real value of the temperature at the outlet. To do so, the equation relating the temperatures and the performance of the turbine has to be used acquiring the following results:

$$\eta_T = 0.93 = \frac{T_3 - T_4}{T_3 - T'_4} ; T_4 = T_3 - 0.93 \cdot (T_3 - T'_4) = 1689.29 - 0.93 \cdot (1689.29 - 888.5)$$

$$T_4 = 944.55 \text{ K}$$

Being in possession all the temperatures involved in the gas cycle as well as the mass flows concerning air and fuel, the power produced by the turbine and consumed by the compressor may be calculated. Rearranging equation (2):

Turbine power:

$$\dot{W}_{GT} = \dot{m}_a \cdot Cp \cdot (T_3 - T_4) = 624.05 \cdot 1.1105 \cdot 10^3 \cdot (1689.29 - 944.55) = 516.11 \text{ MW}$$

Compressor power:

$$\dot{W}_C = \dot{m}_a \cdot Cp \cdot (T_1 - T_2) = 625.12 \cdot 1.1105 \cdot 10^3 \cdot (286.65 - 642.08) = -246.32 \text{ MW}$$

Net power

$$\dot{W}_{NGT} = \dot{W}_{GT} + \dot{W}_C = 516.11 - 246.32 = 269.79 \text{ MW}$$

$$\eta_{GC} = \frac{\dot{W}_{NTG}}{\dot{Q}_{in}} = \frac{269.79}{725.72} = 0.37 \quad (8)$$

Negative results have some important relevance. In the case of power, they express consumption and, therefore, energy loss. Having negative heat values represent the energy generated by the own system, therefore negative values in heat represent benefit, as less heat has to be transferred to the system.

Once the gas cycle has been detailed, the steam cycle can be studied. In table 18 below the information obtained concerning the gas cycle is detailed.

Temperatures (K)	Power and heat (MW)	Mass flow (kg/s) and efficiency
$T_1 = 286.65$	$\dot{W}_{NGT} = 269.79$	$\dot{m}_{esc} = 641.4$
$T_2 = 642.08$	$\dot{W}_{GT} = 516.11$	$\dot{m}_a = 624.05$
$T_3 = 1689.29$	$\dot{W}_c = -246.32$	$\dot{m}_c = 17.35$
$T_4 = 944.55$	$\dot{Q}_{in} = 725.72$	$\eta_{GC} = 0.37$

Table 18. Gas cycle relevant information.

7.2.2. Steam/Vapour Cycle

As a way of saving money and helping to preserve environment, the high temperature at which the gases exiting the gas turbine is going to be used to heat water converting it into steam by means of a HRSG boiler. This product will be introduced into a vapour turbine (VT) in order to obtain additional power to generate electricity.

As mentioned before, the working fluid is water, which is obtained from Nalón River. There are significant differences dragged by the change of fluid. First of all, being water compressible, even at gaseous phase ($\Delta h = \Delta P v + C_p \Delta T$; with $\Delta P \neq 0$), makes unaffordable to continue using temperatures as before to calculate heats and powers. Therefore, the study will be done with enthalpies, as the values desired to reach. Secondly, being water a fluid which properties vary sharply with changes in pressure and temperature, the properties will be obtained from reference [2].

Usually, Rankine cycles operate at different levels of pressure, offering an added complexity to the calculations. In this case, Soto 4 operates at three different levels, which are going to be named during this paper as high pressure level (HP), medium pressure level (MP) and low pressure level (LP) (see figure 33). Soto 4 counts with some improvements with respect to the simple cycle described in chapter 2. They will be briefly detailed during the calculation process.

To refresh the devices involved in the cycle submitted to study, the cycle is shown below:

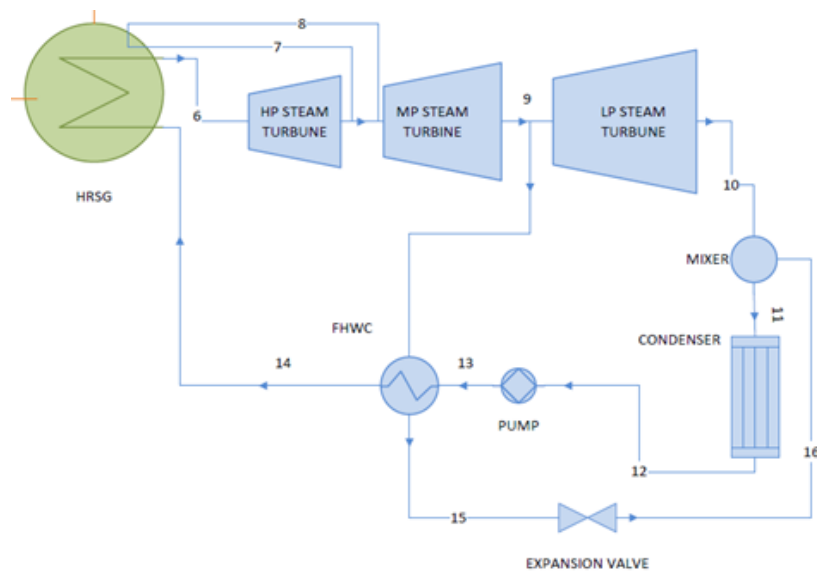


Figure 33. Soto 4 hypothetical steam cycle designed in Microsoft Visio.

Starting data:

Temperature and pressure at turbine stages

Attending to EDP Spain online website, Soto 4 operates with the following temperatures and pressures during the three different turbine stages. It has to be mentioned that the following information states the conditions at the entrance of the corresponding turbine stage (see table 19).

Device	Temperature	Pressure
HP Turbine	$T_6 = 565 \text{ }^\circ\text{C}$	$P_6 = 136 \text{ bar}$
MP Turbine	$T_8 = 565 \text{ }^\circ\text{C}$	$P_8 = 29 \text{ bar}$
LP Turbine	$T_9 = 286 \text{ }^\circ\text{C}$	$P_9 = 4,6 \text{ bar}$
Condenser	T_{11}	$P_{11} = 0,1 \text{ bar}$

Table 19. Steam cycle temperatures and pressures. [20].

The pressure at which the steam is condensed is assumed and fixed in the value seen above. However, the temperature of that point is a variable that will be computed during the analysis. It is sensible to highlight that the temperatures involving Rankine cycle will appear in degrees Celsius ($^\circ\text{C}$) instead of Kelvin (K).

Net power and irreversibility.

Resembling to the preceding cycle, the net power is fixed by the results found before, while the irreversibilities concerning the devices performance are assumed based on the fabricant's knowledge. In this sense, it is reasonable to say that steam devices work in a less efficient way as gas ones do, because of the least homogeneous conditions water has. To add more justification to this, the efficiency will also be conditioned by the conditions held by the HRSG. Then:

$$\eta_T = 0.9 \quad \eta_P = 0.85$$

$$\dot{W}_{NVT} = \dot{W}_N - \dot{W}_{NGT} = 426 - 269.79 = 156.21 \text{ MW}$$

Objectives

With the information given and the support of the tables that appear attached to this document in Appendix C it is possible now to start computing all the enthalpies that are involved in the steam cycle. For this purpose it is necessary to make use of a T-S diagram that is also available at Appendix A. Once all the enthalpies are known, the water mass flow needed to achieve the desired power will be calculated.

$$h_6, h_7, h_8, h_9, h_{10}, h_{11}, h_{12}, h_{13}, h_{14}, h_{15}, h_{16}, y, \dot{m}_w$$

The starting point from which the calculations will begin is point 6 in the diagram, which corresponds to the entrance to HP turbine.

Temperature and pressure	Enthalpy (kJ/kg)
HP entrance	
$T_6 = 565 \text{ }^\circ\text{C}$	$h_6 = 3503.67$
$P_6 = 136 \text{ bar}$	
Reheat entrance	
$T_7 = 302 \text{ }^\circ\text{C}$	$h'_7 = 2999.38$
$P_7 = 29 \text{ bar}$	$h_7 = 3049.71$
MP entrance	
$T_8 = 565 \text{ }^\circ\text{C}$	$h_8 = 3603.46$
$P_8 = 29 \text{ bar}$	
LP entrance	
$T_9 = 286 \text{ }^\circ\text{C}$	$h'_9 = 3033.99$
$P_9 = 4.6 \text{ bar}$	$h_9 = 3090.86$
Mixer entrance 1	
$T_{10} = 45.81 \text{ }^\circ\text{C}$	$h'_{10} = 2392.8$
$P_{10} = 0.1 \text{ bar}$	$h_{10} = 2462.61$
Condenser entrance	
$T_{11} = 45.81 \text{ }^\circ\text{C}$	$h_{11} = 2152.08$
$P_{11} = 0.1 \text{ bar}$	
Pump entrance	
$T_{12} = 45.81 \text{ }^\circ\text{C}$	$h_{12} = 191.83$
$P_{12} = 0.1 \text{ bar}$	
FWHC entrance	
$T_{13} = 46.38 \text{ }^\circ\text{C}$	$h'_{13} = 205.42$
$P_{13} = 136 \text{ bar}$	$h_{13} = 207.82$

HRSG entrance	
$T_{14} = 148.70 \text{ }^{\circ}\text{C}$	$h_{14} = 635.99$
$P_{14} = 136 \text{ bar}$	
Expansion Valve entrance	
$T_{15} = 148.70 \text{ }^{\circ}\text{C}$	$h_{15} = 626.65$
$P_{15} = 4.6 \text{ bar}$	
Mixer entrance 2	
$T_{16} = 45.81 \text{ }^{\circ}\text{C}$	$h_{16} = h_{15} = 626.65$
$P_{16} = 0.1 \text{ bar}$	

Table 20. Relevant results from steam cycle. Source: Appendix C.

After analyzing and calculating each point, as it is shown in Appendix C, the relevant results are shown on table 20. However, there is an important step that needs to be completed before calculating the cycle's efficiency, water mass flow and devices powers. After condensation takes place, the feed water passes through a device called Feed Water Heater Closed (FWHC). Basically, this item is a heat exchanger that is going to receive two feeds; water, which will be heated up and vapour obtained from an extraction of MP turbine to heat water (see figure 34).

To compute the proportion of steam extracted, it is necessary to make an energy balance assuming the device as CV and taking into account some assumptions that will be stated moreover. Rescuing equation (1):

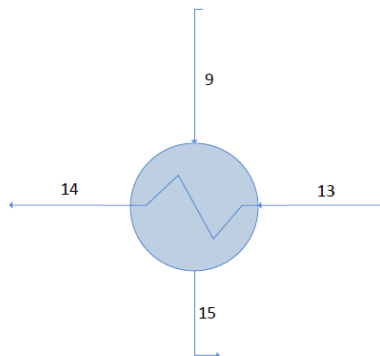


Figure 34. FWHC scheme performed in Microsoft Visio.

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_1^{in} \dot{m}_{in} \cdot h_{in} - \sum_1^{out} \dot{m}_{out} \cdot h_{out} \quad (1)$$

Assumptions:

- Stationary process $\frac{dE_{CV}}{dt} = 0$
- Mass flows inside a FHWC don't mix as they flow in separate pipelines. This is the reason why they can enter at different pressures.
- No work is done or received by the system during the process $\dot{W}_{CV} = 0$
- Adiabatic FHWC $\dot{Q}_{CV} = 0$

Therefore:

$$y \cdot \dot{m}_w \cdot h_9 + \dot{m}_w \cdot h_{13} = \dot{m}_w \cdot h_{14} + y \cdot \dot{m}_w \cdot h_{15} \quad (10)$$

Rearranging equation (10) to isolate y and introducing the known values concerning the enthalpies involved, it is obtained:

$$y = \frac{\dot{m}_w(h_{14} - h_{13})}{\dot{m}_w(h_9 - h_{15})} = \frac{635.99 - 207.82}{3090.86 - 626.99} = 0.17$$

$$y = 0.17$$

Finally, water mass flow can be computed with the data calculated up to this point. To do so, it is necessary to start from equation (1) knowing that turbines and pump are assumed as adiabatic devices and the process is done under stationary conditions.

$$\dot{W}_{NVT} = 156.21 \text{ MW} = \dot{W}_{VT} + \dot{W}_P \quad (11)$$

$$\dot{W}_{VT} = \dot{m}_w \cdot [(h_6 - h_7) + (h_8 - h_9) + y \cdot (h_9 - h_{10})]$$

$$\dot{W}_P = \dot{m}_w \cdot (h_{12} - h_{13})$$

Substituting the values and rearranging the equations to isolate \dot{m}_w , water mass flow needed to obtain the desired output can be calculated:

$$\dot{m}_w = \frac{\dot{W}_{NVT}}{(h_6 - h_7) + (h_8 - h_9) + y \cdot (h_9 - h_{10}) + (h_{12} - h_{13})} \quad (12)$$

