



Dissertation Report

Master in Electrical Engineering

High Efficient Cogeneration Potential

GABRIEL NAPOLEON PESANTEZ PALACIOS

Leiria, September 2017

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Dissertation/Report developed under the supervision of Doctor Luís Neves, professor at the School of Technology and Management of the Polytechnic Institute of Leiria and co-supervision of Engineer Rodrigo Sempértegui, professor at the Faculty of Engineering of the University of Cuenca.

Leiria, September 2017

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Dedication

I dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents, Jaime and Fanny whose words of encouragement and push for tenacity ring in my ears

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Acknowledgements

I would like to thank to SENECYT, University of Cuenca and Polytechnic Institute of Leiria, for the support which allowed the development of the work here described.

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Resumo

Devido aos problemas atuais que surgem nas áreas ambiental, energética e económica, é necessário um aumento na eficiência no uso de combustível fóssil para reduzir a dependência dos hidrocarbonetos e melhorar a qualidade de vida. A cogeração é uma opção que visa alcançar esse objetivo, através do uso dos gases de escape e energia térmica dos sistemas de refrigeração de equipamentos térmicos, para fornecimento de energia térmica a outros processos, produzindo assim várias formas de energia final de forma combinada, habitualmente energia mecânica ou elétrica, e térmica.

O principal objetivo deste trabalho é avaliar o potencial de cogeração no setor industrial do Equador. Neste quadro, é apresentada uma breve introdução sobre o desenvolvimento da cogeração nas últimas décadas, e também uma classificação da cogeração de acordo com a sequência usada na produção de eletricidade e calor, e de acordo com o tipo de motor primário. O conceito de cogeração é analisado brevemente. É também apresentado um resumo dos estudos realizados como base para o trabalho, bem como a situação atual do mercado de eletricidade no Equador, sendo igualmente analisados os dados de consumo de energia publicados pelo INEC em 2011.

Com base nos fatores apresentados na bibliografia consultada, foi calculado o potencial de cogeração, nas atuais condições do mercado de eletricidade no Equador, usando-se as necessidades elétricas das indústrias como base para o cálculo. A análise económica foi realizada usando quatro tipos de equipamento e considerando os efeitos da altitude acima do nível do mar como um fator particularmente importante. Finalmente, foram analisadas duas indústrias específicas, um caso na indústria do papel e outro da indústria alimentar, como estudo de casos para avaliar a implementação da cogeração.

Palavras-chave: Cogeração, Uso Eficiente de Energia na Indústria

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Abstract

Due to the current problems that arise in the environmental, energy and economic areas, an increase of the efficiency of the use of fossil fuels is absolutely needed to reduce the dependence on hydrocarbons and improve the quality of life. Cogeneration is a supply option that aims to achieve this goal, cogeneration by using the exhaust gases, and thermal energy from cooling systems from thermal equipment to supply useful thermal energy to other processes, producing two useful energy streams combined, usually mechanical or electric and thermal energy at the same time.

The principal objective of this work is to evaluate the potential of cogeneration in the industrial sector of Ecuador. In this framework, a short introduction about the development of cogeneration over the last decades is presented, and a classification of cogeneration according to the sequence of production of electricity and heat, and according to the prime mover type is also presented. The concept of trigeneration is analyzed briefly. A summary of the studies used as a source for the present work as well as the current situation of the electricity market in Ecuador is also shown, being also analyzed the energy consumption data published by the INEC in 2011.

Using the factors presented in the consulted bibliography, the cogeneration potential was calculated, considering the current electricity market structure of Ecuador, and using the electrical needs of industries as a base-line. An economic analysis was carried out using as four types of equipment and considering the effects of altitude above sea level as an important parameter. Finally, two specific facilities, representing the paper and the food industry were used as case studies to evaluate the implementation of cogeneration.

Keywords: Cogeneration, Efficient Use of Energy in Industry.

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List of Acronyms

BHPP	Block Heat and Power Plant
BOE	Barrel of Oil Equivalent
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
CHPP	Combined Heat and Power Plant
CTS	Commerce, Trade, Services
DGEG	Portuguese Directorate Energy Association
EU	European Union
FLO	Full Load Operation
G&S	Gas & Steam
GT	Gas Turbine
ICE	Internal Combustion Engine
IDEA	International District Energy Association
IEA	International Energy Agency
INEC	National Institute of Statistics and Census
IRR	Internal Rate of Return
ISIC	International Standard Industrial Classification of all Economic Activities
LHV	Lower Heating Value
LPG	Liquid Petroleum Gas
MNI	Manufacturer's News Inc High Tech Database
NG	Natural Gas
NPV	Net Present Value
ORC	Organic Rankine Cycle
P/H	Power-to-Heat
PES	Primary Energy Saved
PURPA	Public Utility Regulatory Act
RES	Renewable Energy Source
ST	Steam Turbine
USA	United States of America
WHP	Waste Heat to Power

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1. INTRODUCTION

Generally, thermal energy is locally generated in industry from fossil fuels while electricity is obtained from the electric power grid. However, a significant part of electric energy is generated in thermal power plants which waste a large part of the input energy through exhaust gases and cooling systems. The waste of energy can be partly reduced by taking advantage of the heat in exhaust gases and cooling water of the prime movers to produce useful energy. This can be a way to raise the global efficiency of the system, reducing cost, pollution and other problems.

Figure 1.1 shows the energetic benefit produced by applying this concept called Cogeneration. The primary energy saved is 20% of the input energy when compared with the traditional system.

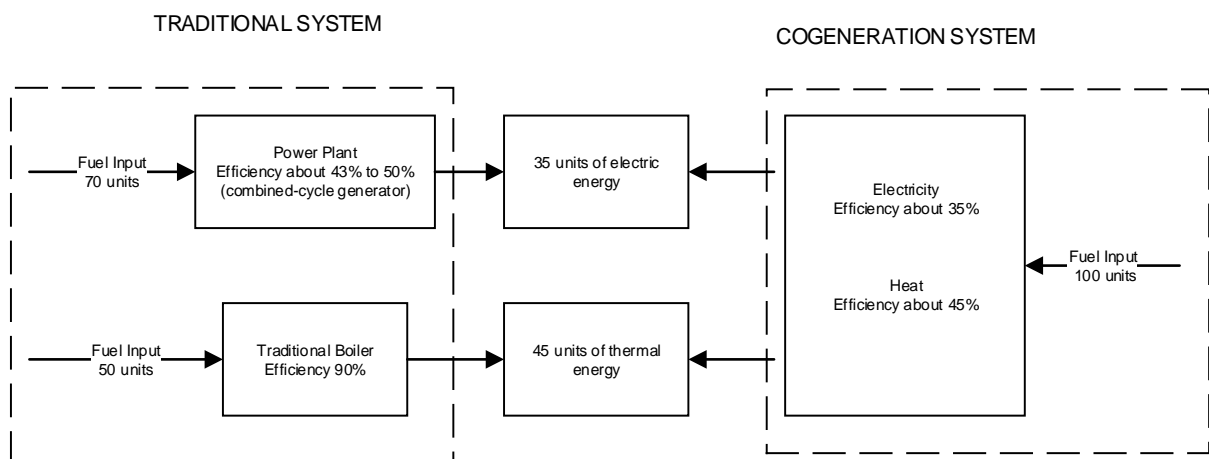


Figure 1. 1 Traditional System compared with a Cogeneration System

Based on this advantage produced by cogeneration as well as the continuous increment in fossil fuel price, many countries look at this alternative as a way to elevate efficiency as well as a move to clean energies. It is not possible to eradicate fossil fuel dependence at the moment, but cogeneration allows to reduce its negative impacts, begins a form to reduce primary energy consumption and greenhouse gases emissions, which can be economically attractive, thus getting acceptance for investment by the private sector.

Industrialized countries have already chosen this option in their energy policies, issuing programs and laws to promote cogeneration since the 1960s, but the remaining untapped potential for efficient cogeneration is still high. Figure 1.2 shows the cogeneration potential for the main industrialized countries.

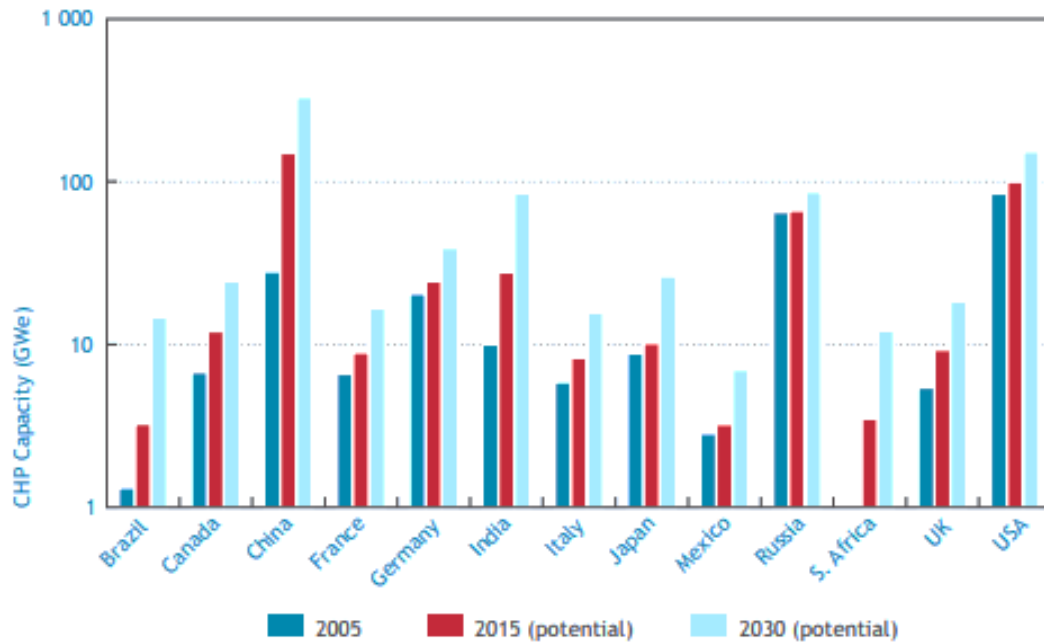


Figure 1. 2 Current and project CHP capacities under and accelerated CHP scenario, 2015 and 2030 (IEA, 2008, p. 21)

In this dissertation, the cogeneration potential of Ecuador is evaluated as an alternative way to promote a reduction in fossil fuel consumption and its related problems, increasing industrial efficiency. An economic analysis is also performed with the purpose of evaluating possible investment.

The document is organized in 5 chapters. Chapter one presents a brief introduction. Chapter two gives a first approach about cogeneration, dealing with topics such as definitions, classifications according to sequence, general prime movers, and finally different studies developed in other countries.

In chapter three, a review of the available information about the economic sector is carried out. Some considerations about the industrial sector are taken. Furthermore, thermal and electrical needs are established, and the procedure to evaluate cogeneration potential is presented. Finally, an economic analysis is carried out to evaluate the feasibility of cogeneration.

Chapter four presents an individual analysis for two industries in the country. The first industry manufactures paper products, and the second industry produces milk and natural juice products.

Conclusions obtained from this work are presented in chapter five, including a future work discussion.

2. STATE OF THE ART

2.1 Brief history of Cogeneration

Cogeneration started to be used more than 100 years ago, at first in Europe and from them expanding to the USA.

In the 1900s, the electric grid was small, unreliable and expensive, leading to the use of local electricity generation.

In this situation, cogeneration was an economic and practical form to fix the problem. Some industries applied this solution, and as an example, in the USA in 1900, cogeneration produced around half of the electric energy needed for industrial, when steam for the in industrial facilities, such as petroleum refineries, pulp and paper mills or chemical plants (Joseph A. Orlando, 1991, p. 2), industries where still today cogeneration is a natural option, proving good rentability.

The construction of a better and interconnected electric grid, is a reliable source of cheap electric energy, reduced the economic interest in cogeneration.

However, the petroleum crisis in the 1970s and 1980s, leading to a huge increment in the price of the fuel, led to a new interest in alternative forms to produce energy, and to generally increase efficiency, with a main purpose of ending or reducing the petroleum dependence of the USA and several other countries, namely in Europe.

The legislation needed for the introduction or expansion of cogeneration in some countries, considered significant differences when compared with traditional generation entities. In the USA, the Public Utility Regulatory Act (PURPA) introduced some benefits, eliminated constraints to the grid access for cogeneration and renewable based independent producers, a move followed by several European Countries. Later, the European Union prepared and started a Directive to promote the development of high efficiency cogeneration and clarifying the benefits to the potential investors (Joel Bluestein and Marie Lihn, n.d., p. 481).

2.2 Concepts

Consumption of thermal, mechanical and electrical energy is a common issue in almost every industry. At the same time, the traditional process to produce electricity from any fossil fuel combustion has important problems (Neil Petchers, 2003).

The principal problem in the conversion of heat to mechanic energy is due to losses of thermal energy, which are unavoidable. According to the second thermodynamic law, the best performance is around 50%, being the other 50% converted in heat lost in the exhaust gases and absorbed in the necessary cooling systems.

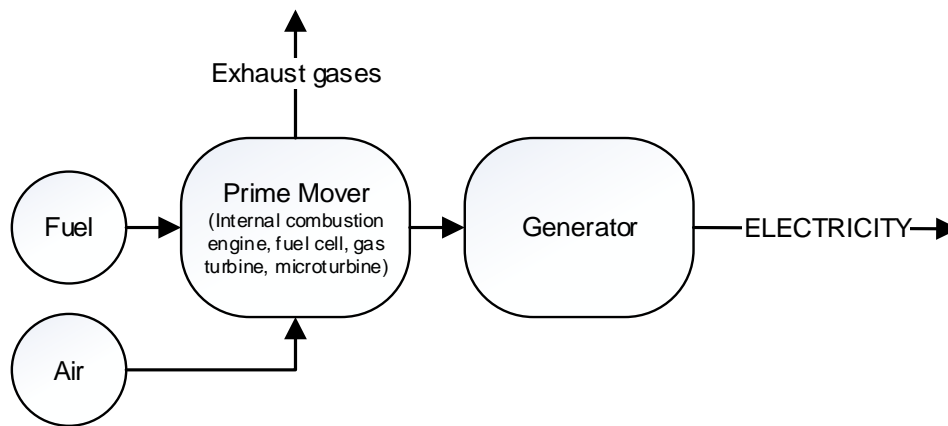


Figure 2. 1 Classic System to Produce Electrical Energy

Cogeneration or CHP (Combined Heat and Power) is defined as the sequential use of a primary energy stream to produce two useful energy forms-thermal and power. (Joseph A. Orlando, 1991, p. 4), in a way that increases the global efficiency when compared to the separated production of the two forms of useful energy.

The use of cogeneration elevates the global efficiency in the system, making it a good option for society as a whole, but, in a few cases, a natural and a traditional option in the industry, namely when the combination of a cheap fuel, like residual of the industrial process, and a significant demand for heat makes it very attractive to also locally produce electricity, as, e.g. in Pulp & Paper.

2.2.1 Classification of Cogeneration

According to the sequence in which heat and power are generated, which will strongly depend on the industrial process (figure 2.2), two types of cogeneration cycles are defined; topping and bottoming.

Topping Cycle

Topping cycle is the most common. In this type of cycle a fuel source is typically used to produce mechanical or electrical energy as a first main output, and the residual heat is used to feed a manufacturing process in the industry or the heating system of a building. These systems are characterized by the use of a fluid at high temperature and pressure,

as a means for energy transfer, being more effective when the end use processes have lower requirements for temperature and pressure. (Javier Miranda, 2010)

For industrial processes that have temperature requirements from 250 °C to 600 °C, the use of topping cycle is common, e.g. in the pulp & paper, beer, food, sugar, petroleum, textile and other industries.

The first element of the process, are the prime movers, typically one of the following technologies:

- Gas Turbine
- Steam Turbine
- Internal Combustion engine
- Combined Gas Turbine and Steam turbine (Combined cycle).

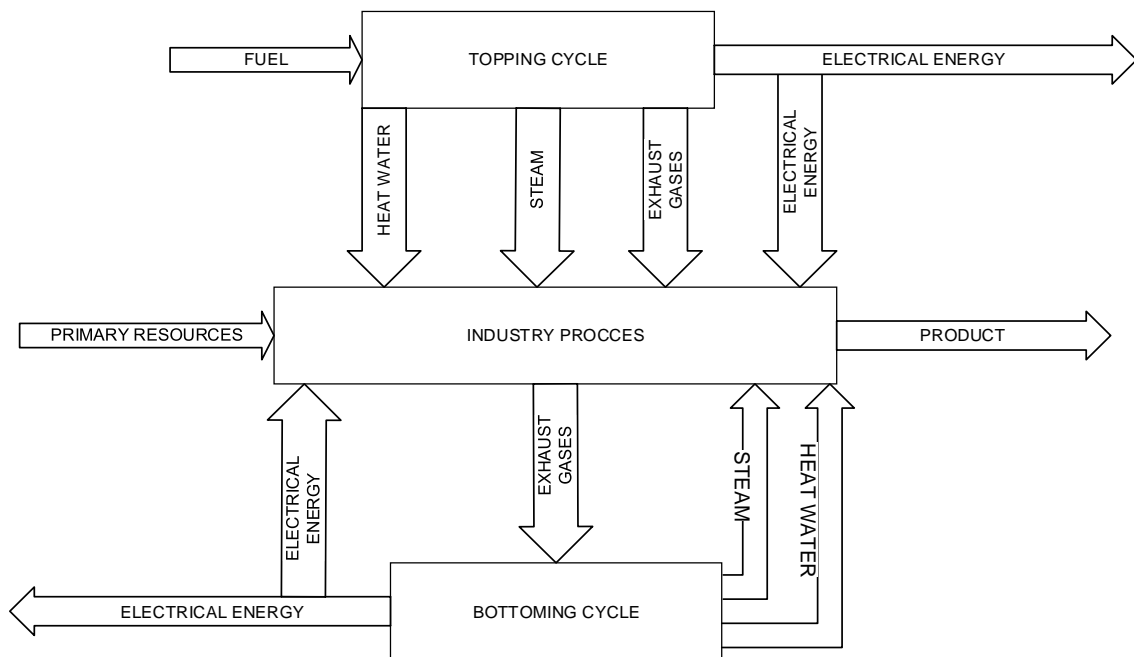


Figure 2. 2 Classification of Cogeneration Systems According to sequence production of Electricity and heat

Bottoming Cycle

As the opposite to topping cycle, in the bottoming cycle, the primary energy is used in the industrial process and the exhaust heat is recycled to produce electrical or mechanical energy in a second step. (Neil Petchers, 2003)

The bottoming cycle has been common use in cement, steel, glass, chemical, mining and other industries that have residual heat from around 250°C to 1200°C.

2.1.1 Prime Movers

This subsection describes the main technologies used for prime movers

Steam Turbine

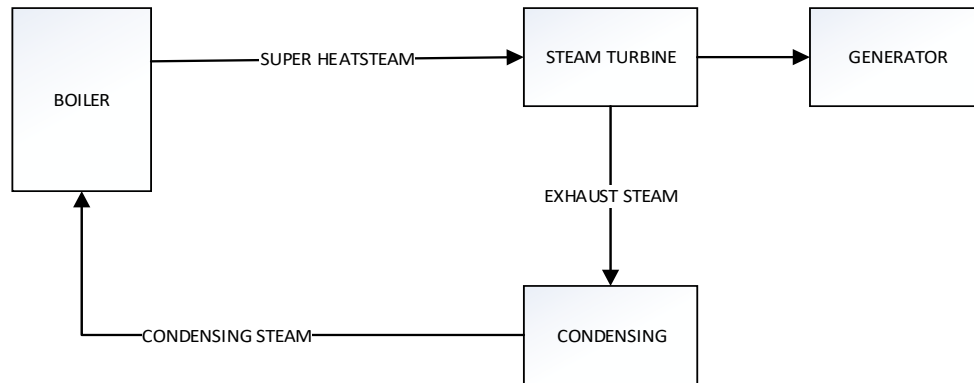


Figure 2. 3 Basic schematics of Steam Turbine

It is a system used for industries that need steam at medium and high pressure. Usually is formed by a boiler, steam turbine, the condenser and a generator.

