Universitat Rovira i Virgili

Escola Tècnica Superior d'Enginyeria Química

Boston Consulting Group

Comparative Study of Fuel Switch as a Decarbonization Strategy in Latin American Refinery Complexes

Master thesis presented by Júlia Jiménez i Cristià

to obtain the Master degree in Chemical Engineering from the Universitat Rovira i Virgili

Company Supervisor: Eric Crusafon

URV Tutor: Youssef Stiriba

Tarragona, January 2024

Table of contents

Nomenclature

- BCG: Boston Consulting Group
- BG: Biogas
- BICGT: Biomass internal combustion gas turbine
- BIGCC: Biomass internal gasification combined cycle
- CapEx: Capital Expenses
- CCUS: Carbon Capture and Utilization or Storage
- EBITDA: Earnings Before Interests, Taxes, Depreciation and Amortization
- ETSAP: Energy Technology Systems Analysis Program
- FCF: Free Cash Flow
- FS: Fuel Switch
- GHGs: Green house gases
- HTC: Hydrothermal Carbonization
- HTL: Hydrothermal Liquefaction
- IEA: International Energy Agency
- IRENA: International Renewable Energy Agency
- ktpy or ktp/y: kilo tonnes per year
- LF: Location Factor
- LHV: Low Heating Value
- MACC: Marginal Abatement Cost Curve
- NG: Natural Gas
- NOPLAT: Net Operating Profit Less Adjusted Taxes
- NPV: Net present value
- OpEx: Operational Expenses
- Tpy or tp/y: tonnes per year
- TRL: Technology Readiness Level
- WACC: Weighted Average Cost of Capital
- WISDOM: Woodfuels Integrated Supply/Demand Overview Mapping
- Wt. %: Weight percentage

List of figures and table

Summary

This study aims to explore the potential of implementing Fuel Switch as a possible lever to elaborate a decarbonization plan for some specific refineries placed in Latin America.

To accomplish this, the refining concept is introduced, exposing its activity, the sectors it involves, the processes carried out and the products obtained through them, the associated emissions and their scope, and other key factors related to refineries' operations.

Overall, the project looks into the use of Fuel Switch as a sustainable lever that entails using low-emission fuels in refinery processes, such as sustainable biogas or syngas, instead of consuming traditional fossil fuels. This approach is the basis of the proposal since, together with additional decarbonization levers, it leads to the reduction of the linked greenhouse gases emissions (GHGs) that refinery complexes generate during operations across upstream, midstream and downstream processes.

Some research has been done with respect to composition and use of biogas, to discover how different organic wastes are anaerobically digested to produce it. Additionally, various implementation scenarios have been considered for the fuel switch strategy, which will ensure the adequate execution of the individual projects according to the feedstock and operational requirements.

The study also includes a detailed analysis of how fuel switching affects the economic and energetic performance of the studied facilities, as well as a consideration of whether such modifications to refinery operations are feasible.

In summary, the project intends to provide an exhaustive understanding of how Fuel Switch may help in the environmental issues held by refineries, by offering a combination of research and a practical case study.

1. INTRODUCTION

Greenhouse gases (GHGs) are gaseous components that contribute to the accumulation of heat in the Earth's atmosphere, which results in a phenomenon called global warming. Some of the most common GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and some industrial gases such as chlorofluorocarbons (CFCs).

Despite the fact that GHGs are natural and vital to maintaining a certain temperature on Earth (the so-called greenhouse effect), they are excessively increasing because of human activity, especially through the burning of fossil fuels, deforestation and other industrial processes. This is becoming a serious problem since it is unbalancing the greenhouse effect. As a result, the global temperature is rising at an accelerated rate, which has significant consequences for today's world and the future.

Taking a look at *Figure 1*, the mentioned phenomenon can be appreciated; according to the Global Carbon Budget 2022 Report, CO_2 emissions coming from fossil fuels and industry emissions have increased exponentially through the years, reaching more than 37 billion tonnes nowadays.