Introducing the values for enthalpies previously calculated:

$$\begin{aligned} & \dot{W}_{NVT} \\ &= \frac{156.21 \cdot 10^6}{(3503.67 - 3049.71 + 3603.46 - 3090.86 \cdot (1 - 0.17) - 0.17 \cdot 2462.61 + 191.83 - 207.82) \cdot 10^3} \\ &= 147.73 \frac{\text{kg}}{\text{s}} \end{aligned}$$

$$\dot{m}_w = 147.73 \frac{\text{kg}}{\text{s}}$$

7.2.3. HRSG

Due to the complexity inside the HRSG regarding heat transfers and how they are produced, during this document this device is going to be assumed as a normal heat exchanger. In this sense, the operations involved will be concerning the heat transferred by the exiting gases of the GT and the heat received by the water after being pumped. Knowing that the heat received and transferred has to be the same:

$$\dot{Q}_{transferred} = \dot{m}_a \cdot Cp \cdot (T_4 - T_5)$$

$$\dot{Q}_{recieved} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)]$$

The type of HRSG used in the cycle consists of an external source of heat that will give the difference between the transferred and received, as the gas is not able to rise the temperature from point 14 to 6 and couple with the reheat at the same time, therefore:

$$\dot{m}_a \cdot Cp \cdot (T_4 - T_5) + \Delta\dot{Q} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)] \quad (13)$$

Knowing that T_5 (exiting air of the HRSG) has to be higher than T_{14} (entering water in the HRSG), the difference between them is assumed to be 10. Inserting the rest of values known the extra heat input can be calculated:

$$\Delta\dot{Q} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)] - \dot{m}_a \cdot Cp \cdot (T_4 - T_5)$$

$$\begin{aligned} \Delta\dot{Q} &= 147.73 \cdot [(3503.67 - 635.99) + (3603.46 - 3049.7)] \cdot 10^3 - 624.05 \\ &\quad \cdot 1.1105 \cdot 10^3 (944.55 - 433.70) = 151.13 \text{ MW} \end{aligned}$$

The difference is going to be given by an extra input of natural gas. To calculate it, equation (5) is going to be used in the following way:

$$\Delta\dot{Q} = \dot{m}_c \cdot Li \cdot \eta_{CC}$$

Rearranging for \dot{m}_c and introducing the known values:

$$\dot{m}_c = \frac{151.13 \cdot 10^6}{49.22 \cdot 10^6 \cdot 0.85} = 3.62 \frac{\text{kg}}{\text{s}}$$

$$\dot{m}_c = 3.62 \frac{\text{kg}}{\text{s}}$$

7.3. Reasons for election

Once the thermal behaviour of Soto 4 has been detailed, it is sensible to justify the reasons that have led to choose this power plant in particular. First of all, as it was said before, one of the main reasons lies on the combustion chamber's design. The fact of allowing different types of fuel, including syngas, for the process is vital. However, there is a bunch of other reasons that justify the election, such as:

- Location: the target is to try to recycle some of the components that composed Puertollano's power plant. In this sense, the nearer the location, the cheaper the transport. On the other hand, it is important to fix a location that enables a proximate supply source. To this extent Asturias, where the cycle is installed, is placed in a mean point between two important oil refinery locations (La Coruña and Bilbao) and is one of the main coal producers in Spain (see figure 35). The images below reflect the placement of the mentioned facilities.

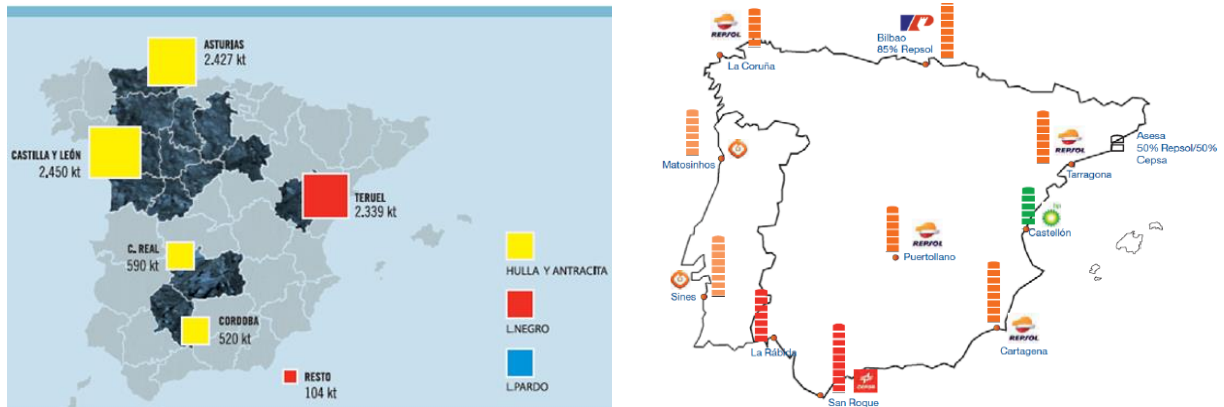


Figure 35. At right hand side Spanish principal coal produces. At left hand side Spanish principal oil refineries. Sources: Profesor Pedro Oña blog and CNMC blog. Online websites.

- Along with location, other premises were taken into consideration. The fact of trying to use a determined gasifier, which operates with the designed conditions relative to Puertollano's combined cycle, occasioned that the new destiny for it should operate at similar conditions. Soto 4 gives more power as a result, however the differences aren't as unreachable as happened with other plants that accomplished the required location characteristics. It has to be mentioned that combined cycle power plants such as Puentes de García Rodríguez (La Coruña) was studied due to the supplies facilities, but rejected because of the great differences in power generation (over 812 MW).
- Finally, other of the reasons that favoured Soto 4's election was the chance of implementing gasification technology in Spain, due to the closure of the previous example. This fact wouldn't only bring Spain to a higher step in technological development worldwide, but also could bring economic benefits concerning European subsidies for commitment with environment or inverting money in Spanish fuel source instead of fully relying on foreign supply.

8. Thermal viability analysis of recycling Puertollano's gasifier and ASU

When the thermal characteristics of Soto 4 are finished, the viability study for hybridizing some of the components from Puertollano's power plant can be done. For this purpose, two main components are going to be involved in the process, ASU and gasifier. Nonetheless, the only one that has to undergo further study is the gasifier. The reason for this is that ASU's properties will remain the same, as the air mass flow in the whole process is higher than in Puertollano's power plant, so the same extraction can be made. On the other hand, it has to be proved that the gasifier is able to produce the amount of syngas necessary to remain Soto 4's power and heat values unchanged.

To prove it, the combustion chamber has to be submitted to analysis with the properties corresponding to syngas instead of natural gas. In addition, the properties at the entrance of the combustion chamber are detailed based on Puertollano power plant's information (see table 21) [3]:

Pressure	19.4 bar
Temperature	302°C
Mass flow	120.2 kg/s
Lower Heating Value (LHV)	4.242 MJ/kg

Table 21. Syngas properties at the entrance of the gas cycle [3].

An expansion valve and successive heat exchangers are employed to adequate the conditions to those corresponding to Soto 4. Therefore, the mass flow needed to feed the cycle is calculated from equation (5), remarking that \dot{m}_a , T_3 , and T_2 remain unchanged:

$$\dot{Q}_{in} = \dot{m}_a \cdot Cp \cdot (T_3 - T_2) = \dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} = 725.72 \text{ MW}$$

Rearranging for \dot{m}_{sg} :

$$\dot{m}_{sg} = \frac{\dot{Q}_{in}}{Li_{sg} \cdot \eta_{CC}} = \frac{725.72 \cdot 10^6}{4.242 \cdot 10^6 \cdot 0.85} = 201.27 \frac{\text{kg}}{\text{s}} > 120.2 \frac{\text{kg}}{\text{s}}$$

With this in mind, the result is that the gasifier proposed to be implemented on the combined cycle isn't able to fulfil the requirements on its own. Even though the task seems to be failed at first sight, the proposed solutions to accomplish the hybridization process are taken into consideration in the next pages.

8.1. Solutions to the problem

Apparently, the idea proposed was to entirely substitute natural gas by syngas, leaving the first one as reserve in case some problems rose up. However, the new problematic that has showed up makes necessary the co-firing of both fuels simultaneously. Besides, the change should bring money savings from a lower use of natural gas. It is sensible to say that the hypotheses that are being made until this point are for full load capacity. Taking into account that normally power plants don't operate continuously at this regime, the mass flow generated by the gasifier could be enough until a limiting power is reached. Therefore, two possible solutions are going to be submitted to study.

8.1.1. Co-firing syngas with natural gas

The first possibility is required when the power demand exceeds the calculated power, as the plant has to respond to the mentioned demand in an adequate manner. According to the studies performed by GE regarding IGCC implementation and fuel analysis, it is determined that the mixture of both gases as combustible is not only tangible, but also enables significant advantages when talking about fuel flexibility. Therefore, assuming co-fire of syngas and natural gas is a justified solution to the problem [27]. In the document, it is also reflected the continuous advances in IGCC technology, which substantially reduces the investment costs in a future.

Thus, assuming that the operating conditions are fixed for maximum load capacity, it is important to see how the final combustible mixture varies as a function of the syngas generation rate of the gasifier. In other words, as the gasifier is going to start producing from 0 kg/s up to 120.2 kg/s, it is sensible to introduce syngas from the first moment it is produced, no matter the quantity.

To do so, a previous analysis has to be performed and as a result it will be obtained an equation that expresses a linear relationship between syngas introduced and the percentage of natural gas saved in consequence. The starting point will be the equation of total heat transferred by co-firing fuels:

$$\dot{Q}_{in} = \dot{m}_c \cdot Li_c \cdot \eta_{CC} \cdot (1 - z) + \dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} \quad (14)$$

As it can be proved, at the starting point the value for \dot{Q}_{in} is the same as before, what makes the percentage of natural gas saved and the syngas introduced null. In order to remain the same value for the heat transferred it is necessary that the heat generated by the input of syngas is the same as the heat lost by the natural gas saved, in this sense:

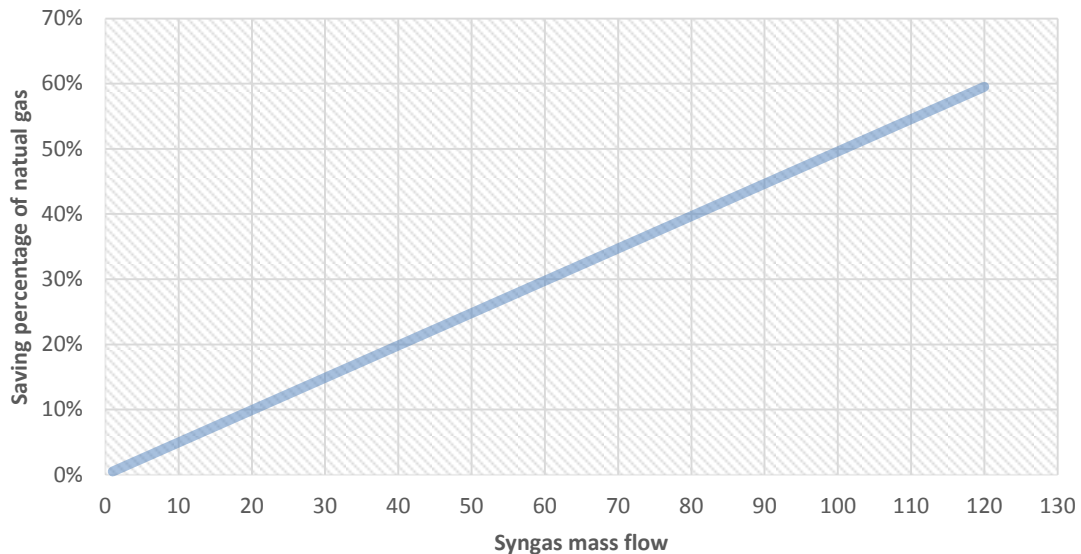
$$\dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} = z \cdot \dot{m}_c \cdot Li_c \cdot \eta_{CC}$$

Isolating z , a linear relationship between the amount of syngas introduced to the system and the amount of natural gas saved is obtained.

$$z = \frac{\dot{m}_{sg} \cdot Li_{sg}}{\dot{m}_c \cdot Li_c} = \frac{\dot{m}_{sg} \cdot 4.242}{17.35 \cdot 49.22} = \dot{m}_{sg} \cdot 4.98 \cdot 10^{-3}$$

$$z = \dot{m}_{sg} \cdot 4.98 \cdot 10^{-3}$$

Then, giving values to \dot{m}_{sg} from 0 to 120.2 (minimum and maximum respectively), the values for the percentage of natural gas saved are obtained. With the help of Microsoft Excel, the results were translated to the graph (see graph 1) shown below.



Graph 1. Syngas production vs saving percentages corresponding to natural gas.

Scanning the graph it can be seen that almost 60% percent of the fuel employed until today in Soto 4 could be saved. This fact shouldn't go unnoticed, as the price of natural gas is higher than the price for gasification fuels and keeps sharply rising year to year. It is sensible to say that if the convenient modifications on the gasification unit were made, the percentage of natural gas saved could increase. However, that would be a completely different project.

8.1.2. Maximum power obtained with syngas

As it was stated before, when the plant isn't operating at full capacity there is a chance to use syngas as unique feedstock into the system. However, some limitations are going to be dragged from this hypothesis, hence further analysis has to be done.