This system is based on the Rankine cycle, and its performance depends on the maximum temperature supplied by the boiler as well as the minimum practical temperature of the working fluid at the input of the boiler. It uses steam pressure around 90 to 110 bars (9000 to 11000 kPa) bars and temperatures above 450°C

Fuel is burnt to heat the working fluid (water or steam) converting it to superheated steam at high pressure and temperature, which will be used to produce electrical or mechanical energy in a turbine. The steam loses temperature and pressure throughout this latter process, and the exhaust steam can then be used for an industrial process or re-introduced in the system again.

Steam turbine according to steam discharge can be classified in two categories:

Condensing Steam turbine. – In this case the steam has two exit points, in the first outlet the steam still has a medium to low pressure, and in a second outlet the remaining steam has already a low pressure and is normally carried to the condenser, where it will turn into water again, re-entering the cycle. This is shown in Figure 2.5

Back Pressure Steam Turbine. – In this case, all steam is used to produce rotation, and the exhaust steam at low pressure, in some cases lower than ambient pressure, is used for other industrial processes, not being immediately condensation.

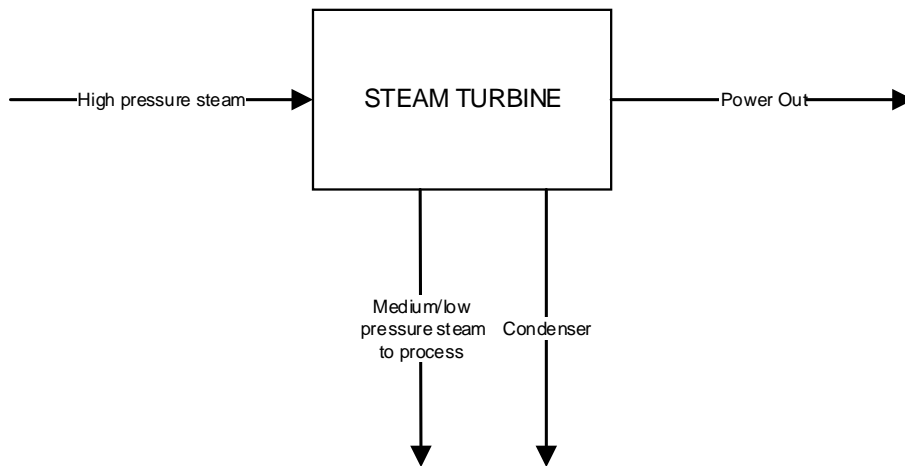


Figure 2. 4 Condensing Steam Turbine

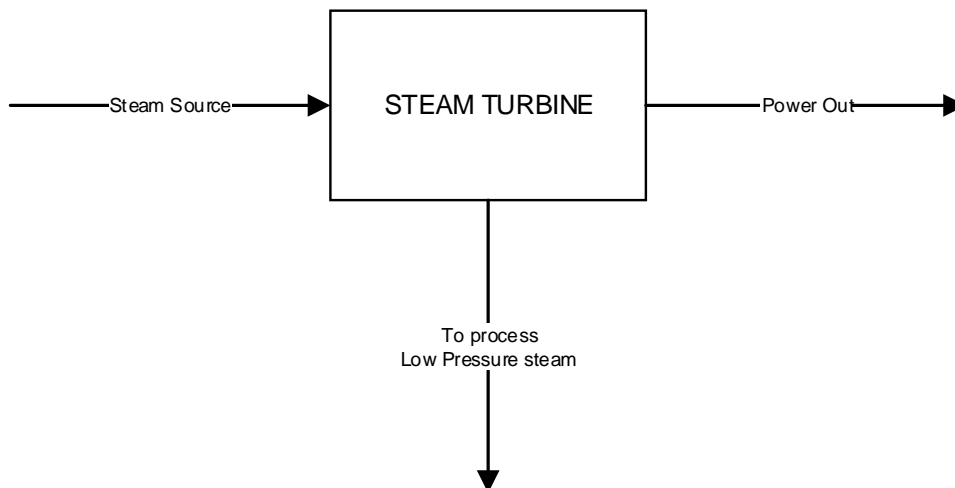


Figure 2. 5 Back Pressure Steam Turbine

Gas Turbine

This type of turbine burns gaseous or thin liquid fuels which can be injected at high pressure in the combustion chamber. It is generally formed by a compressor, combustion chamber and turbine.

The gas turbine functions according to the Brayton thermodynamic cycle, using a gas, normally air as a work fluid. The work fluid is compressed by an adiabatic process in the compressor, producing an increment of pressure (four to thirty times) and temperature.

The compressed and hot gas is introduced into the combustion chamber with the fuel, where the mixture is burned to produce high pressure and temperature exhaust gases at around 800°C to 1200°C. These gases are expanded in the turbine to produce work

that moves the compressor and an electric generator or mechanical parts (Javier Miranda, 2010, p. 31). Exhaust can then be used in other steps on the system or as an input to another system, e.g. a recovery boiler to produce steam.

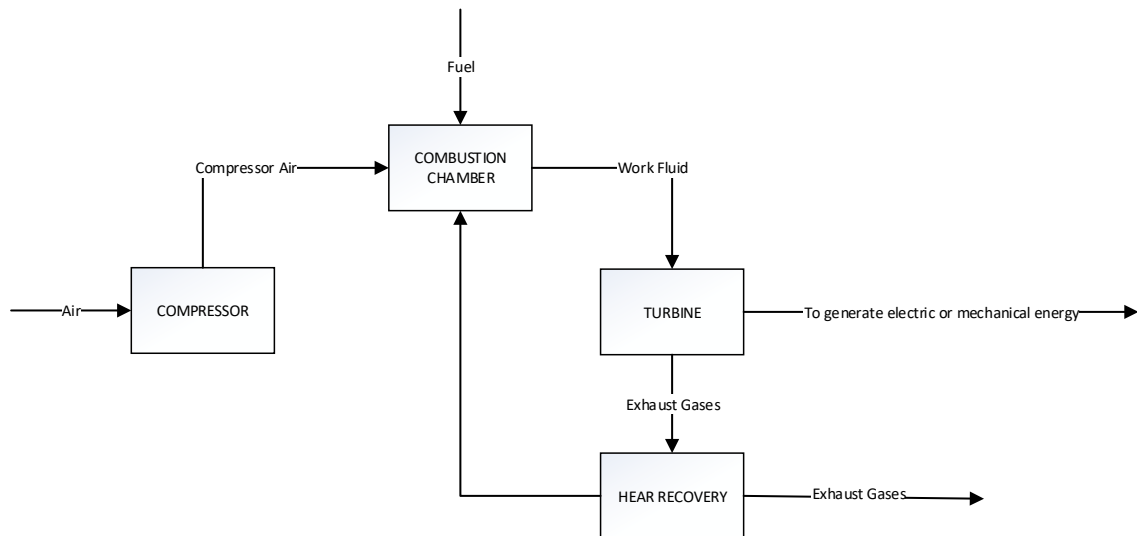


Figure 2. 6 Basic Schematic of Gas Turbine

Internal Combustion Engine

Internal combustion engines (ICE) used for power generation can be based on the Otto thermodynamic cycle (similar to the engines of gasoline powered cars) or on the Diesel thermodynamic cycles. The main difference of both is the ignition process, which in the former is caused by a spark produced electrically, and in the second results from the compression of the fuel. The ICE is capable of taking faster load changes than other technologies.

Compared to the above described thermodynamic cycles based on turbines, ICEs have a lower power-to-size ratio, being more limited in power ratings and increased maintenance costs. However, they present better efficiencies, namely the big, low speed, diesel engines derived from marine applications (Joseph A. Orlando, 1991).

As in other prime movers, the high temperature exhaust gases can be used by a recovery boiler to produce steam, eventually with additional fuel burning.

Hot water can be also produced through the use of a heat exchanger, both in the exhaust, or using the engine cooling fluid (radiator).

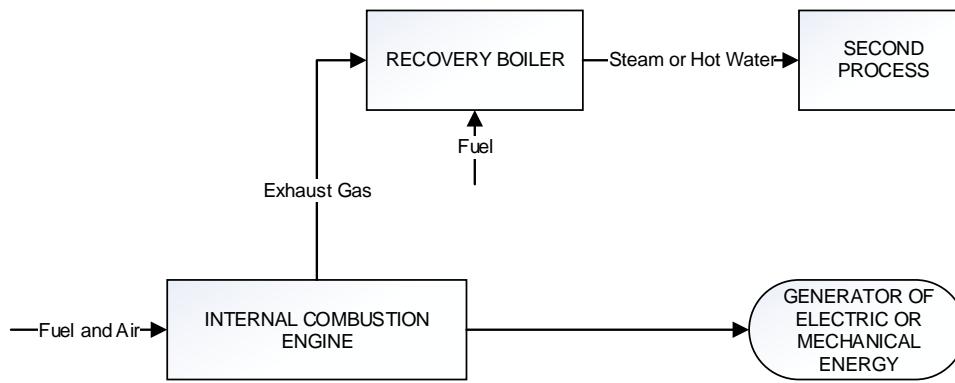


Figure 2. 7 Basic Schematic of Internal Combustion Engine

2.3. Trigeneration

The traditional system to produce cooling energy is formed by a compressor driven by an electrical motor in a configuration known as a heat pump. Although such a device has a very high efficiency, it needs electricity that is probably generated in thermal power plants with low efficiency. As an alternative, there are technologies that can use the residual heat for this purpose, namely the absorption and adsorption chillers. Generally, this technology present interesting alternative in industrial sector with important consumption of energy for cooling needs.

Using an absorption or adsorption chiller to convert part of the heat produced in a cogeneration plant into cooling energy makes what is called as a trigeneration system. The first part of this system produces mechanical energy, typically converted into electrical power. Secondly, the residual heat is used to produce steam or other useful form heat as for heating buildings. A third part uses the unused residual heat to produce cooling energy.

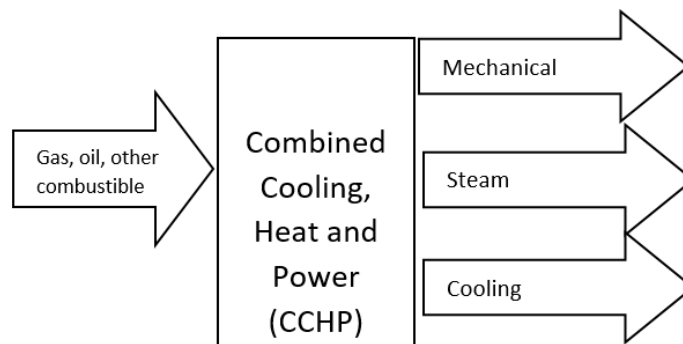


Figure 2. 8 Combined Cooling, Heat and Power

2.3.1 Absorption Chillers

Absorption chillers function based on a sorption process, where a liquid or solid sorbent absorbs refrigerant molecules and charges physically and/or chemically the process.

The absorption chiller cycle, starting with the evaporator, allows the refrigerant to evaporate and to be absorbed by the absorbent, a process that extracts heat from the building. The combined fluids then go to the generator, which is heated by the heat source in the form of gas or steam, driving the refrigerant back out of the absorbent. The refrigerant then goes to the condenser to be cooled back down to a liquid, while the absorbent is pumped back to the absorber. The cooled refrigerant is released through an expansion valve into the evaporator, and the cycle repeats itself. Typically, absorption chillers use either lithium bromide-water (LiBr/H₂O) or ammonia-water solution, the former used to produce chilling water at 5-7 °C, being the later more used for freezing temperatures. The LiBr/H₂O system uses lithium bromide as the absorber and water as the refrigerant. The ammonia-water system uses water as the absorber and ammonia as the refrigerant. (New Buildings Institute for the Southern California Gas Company, 1998, p. 3)

Generally, absorption chillers are classified according to the exposition to the heat source, as direct or indirect fired. Also, regarding the type of construction and number of phases, the absorption chillers can be built as single, double or triple stage.

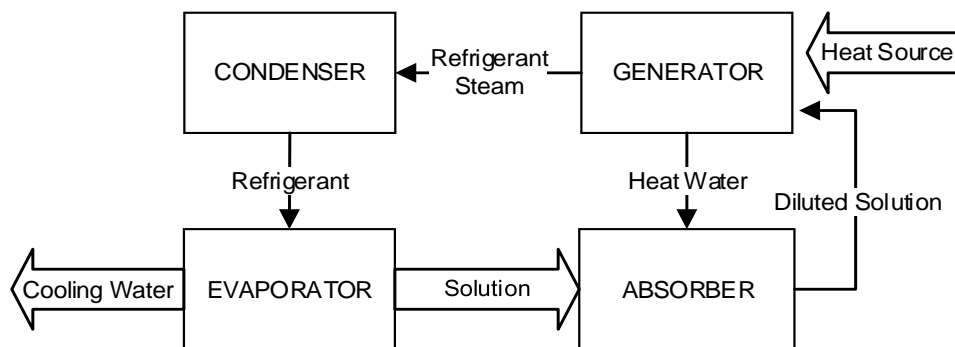


Figure 2. 9 Absorption Chiller Cycle

2.3.2 Adsorption Chillers

The adsorption chillers consist of two sorbent compartments, one evaporator and one condenser. While the sorbent in the first compartment is regenerated using hot water from the external heat source, e.g. a solar collector, the sorbent in the second compartment adsorbs the water steam entering from the evaporator. Compartment 2 must then be cooled in order to enable a continuous adsorption. Due to the low-pressure conditions in the evaporator, the refrigerant in the evaporator is transferred into the gas

phase by taking up the evaporation heat from the chilled water loop and thereby producing the useful "cold". If the sorption material in the adsorption compartment is saturated with water steam to a certain degree, the chambers are switched over in their function. The simple mechanical construction of adsorption chillers and their expected robustness is an advantage. A disadvantage is a comparatively large volume and weight. Furthermore, due to the small number of produced items, the price of adsorption chillers is currently still high.

2.4 Cogeneration Potential at a Country Level

This section presents different methodologies used in different countries to estimate the potential for cogeneration at a national level

Several countries have developed studies for estimating the potential for CHP as an autonomous initiative or as result of obligations imposed by pluri-national agreements and structures (e.g. E.U.). In the particular case of the European Union, a recent legislation mandated the member countries to assess the potential for high efficiency cogeneration according to specific rules.

The following cases describes the approaches used by different countries.

- USA
- Portugal
- Spain
- Germany

2.4.1 United States of America.

According to the study: "Combined Heat and Power Technical Potential in the United States" realized in 2016, three different types of CHP applications were included in the evaluation of technical potential (Anne Hampson et al., 2016), namely:

- Traditional Topping Cycle CHP (including cooling)
- Waste Heat to Power (WHP) CHP
- District Energy including CHP

The document only considered sites with a CHP Technical Potential of 50kW and higher. For all cases, the document makes the determination of the technical market potential, including the following steps:

- Identification of the target market where CHP provides a reasonable adjustment to the electric and thermal needs of the user.
- Quantification of the number and size distribution of target candidate facilities in each target application, that meet the electric and thermal load requirement for CHP.
- Estimation of the CHP potential in terms of MW electric capacity. The CHP potential is derived from the thermal and electric load for each site. The total CHP potential for each target market is then calculated by the amount of CHP potential in each size category.
- Subtraction of the existing CHP from the identified sites to determine the remaining technical potential.

Traditional Topping Cycle CHP

In this case, the selected cases were commercial buildings and industrial facilities that characteristically have sufficient and coincident thermal and electric loads for CHP. The next two tables show the industrial and commercial target market

Industrial Facility Type	Market Type
Food & Beverage	High Load Traditional
Textiles	High Load Traditional
Lumber and Wood	High Load Traditional
Furniture	High Load Traditional
Paper	High Load Traditional
Printing/Publishing	High Load Traditional
Chemicals	High Load Traditional
Petroleum Refining	High Load Traditional
Rubber/Miscellaneous Plastics	High Load Traditional
Stone/Clay/Glass	High Load Traditional
Primary Metals	High Load Traditional
Fabricated Metals	High Load Traditional
Machinery/Computer Equip.	High Load Traditional
Transportation Equip.	High Load Traditional
Instruments	High Load Traditional
Miscellaneous Manufacturing	High Load Traditional
Gas Processing	High Load Traditional

Table 2. 1 Industrial CHP Market (Anne Hampson et al., 2016)

Commercial Building Type	Market Type
Post Offices	Low Load Cooling
Big Box Retail	Low Load Cooling
Refrigerated Warehouses	High Load Cooling
Airports	Low Load Cooling
Waste Water Treatment Plants	High Load Traditional
Food Sales	Low Load Cooling
Restaurants	Low Load Cooling
Commercial Buildings	Low Load Cooling
Multi-Family Buildings	High Load Cooling
Hotels	High Load Cooling
Laundries	Low Load Traditional
Data Centers	High Load Cooling
Carwashes	Low Load Traditional
Movie Theaters	Low Load Cooling
Health Clubs	Low Load Traditional
Golf/Country Clubs	Low Load Traditional
Nursing Homes	High Load Cooling
Hospitals	High Load Cooling
Schools	Low Load Cooling
Colleges/Universities	High Load Cooling
Museums	Low Load Cooling
Government Facilities	Low Load Cooling
Prisons	High Load Traditional
Military	High Load Cooling

Table 2. 2 Commercial CHP Target Market (Anne Hampson et al., 2016)

For identifying potential targets, two primary sources were the Dun and Bradstreet (Hoover's) database and the Manufacturer's News (MNI) database.

For the identification of Traditional CHP target facilities, they use two different estimations.

- The first reference is the estimated electric load. To estimate the electric load, they considered consumption factors applied to the number of employees on the site or another similar characteristic, e.g. number of students, numbers of beds. For some cases, they have specific information about the site, e.g. consumption of equipment, production, or others (Anne Hampson et al., 2016).
- The second reference is the estimated thermal load, as it is important to properly size the CHP system for high thermal utilization. CHP systems should be sized to meet the base thermal loads of each site, as this makes the most efficient CHP system operation. An important indicator of the use of the produced energy is the power-to-heat ratio (P/H) of the facility which should be compared with the P/H ratio of a typical CHP system of identical size range. This factor indicates the ratio of electricity generation to thermal energy generation. (Anne Hampson et al., 2016)

Lastly, the work considered five varied sizes for CHP, according to the final application:

- 50kW – 500kW
- 500kW – 1MW
- 1 – 5MW
- 5 – 20MW
- >20MW CHP

These sizes were used for characterization purposes, especially in the economic analysis. (Anne Hampson et al., 2016)

Waste Heat to Power (Bottoming-Cycle CHP)

Anne Hampson et al. (2016) defined waste heat to power technologies as the ones that produce power by taking some form of waste heat as input energy, typically steam, and converting it into electricity. The industrial process equipment, e.g. a kiln or furnace, uses a fuel as energy input to a combustion process, and the heat rejected from the process is then captured and used for power production.

According to those authors, the determination of the waste heat to power cogeneration (WHP CHP) technical potential includes the following stages:

- Identification of target markets with available waste heat flow and where WHP CHP provides a reasonable fit to the electric needs of the user.
- Quantification of the number and size distribution of target markets.
- Estimation of WHP CHP potential in terms of MW electric capacity, derived from the waste heat quality and electric load for each site.