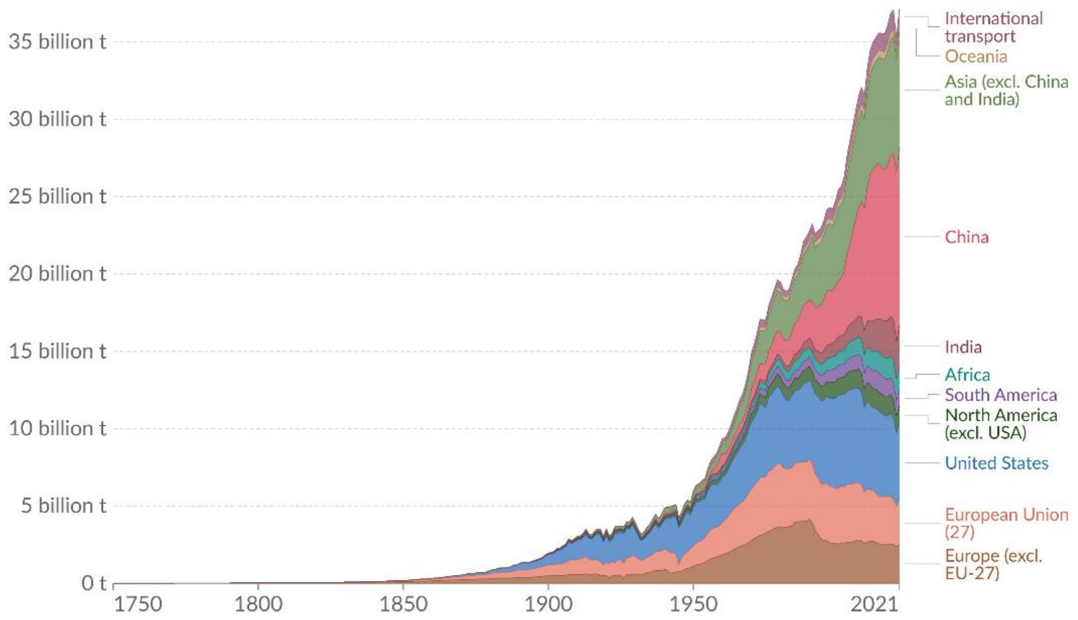

Figure 1. Annual CO2 emissions by world region, 2022 (billion tpy) [1]

As it is clearly represented, Asian countries contribute significantly to global CO_2 emissions mainly due to the rapid industrialization that they have experienced for the last decades, as well as to the large populations and the economic growth that has consequently been developed. This growth has led to an increase in energy demand, which has been met by burning fossil fuels such as coal. In addition, rapid urbanization in these regions increases energy consumption and emissions even more.

Despite the fact that European countries do not emit such a level of GHGs, it is imperative to consider the magnitude of their emissions, as these exceed 5 billion tonnes nowadays.

In this way, long-term risks related to this phenomenon are gaining more importance as they become diverse and impactful.

Some of these risks include the concerning concept of climate change. This phenomenon involves long-term changes regarding temperatures and climate patterns in an extreme way, such as heatwaves, the melting of polar ice caps and glaciers, intense storms… Although it can have natural causes such as the solar activity or volcanic eruptions, human activities have been the main factor for the last centuries, especially with the burning of fossil fuels (coal, oil and gas). Activities such as driving cars or heating buildings are the ones that involve this burning, which produces GHGs. There are some other human activities like agriculture, deforestation and the oil and gas industry that produce these GHGs that cause the increase of the globe's temperature. Actually, sectors such as energy, industry, transport, construction and agriculture are currently the biggest emitters. This entails that the average temperature of the Earth is now 1.1 °C higher than at the end of the 19th century.

Furthermore, the contribution of these phenomena leads to an impact on biodiversity that may involve changes in ecosystems and in species distribution, since atmospheric changes significantly affect their habitats. Focusing on the marine life, the increase and accumulation of CO_2 in the atmosphere leads to the absorption of a large portion of it by the oceans. Consequently, the so-called ocean acidification phenomenon occurs, which basically refers to the decrease in ocean pH levels; that is, when atmospheric carbon dioxide dissolves in seawater, carbonic acid is formed, making the oceans more acidic. This process particularly affects marine life that relies on calcium carbonate for shells and skeletons, such as corals, plankton, among others, causing the disruption of marine ecosystems and its biodiversity.
Moreover, global warming is changing how long the growing season lasts in many parts of the world, which can consequently alter how insects, weeds and diseases that can damage plants and crops grow. At the end, this can be translated into food shortages due to a decline in agricultural production and safe crops. In the same way, changes in the weather also affect farm animals, influencing how they reproduce, grow and keep healthy.