Assuming that the only feed inside the combustion chamber comes from the syngas pipeline, the maximum heat obtained would be as following:

$$\dot{Q}_{maxsg} = \dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} = 120.2 \cdot 4.242 \cdot 10^6 \cdot 0.85 = 433.41 \text{ MW}$$

In order to keep the same operating conditions, none of the temperatures involved in the cycle should experience changes. Thus, the variable that has to be recalculated, ensuring the maintenance of the temperatures and the new heat transferred, is air mass flow. Bringing up equation (5) again, \dot{m}_a is isolated and the values for the rest of the variables are known, therefore:

$$\dot{m}_a = \frac{\dot{Q}_{maxsg}}{C_p \cdot (T_3 - T_2)} = \frac{433.41 \cdot 10^6}{1.1105 \cdot 10^3 \cdot (1689.29 - 642.08)} = 372.69 \frac{kg}{s}$$

$$\dot{m}_a = 372.69 \frac{kg}{s}$$

With this new figure for mass flow, now all the powers generated and consumed by the system can be calculated to determine the limit power for the gas cycle. Performing the same calculations as before with this new value, the relevant information for the gas cycle operating with syngas as feedstock is stated in table 22.

Temperatures (K)	Power and heat (MW)	Mass flow (kg/s) and efficiency
$T_1 = 286.65$	$\dot{W}_{NGT} = 161.12$	$\dot{m}_{esc} = 744.25$
$T_2 = 642.08$	$\dot{W}_{GT} = 308.22$	$\dot{m}_a = 624.05$
$T_3 = 1689.29$	$\dot{W}_C = -147.10$	$\dot{m}_{sg} = 120.2$
$T_4 = 944.55$	$\dot{Q}_{in} = 433.41$	$\eta_{GC} = 0.37$

Table 22. Relevant information of gas cycle operated with syngas.

In a similar way, as the temperatures of the gas cycle haven't varied, the points involved in the steam cycle will be exactly the same. In other words, all the enthalpies calculated remain as before and so does the percentage of steam extracted at point 9. This occurs because enthalpy depends on temperature and pressure and both remain unchanged. However there will be a loss of net power derived from the decrease of water mass flow. This decrease is necessary to maintain the cycle unchanged.

The explanation is quite simple. Air mass flow in the gas cycle has decrease as consequence of remaining the temperatures, therefore the heat that is going to be transferred to water in the HRSG decreases. As a result, the water mass flow that is going to be able to heat up is less than before, despite the fact the external extra combustor aids. To quantify the value, two paths may be taken:

External combustor turned off

If the combustor is not working, therefore saving fuel, water mass flow will be calculated performing the energy balance done before at the HRSG without extra input $\Delta\dot{Q}$:

$$\dot{Q}_{transferred} = \dot{m}_a \cdot Cp \cdot (T_4 - T_5)$$

$$\dot{Q}_{recieved} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)]$$

$$\dot{m}_a \cdot Cp \cdot (T_4 - T_5) = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)]$$

Rearranging for \dot{m}_w and introducing the known data:

$$\begin{aligned} \dot{m}_w &= \frac{\dot{m}_a \cdot Cp \cdot (T_4 - T_5)}{(h_6 - h_{14}) + (h_8 - h_7)} = \frac{372.69 \cdot 1.1105 \cdot 10^3 \cdot (944.55 - 433.70)}{(3503.67 - 635.99 + 3603.46 - 3049.71) \cdot 10^3} \\ &= 61.79 \frac{kg}{s} \end{aligned}$$

$$\dot{m}_w = 61.79 \frac{kg}{s}$$

External combustor turned on

In this case, the combustor is working and, therefore, the heat transferred increases. This will lead to an increase in the water mass flow heated up. Assuming the same fuel mass flow for the external combustor as before, water mass flow would be calculated as:

$$\dot{m}_a \cdot Cp \cdot (T_4 - T_5) + \Delta\dot{Q} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)]$$

Rearranging as before for \dot{m}_w :

$$\dot{m}_w = \frac{\dot{m}_a \cdot Cp \cdot (T_4 - T_5) + \Delta\dot{Q}}{(h_6 - h_{14}) + (h_8 - h_7)} = \frac{372.69 \cdot 1.1105 \cdot 10^3 \cdot (944.55 - 433.70) + 151.13 \cdot 10^6}{(3503.67 - 635.99 + 3603.46 - 3049.71) \cdot 10^3}$$

$$\dot{m}_w = 105.98 \frac{kg}{s}$$

Conclusion

With these results, the limiting steam cycle net power can be calculated for each water mass flow. Then, the total net power for the whole cycle is obtained by summing up the results obtained from the mentioned operation with the gas limiting power respectively.

$$\begin{aligned}\dot{W}_{NVT} &= \dot{W}_{VT} + \dot{W}_P \\ \dot{W}_{VT} &= \dot{m}_w \cdot [(h_6 - h_7) + (h_8 - h_9) + y \cdot (h_9 - h_{10})] \\ \dot{W}_P &= \dot{m}_w \cdot (h_{12} - h_{13}) \\ \dot{W}_{Nsg} &= \dot{W}_{NGTsg} + \dot{W}_{NVTsg} \\ \text{Load capacity \%} &= \frac{\dot{W}_{Nsg}}{\dot{W}_{Nc}} \quad (15)\end{aligned}$$

The relevant results are stated in table 23:

	CASE 1	CASE 2
\dot{W}_{NVTsg}	65.38 MW	112.13 MW
\dot{W}_N	226.50 MW	273.26 MW
Load capacity %	53.17%	64.14%
$\eta_{Soto4sg}$	0.52	0.63

Table 23. Net power and load capacity in each case studied. Source Appendix E.

Taking a look to the results, it is noticeable that when power services don't overpass 53.17% of the load capacity, in other words, for power demands that doesn't overpass 226.5 MW; the whole process can be fed with only syngas. The range between these values and those of the second case, 64.14% load capacity or 273.26 MW can be held by syngas fully, in addition to natural gas concerning the external combustor. For values that are higher than these ones, an extra natural gas feed has to be considered, as is explained in the first solution.

9. Economic viability analysis

It has to be mentioned from a start that the main idea favoring economically the idea of recycling the devices used at Puertollano is that the investment cost will substantially decrease. The reason is that these components are built up and have proved they can operate adequately. In this sense, the main spent will be derived from the loan or purchase of the second hand equipment, technical advice and transport. It is remarkable that this process wouldn't mean a similar cost to the one that was paid when Puertollano was built. Other costs such as the increase of Operation and Maintenance (O&M) or time cost, the plant has to rest more time due to the increased maintenance time required, will be taken into account.

However, the main factor to compare the cost and saving profits regarding the hybridization is going to lie on the combustibles. In this sense, the prices of each fuel for the different situations that were explained in the preceding chapter have to be calculated.

To sum up, the first situation, assumed to be the worst, is ranged from 100% to 64.14% of load capacity, where co-firing of syngas and natural gas has to be completed in order to achieve the demand. The second range is between 64.14% and 53.17% of load capacity, where the only feed into the combustion chamber is syngas produced by gasification. In addition, it has to be mentioned that the post-combustor, needed to help the HRSG, will be turned on, consuming an additional feed of natural gas for this first stages. Finally the third stage is between 0% and 53.17% of load capacity, the post combustor is turned off and the only feed is syngas. All of the ranges will be adequately described during the analysis, but first the calculations to obtain the costs for fuels of the cycle will be calculated.

9.1. Cost of fuel in €/kWh

The fact of needing solid coal to produce syngas makes the procedure for calculating the cost of fuel in €/kWh generated proceed in different ways.

9.1.1. Coal

The first thing that needs to be done is the recompilation of data concerning the price for coal in the market. For this purpose, the information is searched in the BP statistical review to handle the most updated values [28]. It can be seen in figure 36 that the value corresponding to North-Western EU market is 56.64 \$/ton in 2015.

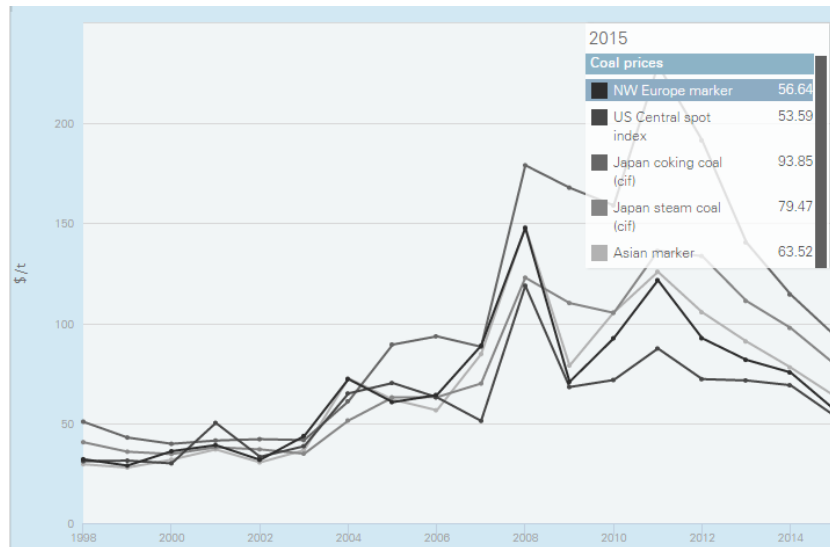


Figure 36. Coal prices from 1996 to 2015 [28].

The convenient conversion factors will be applied in order to convert the units into €/kg [29]. In this sense:

$$56.64 \frac{\$}{\text{ton}} \cdot \frac{0.886 \text{ €}}{1 \$} \cdot \frac{1 \text{ ton}}{1000 \text{ kg}} = 0.05 \frac{\text{€}}{\text{kg}}$$

As it was said before, this is the price of solid coal; however, the amount of solid coal needed to produce a certain amount of syngas has to be computed. In order to achieve this ratio, it is necessary to start from the known data. In this sense, the data released by ELCOGAS says that, in order to reach the maximum mass flow of syngas, the gasifier has to be fed with 2600 tons of solid coal per day. To make the comparison and calculate the rate the conversion to kg/s is compulsory. Then:

$$2600 \frac{\text{ton}}{\text{day}} \cdot \frac{1000 \text{ kg}}{1 \text{ ton}} \cdot \frac{1 \text{ day}}{24 \text{ hours}} \cdot \frac{1 \text{ hour}}{3600 \text{ s}} = 30.09 \frac{\text{kg}}{\text{s}}$$

Hence the ratio between solid coal and syngas:

$$r = \frac{120.2}{30.09} = 3.99$$

So for each kg of coal gasified, almost 4 kg of syngas is going to be produced. This fact has certain relevance, as with less kg of solid coal more fuel is produced.

9.1.2. Natural gas

Once the price for coal is set in kg/s, a similar operation is going to be done concerning natural gas. Nonetheless, the process has a fewer steps due to the units in which the price is usually set for this particular fuel. Again, the source for the initial price of natural gas is BP statistical review for 2015 [30]. Here it can be seen that the price for German imports of natural gas during 2015 had an average price of 6.61 \$/mBtu (see figure 37).

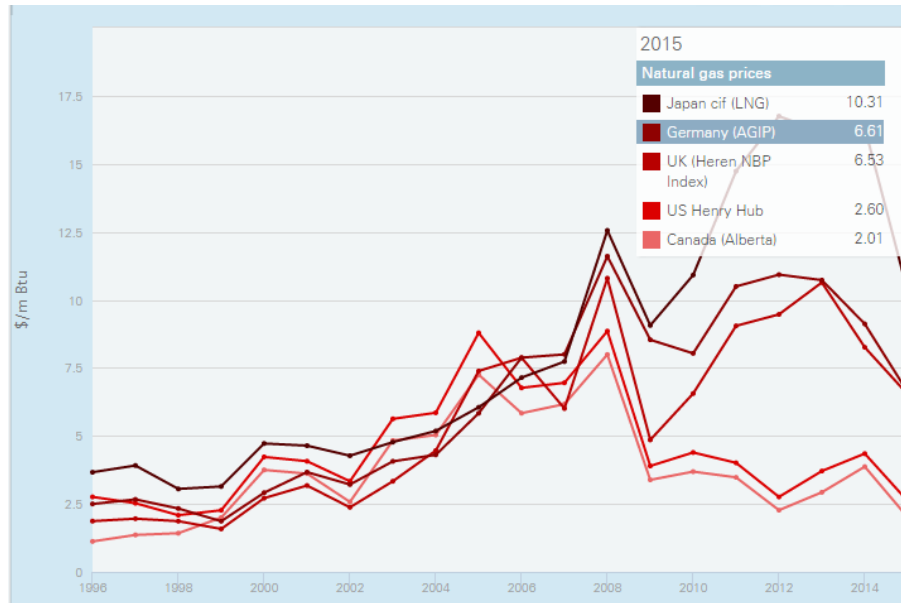


Figure 37. Natural gas prices from 1996 to 2015 [30].