WHP CHP systems require a constant and ample supply of waste heat, because WHP CHP systems will typically run for most hours of a year. Typically, heavy industrial processes such as cement production, advanced oil extraction and refining, or paper, production, have the waste heat stream necessary to drive a WHP CHP system (Anne Hampson et al., 2016).

SIC	NAICS	Application Description
29	324	Total Petroleum and Coal Products
	324111	Petroleum Refining
	Other 324	Other Petroleum and Coal
33	331	Total Primary Metals
	331111	Primary Metals - Iron and Steel
	331511	Primary Metals - Iron Foundries
	Other 331	Primary Metals - Other
32	327	Total Non-Metallic Minerals
	3272	Non-Metallic Minerals - Glass
	327310	Non-Metallic Minerals - Cement
	327410	Non-Metallic Minerals - Lime
	Other 327	Non-Metallic Minerals - Other
13	211	Oil and Gas Extraction
28	325	Chemicals
12	212	Mining, except Oil and Gas
20	311	Food
26	322	Paper
35	333	Machinery
37	336	Transportation Equipment
24	321	Lumber and Wood
21	312	Beverage and Tobacco
27	323	Printing
38	334	Computer and Electronic Products
8221	611	Colleges/Universities
30	326	Rubber/Misc. Plastics
4222	493	Warehousing and Storage

Table 2. 3 WHP CHP Target Markets (Anne Hampson et al., 2016)

The methodology to estimate the WHP CHP system size used the temperature of the stack gas emissions minus an assumed minimum temperature of 122°C. This difference was then multiplied by the average specific heat for combustion of 0.26 BTU/lb (60.476 kJ/kg). The result was the energy content of the stack gas emissions (Anne Hampson et al., 2016).

Technical Potential for District Energy

Other market included in the analysis performed in the USA as a target market for CHP is district energy. It is a system that produces and delivers steam, hot water and/or chilled water, through dedicated underground piping networks, to heat or cool buildings in a

given area. Typical settings ideal for district energy are downtown urban areas, college campuses, military bases, airports, or hospital campuses. (Anne Hampson et al., 2016)

For this study, a dataset of existing district energy systems compiled by the International District Energy Association (IDEA) was used to identify district energy loops operating in the U.S. that have CHP and those that do not.

This system is unique from other energy markets because multiple legal entities are recipients of energy generated on the system. This may create a complex scenario on how trade the energy generated inside (Anne Hampson et al., 2016).

2.4.2 Portugal

The Portuguese Study used mainly public data or existing data supplied by the Portuguese Directorate General for Energy and Geology (DGEG), (ISR-UC and INESC Coimbra, 2016) namely:

- National energy Balance
- Consumption of electricity and of the main fuels by council area
- Survey on the consumption of energy in the domestic sector 2010.
- Statistics on construction and housing and censuses (National Statistics Institute).

Due to limitations in data, some simplifications were assumed in order to estimate consumption as accurately as possible.

The study looked for compliance with the Annex VII of Directive 2012/27/EU, aiming to identify:

- Heating and cooling demands, including
 - o Municipalities and urban area with a plot ratio of at least 0.3
 - o Industrial zones with a total annual heating and cooling consumption of more than 20GWh.
- Existing and planned district heating and cooling infrastructures.
- Potential heating and cooling supply points, including
 - o Electricity generation installations with a total annual electricity production of more than 20GWh.
 - o Waste incineration plants.
 - o Existing and planned cogeneration installations and district heating installations.

As part of this effort, the following hypotheses were therefore formulated in order to estimate residential consumption at the smallest possible administrative level:

- The application of the average consumption by dwelling and the number of dwellings in each civil parish.
- The application of statistics on consumption or sales by council area for all energy sources, with the exception of biomass.
- The application of the above and an estimation of the total consumption for space heating using statistics on heating systems possession by civil parish.
- Complementing the above statistics with estimations on cooling energy by using statistics on air conditioning possession.

For the case of the sectors of agriculture and fishing, industry and services, the mapping was made based on the administrative and geographic boundaries of the Portuguese municipalities, due to limitations in the data. (ISR-UC and INESC Coimbra, 2016)

The Annex VII of Directive 2012/27/EU also requires the mapping of industrial zones with a total annual heating and cooling consumption of more than 20GWh but the lack of data regarding the location and consumption of industrial areas prevented this determination.

For the case of the manufacturing industry, only the subsectors with greater cogeneration potential were considered, the selection being made based on the amount of heat consumed, and the typical share of heat that can be replaced, namely:

- Food, drink and tobacco
- Textiles
- Paper and paper products
- Chemical and plastics
- Wood and wooden articles
- Rubber

ISR-UC and INESC Coimbra (2016) used reference data from Eva-Maria Klotz et al., (2014), the consumption of heat at temperatures under 300°C, which are considered as replaceable by a source of residual heat, are distributed by the different sub-sectors of the manufacturing industry.

In the case of the services buildings, the use of cogeneration was considered in the sub-sectors where this option already meaningful, and whose total consumption accounts to around 40% of the consumption of electricity and thermal energy in buildings (INESC Coimbra, ISR-UC, 2016).

Food and tobacco	100.00 %
Car manufacturing	82.00 %
Quarries and mines	99.00 %
Glass and ceramic products	7.00 %
Raw chemicals	41.00 %
Rubber and plastic	100.00 %
Machinery	69.00 %
Processing of metals	19.00 %
Metal fabrication	30.00 %
Non-ferrous metals/foundries	32.00 %
Paper	100.00 %
Other chemicals	90.00 %
Processing of stone and soil	10.00 %
Rest of the economy	81.00 %

Table 2. 4 Proportion of the consumption of heat that can be supplied through a source residual heat (Eva-Maria Klotz et al., 2014)

The analysis was performed considering four sectors

- Agriculture and fisheries
- Industry
- Services
- Residential Sector

In the case of Agriculture and Fisheries sector an adequate profile of energy needs was created, namely the demand for heat and cooling. For such, the main energy sources as well as the consumption of primary energy in this sector. As the sector is very heterogeneous, only the locations where both the climate and soil are adequate for agriculture, were considered, such as Évora, Porto, Braga and Aveiro. These areas have a high density of agricultural holdings (ISR-UC and INESC Coimbra, 2016).

The consumption of the energy in this sector is mostly associated with the production of cooling. This represents 72% of the electricity consumption. The thermal needs represent 4.66% (ISR-UC and INESC Coimbra, 2016).

Regarding the industrial sector, the first important information gathered was the shares of different energy sources, being the most important, Natural Gas (NG), electricity, petroleum coke and Liquid Petroleum Gas (LPG). The consumption of diesel and regular gasoline is also relevant.

As for the case of agriculture, an attempt was made to identify areas with a consumption of 20GWh or more. In this sector the heating needs account for 67.1% of the energy consumption of the sector, and the cooling needs are around 4% of the electricity consumption (ISR-UC and INESC Coimbra, 2016).

The service sector is very heterogeneous, ranging from small commercial units to large shopping centers, large hospitals and also including office blocks, schools, sporting facilities, hotels, etc. The wide variation in terms of size and number of hours of use, makes the determination of the typical thermal needs by subsector, extremely difficult, not forgetting that, in general, terms this sector is influenced by the climate zone, purpose of the building and large population centers. The principal energy source are diesel, NG, electricity and regular gasoline. The use of fuel and PLG is low (ISR-UC and INESC Coimbra, 2016).

The heat and cooling needs represent 21.8% and 17.7% respectively, of the total energy consumption of the sector (ISR-UC and INESC Coimbra, 2016).

In the case of residential sector, Portugal has a very low consumption, namely regarding the consumption for heat and for space cooling. The main energy sources in this sector are electricity, LPG, solar thermal, gas, fuel and Biomass.

2.4.3 Spain

Spanish government ordered a “Full Assessment of the potential use of High-Efficient Cogeneration and Efficient District Heating and Cooling Systems”, also in compliance with the Annex VII of Directive 2012/27/EU (Ministry of Industry, Energy and Tourism of Spain, 2016).

As a first step to localize demand for energy, a database was created using as main source of information for each of the country’s municipalities, the Land Registry of Spain, completed with other sources for more singular centers. In parallel, a second database was prepared, including a set of consumer centres with high thermal demands that require different treatment (Ministry of Industry, Energy and Tourism of Spain, 2016), as represented in Table 2.5

On a second step, for facilitating analysis of the energy demand, consumers were separated in two major categories, as represented in Table 2.6, and described below:

- Direct Demand Centre's: This include demand centers with particularly relevant consumption that require individual treatment. In industrial level, they include all

the installations that have thermal demands essentially due to productive processes and not to heating and cooling systems.

- Indirect Demand Centre's: this refers to those points of the tertiary and industrial sector not included in the previous section.

Typology	Information
Hospital and healthcare centres	Number of Beds
	Geographical coordinates
	Area
Buildings belonging to the Central Government	Final energy savings
	Geographical coordinates
	Area
Prisons	Final energy savings
	Number of prisoners
	Geographical coordinates
Airports	Annual traffic
	Altitude
	Geographical coordinates
	CNAE (National Classification of Economic Activities) code
Major Industries	Annual CO ₂ emissions
	Cogeneration plant availability
	Characteristics of the cogeneration plant
	Availability of natural gas
Shopping Malls.	Final energy savings
	Area
	Geographical coordinates
	CNAE (National Classification of Economic Activities) code

Table 2. 5 Structure of the Demand Centre's (Ministry of Industry, Energy and Tourism of Spain, 2016)

INDIRECT CATEGORY	DIRECT CATEGORY
Demand	Demand
- Residential Sector	- Tertiary Sector
- Indirect Tertiary Sector	Hospitals
Offices	Prisons
Health	Institutional buildings
Sports	Airports
Shows	Shopping malls
Leisure and hospitality industry	- Industrial Sector
Cultural	
- Indirect Industrial Sector	

Table 2. 6 Classification of indirect and direct categories (Ministry of Industry, Energy and Tourism of Spain, 2016)

Additionally, supplementary classifications were made in accordance with climate variation, establishing three different climatic zones:

- North Atlantic
- Continental
- Mediterranean

This additional classification affects the residential and tertiary sector but not the industrial sector.

To characterize the thermal demand of each of the three defined sectors.

Residential Sector.

Regarding this sector, the Spanish study establishes that the energy demand is characterized as being very sensitive to the climatic zone where it is located, due to the heavy influence this has on the overall consumption of dwellings. Another factor is the type of dwelling mainly regarding the thermal insulation and the surfaces in contact with the outside.

The characterization of the residential sector in Spain used the SECH-SPAHOUSEC project (Ministry of Industry, Energy and Tourism of Spain, 2016).

The energy consumption is there divided between:

- Type of dwelling
 - o One-dwelling building
 - o Block
- Climate Zone
 - o North Atlantic
 - o Continental
 - o Mediterranean
- Breakdown of energy consumption by household
 - o Heating
 - o Hot Water
 - o Cooling
 - o Lighting + electricity
 - o Others (kitchen)

Tertiary Sector

This sector is still characterized by a thermal demand highly depending on atmospheric conditions.

There are centers with a relevant volume of energy consumption that require individual treatment. Consequently, the following have been considered as direct demand centers (Ministry of Industry, Energy and Tourism of Spain, 2016):

- Hospitals and health centers
- Buildings belonging to the Central Government (including prisons)

- Airports
- Shopping Malls

Table 2.7 summarizes the classification of each type of building regarding the type of demand.

Id	Use	Direct Demand	Indirect Demand
4	Offices	X	Ok
5	General trade	X	Ok
6	Market or Supermarket	X	Ok
7	Indoor sports; swimming pools	X	Ok
8	Auxiliary sports	X	Ok
9	Shows	X	Ok
10	Leisure and Hospitality industry with residence	X	Ok
11	Leisure and Hospitality industry without residence	X	Ok
12	Health and welfare with residence	Hospitals	Ok
13	Health and welfare without residence	Health Centers	Ok
14	Cultural and religious with residence	X	Ok
15	Cultural and religious without residence	X	Ok
16	Administrative	Central Government buildings	Ok
17	Prison	Prisons	Ok
39	Service Stations	X	Ok
40	Airports	Airports	Ok

Table 2. 7 Uses of the tertiary sector and classification into direct and indirect demand (Ministry of Industry, Energy and Tourism of Spain, 2016)

Thermal and cooling demand for the indirect type was determined from energy audits classifying these by climatic zone. The following data was obtained:

- Energy consumption by floor area unit (kWh/m²)
- Energy balance (%), divided into:
 - o Climate
 - o Office IT equipment
 - o Lighting
 - o Other equipment
 - o Hot Water
 - o Other

Industrial, Agricultural and Fishing sectors.

This sector has an appreciable variation in the energy consumption of the productive process, depending on the type of industry analysis. For this reason, an individualized treatment is required.

The sector was divided according to the type of demand, as Direct and Indirect, following the same direction followed in the tertiary sector.

Regarding Direct Demand, heat and cooling needs were determined, based on the records of CO₂ emissions in 2013. (Ministry of Industry, Energy and Tourism of Spain, 2016).

The process followed four steps, namely:

- Identification and characterization of the industries based on the registry of CO₂ emissions, using their total carbon dioxide emissions.
- Calculation of fuel consumption associated with CO₂ emissions.
- Calculation of overall fuel consumption by industrial sectors.

Additionally, cooling demand requirements in the industry are also very heterogeneous in terms of its use, and therefore complex to characterize. The most common uses regarding cooling services, are:

- Pharmaceutical industry.
- Food industry.
- Chemical Industry
- Beverage manufacturing industry.

To estimate the cooling demand in the aforementioned sectors, energy studies and audits in different industries, were consulted. The methodology followed included the following steps:

- Calculation of the electricity consumption of each industry.
- Calculation and standardisation of electricity consumption in each subsector.
- Direct cooling consumption in industries.

2.4.4 Germany

German also developed the study according to the Directive 2012/27/EU (Eva-Maria Klotz et al., 2014).

The first of the step study considered two sectors for realizing a Cost-Benefit analysis, namely:

- “Private Houses” and “Commerce, Trade, Services” (CTS).
- Industrial Generation

A Second step considered for both cases, the energy prices reference prognosis conditions 2014 - 2050. It is assuming that the law is the same in the period 2014 - 2050.

A third step considered uniform assumptions for calculation in both sectors, namely

- The applicable prices for varied sizes of cogeneration equipment were based of the 2012 Cogeneration act, and can be found in Table 2.8.
- Finally, the calculation was based on 14 typical CHPP and their capacity parameters, costs and revenue, as seen in Table 2.9.

Plants entitled to a surcharge	By Capacity	Cogeneration euro charge	Payment Period
Small CHPP up to and including $50kW_{el}$		5.41 cents/kWh	10 years or 30000 hours' full load operation (FLO); fixed payment possible for plants < 2kW
Small plants $>50kW_{el}$	$50-250kW_{el}$	4.00 cents/kWh	30000h FLO
	$>250kW_{el}$	2.40 cents/kWh	
New high-efficiency plants	$<50kW_{el}$	5.41 cents/kWh	30000h FLO (for plants in emissions trading, the surcharge rises as of 1 January 2013 by 0.3 cents/kWh)
	$50-250kW_{el}$	4.00 cents/kWh	
	$250kW_{el} - 2MW_{el}$	2.40 cents/kWh	
	$>2MW_{el}$	1.80 cents/kWh	
Modernised/ retrofitted high- efficiency plants ($>2MW_{el}$)	As for new high efficiency plants	As for new high-efficiency plants	Max. 30000h FLO (plants $<50kW_{el}$: max. 10 years or 30000h FLO)

Table 2. 8 2012 Cogeneration Act surcharge rates (Eva-Maria Klotz et al., 2014)

Private Households and CTS

This analysis considered individual properties in the private household and the CTS sector to compare the economic viability of various heat supply options, based on the net present value of typical applications (Eva-Maria Klotz et al., 2014).

The assumptions made, included:

- Heat pumps are considered only in new buildings.
- In the residential sector, four single-houses, and eight apartment blocks, was selected as a standard sample.
- Centralized building heating systems (Block Heat and Power Plant (BHPP)) are not considered for private households in apartment blocks.
- In the CTS sector, the economic viability of BHPP depends enormously on the specific building and the perspective taken.
- For the case of BHPP five parameters were calculated:
 - o A cogeneration Index, qualifying the solution (power production/heat production).
 - o Electrical efficiency rating.

- Specific investment sum.
- Specific fixed operating costs.
- Specific variable operating costs.
- In the CTS sector, the following three typical applications were considered:
 - Hospital with heat requirement of 2000 MWh/year
 - Office building with heat requirement of 100MWh/year.
 - Commercial undertaking with heat requirement of 2000 MWh/year.
- For one-family house, both air-water heat pumps and brine-water heat pumps are taken into account, both in combination with geothermal sources and solar water heaters.

Plant		BHPP 1	BHPP 2	BHPP 3	BHPP 4	BHPP 5	ST1	GT1	
Network level		Low Voltage				Medium Voltage			
Size	kW_{el}	1	5	50	500	200	5000	10000	
Investment cost incl. planning costs	EUR_{2013}/kW	150000	5300	2750	1300	850	1500	800	
Efficiency rating - electrical	%	26%	27%	34%	39%	42%	25%	30%	
Efficiency rating - thermal	%	66%	66%	57%	51%	48%	60%	55%	
Efficiency rating – overall	%	92%	93%	91%	90%	90%	85%	85%	
Calculation period	a	10	10	10	15	15	15	15	
Fixed operating costs	$EUR_{2013}/kW, a$	280	110	30	15	10	10	16	
Variable operating costs	EUR_{2013}/MWh	60	40	25	13	9	8	6	
Revenue from network user fees saved	EUR_{2013}/MWh	7	7	7	5	5	5	5	
Plants:		BHPP 6	G&S 1	G&S 2	G&S 3	G&S 4	Coal 1	Coal 2	
Network level		MV	High Voltage						
Size	kW_{el}	10000	20000	100000	200000	450000	400000	800000	
Investment cost incl. planning costs	EUR_{2013}/kW	700	1300	1300	1200	1100		1500	
Efficiency rating - electrical	%	46%	35%	45%	50%	55%	38%	45%	
Efficiency rating - thermal	%	42%	53%	43%	38%	33%	15%	15%	
Efficiency rating – overall	%	88%	88%	88%	88%	88%	53%	60%	
Calculation period	a	15	20	20	20	20	20	20	
Fixed operating costs	$EUR_{2013}/kW, a$	9	20	16	16	16	24	22	
Variable operating costs	EUR_{2013}/MWh	6	4	1.8	1.5	1.5	3	2.5	
Revenue from network user fees saved	EUR_{2013}/MWh	5	2	2	2	2	2	2	

Table 2. 9 CHP considered (Eva-Maria Klotz et al., 2014, p. 27)

Preliminary conclusions showed that

- For BHPP applications, large apartment block are large preferable to small residential buildings.
- In the CTS, the economic viability of BHPP depends enormously on the specific building.

Industrial Cogeneration

For industrial case in order to determine the economic viability of private generation in a CHPP, the electricity production costs were compared to the costs of purchasing electricity from third parties, which depend on the quantity purchased, the voltage level and the energy intensity, as well as the negotiating skills of the individual undertaking, which may vary within very wide margins. (Eva-Maria Klotz et al., 2014).

The analysis of industry allowed the identification of 6 typical applications of cogeneration, as shown in table 2.10 with their average characteristics.