From here [29] [31]:

$$6.61 \frac{\$}{mBtu} \cdot \frac{0.886 \text{ €}}{1 \$} \cdot \frac{1 mBtu}{24.02 m^3} \cdot \frac{1.14 m^3}{1 kg} = 0.277 \frac{\text{€}}{kg}$$

Summing up, the prices per kilogram for each fuel are calculated and stated below. It is remarkable to say that the difference between both of them is very significant; natural gas is almost 6 times higher. On the other hand, it is true that the amount of syngas is much bigger than the amount of natural gas needed for generating the same amount of power. Therefore, further comparison regarding the three different regimes has to be done.

$$\text{coal price} = 0.05 \frac{\text{€}}{kg} \quad ; \quad \text{natural gas price} = 0.277 \frac{\text{€}}{kg}$$

9.1.3. 1st Range: 100% to 64.14% load capacity (426-273.26 MW).

In this case, the savings are going to be the lowest, because to achieve the power demanded it is required the inclusion of natural gas for co-firing it with the maximum feed of syngas. Also, and as it was mentioned previously, there is an extra feed of natural gas to an external post-combustor after heating the feed water in the HRSG. During this range, this feed is going to be assumed as constant and fixed at 3,62 kg/s.

The main variable that is going to vary the saved money between 100% and 64.14% load capacity is natural gas mass flow in the combustion chamber. In this sense, as the mass flow decreases (taking values for z from 0 to 1), also does \dot{m}_a as ΔT , Cp , Li_c , Li_{sg} and η_{CC} are constants.

$$\dot{Q}_{in} = \dot{m}_c \cdot (1 - z) \cdot Li_c \cdot \eta_{CC} + \dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} = \dot{m}_a \cdot Cp \cdot \Delta T$$

As a consequence, the power generated decreases for each value of z taken and the range mentioned is covered until no more natural gas enters the combustion chamber. Now the saving margin for full capacity is going to be shown as an example of the range. However, using Microsoft Excel, the complete process for the range has been calculated and is shown moreover.

Full load capacity: as it was calculated in 8.2.2, the relationship between percentage of natural gas saved, z , and syngas mass flow was calculated. Introducing the maximum value for syngas available, the result is as follows:

$$z = \dot{m}_{sg} \cdot 4.98 \cdot 10^{-3} = 120.2 \cdot 4.98 \cdot 10^{-3} = 0.599$$

With hybridization (syngas + natural gas + post-combustor):

Natural gas

$$\dot{m}_{c100\%} = \dot{m}_c \cdot (1 - z) + \dot{m}_{cpc} = 17.35 \cdot (1 - 0.599) + 3.62 = 10.58 \frac{kg}{s}$$

Coal

$$\dot{m}_{sg} = 120.2 \frac{kg}{s} (\text{syngas}) = 30.09 \frac{kg}{s} (\text{coal})$$

Now each mass flow is going to be multiplied by its corresponding price per kilogram calculated before. Afterwards, the convenient conversion factors will be used to transform the results into €/kWh generated. In this sense:

$$\text{Natural gas cost} = 0.277 \frac{\text{€}}{kg} \cdot 10.58 \frac{kg}{s} \cdot \frac{3600 s}{1 h} \cdot \frac{1}{426 \cdot 10^3 kW} = 0.0248 \frac{\text{€}}{kWh}$$

$$\text{Syngas cost} = 0.05 \frac{\text{€}}{\text{kg}} \cdot 30.09 \frac{\text{kg}}{\text{s}} \cdot \frac{3600 \text{ s}}{1 \text{ h}} \cdot \frac{1}{426 \cdot 10^3 \text{ kW}} = 0.0128 \frac{\text{€}}{\text{kWh}}$$

$$\text{Total cost} = 0.0248 + 0.0128 = 0.0376 \frac{\text{€}}{\text{kWh}}$$

Without hybridization (natural gas + post-combustor):

Natural gas

$$\dot{m}_{c100\%} = \dot{m}_c + \dot{m}_{cpc} = 17.35 + 3.62 = 20.97 \frac{\text{kg}}{\text{s}}$$

Performing in the same manner as before, the results of the power plant operating at full load capacity and with natural gas as only feedstock is:

$$\text{Natural gas cost} = 0.277 \frac{\text{€}}{\text{kg}} \cdot 20.97 \frac{\text{kg}}{\text{s}} \cdot \frac{3600 \text{ s}}{1 \text{ h}} \cdot \frac{1}{426 \cdot 10^3 \text{ kW}} = 0.0491 \frac{\text{€}}{\text{kWh}}$$

Money saved:

$$\text{Savings} = 0.0491 - 0.0376 = 0.0115 \frac{\text{€}}{\text{kWh}} = 1.15 \frac{\text{cent €}}{\text{kWh}}$$

9.1.4. 2nd Range: 64.14% to 53.17% of load capacity (273.26-226.5 MW)

In case that the power demanded by the market is lower than the one generated at 64.14% of load capacity, no more natural gas will enter the combustion chamber. This makes that the heat generated in it takes a constant value, as syngas mass flow will be fixed at the maximum possible. Therefore the net power generated at the gas cycle is also constant. The variable then, when the load capacity decreases, is the net power generated at the steam cycle, which will decrease with the net power for the whole cycle.

$$\dot{Q}_{maxsg} = \dot{m}_{sg} \cdot Li_{sg} \cdot \eta_{CC} = 120.2 \cdot 4.242 \cdot 10^6 \cdot 0.85 = 433.41 \text{ MW} = ct$$

$$\dot{m}_a = \frac{\dot{Q}_{maxsg}}{Cp \cdot (T_3 - T_2)} = \frac{433.41 \cdot 10^6}{1.1105 \cdot 10^3 \cdot (1689.29 - 642.08)} = 372.69 \frac{\text{kg}}{\text{s}} = ct$$

$$\dot{W}_{NGT} = \dot{W}_{GT} + \dot{W}_C = \dot{m}_a \cdot Cp \cdot (T_3 - T_4 + T_1 - T_2) = 161.12 \text{ MW} = ct$$

The reason for this will lie in the amount of feed water that can be heated up in the HRSG and the post-combustor. The idea is to reduce progressively the natural gas entering in

the post-combustor and, therefore, continue saving money. When the value for \dot{m}_{cpc} falls, the amount of feed water heated up for the steam cycle drops, so less power is generated.

$$\dot{m}_a \cdot Cp \cdot (T_4 - T_5) + \Delta\dot{Q} = \dot{m}_w \cdot [(h_6 - h_{14}) + (h_8 - h_7)]$$

$$\dot{m}_w = \frac{\dot{m}_a \cdot Cp \cdot (T_4 - T_5) + \Delta\dot{Q}}{(h_6 - h_{14}) + (h_8 - h_7)}$$

$$\Delta\dot{Q} = \dot{m}_c \cdot Li_c \cdot \eta_{CC}$$

The breakdown from 64.14% to 53.17% of load capacity is done with Microsoft Excel and it is shown moreover. Now it is time to calculate the worst case for this range, maximum load capacity available.

With hybridization (syngas + post-combustor):

Natural gas

$$\dot{m}_{c64\%} = \dot{m}_{cpc} = 3.62 \frac{kg}{s}$$

Coal

$$\dot{m}_{sg} = 120.2 \frac{kg}{s} \text{ (syngas)} = 30.09 \frac{kg}{s} \text{ (coal)}$$

Now each mass flow is going to be multiplied by its corresponding price per kilogram calculated before. Afterwards, the convenient conversion factors will be used to transform the results into €/kWh generated. The net power of the whole cycle for this load capacity was calculated at 8.2.3.

$$\text{Natural gas cost} = 0.277 \frac{\text{€}}{kg} \cdot 3.62 \frac{kg}{s} \cdot \frac{3600 s}{1 h} \cdot \frac{1}{273.26 \cdot 10^3 kW} = 0.0132 \frac{\text{€}}{kWh}$$

$$\text{Syngas cost} = 0.05 \frac{\text{€}}{kg} \cdot 30.09 \frac{kg}{s} \cdot \frac{3600 s}{1 h} \cdot \frac{1}{273.26 \cdot 10^3 kW} = 0.0198 \frac{\text{€}}{kWh}$$

$$\text{Total cost} = 0.0132 + 0.0198 = 0.0330 \frac{\text{€}}{kWh}$$

Without hybridization (natural gas + post-combustor)

In order to compute this value it is necessary to perform a previous step; calculate the required natural gas introduced into the combustion chamber. To do so, the constant value for the transferred heat, \dot{Q}_{maxsg} , is taken and equalized to the heat generated by any fuel.

$$\dot{Q}_{in} = \dot{Q}_{maxsg} = \dot{m}_c \cdot Li_c \cdot \eta_{CC}$$

Rearranging for \dot{m}_c :

$$\dot{m}_c = \frac{\dot{Q}_{maxsg}}{Li_c \cdot \eta_{CC}} = \frac{433.41 \cdot 10^6}{49.22 \cdot 10^6 \cdot 0.85} = 10.36 \frac{kg}{s} = ct$$

Then,

Natural gas

$$\dot{m}_{c64\%} = \dot{m}_c + \dot{m}_{cpc} = 10.36 + 3.62 = 13.98 \frac{kg}{s}$$

Performing in the same manner as before, the results of the power plant operating at full load capacity and with natural gas as only feedstock is:

$$\text{Natural gas cost} = 0.277 \frac{\text{€}}{\text{kg}} \cdot 13.98 \frac{\text{kg}}{\text{s}} \cdot \frac{3600 \text{ s}}{1 \text{ h}} \cdot \frac{1}{273.26 \cdot 10^3 \text{ kW}} = 0.0510 \frac{\text{€}}{\text{kWh}}$$

Money saved:

$$\text{Savings} = 0.0510 - 0.0330 = 0.0179 \frac{\text{€}}{\text{kWh}} = 1.79 \frac{\text{cent €}}{\text{kWh}}$$

9.1.5. 3rd Range: 53.17% to 0% (226.5-0 MW)

To finish spanning all the possibilities, this third scenario contemplates the option of only using syngas as feedstock, without using the post-combustor. As a result, the only fuel to be calculated is coal, which is going to vary as a function of the demanded power. In fact, the variation of fuel leads to variations on air mass flow, which is going to be directly proportional to the power generated because temperatures and Cp remain unchanged. As a consequence, the cost of fuel will remain the same independently of the power demanded. In the same way, the cost of natural gas if no hybridization is done will suffer the same phenomenon. This will make savings constant from 0% to 53.17% of load capacity.

However, the calculations for the savings in this range have been also studied via Microsoft Excel. The results will be stated moreover. As an example, again, the supposedly worst situation is going to be studied to show how the savings for this range should be calculated. This corresponds to 53.17% of the load capacity, which mass flow is known:

With hybridization (syngas):

Coal

$$\dot{m}_{sg} = 120.2 \frac{kg}{s} \text{ (syngas)} = 30.09 \frac{kg}{s} \text{ (coal)}$$

$$\text{Syngas cost} = 0.05 \frac{\text{€}}{kg} \cdot 30.09 \frac{kg}{s} \cdot \frac{3600 s}{1 h} \cdot \frac{1}{226.50 \cdot 10^3 kW} = 0.0239 \frac{\text{€}}{kWh}$$

Without hybridization (natural gas):

For natural gas, the same value calculated before remains the same in this case, as the heat transferred by the fuel is the same than 64.14% in the combustion chamber. The difference is the net power generated by the cycle, which decreases because the post-combustor isn't working. It is sensible to say that when the required net power decreases, less fuel is required, decreasing the mass flow. The net power for this load capacity was calculated at 8.2.3. To this extent:

Natural gas

$$\dot{m}_{c53\%} = \dot{m}_c = 10.36 \frac{kg}{s}$$

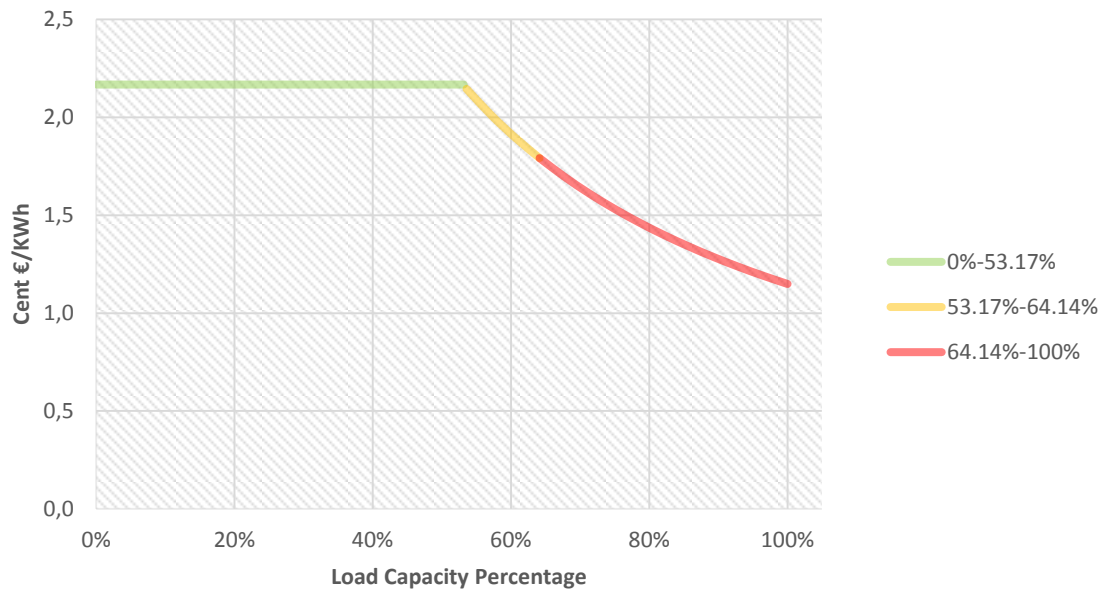
$$\text{Natural gas cost} = 0.277 \frac{\text{€}}{kg} \cdot 10.36 \frac{kg}{s} \cdot \frac{3600 s}{1 h} \cdot \frac{1}{226.5 \cdot 10^3 kW} = 0.0456 \frac{\text{€}}{kWh}$$

Money saved:

$$\text{Savings} = 0.0456 - 0.0239 = 0.0217 \frac{\text{€}}{kWh} = 2.17 \frac{\text{cent €}}{kWh}$$

9.1.6. From 0% to 100% load capacity

During the preceding lines, the results for the whole span in each range were postponed. Now, joining the different savings calculation in each range and plotting the results into a graph, the whole span for the power plant is obtained (see graph 2).



Graph 2. Savings vs Load capacity in IGCC designed for Soto 4.

It is sensible to mention that, as it can be seen clearly in the graph, the saving is boosted at lower load capacity percentages. The reason is simple, the lower the percentage the less or none natural gas is needed to achieve the requested power. The data for the completion of the plotting is stated at Appendix D.

9.2. Investment and maintenance costs

Regardless of the positive evaluation seen before, obtaining this technology drags some added costs. As it can be seen in figure 29, where the breakdown for investment costs of Puertollano's power plant is shown, the investment made regarding gasification and ASU devices is around 260 million €. However, being a second hand purchase, the costs will sharply decrease. Assuming that usually power stations are design to operate at least for 40 years, part of the amortization process has been covered. In this sense, the initial cost of this technology can be calculated as the initial cost minus the amortized part. Knowing that Puertollano's plant has been operating from 1997 to 2016 and that the amortization base is calculated with a residual value of 10%:

$$APY = \frac{IIP}{TAY} = \frac{260 \cdot (1 - 0.1)}{40} = 5.85 \text{ million } \frac{\text{€}}{\text{year}}$$

Multiplying this figure by the remaining years of amortization it is obtained the total amount amortized. The total cost, *IIP*, minus the figure calculated will be the initial cost for Soto 4.

$$IIS4 = 260 - 5.85 \cdot 20 = 117 \text{ millions €}$$

It is sensible to highlight that the rest of components are already at Soto 4, therefore the reduction of the costs is quite significant. Dividing the initial investment for Soto 4 by the initial investment of Puertollano's power plant:

$$\frac{IIS4}{IIP} = \frac{117}{260} = 45\% \text{ of investment.}$$

Now the initial investment has to be transformed into €/kWh in order to achieve a suitable figure to compare with fuel savings. In this sense, a series of operation days are going to be studied to see the normal functioning of this power plant. For simplification matters, the operation at the mentioned days is going to be extrapolated to the whole year as a mean value. Using the values obtained from *ESIOS REE*, where all operation days for all Spanish power plants is tabulated, one day from the last five months have been randomly elected to elaborate the convenient mean values. All the values and calculations are stated at Appendix E and the results in table 24 [32].

	Total	Mean per day	Per hour
<i>Energy/power</i>	11263,4 MWh	2252.68 MWh	181.67 MW
<i>Hours</i>	62	12.4	1

Table 24. Results of calculating mean power and hours for five different days [32].

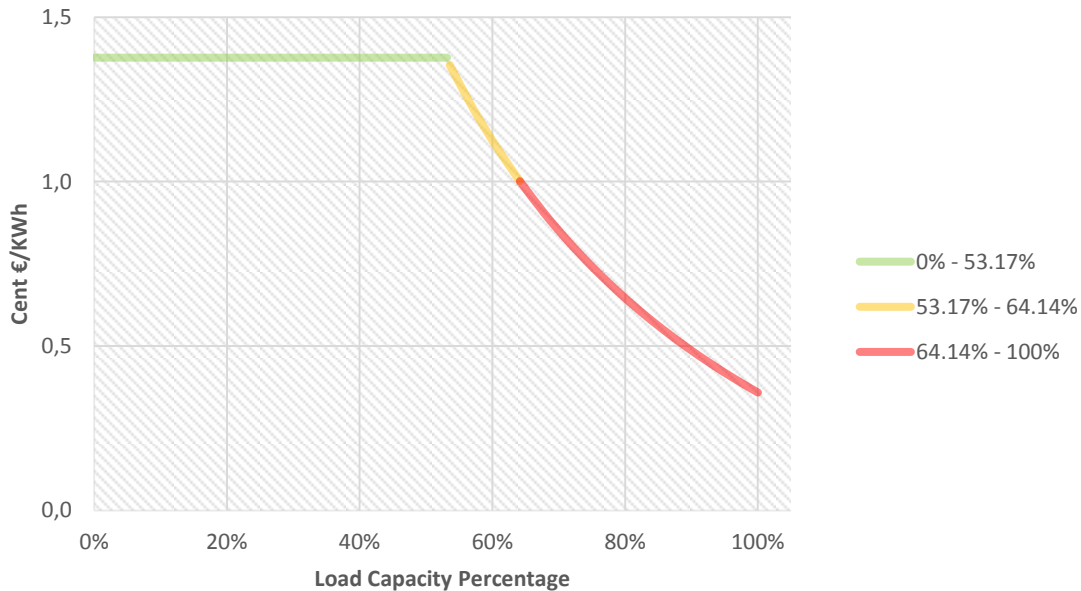
With this, the cost of the initial investment can be calculated assuming the plant needs one month per year to perform the convenient maintenance operations. Therefore:

$$5.85 \cdot 10^6 \frac{\text{€}}{\text{year}} \cdot \frac{1 \text{ year}}{335 \text{ days}} \cdot \frac{1 \text{ day}}{12.4 \text{ h}} \cdot \frac{1}{181.66 \cdot 10^3 \text{ kW}} = 0.0075 \frac{\text{€}}{\text{kWh}} = 0.75 \frac{\text{cent €}}{\text{kWh}}$$

Adding to this the maintenance costs that are estimated to be around 0.4 cent €/kWh according to the data released by ELCOGAS [3]. Therefore, the global costs that have to be taken into account are the sum of both figures.

$$\text{Total costs} = 0.75 + 0.4 = 0.79 \frac{\text{cent } \text{€}}{\text{kWh}}$$

Adding this figure to the savings in the three scenarios proposed, a new graph with the global economic analysis is calculated (see graph 3). Afterwards, the savings of one year of operation will be estimated to launch a final clarifying value.



Graph 3. Economic analysis with costs and savings.

9.3. Savings for a year

To clarify the discussion explained above, the data concerning the 21st of March of 2016 will be used as an example of how much money could be saved with hybridization. The election of this day isn't trivial; as combined cycles operate more hours during winter season and less during summer season. Therefore, March is a suitable mean operating month.

The results shown below (see table25), stating the operating hours during that day and the power demanded at each of them. Next, the savings for each hour have been calculated using the parameters that were used to plot graph 3 for each range (each range has been highlighted in the same color as the graphic representation). Hence:

Hour	Energy Required (MWh)	Savings (€/kWh)	Savings €
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	30	0.0138	414
8	130	0.0138	1794
9	263,3	0.0107	2817.31
10	298	0.0085	2533
11	309	0.0079	2441.1
12	334	0.0068	2271.2
13	120	0.0138	1656
14	70	0.0138	966
15	70	0.0138	966
16	70	0.0138	966
17	70	0.0138	966
18	70	0.0138	966
19	120	0.0138	1656
20	188	0.0138	2594
21	235,2	0.0129	3034.08
22	60	0.0138	828
23	0	0	0
24	0	0	0
Total		0.1986	25998.69

Table 25. Savings of a normal operation day for Soto 4.

It is sensible to say that, according to the results seen in the graph, the power generated has a vital impact in the savings earned. The truth is that when the power demanded is higher, the conversion of €/kWh to € increases sharply despite of suffering the differences in the saving ratios. This makes that the second range values achieve equilibrium that boost savings. Assuming this results as an hypothetical mean value for all the year and guessing the worst conditions possible, which make the plant only function more or less five out of seven days per week (including maintenance time), the total money saved for a year will be:

$$365 \cdot \frac{4}{7} = 208.57 \approx 208 \frac{\text{days}}{\text{year}}$$

$$25998.69 \frac{\text{€}}{\text{day}} \cdot \frac{208 \text{ days}}{1 \text{ year}} = 5.41 \text{ million} \frac{\text{€}}{\text{year}}$$

Annual savings = 5.41 million $\frac{\text{€}}{\text{year}}$

In remaining years = 5.41 · 20 = 108.2 millon €

10. Conclusions and Improvements

Gasification technology has some advantages and drawbacks that have been widely discussed throughout this paper. At the end of the day, enough proof has been given to take into serious consideration this technology as a clean and reliable way of generating power using fossil fuels. At a start, the idea of considering this kind of fuels as clean energy generation was utopist. However, a deep explanation on how gasification processes take place, and the results obtained from them, have manifested that a clean use of carbon as feedstock is possible.

Taking this as a basis, the objectives pursued in this document were established and ready to be accomplished. Starting from the reactions that have to take place when talking about gasification, passing through the possible gasifiable elements and finishing with the main elements involved in IGCC power plants, the technology from a technical point of view has been detailed. Afterwards, once a comprehensive understanding of the technology was done, the nearest example of this technology was shown in order to clarify the theoretical concepts proposed before. However, the mentioned power plant was forced to closure, besides of having demonstrated the high efficiency and correct functioning of the gasification process. To this extent, a problem to solve was proposed in order to take advantage of the components concerning gasification.

A hybridizing project was submitted to viability analysis. Moreover, the process for electing the adequate combined cycle to perform the hybridization started. The key points were; near location to supplies (carbon mines and refineries) and similar power production to Puertollano's power plant. As a result, Soto de Ribera group 4 fulfilled the requirements and was subjected to thermal analysis to understand and calculate each point involved in the cycle. As a result, the needed natural gas to perform the cycle was calculated. This result was used moreover in the economic analysis. The next step was to calculate the amount of syngas needed to perform Soto 4's cycle without changing the temperatures or pressures. This analysis led to an inconvenient; the gasifier wasn't able to produce the amount required for full capacity (426 MW). Therefore, some solutions had to be studied.

The first thing to do was to assume full capacity and see how it could be managed. In this sense, co-firing technologies were evaluated and the needed mass flow of natural gas to be added to syngas was obtained. Also, knowing that when the gasifier starts working doesn't give maximum mass flow, a breakdown was performed to see the amount of natural gas saved when the syngas output from the gasifier grew from minimum (0 kg/s) to maximum (120,2 kg/s) capacity.

Secondly, a solution for having the cycle operating on less than full capacity was considered. In this sense, the maximum power that could be achieved by the cycle only using syngas has to be calculated. As was explained before, the use of a post-combustor attached to the HRSG is needed, being its feed of natural gas. Therefore, in this part two solutions were contemplated; combustion chamber with syngas and post-combustor turned on or combustion chamber with syngas and post-combustor turned off. It is sensible to say that the

post-combustor is going to vary the amount of water heated up for the steam cycle. Being the mass flow of water directly proportional to the power generated in the VT, the net power generated is going to decrease while the natural gas mass flow decreases.

With all of this data, three ranges of operation can be defined. After calculations, the ranges span from 100% to 64.14% for the first, 64.14% to 53.17% for the second and from 0% to 53.17% for the third. For each of them an economic viability analysis was performed, reaching the next consequences. The rate of savings in €/kWh stated that when the plant operates at the third range mentioned, the savings where the highest. It is sensible to say that when less natural gas is used, the less money cost is achieved. However, as the rate is inversely proportional to the power generated, when multiplying by the power generated in one hour, the savings in € increase. Therefore, it is sensible to conclude that the better operation range when talking about savings is the second one, as equilibrium is reached. This fact is visible at point 9.3 of the document.

Taking all of these facts into account, it is sensible to conclude that the hybridization of gasification processes into combined cycles is proved by far. In fact, not only thermal viability has been solved, in order to accomplish all possible demands, but also economic relevance has appeared in form of savings. The fact of achieving a profitable margin that can reach almost 110 million € in 20 years has to be considered as a victory. Regarding the technology, being profitable as it has been said, more advantages in environment field will continue summing up reasons to take this technology to a higher step. It is recommendable to say that all PC-fired power plants should be substituted by IGCC power plants, in case the same fuel wants to be used. Regarding NGCC power plants, the profitable margin and the possibility of accomplishing the power demand, makes the idea of changing suitable. However, as the technology is rather new, the investment costs are still high. Therefore, in case of being possible to recycle any kind of gasifier and ASU systems, to perform hybridization should be taken as an opportunity, as has been demonstrated along this paper.