Designation	Unit	Type of plant					
		BHPP			Steam turbine	Gas Turbine	Gas and Steam Turbine
Size of plant (el.)	kW/MW	50kW	500kW	2MW	5MW	10MW	20MW
Network Level	Voltage	LV	MV	MV	MV/HV	MV	HV
Application	-	Property cogeneration	Property Cogeneration,	DH, Industry	Industry	Industry	Industry, DH
Investment cost incl. planning costs	Euro2013/kW	2750	1300	850	1500	800	1300
Lifetime	years	10	10	15	15	15	15
Efficiency rating - electrical	%	34	39	42	25	30	35
Efficiency rating – thermal	%	57	51	48	60	55	53
Overall efficiency rating	%	91	90	90	85	85	88
Fixed operating costs	EUR ₂₀₁₃ /kW, a	30	15	10	10	16	20
Variable operating costs	EUR ₂₀₁₃ /MWh	20	13	9	8	6	4
Revenue from network user fees saved	EUR ₂₀₁₃ /MWh	7	5	5	5	5	2
Cogeneration Act cogeneration surcharge	Cent/kWh	5.41	3.34	32.64	2.43	2.27	2.18

Table 2. 10 Characteristics of CHPP Types of Plants (Eva-Maria Klotz et al., 2014)

For the analysis fuel taxes were not considered and the renewable energy sources (RES) act and cogeneration levies were disregarded (Eva-Maria Klotz et al., 2014).

In a following step, they analyzed the cost-effectiveness of trigeneration as a way to increase the utilization of CHPP in the summer. However, the high cost of absorption

chiller compared with conventional compression chiller, makes this option only viable in very specific situations, namely in the chemical industry or food industry.

The economic viability of Organic Rankine Cycle (ORC) plants was also assessed. This thermodynamic cycle uses organic substances with a low boiling point as its working thermofluid. The use of this fluid allows the use of heat sources between 90°C and 450°C, ORC use heat sources, namely ground heat, waste heat from use of biomass, industrial waste heat, etc. (Eva-Maria Klotz et al., 2014).

Analysis of the Potential

In the case of Private Households and CTS, 41 representative model towns were used, extrapolating the results for comparable towns (Eva-Maria Klotz et al., 2014). A distinction was made when determining potential between:

- The potential of settlement cogeneration (urban heating)
- The potential of property cogeneration.

Potential of heat line-bound cogeneration.

For the calculation of this value, a number of assumptions were made, namely:

- The heat requirement must be estimate or extrapolated for all towns.
- A large number of towns (model towns) was investigated in detail.
- These model towns were also clustered in order to take account of different settlement conditions
- The town clusters were analyzed in an economic viability calculation to determine the economic viability of district heating cogeneration.
- Finally, the information obtained from the clusters and model towns was used to extrapolate the settlement cogeneration potential for Germany.

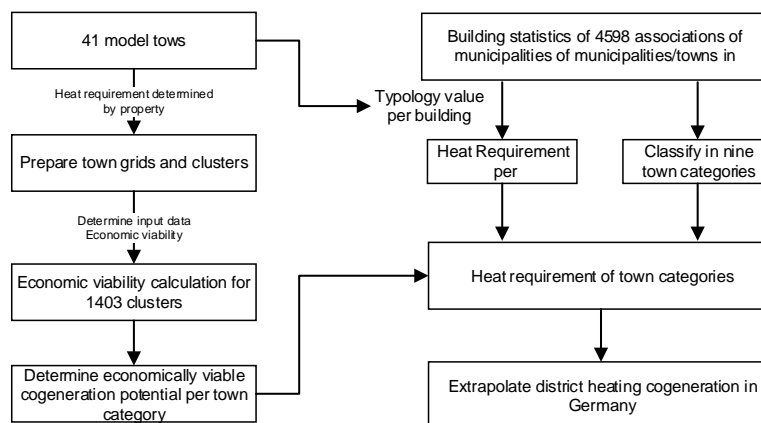


Figure 2. 10 Flowchart for determining district heating cogeneration potential (Eva-Maria Klotz et al., 2014)

In base of the number of inhabitants for km² of settlement area, nine categories were defined as shown in Table 2.11.

Category	Town Categories	Number
	Old Federal States:	
I	Municipalities with more than 350 000 inhabitants	14
II	Municipalities with 150 001 to 350 000 inhabitants	30
III	Municipalities with 80 001 to 150 000 inhabitants	48
IV	Municipalities with 50 001 to 80 000 inhabitants	79
V	Municipalities with 20 000 to 50 000 inhabitants	476
VI	Municipalities with 20 000 to 80 000 inhabitants in the periphery of a city.	22
	Total Old Federal States:	669
	New Federal States:	
VII	Municipalities with more than 80 000 inhabitants	14
VIII	Municipalities with 20 000 to 80 000 inhabitants	97
	Total new federal states:	111
	Total in Germany:	780
	Other:	
	Municipalities with fewer than 20 000 inhabitants	3818

Table 2. 11 Town Categories (Eva-Maria Klotz et al., 2014, p. 58)

The study of economic viability has been performed for each of the 1403 existing clusters in accordance with the following conditions:

- The distribution costs are divided in practice between the energy supply companies and customers, such that the customers pay an additional connection cost.
- Competitive distribution heat price is not differentiated by region for this investigation, in the case of buildings that have an annual heat requirement of 20-400GWh/y, but in the smaller buildings, the initial investment is bigger than in large buildings, in this the price of fuel are more relevant.
- Specific production cost depends primary on the CHPP used but also on insurance and administrative costs, distribution costs, costs of crowding out natural gas

Potential Cogeneration.

Based on the results of the model cost-benefit analysis is determinate the settlement cogeneration potential analysis.

The approach used the following operations, carried out to calculate a national potential (Eva-Maria Klotz et al., 2014), namely:

- The numerical data for economic viability testing of a property cogeneration solution, were formed and prepared based on town clustering and the results of the district heating cogeneration potential.
- Eight types of building/applications were considered.

- A full cost comparison based on the results of the cost-benefit analysis, order to determine the lowest heat requirement for each type of building.
- An economic viability test was carried out for each building.
- The size of the CHPP was calculated to obtain the cogeneration index, and the quantities of cogenerated heat and power were than determined for each property.
- The results were used to determine the potential of nine town categories.

Potential of Industrial Cogeneration, including use of waste heat.

This potential was determined for two cases. First a possible reference development was outlined (baseline scenario) and then a policy-driving variation was considered.

The baseline scenario essentially assumed that the basic conditions that apply at the date of the reported work will continue to apply.

According to (Eva-Maria Klotz et al., 2014) the potential is determined from:

- An analysis of heat requirement up to 300°C of the individual branches in 2012 which could theoretically be satisfied by cogeneration heat.
- An estimate of its development in the following decades.
- Assumptions on the technology used and their specific power as well as from the heat production conditions of the resultant cogenerated power production.

2.2.5 Comparison of the Presented Methodologies.

The four, methodologies reviewed in the previous sections followed different strategies, although aiming essentially the same output. Their differences come in part from the use of data sets of different natures, but a summary of their advantages and disadvantages is presented in Table 2.12.

2.3 Development of Cogeneration

During the last 25 years cogeneration experimented an important development worldwide, mainly due to the growing price of petroleum and numerous incentives promoted by the governments. These factors make cogeneration economically attractive for private investments.

Cogeneration contributes with a significant share of the global electric energy. An example of this are the USA represents around 8% of the total generated energy (Anne Hampson et al., 2016).

Spain had a considerable increase in cogeneration between 1993 and 2002, mainly due to economic incentives for cogeneration in the UE, and the high price of fossil fuels (Ministry of Industry, Energy and Tourism of Spain, 2016).

Considering the continuous increase in fuel prices, and the requirement to elevate general efficiency in the industry to reduce greenhouse emissions: cogeneration will be an interesting option in the future

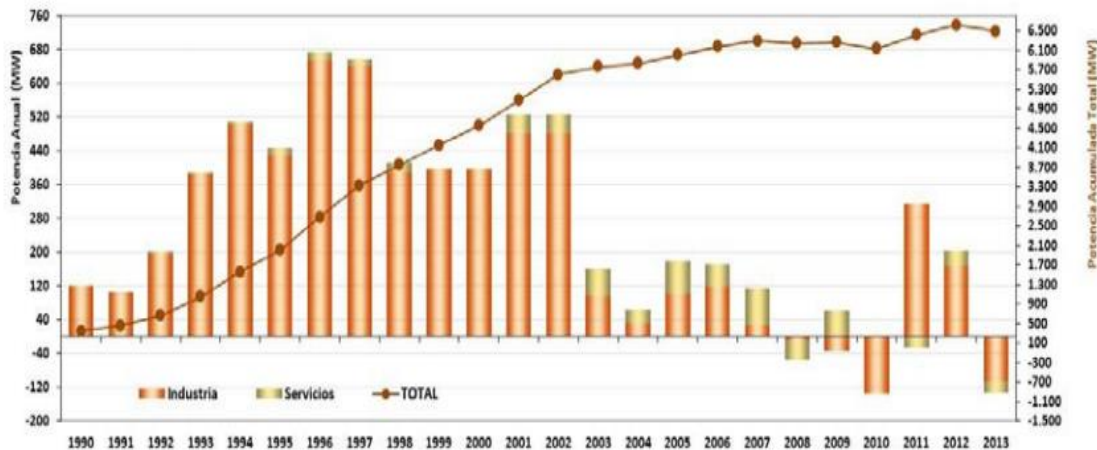


Figure 2. 11 Annual and cumulated installed power of cogeneration in Spain (Ministry of Industry, Energy and Tourism of Spain, 2016)

COUNTRY	STRENGTHS	WEAKNESSES
USA	Considered three different markets for CHP, allowing to a gathering of more exhaustive information	Requires a considerable database to evaluate potential.
PORTUGAL	Agriculture and fishing industries were considered as an isolated sector.	The cogeneration potential is restricted by the European directive definitions. The total reliance on external information limits the accuracy of the study.
SPAIN	A detailed work to obtain information was carried out	The cogeneration potential is restricted by the European directive definitions. The detail level in the study requires high resources and time of development.
GERMANY	The use of economic indicators to evaluate cogeneration produce realistic results.	The cogeneration potential is restricted by the European directive definitions. Significant requirements regarding historic data.

Table 2. 12 Comparative Table

2.4 Market Characteristics

The Electric market in Ecuador is a monopoly managed by the National Government. Rules for a free electric market do not exist, but some regulations for renewable energy generation were in operative until 2016, namely:

- CONELEC 001/09: introduction of cogeneration
- ARCONEL 004/15: introduction of renewable energy.
- CONELEC 003/11: determination of the price of generation and autogenerating projects

These regulations were operative until 2016. Today, clear rules for especial generation systems do not exist. For this reason, the implementation of new forms of alternative energies stopped.

3. METHODOLOGY

3.1 Objectives

The main objective of this chapter is to determine the cogeneration potential in the industrial sector. A technical and economic characterization is made, considering there are no regulations or laws available that will allow preferential market prices.

3.2 Ecuador Energy Outlook.

Ecuador is located in northeast South America. Its economy mainly depends on oil exploitation, followed by the services sector. There is also a small contribution from its industrial sector, focused primarily on meeting the basic needs of the population.

Although oil exploitation remains Ecuador's main economic activity, the country lacks the necessary industrial infrastructures needed to elaborate products from this raw material. Additional oil refineries have not been built accordingly, to meet the needs of the country, and so as the difference between the internal consumption of fuel and production increases, the government is forced to import the growing difference.

Table 3.1 illustrates the importation of energy to Ecuador, and Figure 3.1 shows the difference between supply and demand.

The main problem is clearly the consumption of regular gasoline and diesel. The consumption of fuel by sector is an important indicator and Figure 3.2, indicates the consumption of different fuels.

ITEM YEAR	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Electricity	1018	1069	974	534	310	695	541	803	148	411	519
LPG	4796	5369	5649	6499	6222	6083	6294	6522	6038	3409	7191
Gasolines	4138	5374	5496	6928	5542	8355	10838	11250	12691	14275	17737
Kerosene/Jet Fuel					67	78	53			77	248
Diesel Oil	5540	8122	11325	11845	11160	14460	19930	15089	17023	20841	24970
Fuel Oil	915	2551	2858	3207	3647	2312	3229	3663	2804	2157	1079
Total Secondaries	16407	22485	26302	29013	26948	31983	40885	37327	38704	41170	51744

Table 3. 1 Energy Import (kBOE) (David Delgado, 2015)

Also noteworthy is the consumption of electric energy. In recent years, the government has made a significant investment in this sector, which has contributed to a decrease in the dependency of thermal power plants, reducing fuel consumption and gas emissions. Figure 3.3 illustrates the contribution of each type of power plant to the electric grid.

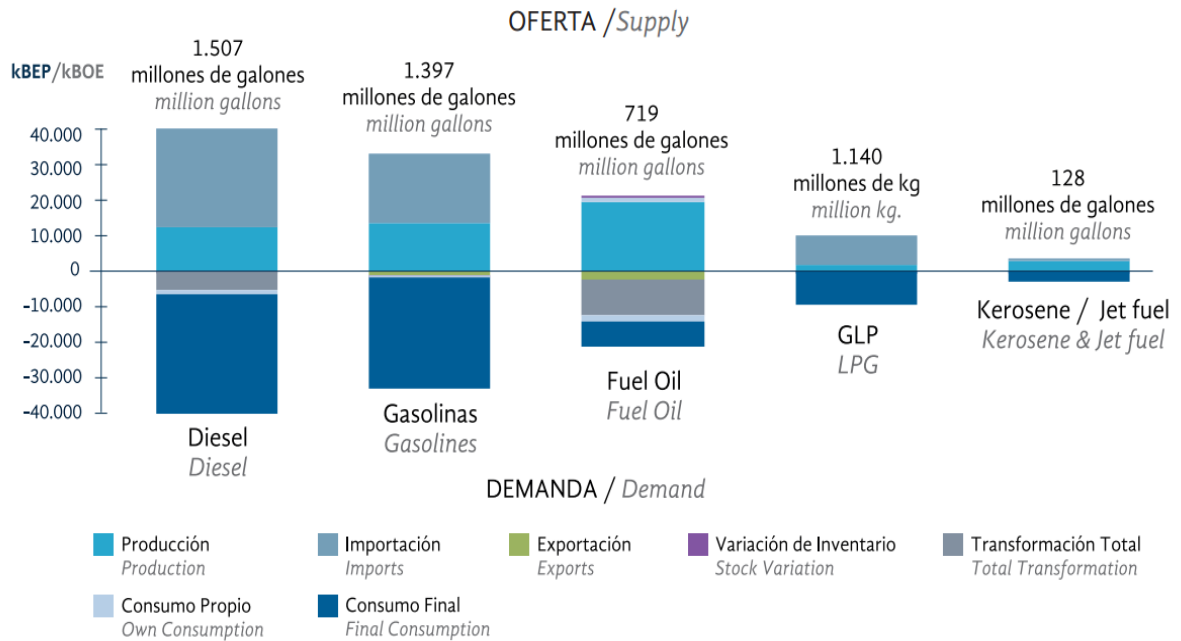


Figure 3. 1 Comparison of Supply and Demand of Oil Products (David Delgado, 2015, p. 24)

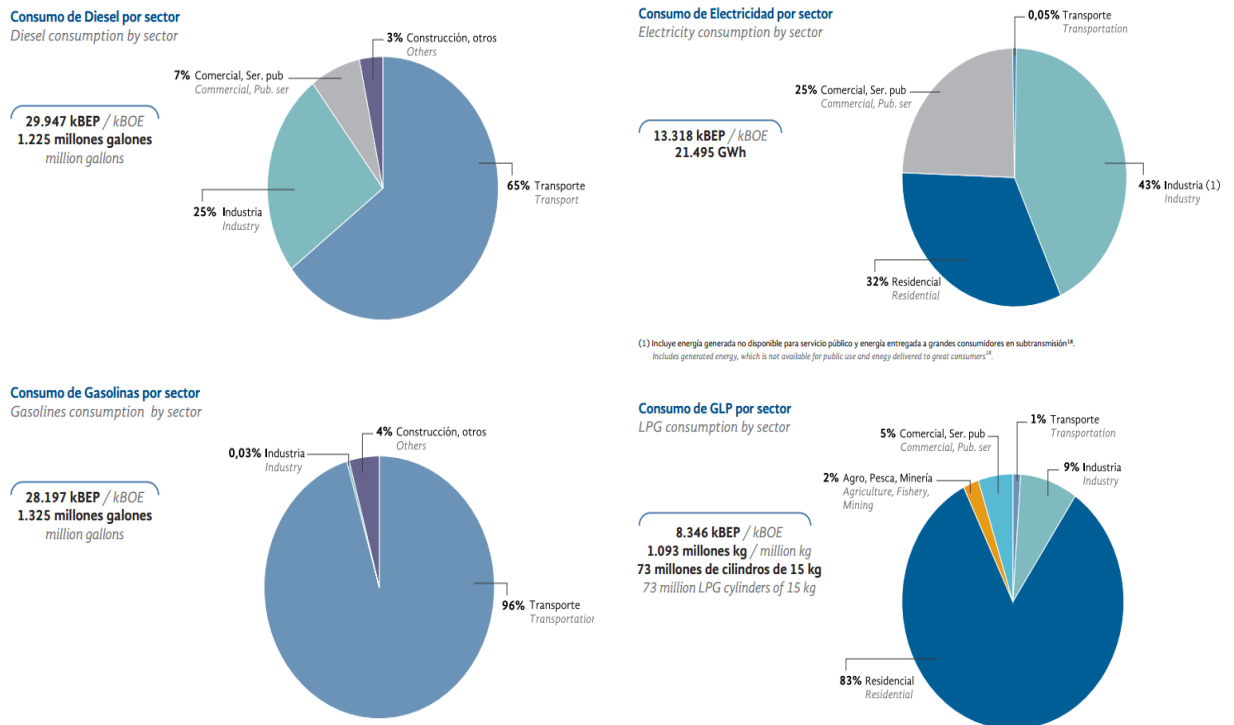


Figure 3. 2 Economic sectors' energy consumption by energy sources (David Delgado, 2015, pp. 30–31)

Considering these facts, and focusing on the study of the industrial sector as our main objective, the possibility of improving energy efficiency is presented, leading to an improvement in the economy of industries by reducing operating costs as well as fuel consumption, and therefore also reduction of the emission of greenhouse gases.

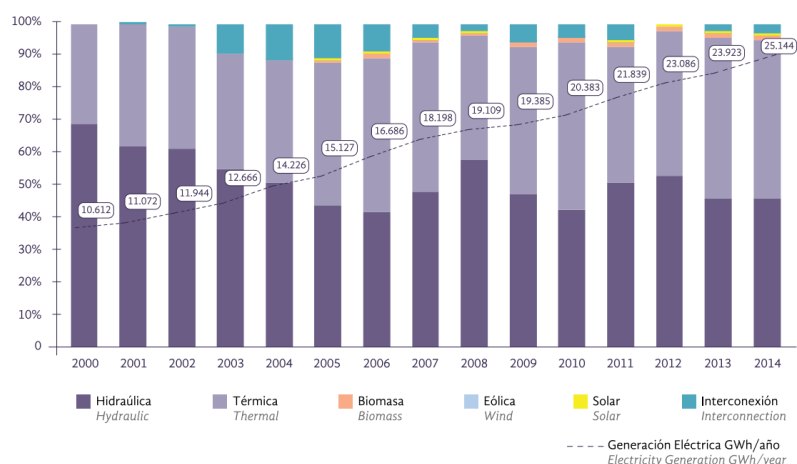


Figure 3.3 Structure of Electricity supply (David Delgado, 2015, p. 69)

3.3 Concepts and Data Requirements

The “National Institute of Statistics and Census” (INEC) 2011 database was used as a starting point for this chapter. The database is provided in the “International Standard Industrial Classification of all Economy Activities” (ISIC) Rev. 4 format of the UN, which is used to catalog and divide economic activities. ISIC ranks in 21 sections according to the economic activity of the industry which is shown in Table 3.2.