Improvements

Despite the fact of having obtained positive results regarding the implementation of the studied technology, many improvements can be done in order to optimize the process. Some of them are stated below:

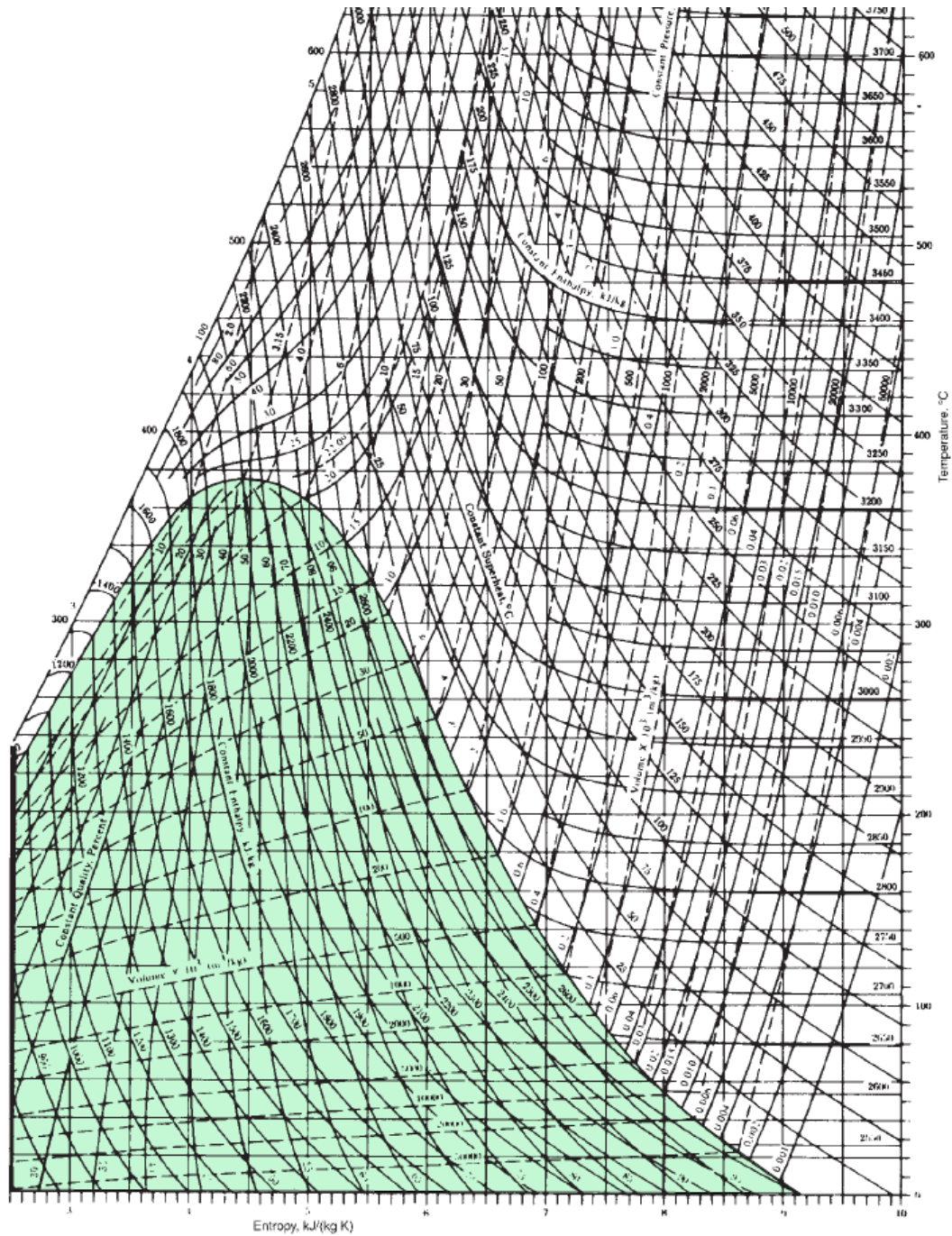
- **Different fuels to gasify:** the reduction of pollutant emission is considerable using carbon and petcoke, however, other carbonaceous such as waste or biomass make CO₂ cycle null. The reason is that biomass is formed by plants principally, which use CO₂ to do photosynthesis. The carbonic part of the molecule is used to form the structure of the plant. When gasification and then combustion take place, it won't generate more CO₂ than the one it has absorbed along its life.
- **Cleaning gas systems:** during the explanation of IGCC power plants it was observed how the cleaning systems for syngas reduced the LHV of the gas introduced into the

combined cycle in a significant way. If the adequate researches in these systems were done, favoring a shallower descent in LHV of the final gas, the heat transferred by its combustion could make the whole process suitable to be fed only with syngas.

- **Gasifier redesigning:** increasing the coal capacity admitted inside the gasifier the syngas produced will be increased. With this increase the power generated will also grow and the possibility of having syngas as unique feedstock would be a reality. However, this rise will mean an additional cost in terms of solid coal bought.

To conclude, it is sensible to say that the objectives proposed at the beginning of the document have been fulfilled along it. To this extent, during the elaboration of this paper the acquirement of knowledge about this technology has been a matter of fact, understanding the relevance of environment and economy when talking about energy and how variable manifest the different results that can be obtained. Afterwards, solving the problem proposed making use of tools such as *Microsoft Visio*, *Microsoft Excel*, *Cyclepad* or *ToolBox* to obtain reasonable results that state that hybridization could be profitable, was hunted and accomplished. With all of this, it is sensible to say that gasification integrated in combined cycle has been proved to be a clean, reliable and long-lasting technology due to the secure supply for many years.

Appendix A: T-s Diagram



Appendix B: Moran-Shapiro tables for different fluids

**Table A-3. Properties of Saturated Water (Liquid-Vapour):
Pressure table:**

Press. bar	Temp. °C	Specific Volume m ³ /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Press. bar
		Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00

Table A-4. Properties of Superheated Water Vapour:

$p = 5.0 \text{ bar} = 0.50 \text{ MPa}$ ($T_{\text{sat}} = 151.86^\circ\text{C}$)					$p = 3.0 \text{ bar} = 0.30 \text{ MPa}$ ($T_{\text{sat}} = 133.55^\circ\text{C}$)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.606	2543.6	2725.3	6.9919
180	0.4045	2609.7	2812.0	6.9656				
200	0.4249	2642.9	2855.4	7.0592	0.651	2587.1	2782.3	7.1276
240	0.4646	2707.6	2939.9	7.2307	0.716	2650.7	2865.5	7.3115
280	0.5034	2771.2	3022.9	7.3865	0.781	2713.1	2947.3	7.4774
320	0.5416	2834.7	3105.6	7.5308	0.844	2775.4	3028.6	7.6299
360	0.5796	2898.7	3188.4	7.6660	0.907	2838.1	3110.1	7.7722
400	0.6173	2963.2	3271.9	7.7938	0.969	2901.4	3192.2	7.9061
440	0.6548	3028.6	3356.0	7.9152	1.032	2965.6	3275.0	8.0330
500	0.7109	3128.4	3483.9	8.0873	1.094	3030.6	3358.7	8.1538
600	0.8041	3299.6	3701.7	8.3522	1.187	3130.0	3486.0	8.3251
700	0.8969	3477.5	3925.9	8.5952	1.341	3300.8	3703.2	8.5892

$p = 20.0 \text{ bar} = 2.0 \text{ MPa}$ ($T_{\text{sat}} = 212.42^\circ\text{C}$)					$p = 30.0 \text{ bar} = 3.0 \text{ MPa}$ ($T_{\text{sat}} = 233.90^\circ\text{C}$)			
Sat.	0.0996	2600.3	2799.5	6.3409	0.0667	2604.1	2804.2	6.1869
240	0.1085	2659.6	2876.5	6.4952	0.0682	2619.7	2824.3	6.2265
280	0.1200	2736.4	2976.4	6.6828	0.0771	2709.9	2941.3	6.4462
320	0.1308	2807.9	3069.5	6.8452	0.0850	2788.4	3043.4	6.6245
360	0.1411	2877.0	3159.3	6.9917	0.0923	2861.7	3138.7	6.7801
400	0.1512	2945.2	3247.6	7.1271	0.0994	2932.8	3230.9	6.9212
440	0.1611	3013.4	3335.5	7.2540	0.1062	3002.9	3321.5	7.0520
500	0.1757	3116.2	3467.6	7.4317	0.1162	3108.0	3456.5	7.2338
540	0.1853	3185.6	3556.1	7.5434	0.1227	3178.4	3546.6	7.3474
600	0.1996	3290.9	3690.1	7.7024	0.1324	3285.0	3682.3	7.5085
640	0.2091	3362.2	3780.4	7.8035	0.1388	3357.0	3773.5	7.6106
700	0.2232	3470.9	3917.4	7.9487	0.1484	3466.5	3911.7	7.7571

$p = 120 \text{ bar} = 12.0 \text{ MPa}$ ($T_{\text{sat}} = 324.75^\circ\text{C}$)					$p = 140 \text{ bar} = 14.0 \text{ MPa}$ ($T_{\text{sat}} = 336.75^\circ\text{C}$)			
Sat.	0.01426	2513.7	2684.9	5.4924	0.01149	2476.8	2637.6	5.3717
360	0.01811	2678.4	2895.7	5.8361	0.01422	2617.4	2816.5	5.6602
400	0.02108	2798.3	3051.3	6.0747	0.01722	2760.9	3001.9	5.9448
440	0.02355	2896.1	3178.7	6.2586	0.01954	2868.6	3142.2	6.1474
480	0.02576	2984.4	3293.5	6.4154	0.02157	2962.5	3264.5	6.3143
520	0.02781	3068.0	3401.8	6.5555	0.02343	3049.8	3377.8	6.4610
560	0.02977	3149.0	3506.2	6.6840	0.02517	3133.6	3486.0	6.5941
600	0.03164	3228.7	3608.3	6.8037	0.02683	3215.4	3591.1	6.7172
640	0.03345	3307.5	3709.0	6.9164	0.02843	3296.0	3694.1	6.8326
700	0.03610	3425.2	3858.4	7.0749	0.03075	3415.7	3846.2	6.9939
740	0.03781	3503.7	3957.4	7.1746	0.03225	3495.2	3946.7	7.0952

Table A-5. Properties of Compressed Liquid Water:

$p = 75 \text{ bar} = 7.5 \text{ MPa}$ ($T_{\text{sat}} = 290.59^\circ\text{C}$)					$p = 100 \text{ bar} = 10.0 \text{ MPa}$ ($T_{\text{sat}} = 311.06^\circ\text{C}$)				
20	.9984	83.50	90.99	.2950	.9972	83.36	93.33	.2945	
40	1.0045	166.64	174.18	.5696	1.0034	166.35	176.38	.5686	
80	1.0256	333.15	340.84	1.0704	1.0245	332.59	342.83	1.0688	
100	1.0397	416.81	424.62	1.3011	1.0385	416.12	426.50	1.2992	
140	1.0752	585.72	593.78	1.7317	1.0737	584.68	595.42	1.7292	
180	1.1219	758.13	766.55	2.1308	1.1199	756.65	767.84	2.1275	
220	1.1835	936.2	945.1	2.5083	1.1805	934.1	945.9	2.5039	
260	1.2696	1124.4	1134.0	2.8763	1.2645	1121.1	1133.7	2.8699	
Sat.	1.3677	1282.0	1292.2	3.1649	1.4524	1393.0	1407.6	3.3596	

$p = 150 \text{ bar} = 15.0 \text{ MPa}$ ($T_{\text{sat}} = 342.24^\circ\text{C}$)					$p = 200 \text{ bar} = 20.0 \text{ MPa}$ ($T_{\text{sat}} = 365.81^\circ\text{C}$)				
20	.9950	83.06	97.99	.2934	.9928	82.77	102.62	.2923	
40	1.0013	165.76	180.78	.5666	.9992	165.17	185.16	.5646	
80	1.0222	331.48	346.81	1.0656	1.0199	330.40	350.80	1.0624	
100	1.0361	414.74	430.28	1.2955	1.0337	413.39	434.06	1.2917	
140	1.0707	582.66	598.72	1.7242	1.0678	580.69	602.04	1.7193	
180	1.1159	753.76	770.50	2.1210	1.1120	750.95	773.20	2.1147	
220	1.1748	929.9	947.5	2.4953	1.1693	925.9	949.3	2.4870	
260	1.2550	1114.6	1133.4	2.8576	1.2462	1108.6	1133.5	2.8459	
300	1.3770	1316.6	1337.3	3.2260	1.3596	1306.1	1333.3	3.2071	
Sat.	1.6581	1585.6	1610.5	3.6848	2.036	1785.6	1826.3	4.0139	

Appendix C: steam cycle calculations for natural gas feedstock

To begin, it is interesting to enumerate the different stages of which the cycle consists of. In this sense, the points in the diagram follow the next order:

- **Stage 6-7: Isentropic and adiabatic expansion from 136 bar to 29 bar**

In order to calculate the value for h_6 , given the temperature and pressure at that point, it is used Table A-4 of APPENDIX B. By interpolating the values for enthalpy for $T = 560^{\circ}\text{C}$; $T = 600^{\circ}\text{C}$ and $P = 120 \text{ bar}$; $P = 140 \text{ bar}$ achieving as mean value the pressure and temperature required.

$$h_6 = 3503.67 \frac{\text{kJ}}{\text{kg}}$$

The value for h'_7 is obtained by performing an ideal expansion in the T-s diagram, what is traduced in performing in the graph a vertical line until matching $P = 29 \text{ bar}$. Here it is obtained the value for $T_7 = 302^{\circ}\text{C}$. Again interpolating with Table A-4 and $T = 280^{\circ}\text{C}$; $T = 320^{\circ}\text{C}$ and $P = 20 \text{ bar}$; $P = 30 \text{ bar}$ with the convenient adjustments achieving as mean values the temperature and pressure present on point 7.

$$h'_7 = 2999.38 \frac{\text{kJ}}{\text{kg}}$$

In order to obtain the real value for the enthalpy at point 7, the next equation is used. It is sensible to mention that all turbine processes will be calculated in the same way.

$$\eta_T = 0.9 = \frac{\dot{W}_{real}}{\dot{W}_{ideal}} = \frac{h_i - h_j}{h_i - h'_j}$$

$$h_7 = h_6 - 0.9 \cdot (h_6 - h'_7) = 3049.81 \frac{\text{kJ}}{\text{kg}}$$

- **Stage 7-8: Reheat in HRSG**

To find the enthalpy at point 8, the same procedure as with 6 should be applied. As temperature and pressure are known, by interpolating in Table A-4 with $T = 540^{\circ}\text{C}$; $T = 600^{\circ}\text{C}$ and $P = 20 \text{ bar}$; $P = 30 \text{ bar}$:

$$h_8 = 3603.46 \frac{\text{kJ}}{\text{kg}}$$

- **Stage 8-9: Isentropic and adiabatic expansion form 29 bar to 4,6 bar with steam extraction**

As temperature and pressure are known for point 9, the ideal value for enthalpy at the mentioned point can be calculated by interpolation of data of Table A-4 with $T = 280^{\circ}\text{C}$; $T = 320^{\circ}\text{C}$ and $P = 3 \text{ bar}$; $P = 5 \text{ bar}$ obtaining:

$$h'_{9} = 3033.99 \frac{\text{kJ}}{\text{kg}}$$

Following the same path as with stage 6-7, the real value for enthalpy at point 9 is:

$$h_{9} = h_{8} - 0.9 \cdot (h_{8} - h'_{9}) = 3090.86 \frac{\text{kJ}}{\text{kg}}$$

- **Stage 9-10: Isentropic and adiabatic expansion from 4,6 bar to 0,1 bar**

In this case, when performing the vertical line representing the ideal expansion of the fluid it can be seen in the T-s diagram that the point is inside the bell-shaped region. This represents that steam has started to change phase into water and, therefore, instead of using Table A-4 now it is needed to use Table A-3.

Knowing temperature and pressure at point 10, as temperature is fixed at each condensation pressure due to phase change; the enthalpy of vaporization can be obtained directly from the table:

$$h'_{10} = 2392.80 \frac{\text{kJ}}{\text{kg}}$$

As before, taking into account the turbine's efficiency:

$$h_{10} = h_{9} - 0.9 \cdot (h_{9} - h'_{10}) = 2462.61 \frac{\text{kJ}}{\text{kg}}$$

Being the last turbine step and being inside the bell-shape region, an additional proof has to be performed. This statement establishes that the percentage of vapour over water at the last stages of turbine have to be over 80%. To compute this, the following expression is used:

$$h_{10} = (1 - x) \cdot h_f + h_g \cdot x$$

Where h_f and h_g are obtained from Table A-3. Isolating x :

$$x = \frac{h_{10} - h_f}{h_g - h_f} = \frac{2462.61 - 191.83}{2584.70 - 191.83} = 0.95 > 0.8$$

This demonstrates that the mixture is sufficiently gasified what means that the turbine will not suffer damages or losses due to water drops.

- **Stage 10-16-11: Mixer**

To compute the enthalpy of point 11 it is necessary a previous calculation of point 16. Therefore this point will be calculated moreover.

- **Stage 11-12: Isobaric condensation to saturated water**

This isobaric and isothermal change of phase has as objective to give saturated water at the end of the process. For this reason, it is easy to compute the value for enthalpy by looking into Table A-3:

$$h_{12} = 191.83 \frac{kJ}{kg}$$

- **Stage 12-13: adiabatic pumping to boiler pressure, 136 bar**

Due to the proximity of all the pressure lines in the superheated water part, it is impossible to estimate an accurate value for temperature in point 13. For that purpose, it is going to be used the entropy law for calorically perfect liquids assuming ideal reversible pumping.

$$\Delta s = 0 = C_v \cdot \ln\left(\frac{T_{13}}{T_{12}}\right)$$

The only thing that is going to make the variation of entropy null is that $T_{13} = T_{12}$. This is going to lead to the next result in the variation of enthalpy equation:

$$\Delta h = \Delta P \cdot v + C_p \Delta T = \Delta P \cdot v$$

Then;

$$h'_{13} = h_{12} + (P_{13} - P_{12}) \cdot v$$

Introducing the values corresponding to the pressures in MPa and the value of the specific volume at point 12, enthalpy has a value of:

$$h'_{13} = 191.83 \cdot 10^3 + (13.6 \cdot 10^6 - 0.01 \cdot 10^6) \cdot 1.004 \cdot 10^{-3} = 205.42 \frac{kJ}{kg}$$

Due to the irreversibilities in the pump, the real value has to be computed in a similar way to the enthalpies calculated during the turbine stages.

$$\eta_T = 0.85 = \frac{\dot{W}_{ideal}}{\dot{W}_{real}} = \frac{h'_i - h_j}{h_i - h_j}$$

$$h_{13} = h_{12} + \frac{(h'_{13} - h_{12})}{0.85} = 207.82 \frac{kJ}{kg}$$

Introducing this datum in the variation of enthalpy equation and isolating for T_{13} , the temperature of point 13 can be calculated:

$$T_{13} = 46.38 \text{ } ^\circ\text{C}$$

- **Stage 13-14: Water heating with steam extraction**

Similarly to point 11, point 14 needs of additional information that will be stated moreover.

- **Stage 9-15: Steam extracted gives heat to water**

Regarding the condition attached to FHWC, the extraction steam after given away heat to raise water's temperature, exists the heat exchanger as saturated water. Therefore, having knowledge of point 15 pressure, the temperature and enthalpy can be calculated from Table A-3. Also due to its FHWC condition, the outlet temperatures of both pipelines are assumed to be the same:

$$T_{14} = T_{15} = 148.7^{\circ}C$$

$$h_{15} = 626.65 \frac{kJ}{kg}$$

- **Stage 15-16: isentropic expansion by means of expansion valve to 0,1 bar**

Finally, the valve is assumed to be perfect. This means that the enthalpy before and after it remains the same.

$$h_{15} = h_{16} = 626.65 \frac{kJ}{kg}$$

With all of this information and with the additional datum of steam extraction at point 9, the enthalpies for 11 and 14 can be now calculated. For this purpose an energy balance on the mixer has to be done. However, it is important to compute point 14 before. Knowing the temperature and pressure at that point, and using table A-5 interpolating $T = 140^{\circ}C$; $T = 180^{\circ}C$ and $P = 100 \text{ bar}$; $P = 150 \text{ bar}$ obtaining:

$$h_{14} = 635.99 \frac{kJ}{kg}$$

Energy Balance solved:

$$(1 - y) \cdot h_{10} + y \cdot h_{16} = h_{11} = (1 - 0.17) \cdot 2462.61 + 0.17 \cdot 635.99 = 2152.08 \frac{kJ}{kg}$$

Appendix D: Excel data for savings per load capacity percentage

1st Range: 100% to 64,14% load capacity

z	mc	Q	ma	maCPdelt	mw	Wng	Wtv	Wn
0,00E+00	6,990E+00	7,259E+08	6,24E+02	5,05E+08	1,477E+02	2,70E+08	1,562E+08	4,26E+08
1,00E-01	6,291E+00	6,966E+08	5,99E+02	4,91E+08	1,435E+02	2,59E+08	1,518E+08	4,11E+08
2,00E-01	5,592E+00	6,674E+08	5,74E+02	4,77E+08	1,393E+02	2,48E+08	1,474E+08	3,96E+08
3,00E-01	4,893E+00	6,381E+08	5,49E+02	4,62E+08	1,352E+02	2,37E+08	1,430E+08	3,80E+08
4,00E-01	4,194E+00	6,089E+08	5,24E+02	4,48E+08	1,310E+02	2,26E+08	1,386E+08	3,65E+08
5,00E-01	3,495E+00	5,796E+08	4,98E+02	4,34E+08	1,268E+02	2,15E+08	1,342E+08	3,50E+08
6,00E-01	2,796E+00	5,504E+08	4,73E+02	4,20E+08	1,226E+02	2,05E+08	1,298E+08	3,34E+08
7,00E-01	2,097E+00	5,211E+08	4,48E+02	4,05E+08	1,185E+02	1,94E+08	1,254E+08	3,19E+08
8,00E-01	1,398E+00	4,919E+08	4,23E+02	3,91E+08	1,143E+02	1,83E+08	1,209E+08	3,04E+08
9,00E-01	6,990E-01	4,627E+08	3,98E+02	3,77E+08	1,101E+02	1,72E+08	1,165E+08	2,89E+08
1,00E+00	7,760E-16	4,334E+08	3,73E+02	3,63E+08	1,060E+02	1,61E+08	1,121E+08	2,73E+08

only natural gas				savings			
€/kWh (sg)	€/kWh (gn)	€/kWh(sg+g)	mc (gn+combust)	€/kWh (gn)	€/kWh	cent€/kW	%load capac
1,28E-02	2,48E-02	3,76E-02	20,9694904	4,91E-02	1,15E-02	1,15E+00	100,0%
1,32E-02	2,41E-02	3,73E-02	20,2704904	4,92E-02	1,19E-02	1,19E+00	96,4%
1,37E-02	2,32E-02	3,70E-02	19,5714904	4,93E-02	1,24E-02	1,24E+00	92,8%
1,43E-02	2,23E-02	3,66E-02	18,8724904	4,95E-02	1,29E-02	1,29E+00	89,3%
1,49E-02	2,14E-02	3,62E-02	18,1734904	4,97E-02	1,34E-02	1,34E+00	85,7%
1,55E-02	2,03E-02	3,58E-02	17,4744904	4,98E-02	1,40E-02	1,40E+00	82,1%
1,63E-02	1,91E-02	3,54E-02	16,7754904	5,00E-02	1,46E-02	1,46E+00	78,5%
1,70E-02	1,79E-02	3,49E-02	16,0764904	5,02E-02	1,53E-02	1,53E+00	74,9%
1,79E-02	1,65E-02	3,44E-02	15,3774904	5,05E-02	1,61E-02	1,61E+00	71,3%
1,88E-02	1,49E-02	3,38E-02	14,6784904	5,07E-02	1,70E-02	1,70E+00	67,7%
1,99E-02	1,32E-02	3,31E-02	13,9794904	5,10E-02	1,79E-02	1,79E+00	64,1%
1,35E-02	7,25E-03	2,08E-02	13,2804904	3,29E-02	1,218E-02	1,22E+00	94,4%
1,60E+00	6,52E-01	2,25E+00	12,5814904	3,69E+00	1,44E+00	1,44E+02	0,8%

2nd Range: 64,14% to 53,17%

Wng	Wtv	Wn	%load capac	mw	Q combust	mc(combust)
1,61E+08	1,12E+08	2,73E+08	64,1%	1,06E+02	1,51E+08	3,6038798
1,61E+08	9,71E+07	2,58E+08	60,6%	9,18E+01	1,02E+08	2,444526578
1,61E+08	8,21E+07	2,43E+08	57,1%	7,76E+01	5,38E+07	1,285173357
1,61E+08	6,71E+07	2,28E+08	53,6%	6,34E+01	5,26E+06	0,125820135

€/kWh (sg)	€/kWh (gr)	€/kWh(sg+g)	mc(gn+c)	€/kWh (gn)	€/kWh	cent€/kW	%load capaci
1,99E-02	1,32E-02	3,30E-02	13,9638798	5,10E-02	1,79E-02	1,79E+00	64,1%
2,11E-02	9,44E-03	3,05E-02	12,80452658	4,94E-02	1,90E-02	1,90E+00	60,6%
2,24E-02	5,27E-03	2,76E-02	11,64517336	4,77E-02	2,01E-02	2,01E+00	57,1%
2,38E-02	5,50E-04	2,44E-02	10,48582014	4,58E-02	2,14E-02	2,14E+00	53,6%