SECTION	DIVISIONS	DESCRIPTION
A	01-09	Agriculture, forestry and fishing
B	05-09	Mining and quarrying
C	10-33	Manufacturing
D	35	Electricity, gas, steam and air conditioning supply
E	36-39	Water supply; sewerage, waste management and remediation activities
F	41-43	Construction
G	45-47	Wholesale and retail trade; repair of motor vehicles and motorcycles
H	49-53	Transportation and storage
I	55-56	Accommodation and food service activities
J	58-63	Information and communication
K	64-66	Financial and insurance activities
L	68	Real estate activities
M	69-75	Professional, scientific and technical activities
N	77-82	Administrative and support service activities
O	84	Public Administration and defense; compulsory social security
P	85	Education
Q	86-88	Human health and social work activities
R	90-93	Art, entertainment and recreation
S	94-96	Other service activities
T	97-98	Activities of households as employers; undifferentiated goods-and services-producing activities of households for own use
U	99	Activities of extraterritorial organizations and bodies

Table 3.2 Individual categories of ISIC (United Nations, 2008, p. 43)

Other terms used in this chapter include:

The Lower Heating Value (LHV), used for the calculation in order to determine the energy contained in each fuel. (presented in Appendix I)

Economic parameters such as NPV, IRR, cash flow and Payback, used to evaluate the different proposed cases and to determine their viability.

3.4 Demand Estimation.

An estimation of the demand in the industrial sector is based on the database provided by the INEC in 2011, registering 2023 industries which are divided into 9 categories according to the ISIC classification

- Mining and quarrying. (B)
- Manufactured Industry. (C)
- Electricity, gas, steam and air conditioning supply. (D)
- Water Supply; sewage, waste management and remediation activities. (E)
- Construction (F)
- Transportation and Storage(H)
- Accommodation and Food Service Activities. (I)
- Information and Communication. (J)
- Human Health and Social work activities. (Q)

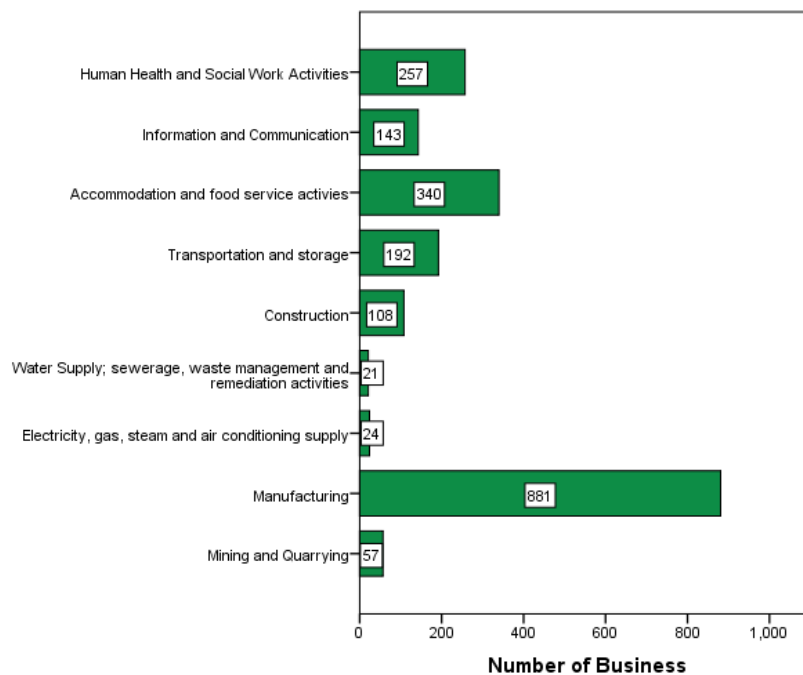


Figure 3. 4 Division of Business according to Principal Activity

Figure 3.4 shows the number of business in all categories. The activities that have a potential for cogeneration are, “Manufacturing”, “Mining and Quarrying”,

“Accommodation and food service activities”, “Human Health” and “Social Work Activities”. The “Information and Communication” sector has a potential if the production of cooling to use in the climatization of servers and electronic equipment gets enough attention, but it is not analyzed in this work.

It is true that sectors of “Accommodation and food service activities”, “Human Health and Social Work Activities” have shown high potential of cogeneration in other studies consulted about this topic, but these were not considered in this work due to lack of information about these sectors and to the specific characteristics of the climate in Ecuador. Needs of heating for climatization do not exist in the most part of the country because it, presents good conditions for human life. In the case of “Human Health and Social Work Activities” the use of heat is also important for sterilization of medical instruments and to wash, dry and other activities, but the information required in this sector is not available.

Sectors “Manufacturing” and “Mining and Quarrying” were considered for an analysis of potential, from which 883 industries were identified and, according to their characteristics, may have cogeneration potential. Very few industries from Sector “Mining and Quarrying” were taken into consideration since mining in the country has not yet been technically developed (except oil extraction) and is mostly carried out by machinery such as trucks, excavators and so on.

In total 883 industries were selected, being divided into 18 sub-sectors as shown in Figure 3.5.

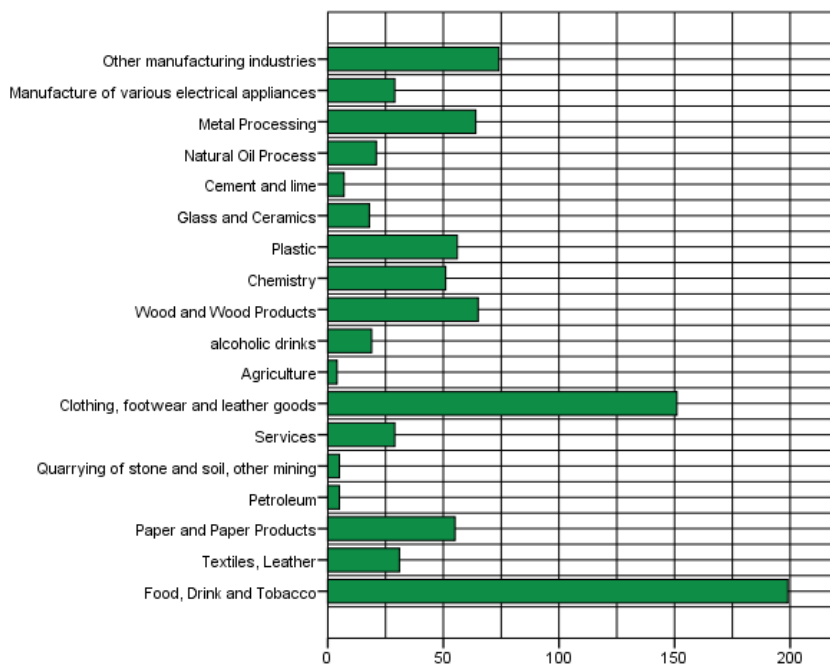


Figure 3. 5 Sub-sector of manufacturing business

The sectors with the highest industrial concentration are “clothing, footwear and leather” goods as well as “food, drink and tobacco”.

Based on this selection and considering the information obtained from the INEC, the most relevant information from each industry was selected and accounted, namely:

- Consumption of liquid fuels.
- Consumption of solid fuels.
- Consumption of LPG in cubic meters or for number and capacity of cylinders.
- Consumption of electricity in a month.
- Number of days worked for year
- A division considering the size of business

It should be noted that for this study, it was considered that 87 and 92 octane gasoline is only used in different vehicles used in transportation.

Heat and Electrical Requirements

In order to calculate the required thermal requirements in each industry, the LHV of each fuel is multiplied by the quantity consumed. Within the database, the fuel was divided into three types, solid, liquid and gas which are maintained and therefore the following hypotheses were made:

- Hypothesis I: A number of hours of operation per day were based on the size of the industry
 - o Small 8 hours to day
 - o Medium 16 hours to day
 - o Big 24 hours to day
- Hypothesis II: The annual consumption was determined provided that only the average monthly consumption of LPG in cubic meters according to the number of working hours was available.
- Hypothesis III: A similar procedure to Hypothesis 2 determined the annual consumption of electrical energy,
- Hypothesis IV: It was assumed that both the climate and the production cycle of the industrial plants remain constant throughout the year.

As a result, the energy required for each sub-sector can be seen in Figures 3.6 and 3.7. It is clear that the petroleum subsector requires a lot of thermal and electrical energy in order to be considered as a target, which is the same case with the food, drink and tobacco sector becoming important points for analysis. Finally, the consumption of thermal energy for the "cement-lime" sub-sector is considerable, although the

consumption of electric energy is not as relevant, which makes it a point of special interest for the analysis.

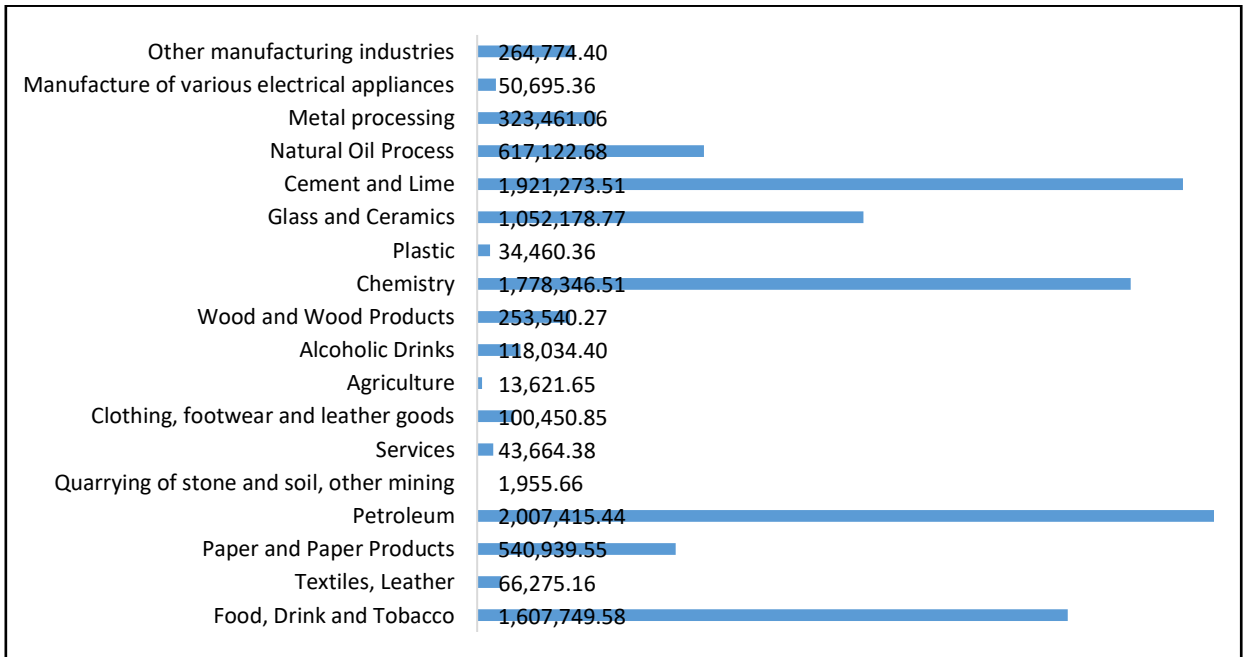


Figure 3. 6 Heat requirement in 2011 (MWh)

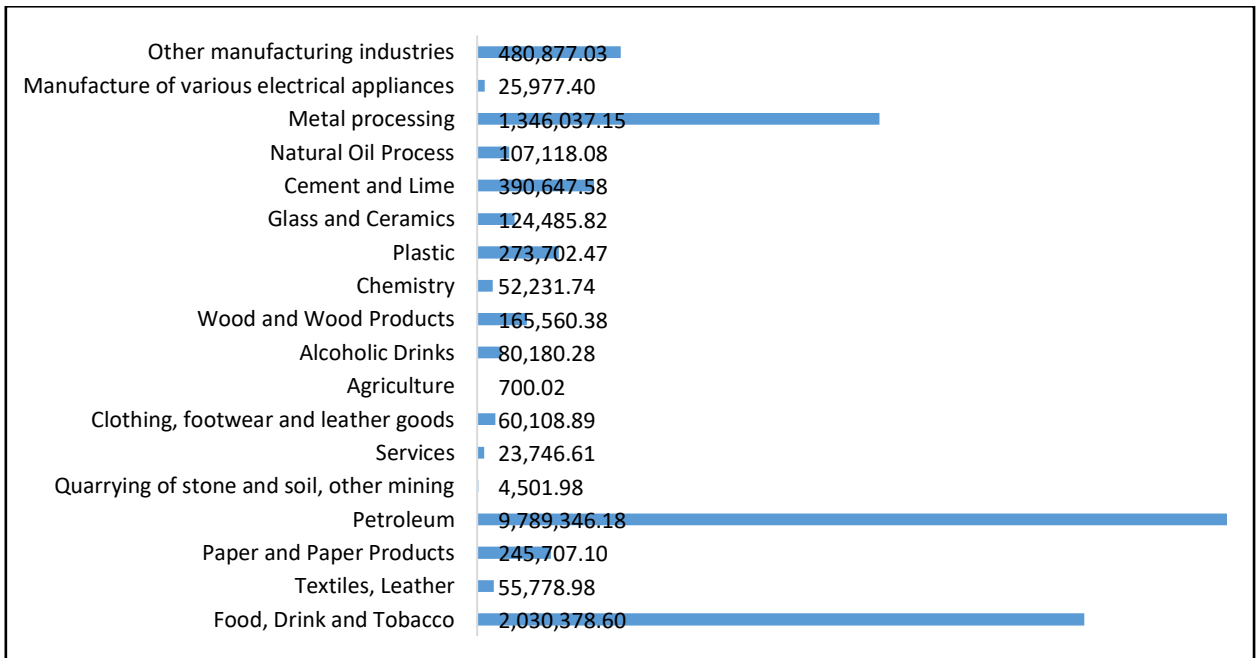


Figure 3. 7 Electrical Requirement in 2011 (MWh)

3.5. Thermal and Electric energy production estimation

3.5.1 General Issues

A detailed and accurate estimation of the technical potential of cogeneration requires strong support from the government as well as control institutions. A great

amount of time and financial support in order to cover the logistics necessary to obtain the data is also unavoidable.

Contrarily to situations in other countries, cogeneration in Ecuador has yet to be developed, so there is no reference database to solidify an accurate study.

Based on this situation, it has become necessary to research all existing literature on the topic. A study conducted in Germany in 2014 (Eva-Maria Klotz et al., 2014, p. 92) proved to be helpful in determining the quantity of useful thermal energy (<300 ° C) for each sub-sector.

#	Sub-sector	<300°C
1	Food, Drink and Tobacco	100.00%
2	Textiles, Leather	40.00%
3	Paper and Paper Products	100.00%
4	Petroleum	40.00%
5	Quarrying of stone and soil, other mining	98.00%
6	Services	0.00%
7	Clothing, footwear and leather goods	40.00%
8	Agriculture	4.66%
9	Alcoholic Drinks	40.00%
10	Wood and Wood Products	40.00%
11	Chemistry	40.00%
12	Plastic	100.00%
13	Glass and Ceramics	7.00%
14	Cement and Lime	90.00%
15	Natural Oil Process	40.00%
16	Metal processing	17.00%
17	Manufacture of various electrical appliances	66.00%
18	Other manufacturing industries	50.00%

Table 3. 3 Percentage to Heat used for Cogeneration (Eva-Maria Klotz et al., 2014), (ISR-UC and INESC Coimbra, 2016)

This is shown in table 3.3 which illustrates the different values and, according to the German study and the fact that the classification is unequal, it was considered that sub-sectors # 2,7,9,10,15 have a percentage equal to sub-sector # 11. A 0% is considered for sub-sector # 6, due to the fact that this type of sub-sector concentrates more on providing different services of a different nature. Only 4.66% can be considered for Sub-sector #8 Finally, in the case of sub-sector # 18, only 50% is considered due to the fact that the development of the industry in the country is inferior to that in Germany.

In order to obtain the electrical energy of cogeneration, the following equation is used which relates thermal and electrical energy of cogeneration:

$$R = \frac{H_{CHP}}{E_{CHP}}$$

However, due to a similar lack of information, as previously mentioned in Point 3.5, it is necessary to resort to further investigation. A study carried out in the USA in 2016 was

reviewed, notably in Appendix B, where a database chart can be used to determine the electricity from cogeneration (Anne Hampson et al., 2016, sec. Appendix B). A selection of different ratios for each sub-sector was established

#	Sub-sector	RATIO HEAT/ POWER
1	Food, Drink and Tobacco	2.00
2	Textiles, Leather	1.50
3	Paper and Paper Products	3.50
4	Petroleum	3.93
5	Quarrying of stone and soil, other mining	2.00
6	Services	0.00
7	Clothing, footwear and leather goods	2.50
8	Agriculture	1.51
9	Alcoholic Drinks	2.50
10	Wood and Wood Products	1.88
11	Chemistry	1.88
12	Plastic	1.88
13	Glass and Ceramics	1.74
14	Cement and Lime	2.50
15	Natural Oil Process	1.51
16	Metal processing	2.50
17	Manufacture of various electrical appliances	2.50
18	Other manufacturing industries	2.50

Table 3. 4 Ratios Considered for each subsector

3.5.2 Limitations due to Topographic

By observing the national topography, it is possible to see that urban centers are localized 2500m above the sea level and in consequence, industrial parks exist mainly at this altitude.

Generally, the machines present problems with high altitudes, presenting power loss and other problems caused for the change in the air pressure.

For this reason, starting from the division realized by INEC for 4 topographic areas it is possible to obtain the percentage of industries that can be affected.

Region	Manufacturing Industries
Andean	65.60%
Coast	33.78%
Amazon	0.63%
Galapagos	0.00%

Table 3. 5 Percentage of Industries in the different region to the country

Table 3.7 shows that 65% of industry is affected by altitude problems. For this reason, and based on different documents about the topic, two particular references were followed to understand the influence of altitude on the technical specifications of engines and turbines.

In the case of an ICE, and according to selected technical specifications of VTA28-G5 (Cummins, 1997):

- Engines may be operated at 1220m without power loss.
- For operation at higher altitude a power loss of 4% per 300m must be considered.
- Taking in consideration the average altitude of most industries, a power loss of 17% was assumed.

For the case of gas turbines, the reference were the technical specifications of Capstone Model C30 (Capstone Turbine Corporation, 2006), which established the following relation:

$$Power\ loss = 1 - \frac{Ambient\ Pressure(2500m)}{Ambient\ Pressure\ ssea\ level} = 1 - \frac{74.671\ kPa}{101.325\ kPa} = 0.264$$

According to the ambient pressure power ratio established as reference, the power loss was assumed as 26% for 2500m above the sea level.

Problems caused by altitude are reflected in the economic part the analysis because of implying higher requirements for power of engines and turbines needed to cover the existing demands, but have no implications on the existing potential for cogeneration.

3.6 Technical Potential

Considering the fact that there is no established regulation for cogeneration, the study was carried out with the intention of covering the basic consumption of electrical energy in the industry, setting aside its thermal needs to be covered partly for the majority of the cases.

Based on the electrical and thermal requirements previously determined, it was decided for this study to only consider the industries that have an electrical consumption of 50kW or more and a thermal consumption of 60kW or more. This is due to the fact that in order to implement a cogeneration system in industries with lower consumption, the cost increases and presents difficulties.

Based on the aforementioned facts, as well as the data in tables 3.3 and 3.4, two possible scenarios may be considered based on the diesel consumption considered for the production of heat. This is due to the lack of information on diesel consumption in the industry which can be used both to produce heat and to operate vehicles.

First scenario

For this scenario, 100% of diesel oil consumption in the industry was assumed to be used for industrial heat generation. Results of this consideration is shown in Figure 3.6.

Now with values calculates and corresponding parameters establish in Tables 3.3 and 3.4 is possible calculate potential of cogeneration according to process establish before.

SUBSECTOR	MW _{ter}	MW _{elect}
Food, Drink and Tobacco	94.724	47.362
Textiles, Leather	4.764	3.176
Paper and Paper Products	68.041	19.440
Petroleum	95.252	24.237
Quarrying of stone and soil, other mining	0.775	0.388
Services	-	-
Clothing, footwear and leather goods	4.936	1.974
Agriculture	-	-
Alcoholic Drinks	9.691	3.876
Wood and Wood Products	-	-
Chemistry	5.258	2.797
Plastic	4.352	2.315
Glass and Ceramics	16.011	9.202
Cement and Lime	0.478	0.191
Natural Oil Process	34.878	23.098
Metal processing	2.606	1.042
Manufacture of various electrical appliances	-	-
Other manufacturing industries	3.432	1.373
TOTAL	345.197	140.471

Table 3.6 Potential of Cogeneration considering 100% of diesel

It is possible to show that potential in some sub-sectors was zero, this is caused for hypothesis considered before.

Second scenario

For this scenario 50% of diesel oil consumption in the industry was assumed to be used for industrial heat generation. Results of this consideration is shown in Figure 3.8.

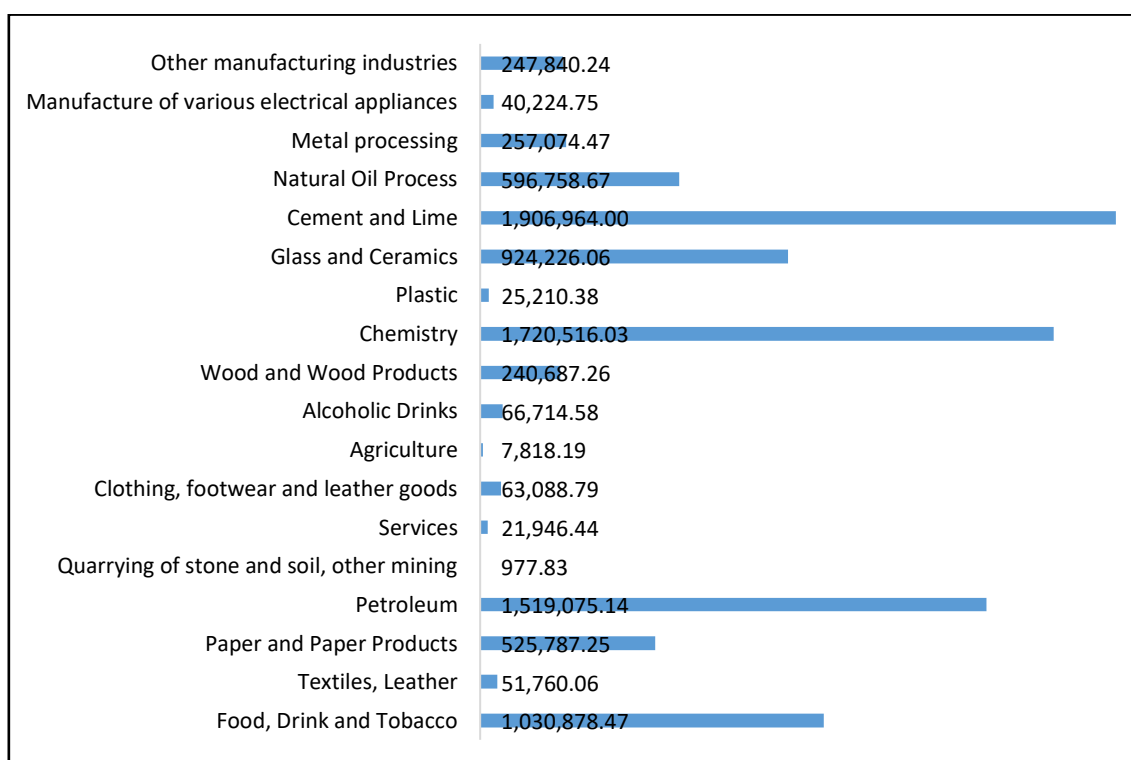


Figure 3.8 Heat Requirement only considered 50% of Diesel oil (MWh)

SUBSECTOR	MW _{ter}	MW _{elect}
Food, Drink and Tobacco	69.813	34.907
Textiles, Leather	3.396	2.264
Paper and Paper Products	65.948	18.842
Petroleum	72.139	18.356
Quarrying of stone and soil, other mining	0.388	0.194
Services	-	-
Clothing, footwear and leather goods	3.065	1.226
Agriculture	-	-
Alcoholic Drinks	5.168	2.067
Wood and Wood Products	-	-
Chemistry	4.029	2.143
Plastic	2.921	1.554
Glass and Ceramics	14.209	8.166
Cement and Lime	0.239	0.096
Natural Oil Process	33.388	22.111
Metal processing	1.979	0.792
Manufacture of various electrical appliances	-	-
Other manufacturing industries	2.800	1.120
TOTAL	279.483	113.837

Table 3. 7 Potential of Cogeneration considering 50% of diesel

The results obtained after applying the proposed methodology are presented in Tables 3.5 and 3.6. The first column presents the estimation for the potential thermal power, which technically could be installed in each industrial sector, and the second column represents the equivalent electric power potential.

As presented in tables 3.5 and 3.6, the principal sub-sectors with cogeneration potential are “Food, Drink and Tobacco”, “Paper and Paper Products”, “Petroleum” and “Natural Oil Process”, representing a good match with the main industrial activities in the country.

For the cases of “Textile, Leathers”, “Cement and Lime” and other important sub-sectors, the potential is low mainly due to the assumption of electric self-consumption, not considering the possibility of selling surplus generation.

It is possible to observe in Figures 3.6 and 3.7 that the thermal energy needs are high when compared with the electric needs. Considering this, and the problem caused by the lack of a law to sell electric energy, important limitations for cogeneration potential are produced.

For the case of “Quarrying of stone and soil, other mining” the potential is low because in the country the mining activity is underdeveloped.

Finally, the uncertainty regarding the use of diesel represent, are around 19%.

3.7 Economic Analysis

The objective of this point is calculating the economic viability of implementing a cogeneration.

In the first place it is necessary to consider two independent economic calculations for different cases, namely:

- Industries that are at sea level, where there are no implications of altitude.
- Industries approximately at 2500m above sea level, where the power loss according to exposed in 3.5.2.

Four types of plants were assumed for the calculation the characteristics of these being shown in Table 3.8.

ITEM	Diesel Engine	GAS ENGINE (or industrial fuel used)	GAS ENGINE	GAS TURBINE
	50kW-250kW	300kW-950kW	1MW or more	3MW or more
Network level Voltage	LV	LV-MV	LV-MV	MV-HV
Application -	Property cogeneration	Property cogeneration	Property cogeneration	Property cogeneration
Investment costs incl. \$ / kW	\$ 720.00	\$ 1,760.00	\$ 1,440.00	\$ 1,200.00
Lifetime years	10	15	15	15
Efficiency rating - electrical %	34%	40%	41%	30%
Efficiency rating - thermal %	46%	46%	46%	50%
Overall efficiency rating %	80%	86%	86%	80%
O&M cost \$/ kW-year	\$ 119.00	\$ 178.00	\$ 137.00	\$ 106.00
Price of Fuel \$/kWh	\$ 43.60	\$ 20,800.00	\$ 20.80	\$ 20.80
Heat Rate Considered kJ/kWh	10,588.24	9,000.00	8,845.21	12,000.00

Table 3. 8 Characteristics of equipment to analysis

In all cases, the prices for kW installed and O&M costs were obtained with the program Retscreen Expert as the principal source of information.

In this situation is considered that the price for electric energy generated is the same that the price when consuming, according to “Pliego Tarifario para las Empresas Eléctricas” (ARCONEL, 2016, pp. 3–16):

- 08h00 to 18h00 0.093 \$/kWh consumed
- 18h00 to 22h00 0.107 \$/kWh consumed
- 08h00 to 18h00 0.075 \$/kWh consumed

Furthermore, the selected discount rate was taken from “Average interest rates by instrument” considered for a fixed time deposit, published by Central Bank of Ecuador for 2017 (Banco Central del Ecuador, 2017). The Methodology presented in the Appendix III calculate the costs for each individual case.

Diesel Engine

A 100kW engine with characteristics:

- Medium level Voltage (13.8-22kV)
- Working 2800 to 7000 hours
- Diesel oil as main fuel.

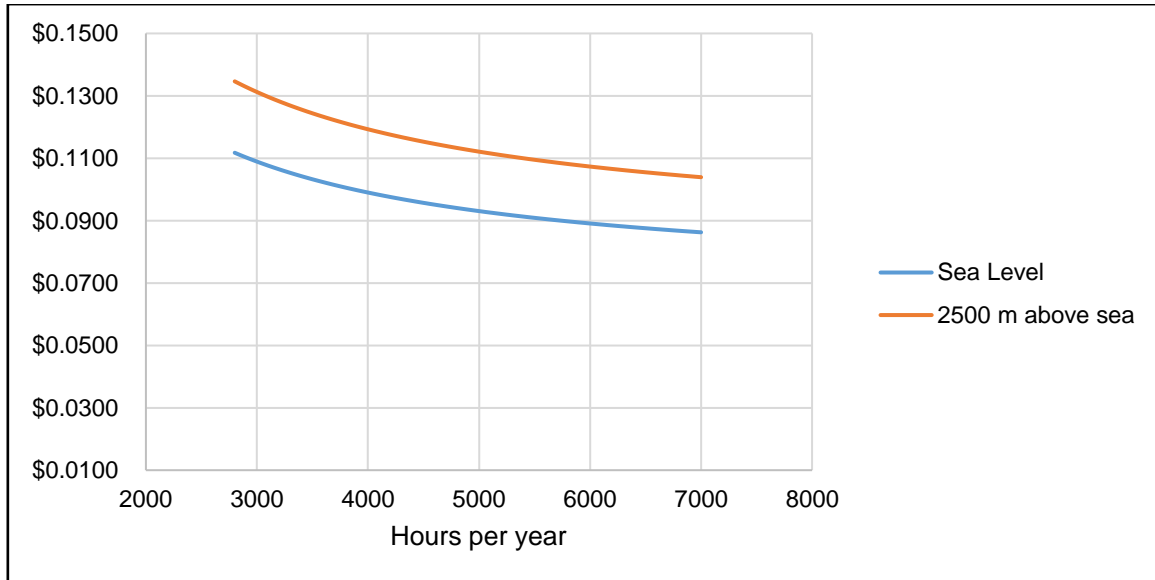


Figure 3. 9 Price of kWh generated for diesel engine

	Hours	Cash flow (\$)	NPV (\$)	IRR (%)	Payback (years)
Sea Level	3500	\$ (3,586.47)	\$ (99,747.65)	----	xxxx
	4500	\$ (21.18)	\$ (72,163.84)	----	xxxx
	5500	\$ 2,506.12	\$ (52,610.78)	-19.67%	xxxx
	6500	\$ 3,081.41	\$ (48,159.87)	-17.16%	xxxx
2500m above sea	3500	\$ (9,119.97)	\$ (142,558.99)	----	xxxx
	4500	\$ (7,337.98)	\$ (128,772.14)	----	xxxx
	5500	\$ (6,417.52)	\$ (121,650.81)	----	xxxx
	6500	\$ (7,117.23)	\$ (127,064.26)	----	xxxx

Table 3. 9 Economic Analysis diesel engine

The results for this scenario are shown in Figure 3.9 and Table 3.9, all with bad results, especially for the unit placed 2500m above sea level.

In an investment perspective, these are not inspiring results, all economic indicators being negative and with a price of kWh generated around 0.10 USD, which is similar or greater than the price of kWh bought to the electric grid.

Gas Engine (350kW-950kW)

A 500kW gas engine was chosen here, with the following characteristics:

- Medium level Voltage (13.8kV-22kV)
- Working 3500 to 8000 hours
- Natural Gas as main fuel.

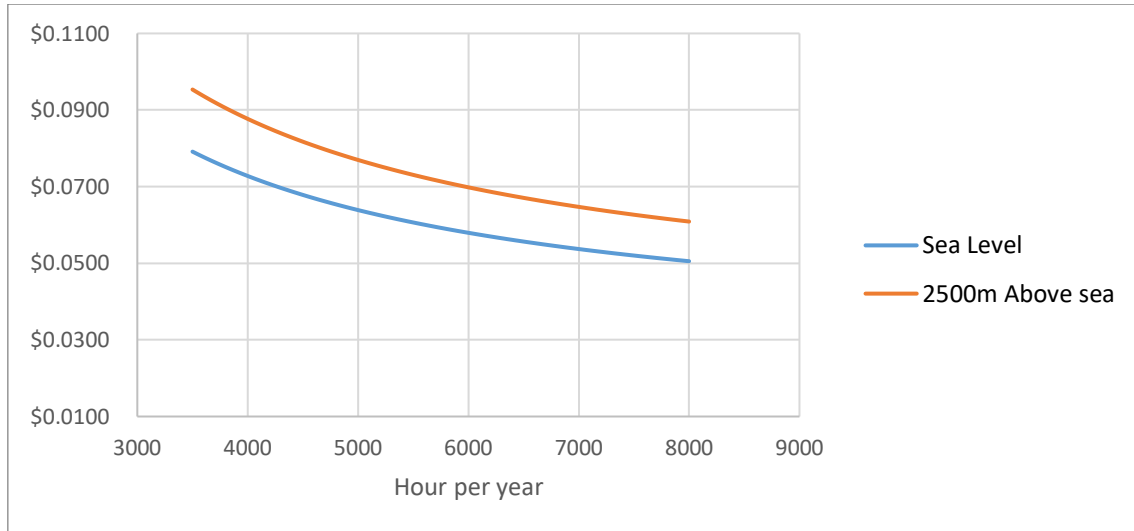


Figure 3. 10 Price of kWh generated for gas engine (350kW -950kW)

	Hours	Chas flow (\$)	NPV (\$)	IRR (%)	Payback (years)
Sea Level	3500	\$ 24,246.00	\$ (107,652.99)	-----	-----
	4500	\$ 62,552.00	\$ 291,027.39	10%	5.8
	5500	\$ 95,668.00	\$ 635,691.40	20%	3.8
	6500	\$ 119,024.00	\$ 878,775.49	26%	3.0
	7500	\$ 142,380.00	\$ 1,121,859.57	33%	2.5
2500m above sea	3500	\$ (3,421.50)	\$ (395,610.22)	-----	-----
	4500	\$ 25,968.00	\$ (89,730.80)	-----	-----
	5500	\$ 51,049.80	\$ 171,315.04	6%	7.1
	6500	\$ 68,030.80	\$ 348,049.53	12%	5.3
	7500	\$ 85,011.80	\$ 524,784.03	17%	4.2

Table 3. 10 Economic Analysis for gas engine (350kW-950kW)

In this scenario the results were already interesting. Figure 3.10 show the value of kWh generated, 0.055 USD and 0.075 USD for 5500 hours work, at the sea level or at 2500m above sea, respectively. The difference regarding the cost of kWh from electric grid is already meaningful.

Table 3.10 shows the results of the economic analysis realized for different work hours per year, which allow the following conclusions:

- Sea Level. Results are positive if the system runs more than 4500 hours per year. A minimum IRR of 10% and results are even better if the working time exceeds this value. The payback is inferior to 4 years.
- 2500m Above sea. - Results are less interesting and the equipment that functions in this situation must work for 5500 hours a year to obtain a positive economic indicator. This situation is possible only for industries that work around 16 hours a day, but the economic indicators are not excellent.

Gas Engine (1MW)

A 1MW gas engine with the following characteristics:

- High Voltage (greater than or equal to 138 kV)
- Run time from 4500 to 8760 hours
- Natural Gas as main fuel.

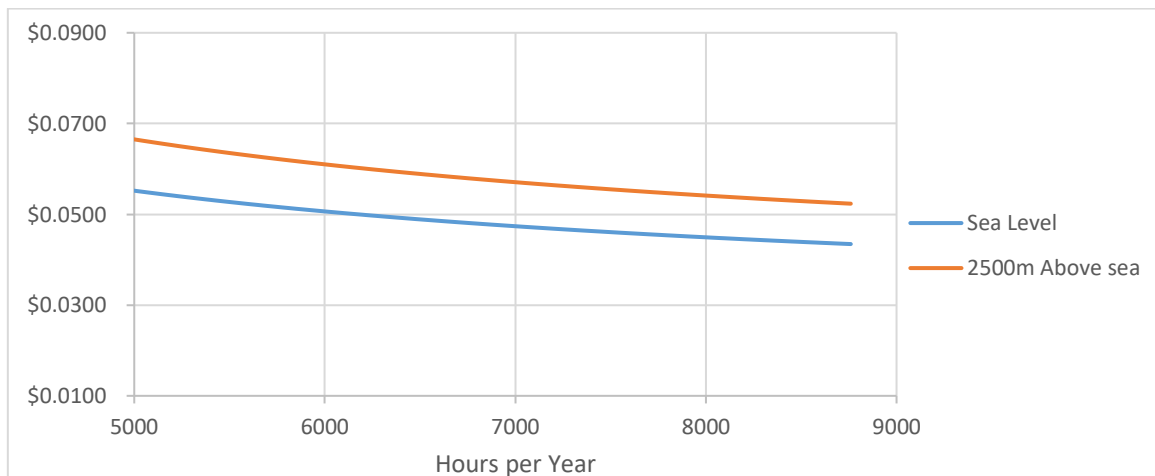


Figure 3. 11 Price of kWh generated for gas engine

	Hours	Cash flow (\$)	NPV (\$)	IRR (%)	Payback (years)
Sea Level	4500	\$ 168,293.37	\$ 1,031,560.16	16%	4.28
	5500	\$ 235,011.89	\$ 1,725,951.83	26%	3.1
	6500	\$ 282,210.42	\$ 2,217,183.66	32%	2.6
	7500	\$ 329,408.94	\$ 2,708,415.48	39%	2.2
	8760	\$ 388,879.09	\$ 3,327,367.58	47%	1.9
2500m above sea	4500	\$ 95,125.37	\$ 270,043.79	5%	7.57
	5500	\$ 145,775.49	\$ 797,199.10	13%	4.9
	6500	\$ 180,224.02	\$ 1,155,731.74	18%	4.0
	7500	\$ 214,672.54	\$ 1,514,264.39	23%	3.4
	8760	\$ 258,077.69	\$ 1,966,015.52	29%	2.8

Table 3. 11 Economic Analysis for gas engine

For this scenario the results were excellent. Figure 3.11 shows the value of kWh generated, of 0.048 USD and 0.065 USD for 7000 hours runtime, according to the altitude. The difference regarding the cost of kWh from electric grid is significant.

Table 3.11 shows the economic analysis performed for different work hours per year. Again, results are interesting and the following conclusions can be drawn:

- Sea Level. – Positive results are guaranteed for runtimes above 5500 hours per year. The IRR gets to 26%, payback is inferior to 3.5 years.
- 2500m Above sea. - For this situation, the results are less interesting. The equipment that functions in this situation must work for 5500 hours per year to obtain a positive economic indicator.

Gas Turbine

A 3MW gas Turbine was chosen with the characteristics shown in Table 3.8 and assuming the following conditions:

- High Voltage (greater than or equal to 138 kV)
- Run time from 6000 to 8760 hours
- Natural Gas as main fuel.