3rd Range: 53,17% to 0%

msg	Q	mcarbor	ma	Wng	maCpDelt	mw	Wtv
1,20E+02	4,33E+08	3,01E+01	3,7E+02	1,6E+08	2,1E+08	6,2E+01	6,5E+07
1,10E+02	3,97E+08	2,76E+01	3,4E+02	1,5E+08	1,9E+08	5,7E+01	6,0E+07
1,00E+02	3,61E+08	2,51E+01	3,1E+02	1,3E+08	1,8E+08	5,2E+01	5,5E+07
9,02E+01	3,25E+08	2,26E+01	2,8E+02	1,2E+08	1,6E+08	4,6E+01	4,9E+07
8,02E+01	2,89E+08	2,01E+01	2,5E+02	1,1E+08	1,4E+08	4,1E+01	4,4E+07
7,02E+01	2,53E+08	1,76E+01	2,2E+02	9,4E+07	1,2E+08	3,6E+01	3,8E+07
6,02E+01	2,17E+08	1,51E+01	1,9E+02	8,1E+07	1,1E+08	3,1E+01	3,3E+07
5,02E+01	1,81E+08	1,26E+01	1,6E+02	6,7E+07	8,8E+07	2,6E+01	2,7E+07
4,02E+01	1,45E+08	1,01E+01	1,2E+02	5,4E+07	7,1E+07	2,1E+01	2,2E+07
3,02E+01	1,09E+08	7,57E+00	9,4E+01	4,0E+07	5,3E+07	1,6E+01	1,6E+07
2,02E+01	7,28E+07	5,06E+00	6,3E+01	2,7E+07	3,6E+07	1,0E+01	1,1E+07
1,02E+01	3,68E+07	2,56E+00	3,2E+01	1,4E+07	1,8E+07	5,2E+00	5,5E+06
2,00E-01	7,21E+05	5,01E-02	6,2E-01	2,7E+05	3,5E+05	1,0E-01	1,1E+05

Wn	€/kWh (sg)	mc	€/kWh (gr)	€/kWh	cent€/kW	%load capaci
2,3E+08	2,39E-02	10,35937424	4,6E-02	2,17E-02	2,2E+00	53,2%
2,1E+08	2,39E-02	9,49752946	4,6E-02	2,17E-02	2,2E+00	48,7%
1,9E+08	2,39E-02	8,635684681	4,6E-02	2,17E-02	2,2E+00	44,3%
1,7E+08	2,39E-02	7,773839902	4,6E-02	2,17E-02	2,2E+00	39,9%
1,5E+08	2,39E-02	6,911995124	4,6E-02	2,17E-02	2,2E+00	35,5%
1,3E+08	2,39E-02	6,050150345	4,6E-02	2,17E-02	2,2E+00	31,1%
1,1E+08	2,39E-02	5,188305567	4,6E-02	2,17E-02	2,2E+00	26,6%
9,5E+07	2,39E-02	4,326460788	4,6E-02	2,17E-02	2,2E+00	22,2%
7,6E+07	2,39E-02	3,46461601	4,6E-02	2,17E-02	2,2E+00	17,8%
5,7E+07	2,39E-02	2,602771231	4,6E-02	2,17E-02	2,2E+00	13,4%
3,8E+07	2,39E-02	1,740926453	4,6E-02	2,17E-02	2,2E+00	8,9%
1,9E+07	2,39E-02	0,879081674	4,6E-02	2,17E-02	2,2E+00	4,5%
3,8E+05	2,39E-02	0,017236896	4,6E-02	2,17E-02	2,2E+00	0,1%

Appendix E: p48 Soto 4 operation data

10/05/2016

v15	codificacion1(v17)	v18	v19	hora	potencia
SRI4	NES	MWH	2016-05-10T2 PT60M	1	0
SRI4	NES	MWH	2016-05-10T2 PT60M	2	0
SRI4	NES	MWH	2016-05-10T2 PT60M	3	0
SRI4	NES	MWH	2016-05-10T2 PT60M	4	0
SRI4	NES	MWH	2016-05-10T2 PT60M	5	0
SRI4	NES	MWH	2016-05-10T2 PT60M	6	0
SRI4	NES	MWH	2016-05-10T2 PT60M	7	0
SRI4	NES	MWH	2016-05-10T2 PT60M	8	0
SRI4	NES	MWH	2016-05-10T2 PT60M	9	0
SRI4	NES	MWH	2016-05-10T2 PT60M	10	30
SRI4	NES	MWH	2016-05-10T2 PT60M	11	220
SRI4	NES	MWH	2016-05-10T2 PT60M	12	402
SRI4	NES	MWH	2016-05-10T2 PT60M	13	112
SRI4	NES	MWH	2016-05-10T2 PT60M	14	0
SRI4	NES	MWH	2016-05-10T2 PT60M	15	0
SRI4	NES	MWH	2016-05-10T2 PT60M	16	0
SRI4	NES	MWH	2016-05-10T2 PT60M	17	0
SRI4	NES	MWH	2016-05-10T2 PT60M	18	10
SRI4	NES	MWH	2016-05-10T2 PT60M	19	30
SRI4	NES	MWH	2016-05-10T2 PT60M	20	130
SRI4	NES	MWH	2016-05-10T2 PT60M	21	258,2
SRI4	NES	MWH	2016-05-10T2 PT60M	22	340
SRI4	NES	MWH	2016-05-10T2 PT60M	23	30
SRI4	NES	MWH	2016-05-10T2 PT60M	24	0

09/04/2016

v15	codificacion1(v17)	v18	v19	hora	potencia
SRI4	NES	MWH	2016-04-09T2 PT60M	1	0
SRI4	NES	MWH	2016-04-09T2 PT60M	2	0
SRI4	NES	MWH	2016-04-09T2 PT60M	3	0
SRI4	NES	MWH	2016-04-09T2 PT60M	4	0
SRI4	NES	MWH	2016-04-09T2 PT60M	5	0
SRI4	NES	MWH	2016-04-09T2 PT60M	6	40
SRI4	NES	MWH	2016-04-09T2 PT60M	7	90
SRI4	NES	MWH	2016-04-09T2 PT60M	8	227
SRI4	NES	MWH	2016-04-09T2 PT60M	9	194
SRI4	NES	MWH	2016-04-09T2 PT60M	10	260
SRI4	NES	MWH	2016-04-09T2 PT60M	11	240
SRI4	NES	MWH	2016-04-09T2 PT60M	12	330
SRI4	NES	MWH	2016-04-09T2 PT60M	13	300
SRI4	NES	MWH	2016-04-09T2 PT60M	14	90
SRI4	NES	MWH	2016-04-09T2 PT60M	15	0
SRI4	NES	MWH	2016-04-09T2 PT60M	16	214
SRI4	NES	MWH	2016-04-09T2 PT60M	17	0
SRI4	NES	MWH	2016-04-09T2 PT60M	18	0
SRI4	NES	MWH	2016-04-09T2 PT60M	19	0
SRI4	NES	MWH	2016-04-09T2 PT60M	20	0
SRI4	NES	MWH	2016-04-09T2 PT60M	21	0
SRI4	NES	MWH	2016-04-09T2 PT60M	22	0
SRI4	NES	MWH	2016-04-09T2 PT60M	23	0
SRI4	NES	MWH	2016-04-09T2 PT60M	24	0

21/03/2016

v15	codificacion1(v17	v18	v19	hora	potencia
SRI4	NES	MWH	2016-03-21T2 PT60M	1	0
SRI4	NES	MWH	2016-03-21T2 PT60M	2	0
SRI4	NES	MWH	2016-03-21T2 PT60M	3	0
SRI4	NES	MWH	2016-03-21T2 PT60M	4	0
SRI4	NES	MWH	2016-03-21T2 PT60M	5	0
SRI4	NES	MWH	2016-03-21T2 PT60M	6	0
SRI4	NES	MWH	2016-03-21T2 PT60M	7	30
SRI4	NES	MWH	2016-03-21T2 PT60M	8	130
SRI4	NES	MWH	2016-03-21T2 PT60M	9	283,3
SRI4	NES	MWH	2016-03-21T2 PT60M	10	298
SRI4	NES	MWH	2016-03-21T2 PT60M	11	309
SRI4	NES	MWH	2016-03-21T2 PT60M	12	334
SRI4	NES	MWH	2016-03-21T2 PT60M	13	120
SRI4	NES	MWH	2016-03-21T2 PT60M	14	70
SRI4	NES	MWH	2016-03-21T2 PT60M	15	70
SRI4	NES	MWH	2016-03-21T2 PT60M	16	70
SRI4	NES	MWH	2016-03-21T2 PT60M	17	70
SRI4	NES	MWH	2016-03-21T2 PT60M	18	70
SRI4	NES	MWH	2016-03-21T2 PT60M	19	120
SRI4	NES	MWH	2016-03-21T2 PT60M	20	188
SRI4	NES	MWH	2016-03-21T2 PT60M	21	192
SRI4	NES	MWH	2016-03-21T2 PT60M	22	60
SRI4	NES	MWH	2016-03-21T2 PT60M	23	0
SRI4	NES	MWH	2016-03-21T2 PT60M	24	0

16/02/2016

v15	codificacion1(v17	v18	v19	hora	potencia
SRI4	NES	MWH	2016-02-16T2 PT60M	1	0
SRI4	NES	MWH	2016-02-16T2 PT60M	2	0
SRI4	NES	MWH	2016-02-16T2 PT60M	3	0
SRI4	NES	MWH	2016-02-16T2 PT60M	4	0
SRI4	NES	MWH	2016-02-16T2 PT60M	5	0
SRI4	NES	MWH	2016-02-16T2 PT60M	6	0
SRI4	NES	MWH	2016-02-16T2 PT60M	7	30
SRI4	NES	MWH	2016-02-16T2 PT60M	8	130
SRI4	NES	MWH	2016-02-16T2 PT60M	9	282
SRI4	NES	MWH	2016-02-16T2 PT60M	10	320,7
SRI4	NES	MWH	2016-02-16T2 PT60M	11	302,7
SRI4	NES	MWH	2016-02-16T2 PT60M	12	297,7
SRI4	NES	MWH	2016-02-16T2 PT60M	13	216,7
SRI4	NES	MWH	2016-02-16T2 PT60M	14	194,9
SRI4	NES	MWH	2016-02-16T2 PT60M	15	216,2
SRI4	NES	MWH	2016-02-16T2 PT60M	16	215
SRI4	NES	MWH	2016-02-16T2 PT60M	17	215
SRI4	NES	MWH	2016-02-16T2 PT60M	18	215
SRI4	NES	MWH	2016-02-16T2 PT60M	19	278,8
SRI4	NES	MWH	2016-02-16T2 PT60M	20	328
SRI4	NES	MWH	2016-02-16T2 PT60M	21	332,5
SRI4	NES	MWH	2016-02-16T2 PT60M	22	284
SRI4	NES	MWH	2016-02-16T2 PT60M	23	60
SRI4	NES	MWH	2016-02-16T2 PT60M	24	0

31/01/2016

v15	codificacion1(v17)	v18	v19	hora	potencia
SRI4	NES	MWH	2016-01-31T2 PT60M	1	0
SRI4	NES	MWH	2016-01-31T2 PT60M	2	0
SRI4	NES	MWH	2016-01-31T2 PT60M	3	0
SRI4	NES	MWH	2016-01-31T2 PT60M	4	0
SRI4	NES	MWH	2016-01-31T2 PT60M	5	0
SRI4	NES	MWH	2016-01-31T2 PT60M	6	0
SRI4	NES	MWH	2016-01-31T2 PT60M	7	0
SRI4	NES	MWH	2016-01-31T2 PT60M	8	0
SRI4	NES	MWH	2016-01-31T2 PT60M	9	0
SRI4	NES	MWH	2016-01-31T2 PT60M	10	0
SRI4	NES	MWH	2016-01-31T2 PT60M	11	0
SRI4	NES	MWH	2016-01-31T2 PT60M	12	0
SRI4	NES	MWH	2016-01-31T2 PT60M	13	0
SRI4	NES	MWH	2016-01-31T2 PT60M	14	153
SRI4	NES	MWH	2016-01-31T2 PT60M	15	298
SRI4	NES	MWH	2016-01-31T2 PT60M	16	40
SRI4	NES	MWH	2016-01-31T2 PT60M	17	0
SRI4	NES	MWH	2016-01-31T2 PT60M	18	30
SRI4	NES	MWH	2016-01-31T2 PT60M	19	130
SRI4	NES	MWH	2016-01-31T2 PT60M	20	241,7
SRI4	NES	MWH	2016-01-31T2 PT60M	21	250
SRI4	NES	MWH	2016-01-31T2 PT60M	22	210
SRI4	NES	MWH	2016-01-31T2 PT60M	23	30
SRI4	NES	MWH	2016-01-31T2 PT60M	24	0

TOTAL POWER MWh	MEAN POWER/DAY
11263,4	2252,68
TOTAL HOURS	MEAN HOURS/DAY
62	12,4

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