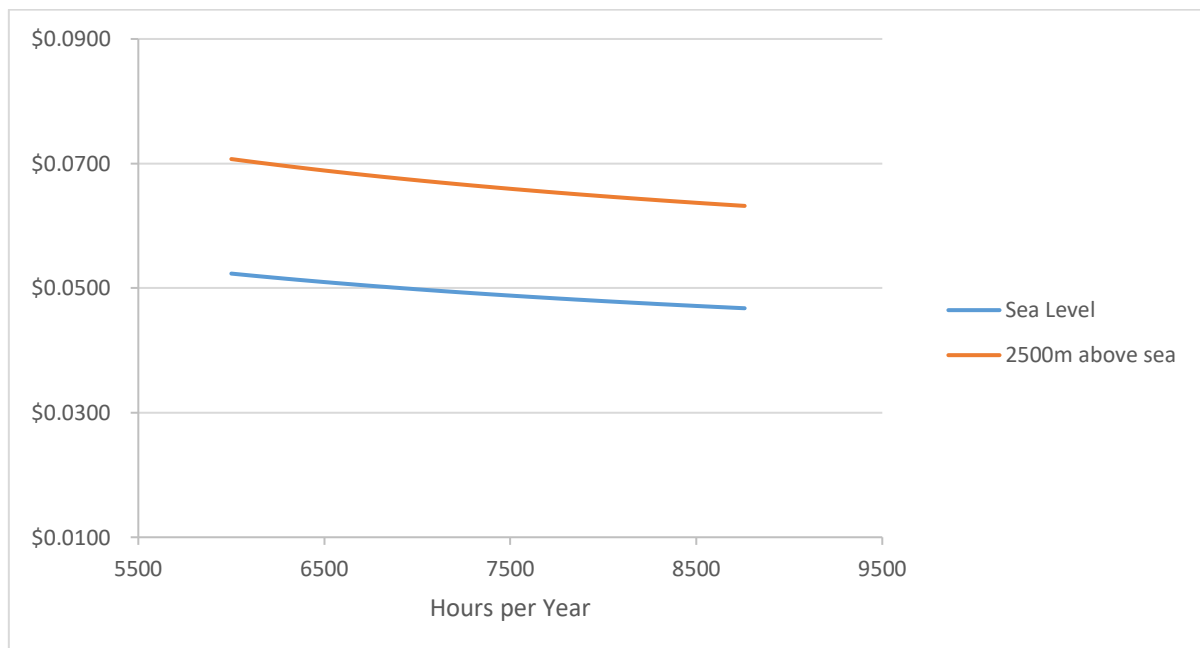


Figure 3. 12 Price of kWh generated for gas Turbine

	Hours	Cash flow (\$)	NPV (\$)	IRR (%)	Payback (years)
Sea Level	6000	\$ 745,260.00	\$ 5,596,501.37	28%	2.9
	7000	\$ 866,260.00	\$ 6,855,842.63	33%	2.5
	8000	\$ 987,260.00	\$ 8,115,183.88	39%	2.2
	8760	\$ 1,079,220.00	\$ 9,072,283.24	43%	2.0
2500m above sea	6000	\$ 306,572.40	\$ 1,030,737.78	6%	7.0
	7000	\$ 369,072.40	\$ 1,681,223.97	10%	5.9
	8000	\$ 431,572.40	\$ 2,331,710.16	13%	5.0
	8760	\$ 479,072.40	\$ 2,826,079.66	15%	4.5

Table 3. 12 Economic Analysis for gas turbine

Table 3.12 shows economic analysis performed for this situation, it is especially interesting the second part of analysis when the equipment is affected by altitude because the economic indicators are positive but do not are good.

- Sea Level. – The Economic result is good comparable as the gas engine. It is considered for bigger industries; these industries work an elevated number of hours per year. This equipment is acceptable for industries that have high requirement of thermal energy
- 2500m Above sea. – For this case, the results are positives but not are good, the altitude affects this equipment, the economic indicators are inferiors.

3.8 Efficiency Analysis

Primary energy savings are the main goal of cogeneration and represent a benefit for the society as a whole, both in terms of the economy and of the environment, namely due to the reduction of greenhouse emissions.

The fuel saved can represent a social indicator by the global improvements produce to the country and the reduction greenhouse emissions.

To determinate the amount of fuel saved is necessary to obtain information about the main technologies used in the thermoelectric power. For this was used as a reference the document “Factor de Emisión de CO₂ del Sistema Nacional Interconectado del Ecuador” shows that main technologies are internal combustion engine with diesel and fuel oil, turbo gas (Alexandra Buri et al., 2013). As most of the plants use internal combustion engine technologies, it is straightforward to obtain the primary energy saved.

Problems caused by altitude were not considered for this calculation because the effects are similar on traditional and on cogeneration plants.

Hours	POWER (Kw)	Total Efficiency	PES	Fuel Saved (kWh)	Fuel Type	Fuel Saved	Unit
4,500	100	80.00%	28.55%	528,752.73	Diesel	13,723.94	gal
5,500	500	85.60%	27.52%	2,610,976.39	Natural Gas	266,955.84	m3
7,500	1,000	86.30%	27.35%	6,937,137.60	Natural Gas	709,278.48	m3
8,000	3,000	80.00%	16.80%	16,152,804.61	Natural Gas	1,651,522.20	m3

Table 3. 13 Energy Efficiency indicators

Table 3.13 shown the primary energy saving (PES) due to cogeneration when compared to separated production of electricity and heat. The calculation are presented in appendix II and use data determined in subsection 3.6.1

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4. CASE STUDY

4.1 Introduction

In this chapter, the analysis for two industries is performed, according to the information used in chapter three and the data obtained from industries.

The cogeneration system proposed for this analysis is based on the use of the topping cycle, in a configuration shown in Figure 4.1.

Based on this hypothesis, two specific cases were considered, namely:

- For the first industry, the equipment required to cover the basic electric energy needs was dimensioned according to chapter three.
- For the second industry, the basic thermal energy needs were considered to size the equipment.

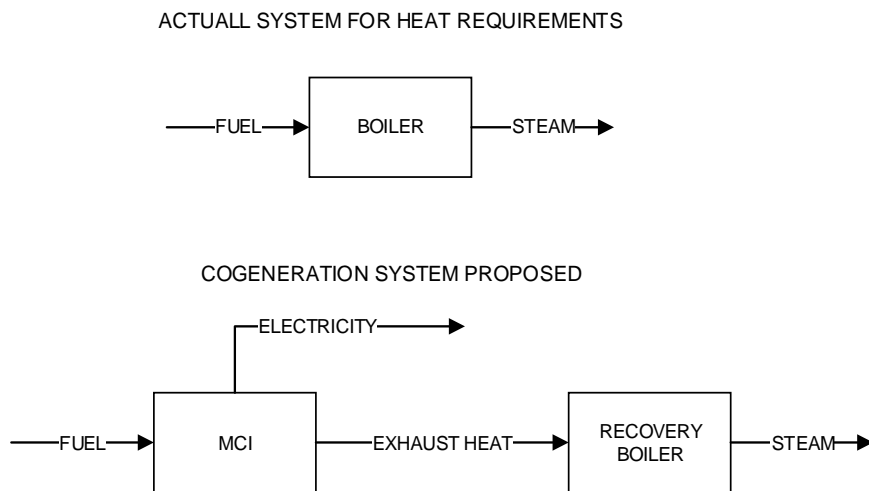


Figure 4. 1 Cogeneration System proposed

All costs for equipment and maintenance was obtained from RetScreen and converted to U.S. dollar, considering the conversion 1US dollar =1.25 Canadian Dollar. All the equations mentioned in the calculation process are presented in appendix.

4.2. Industry A

This industry is located at the south of the country, in the Andean region. Its development is concerned with the production of paperboard and paper products.

Like most of the industry in the country, industry A is characterized by a consumption of fossil fuels as a main source of energy, accompanied by the consumption of electric energy. The main characteristics of this industry are:

- Located in the Andean Region, 2500 meter above the sea level
- Climatic Temperature around 17 °C
- Worked hours per year 8147
- Fuel Type Fuel oil #4
- Medium fuel cost 0.0187\$/kWh (0.7435\$/gallon)
- Annual demand of Fuel 15,517,307.36 kWh (370,000gallons)
- Annual demand of Elect. Energy 4,416,000 kWh
- Steam Demand 20,438.09 ton/ year
- Maximum Steam Demand 2,508.66 kg/hour
- Steam Temperature 200°C
- Steam Pressure 200 PSI
- Air-Conditioned Energy 300000 BTU
- Air-Conditioned temperature 15-18°C

The overall system operates as follows: The fuel feeds a boiler to produce steam that is used in the industrial process. This steam is used to source a group of dryers and return with heat water. Air-conditioning units and other systems use electric energy taken from the grid.

To perform the calculations, the equipment characteristics shown in Table 3.8 were used and the electrical energy prices showed in the chapter 3.6 were applied. With this information, the energy operative costs per year are:

- Cost of Electrical Energy 368,903.26 \$
- Cost of Fuel 280,734.54 \$
- TOTAL COST 649,637.80 \$

4.2.1 Demand Estimation.

The demand estimation was obtained in base on historical industry data, namely:

- Thermal Energy Demand 15,517,307.36 kWh -year
- Electric Energy Demand 4,416,000.00 kWh-year

For the basic electric energy needs, the electric energy demand and the plant working hours were considered, obtaining the average electric power.

$$P = \frac{E_{energy}}{Hour\ of\ work} = \frac{4416000.0\ kWh}{8146\ h} = 542.04\ kW$$

This value is approximately the mean consumption per hour, but a lower power requirement is possible at night and weekends. Nonetheless, the interruption of the production process in the plant is not convenient. For this reason, and, as a normative or law does not exist to regulate the production of cogenerated electricity, only the base electric demand is covered.

The thermal energy recovered from the engine will cover a part of the mean steam demand, which is 0.697kg/s. The remaining steam demand will be covered by the existent boiler.

4.2.2 Economic Analysis

The analysis was performed considering the investment capital and O&M costs for the engine and the recovery boiler, implying the following operations:

- Calculate the fuel consumption for the engine.
- Calculate the thermal energy saved by the recovery boiler and its price.
- Calculate the cost per generated kWh.
- Determinate Net Present Value (NPV), if greater than zero, calculate the Internal Return Rate (IRR) and the payback.

A 17% power loss caused by altitude was considered.

The general engine characteristics are presented in table 4.1:

Voltage	Medium Voltage (22kV)
Power	500 kW
Aspiration	Turbocharged and after-cooled
Exhaust gas flow at set rated load	96 m ³ /s
Exhaust gas flow at set rated load	1.89 kg/s
Exhaust gas temperature	634 °C
Maximum exhaust back pressure	10.1 kPa
Electrical Efficiency	40.7%
Thermal Efficiency	45.6%
Lifetime	15 years
Heat Rate (HR)	9000 kJ/kWh

Table 4. 1 Engine Characteristics

Usually, the exhaust flow is measured in m³/s, and an air density of 1.184 kg/m³ was used to calculate the mass of the exhaust gas.

Cash Flow	NPV	IRR	Payback
\$	\$	%	years
95,234.57	167,292.32	2.69%	8.76

Table 4. 3 Economic parameters

Table 4.3 shows that the economic parameters, although positive, are too low, and the perspective investment is not interesting because it is possible to obtain better incomings in a bank, for this reason, other possibilities need to be considered.

Finally, the cost of the consumption of energy by industry is calculated. Table 4.4. shows the results

ITEM	\$
Cost of fuel for cogeneration	183,307.50
Price of Electric Energy buy to grid	69,346.22
Cost of Fuel to conventional boiler	201,763.91
O&M cost	99,235.00
TOTAL COST	553,652.63

Table 4. 4 Operative cost caused for energy consumption

If the above data is compared with the original plant, it is possible to see a saving of 95,985.17\$. This value is similar to the obtained cash flow.

If a possible increase of fuel and electric prices are considered, the economic parameters are better because the inversion will not change in the equipment lifetime.

4.2.3 Efficiency Analysis

Primary Energy Savings (PES) is an interesting parameter to evaluate as it represents the value of cogeneration in the society perspective. This parameter is not related to the economic development of industry, but represents the monetary savings by the society in primary fuel, as well as the reduction in pollution associated to the burning of fossil fuels.

According to data obtained in point 4.2.2 and considering the thermoelectric plants, with an internal combustion engine technology, it is possible to calculate the PES.

The calculation process to find different paraments is presented in Appendix V, and calculation results are shown in Table 4.5.

Overall Performance	75.50%
Power energy Saved	25.06%
Fuel saved (kWh)	3,404,550.23
Fuel saved (gal)	81,179.33

Table 4. 5 Efficiency energy Dates

The quantity of fuel saved is interesting because in function of this, it is possible to determine the amount of reduced greenhouse gases.

4.3. Industry B

This industry is located at the south of the country, in the Andean region. Its development is concerned with the production of milk products and natural juice.

The operation of this plant is similar to industry A. The fuel feeds a boiler to produce steam that is used in the industrial process. This steam is used to feed a group of dryers. To cope with cooling needs, industry B uses a compressor chiller that uses electric energy taken from the grid.

In this system, steam generation only works 16 hours per day, and the cooling systems work 24 hours per day

The main characteristics of this facility are:

- Localized in the Andean Region, 2500 meter above the sea level.
- Climatic Temperature around 17 °C
- Worked hours per year 8700 (but steam only use for 5840 hour)
- Fuel used Diesel
- Fuel cost 0.044\$/kWh (1.67\$/gallon)
- Annual demand of Fuel 1,810,482.86 kWh (48,000 gallons)
- Annual Demand of Elect. Energy 6,090,000.00 kWh
- Average Elec. Power required 700 kW
- Steam Demand 2,250.00 ton/ year
- Maximum Steam Demand 385.27 kg/hour
- Steam Temperature 140°C
- Steam Pressure 87 PSI

To perform the calculations, the equipment characteristics shown in Table 3.8 are used, along with the electrical energy prices showed in the chapter 3.6. With this information, the energy operative costs per year were determined as:

- Cost of Electrical Energy 539,574.20 \$
- Cost of Fuel 80,507.33 \$
- TOTAL COST 620,081.33 \$

4.3.1 Demand Estimation.

The demand estimation was obtained using historical industry data, namely:

- Thermal Energy Demand 1,810,482.96 kWh-year
- Electric Energy Demand 6,090,000.00 kWh-year
- Medium Electric Power 700 kW

It is clear in this case that the thermal needs are less than the energy needs. This is reasonable because the principal energy needs are focused in cooling systems.

The thermal energy recovered from the engine will cover a part of the average steam demand, 0.10kg/s. The remaining steam demand will be covered by the existent boiler.

4.3.2 Potential Analysis

The equipment is dimensioned in function of the basic thermal needs without considering the electric needs, because it is necessary to exploit all of the exhaust gases in order to elevate the system efficiency.

Based on this consideration, the following steps are established,

- Calculate the power of equipment in base of the quantity of exhaust gases that can be used in the industrial process.
- Consider the prices of inversion, O&M, for the engine and recovery boiler.
- Calculate the energy consumption of fuel used for the engine.
- Calculate the thermal energy saved by the recovery boiler and his price.
- Calculate the cost of not bought electric energy.
- Calculate the cost of the generated kWh.
- Determinate NPV, if greater than zero, calculate IRR and the payback.

According to the above steps, it is necessary to know the steam characteristics, which are:

- Temperature 140 °C
- Pressure 87 PSI
- Latent Heat 2009 kJ/kg
- Specific Enthalpy to saturated 2009 kJ/kg
- Specific Enthalpy to Water 670,501 kJ/kg
- Water Temperature 100 °C

Now, considering steam characteristics and the equations 13 and 14 presented in Appendix IV, it is possible to obtain

$$m_g = \frac{m_{steam} * (h_{a3} - h_{a2})}{(h_{g(T_{g1})} - h_{g(T_{g2})})} \left(\frac{kg}{s} \right)$$

$$m_g = 0.8 \left(\frac{kg}{s} \right)$$

$$m_g = 34.5 \left(\frac{m^3}{s} \right)$$

The maximum flow of exhaust gases is around 34.5 (m³/s) at a temperature around of 474°C.

Based on this information, a 100kW engine which operates with diesel oil was selected. A 17% power loss caused by the altitude effect was considered.

General characteristics of engine are:

Voltage	Nominal Voltage (22kV)
Power	100 kW
Aspiration	Turbocharged and after-cooled
Exhaust gas flow at set rated load	28.94 m ³ /s
Exhaust gas flow at set rated load	0.57 kg/s
Exhaust gas temperature	474 °C
Maximum exhaust back pressure	10.1 kPa
Electrical Efficiency	34.00 %
Thermal Efficiency	46,00 %
Lifetime	10
Heat Rate (HR)	10,588.24 kJ/kWh

Table 4. 6 Engine Characteristics

Based on the analysis carried out in chapter 3 for a diesel engine in the 50kW-250kW range, the characteristics and prices applied for this study were:

- Investment initial cost 720 \$ kW installed
- O&M 119 \$ kW-year

For the recovery boiler:

- Investment initial cost 183 \$ kW installed
- O&M 46 \$ kW-year (25% O&M engine cost)

The steam data are:

- Temperature 140 °C
- Pressure 87 PSI
- Latent Heat 2009 kJ/kg
- Specific Enthalpy to saturated 2009 kJ/kg
- Specific Enthalpy to Water 670,501 kJ/kg
- Water Temperature 100 °C

Based on these data, and considering the process shown in the Appendix IV, it is possible to calculate the requirements of the recovery boiler as well as the total useful steam flow produced by exhaust gases.

$$m_{steam} = 0.089 \text{ kg/s}$$

$$\%_{br} = 88 \%$$

$$P_{boiler} = 135 \text{ kW}$$

In this frame and based on the process presented in Appendix III, it is possible to obtain the different parameters such as the electric energy generated, fuel saved, initial investment, O&M costs.

Work Hours	fuel consumed by cogeneration	Electric Energy Generated	Thermal Energy Saved
hours	kWh	kWh	kWh
5840	1,717,647.06	484,720.00	695,339.44

Table 4. 7 Energy consumed and produced by cogeneration

With the results presented in Table 4.7, the calculated economic parameters to analyze feasibility are

Cash Flow	NPV	IRR	Payback
\$	\$	%	years
(13,346.25)	(212,841.84)	-----	----

Table 4. 8 Economic parameters

For this case, the results are lesser than zero and therefore the inversion is not attractive. An interesting idea in this case is the introduction of a gas engine to reduce fuel costs but the additional thermal energy produced by this engine is not further used in any other system, consequently the cogeneration has not logic unless the exhaust gases can be used in absorption chillers

4.3.3 Efficiency Analysis

According to data obtained in point 4.2.2 and considering thermoelectric plants existing with an internal combustion engine technology, it is possible to calculate the PES.

The calculation process to find different parameters is presented in Appendix IV, and the calculation results are shown in Table 4.9.

Overall Performance	68.70%
Power energy Saved	15.97%
Fuel saved (kWh)	315,747.90
Fuel saved (gal)	8,371.19

Table 4. 9 Efficiency energy data

5. CONCLUSIONS

The principal problem faced in this work was the limitation caused by the electric market which is not liberalized. For this reason, it is not possible to size the systems to cover all thermal needs, and therefore, the systems are sized only regarding electric needs.

From the bibliography, using as example other countries, the potential of cogeneration could be higher, if determined based on covering the thermal loads, leading to an increased efficiency in the generation of electricity from thermal sources.

Table 5.1 shows the cogeneration potential considering thermal and electric requirements presented in Figure 3.6 and 3.7, only considering individual thermal power demand above 60kW.

TECHNICAL POTENTIAL NOT CONSIDER THE ALTITUDE		
SUBSECTOR	MW _{ter}	MW _{elect}
Food, Drink and Tobacco	247.506	123.753
Textiles, Leather	6.563	4.375
Paper and Paper Products	68.101	19.457
Petroleum	95.252	24.237
Quarrying of stone and soil, other mining	0.909	0.454
Services	-	-
Clothing, footwear and leather goods	6.190	2.476
Agriculture	-	-
Alcoholic Drinks	10.371	4.148
Wood and Wood Products	27.103	14.417
Chemistry	179.718	95.595
Plastic	4.648	2.472
Glass and Ceramics	16.011	9.202
Cement and Lime	307.165	122.866
Natural Oil Process	35.049	23.211
Metal processing	14.517	5.807
Manufacture of various electrical appliances	-	-
Other manufacturing industries	25.861	10.344
TOTAL	1,044.964	462.816

Table 5. 1 Technical Cogeneration Potential

Outstanding results were obtained as the potential grows up to around 300%, when compared to the potential obtained with the present electric market conditions. The above results show the importance to establish a law to promote cogeneration and allow the introduction of this energy into the electric market.

Another interesting result was the one obtained in section 3.6 where the economic indicators improve with the increment in the installed electric power when using turbines but get worse in the case of using diesel engines. For equipment installed around 2500m above sea level, in most cases, economic indicators were positive but not especially interesting. An interesting proposal to promote cogeneration systems is the consideration of the additional economic benefits base on the PES indicator. An

additional reward based on the PES could be financed by the money saved on fuel subsidies due to the increased efficiency of using cogeneration. A possible example of this situation is considered in Table 5.2 where different percentages of PES with are considered for a possible additional payment are presented.

Power (Kw)	Percentage of PES
100	80.00%
500	50.00%
1,000	25.00%
3,000	20.00%

Table 5. 2 Example of Percentage of PES with right to additional payment

In this frame, it is possible to obtain new economic indicators to analyze the advantage of the additional reward mechanism. This reward is considered in function of thermal energy calculated from fuel saved. Table 5.3 shows these economic indicators considering the data shown in Table 5.2.

	Hours	POWER (Kw)	CASH FLOW (\$)	NPV (\$)	IRR(%)	PAYBACK (years)
SEA LEVEL	4,500	100	\$ 18,421.72	\$ 70,524.35	16.35%	3.91
	5,500	500	\$ 122,822.15	\$ 918,305.84	27.36%	2.93
	7,500	1,000	\$ 365,482.06	\$ 3,083,856.49	43.53%	1.97
	8,000	3,000	\$ 1,146,415.67	\$ 9,771,640.89	45.76%	1.88
2500m ABOVE SEA LEVEL	4,500	100	\$ 11,104.92	\$ 13,916.05	3.63%	6.48
	5,500	500	\$ 78,203.95	\$ 453,929.47	14.69%	4.60
	7,500	1,000	\$ 250,745.66	\$ 1,889,705.40	28.06%	2.87
	8,000	3,000	\$ 498,768.07	\$ 3,031,067.81	16.15%	4.33

Table 5. 3 Economic Indicators for the example case

With the results obtained in Table 5.3 and the data obtained in point 3.6, it is possible to observe that the economic indicators have improve, leading to a motivation for investment, especially if using private money. This additional benefit can be established according to the estimated payback time. Later, the PES benefits can be modified or eliminated as long as the industry perceives benefits.

The altitude above sea level is an important factor that affects engines and turbines performance, reducing power capacity. Due to altitude effects, the use of equipment with greater power than the required at sea level, will be necessary to obtain similar performance. This will increase the initial investment requirements without obtaining additional benefits, making the economic indicators less attractive.

The altitude problem in Ecuador is a complex situation because of the topography with changing altitudes, being necessary a detailed study about this issue.

Currently, the use of diesel in medium and small industries is subsidized by the government. A change in this combustible for the industrial sector can produce additional benefits for both industry and government. An interesting scenario will be the change of diesel by natural gas or fuel oil #4 because the price is half and therefore operative costs are reduced.

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APPENDIX I

LOWER HEATING VALUE (LHV)

ITEM	kJ/kg	
SOLID FUELS		
Petroleum Coke	29,505.00	
Asphalt	39,910.00	
Anthracite	34,300.00	
Coke Coal	28,610.00	
Other bituminous coal	26,122.00	
Lignite	10,500.00	
Bituminous shale	8,000.00	
Peat	7,800.00	
Remains of Wood and Bark	13,800.00	
Fiber Processing byproduct	74,000.00	
Waste of Tagua	32,000.00	
Solid waste rice husk	15,800.00	
Palm leaf	75,000.00	
Biomass	17,209.00	
Bagasse	15,058.00	
LIQUID FUELS		
	kJ/kg	kJ/gal
Gasoline (92 octanes)	42,358.00	119856.93
Gasoline (87 octanes)	43,448.00	122481.92
Diesel	42,791.00	135786.22
Fuel Oil # 4	41,200.00	150979.09
Fuel Oil # 6	39,780.00	159630.58
Reduced Crude	39,466.00	148080.84
Naphtha 90	44,383.00	126332.88
Fuel for artisanal fishing	43,247.00	137189.45
Natural Gasoline	43,239.00	131070.10
GAS FUELS		
	kJ/kg	kJ/m ³
Liquified Petroleum Gas (LPG)	46607	35396
Natural Gas	43000	35210

APPENDIX II

FUEL PRICES

ITEM	\$/kg	\$/gal	\$/tonelada	\$/m3	\$/kWh
97 octanes gasoline		\$ 1.972			
89 octanes gasoline		\$ 1.878			
Diesel		\$ 1.677			\$ 0.044
Fuel Oil #4	\$ 2.843	\$ 0.759	\$ 284.343		\$ 0.019
Fuel Oil #6		\$ 1.072			\$ 0.025
Crudo Reducido		\$ 0.431			\$ 0.011
Asfalto	\$ 0.304				\$ 0.037
Petroleum Liquid Gas (PLG)	\$ 0.831			\$ 0.631	\$ 0.064
Natural Gas			\$ 300.000	\$ 0.205	\$ 0.021

APPENDIX III

METHODOLOGY USED TO CALCULATE COST

Considering the price of inversion, cost of fuel and cost of O&M:

$$i = P * p_i \quad (1)$$

$$O\&M = P * om_c \quad (2)$$

$$f = \frac{P * h}{\%_{el}} * p_f \quad (3)$$

Where

- i Initial Inversion (\$).
- $O\&M$ Operating and Maintaining cost for year (\$-year).
- f Cost of fuel used in the year (\$).
- p_f Price of fuel (kWh)
- P Power of Engine (kW).
- p_i Price for kW installed (\$/kW).
- om_c Operating and maintenance cost by kW (\$/kW-year).
- HR Heat Rate (kJ/kWh).
- h hours of function in the year

Calculate thermal energy saved and the price of this by

$$H_{CHP} = \frac{P * h}{\%_{el}} * \%_{th} \quad (4)$$

$$f_{saved} = H_{CHP} * p_f \quad (5)$$

Where

- H_{CHP} Thermal Energy saved by year (kWh).
- f_{saved} Price of fuel saved (\$).
- $\%_{th}$ Thermal efficiency (%).
- $\%_{el}$ Electrical efficiency (%).

Calculate the cost of kWh generated by year:

$$E_{CHP} = P * h \quad (6)$$

$$C_{kWh} = \frac{O\&M + f - f_{saved}}{E_{CHP}} \quad (7)$$

Where

- C_{kWh} Cost by kWh generated (\$/kWh)
- E_{CHP} Electrical Energy Produced in the year (kWh).
- t Lifetime to project (years).

Considering the above procedure, it is possible to obtain cash flow and economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and payback

$$Q_n = E_{CHP} * p_{kWh} + f_{saved} - O\&M - f \quad (8)$$

$$NPV = -i + \sum_{n=1}^t \frac{Q_n}{(1+r)^n} \quad (9)$$

Where

p_{kWh} price of kWh according to prices presented in the point 3.6 (\$/kWh)

Q_n cash flow

r discount rate

In the equation (9) if

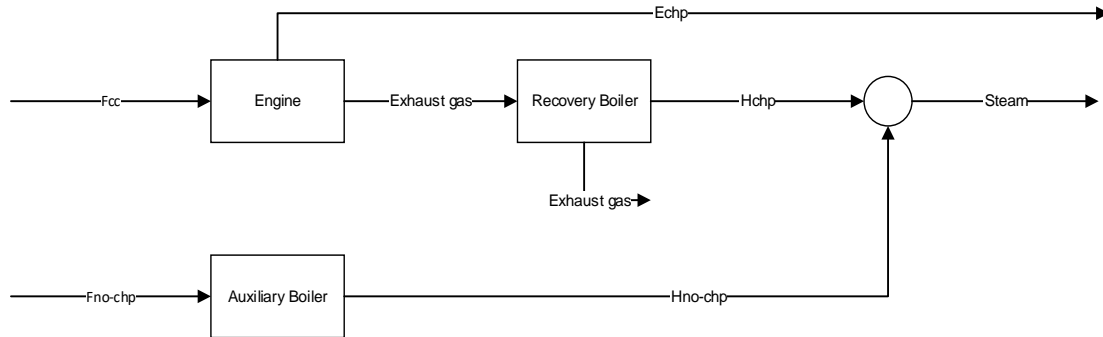
- $NVP > 0$ the project is profitable.
- $NVP < 0$ the project is not profitable.
- $NVP = 0$ is necessary view other indicators.

The economic parameter IRR is possible to determinate when $NPV=0$.

APPENDIX IV

PRIMARY ENERGY SAVINGS

To determine the primary energy saved by cogeneration, it was considered a system as shown in the next Figure.



Appendix Figure. 1 Basic System

This system considers the following:

- Auxiliary boiler consumes 5% of total fuel used by engine or turbine. This energy is used for the fluid to reach industrial characteristics.
- Recovery boiler uses exhaust gases from engine to recover thermal energy.
- H_{chp} and H_{no-chp} are thermal energy from cogeneration and no-cogeneration respectively.

Now based in the European Directive 27/2012/UE, the next process it was considered to determinate different parameters to evaluate efficiency of the system, compared with a traditional process where electricity and thermal energy is produced separately.

Total thermal energy consumed by the system is given by:

$$H = H_{chp} + H_{no-chp} \quad (10)$$

Fuel used to produce this heat is:

$$F_{cc} = F_{chp} + F_{no-chp} \quad (11)$$

Now, the overall performance of system is given by

$$\eta = \frac{E_{chp} + H_{chp}}{F_{cc}} \quad (12)$$

The Primary Energy Saved given by:

$$PES = \left[1 - \frac{1}{\frac{CHP H_{\eta}}{Ref H_{\eta}} + \frac{CHP E_{\eta}}{Ref E_{\eta}}} \right] * 100 \quad (13)$$

The values of $Ref H_{\eta}$ and $Ref E_{\eta}$ are reference values to separate production of electricity and heat respectively.

$$CHP H_{\eta} = \frac{H_{chp}}{F_{CHP}} \quad (14)$$

$$CHP E_{\eta} = \frac{E_{chp}}{F_{CHP}} \quad (15)$$

Finally, it is calculated the fuel save:

$$O_{save} = \frac{PES * F_{chp}}{1 - PES} \quad (16)$$

Where

H_{chp} is the thermal energy from cogeneration.

H_{no-chp} is the thermal energy from auxiliary systems (auxiliary boiler for this case)

F_{chp} Fuel used by cogeneration.

F_{no-chp} Fuel Used by auxiliary systems.

E_{chp} is the electricity from cogeneration.

F_{cc} is the fuel consumed only by cogeneration

$CHP H_{\eta}$ Thermal efficiency.

$CHP E_{\eta}$ Electrical efficiency.

For the case of $Ref H_{\eta}$ and $Ref E_{\eta}$ were based on tables used by the Directive 27/2012/UE. These tables are shown next.

For the $Ref E_{\eta}$ case, the following efficiencies are considered

TYPE OF FUEL USED	
Liquid fuel	44.2%
LPG	44.2%
Natural Gas	52.5%

Appendix Table. 1 Reference value for separate production of electricity. (IDAE and Ministerio de Industria, Tourism and Trade of Spain, 2008, p. 33)

To obtain the final value of $Ref E_{\eta}$ it is necessary to correct the value considering losses caused by transmission.

Voltage Level	Self-consumption
250 kV	0.985
135 kV	0.965
50-100 kV	0.945
5-22 kV	0.925
<0.4kV	0.860

Appendix Table. 2 Correction factor by tension level. (IDAE and Ministerio de Industria, Tourism and Trade of Spain, 2008, p. 34)

For the $Ref H_{\eta}$ case is considered the efficiency

	ITEM	Heat Steam/ water	Direct Use of exhaust gas
LIQUID FUELS	Liquid Fuel	89%	81%
GAS FUELS	Liquified Petroleum Gas (LPG)	89%	81%
	Natural Gas	90%	82%

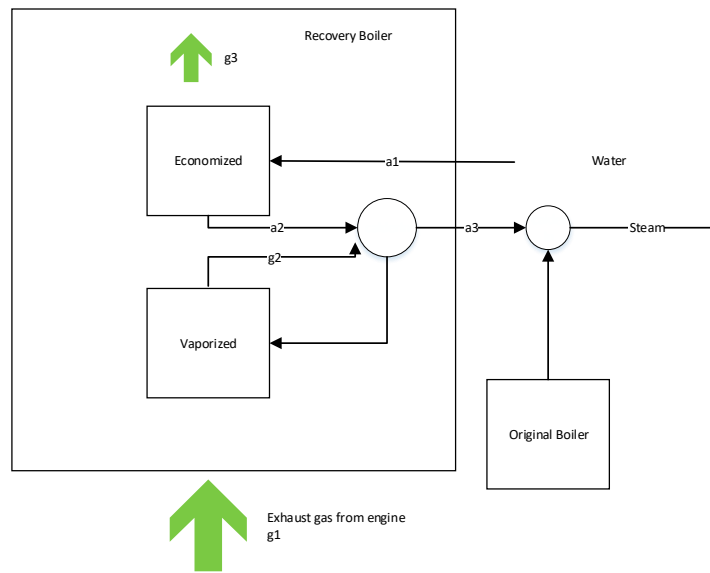
Appendix Table. 3 Reference value for separate production of heat. (IDAE and Ministerio de Industria, Tourism and Trade of Spain, 2008, p. 35)

APPENDIX V

RECOVERY BOILER CALCULATION

In first place, it is necessary to calculate thermal and electric energy that can be produced by cogeneration, equations (4) and (6) are used. Now considering the engine data, the boiler parameters are calculated.

The type of boiler considered was a water tube boiler, unfired and with the possibility to choose a horizontal or vertical positioning depending on the space of the plant.



Appendix Figure. 2 Recovery Boiler scheme

The superheat part is not used. Now considering that the “pinch point” and “approach point” are equal to 25°C and 15°C respectively,

$$\Delta T_p = T_{g2} - T_{a3} = 25 \text{ (}^\circ\text{C)} \quad (17)$$

$$\Delta T_a = T_{a3} - T_{a2} = 15 \text{ (}^\circ\text{C)} \quad (18)$$

According to (IDAE and Ministerio de Industria, Tourism and Trade of Spain, 2008, p. 15), the enthalpy of exhausted gases is determined in function of temperature:

$$h_g = 0.9552 * T + 92.1 * 10^{-6} * T^2 \left(\frac{kJ}{kg} \right) \quad (19)$$

Now, since the heat necessary for the steam is T_{a3} and the temperature of exhausted gases from engine is T_{g1} , using the equations (10), (11) it is possible to calculate T_{g2} and

T_{a2} using tables of temperature and pressure of water, and using equation 19 is possible to obtain h_{a1} , h_{a2} and h_{a3} based on the steam characteristics.

According to the following equations, it is possible to obtain the thermal energy transfer, from exhaust gases to water, and the mass of steam from the recovery boiler.

$$q_{vap} = m_g (h_{g(T_{g1})} - h_{g(T_{g2})}) \left(\frac{kJ}{s} \right) \quad (20)$$

$$m_{steam} = \frac{q_{vap}}{h_{a3} - h_{a2}} \left(\frac{kg}{s} \right) \quad (21)$$

Finally, is necessary to determinate the power that the steam brings into the system, the efficiency of boiler and the energy fuel saved.

$$P_{steam} = m_{steam} (h_{a3} - h_{a1}) \left(\frac{kJ}{s} \right) \quad (22)$$

$$\%_{br} = \frac{P_{steam}}{P * \frac{\%_{th}}{\%_{el}}} \quad (\%) \quad (23)$$

The boiler power is given by

$$P_{boiler} = P * \frac{\%_{th}}{\%_{el}} \quad (kW) \quad (24)$$

When

h	Enthalpy (kJ/kg).
q_{vap}	Energy transfer to exhaust gas to water (kW).
m_{steam}	Steam Production by boiler recovery (kg/s).
P_{steam}	Power steam from boiler recover (kW).
$\%_{br}$	Efficiency of recovery boiler (%).
$\%_{boiler}$	Efficiency of original boiler (%).
q_{vap}	Temperature transfer to exhaust gas to water (kJ/s).

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REFERENCES

- Alexandra Buri, Liliana Sánchez, Andrés Cepeda, Patricio Cañizares, Lenin Haro, Verónica Cárdenas, Wilson Calvopiña, 2013. Factor de Emisión de CO2 del Sistema Nacional Interconectado del Ecuador. Ministerio del Ambiente-- Ministerio de Electricidad y Energía Renovable ----Corporación Centro Nacional de Energía ---Consejo Nacional de Electricidad.
- Anne Hampson, Rick Tidball, Michael Fucci, Rachel Weston, 2016. Combined Heat and Power (CHP) Technical Potential in the United States.
- ARCONEL, 2016. Pliego Tarifario para las Empresas Eléctricas. Sector Público de Energía Eléctrica. Periodo: Enero Diciembre de 2017.
- Banco Central del Ecuador, 2017. Tasas de Interés Julio-2017 [WWW Document]. Tasas Interés Julio-2017. URL <https://contenido.bce.fin.ec/documentos/Estadisticas/SectorMonFin/TasasInteres/TasasVigentes072017.htm> (accessed 9.30.17).
- Capstone Turbine Corporation, 2006. Technical Reference Capstone Model C30 Performance.
- Cummins, 1997. VTA28-G5 Generator Dive.
- David Delgado, 2015. Balance Energético Nacional 2015.
- Eva-Maria Klotz, Marcus Koepf, Frank Peter, Nils Thamling, Marco Marco Wunsch, Inka Ziegenhagen, Dr. Bernd Eikmeier, Max Fette, Karen Janssen, Prof. Dr. Eberhard Jochem, Dr. Felix Reitze, Michael Schön, Dr. Felipe Toro, Markus Gailfuss, 2014. Potential Analysis and cost-benefit analysis for cogeneration applications and review of the Cogeneration Act in 2014.
- IDAE, Ministerio de Industria, Tourism and Trade of Spain, 2008. Guía Técnica para la Medida y Determinación del Calor Útil, la electricidad y del ahorro de energía primaria de Cogeneración de Alta Eficiencia.
- IEA, 2008. Combined Heat and Power. Evaluating the benefits of greater global investment.
- ISR-UC, INESC Coimbra, 2016. Study on the Potential for High-Efficiency Cogeneration in Portugal.
- Javier Miranda, 2010. Potencial de Cogeneración en México y su Posible Desarrollo. Universidad Nacional Autónoma de México, México D.F.
- Joel Bluestein, Marie Lihn, n.d. Historical Impact and Future Trends in Industrial Cogeneration.
- Joseph A. Orlando, 1991. Cogeneration Planner's Handbook. Fairmont Press, Inc., USA.

- Ministry of Industry, Energy and Tourism of Spain, 2016. Full Assessment of the Potential Use of High-Efficiency Cogeneration and Efficient District HEating and Cooling Systems.
- Neil Petchers, 2003. Combined Heating, cooling and power handbook: technologies and applications. The Fairmont Press, INC.
- New Buildings Institute for the Southern California Gas Company, 1998. Absorption Chillers.
- United Nations, 2008. International Standard Industrial Classification of All Economic Activities (ISIC), Rev. 4.