Another long-term risk related to the greenhouse effect is the propagation of diseases and pandemics. The World Health Organization (WHO) states that the rising of global temperatures is expected to result in a wider spread of infectious diseases transmitted by insects such as malaria, cholera, and dengue, which is partly correlated to some extent with the migration of people for economic reasons. In addition, a rise in extreme heat conditions is likely to aggravate cardiovascular and respiratory health issues.

The fact that many other linked reactions may repercuss the planet and our lives, not only in health aspects but also in economic and social concerns, is enough to remedy the situation hence putting into practice decarbonization plans, which are essential to address the problems exposed above and to solve the forthcoming consequences.

According to TWI [2], "Decarbonization is the reduction of carbon dioxide emissions through the use of low carbon power sources, achieving a lower output of GHGs into the atmosphere", which is aligned with the validated definition provided by the Cambridge Dictionary "the process of stopping or reducing carbon gases, especially carbon dioxide, being released into the atmosphere as the result of a process, for example the burning of fossil fuels".

In other words, decarbonization involves reducing or eliminating dependence on fossil fuels, which are the main GHGs emitters. This is achieved through the transition to cleaner and renewable sources of energy, such as solar, wind, hydroelectric and nuclear, as well as through sustainable practices in industry, transport and agriculture. This process is key to meet the global temperature standards set by the Paris Agreement and UK government, among other sustainable practices.

In fact, it all started in the 19th century, when some scientific studies started to understand the environmental effects of fossil fuels and climate change. Specifically, in 1896, a Swedish scientist called Svante Arrhenius first suggested that burning fossil fuels could increase CO_2 levels and cause global warming. Wider awareness of how fossil fuels affect the environment, especially climate change, became more pronounced in the second half of the 20th century.

The current concern for decarbonization grew from this increased understanding. This movement has been driven by scientists, environmental activists, and global organizations, taking important steps that include establishing the Intergovernmental Panel on Climate Change (IPCC) in 1988, holding the Earth Summit in 1992, and creating international agreements like the Kyoto Protocol in 1997 and the Paris Agreement in 2015 (see *Figure 2*).

These decarbonizing plans seek to limit GHGs emissions to avoid global warming and mitigate its impacts. They also focus on adapting to ongoing climate change to reduce future risks. In addition, decarbonization not only has environmental benefits, but can also generate economic opportunities and improve quality of life in the long term.

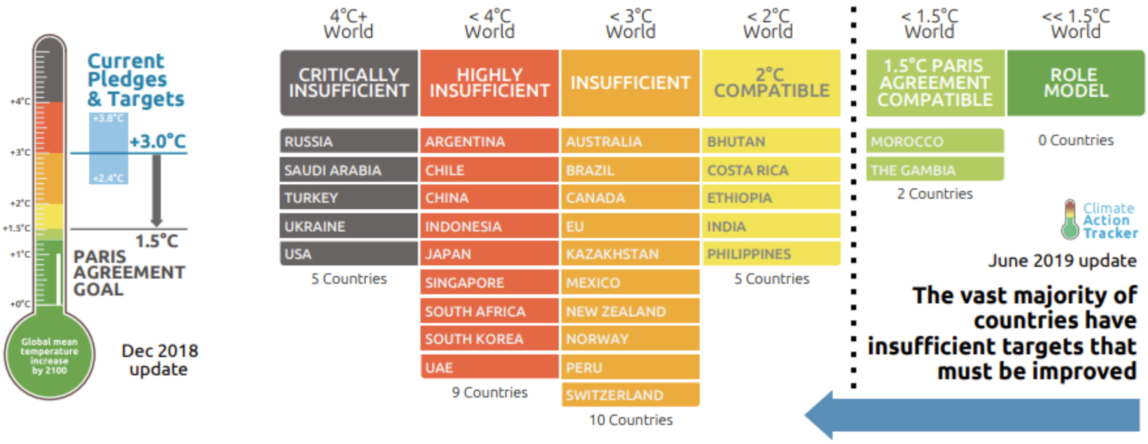

Figure 2. Current Pledges and Targets towards the temperature goal established in the Paris Agreement [3]

Although the vast majority of countries have targets that are inadequate thus, they have no chance of meeting the 1.5°C temperature goal of the Paris Agreement, considering the current situation and according to existing regulations aimed at reducing emissions, it is uncommon to find a company that is not implementing decarbonization measures in its processes yet or contributing to the mitigation of GHGs emissions in any other way. As shown in *Figure 3*, many companies have already set a clear objective that is to achieve "Net Zero" status by 2050.

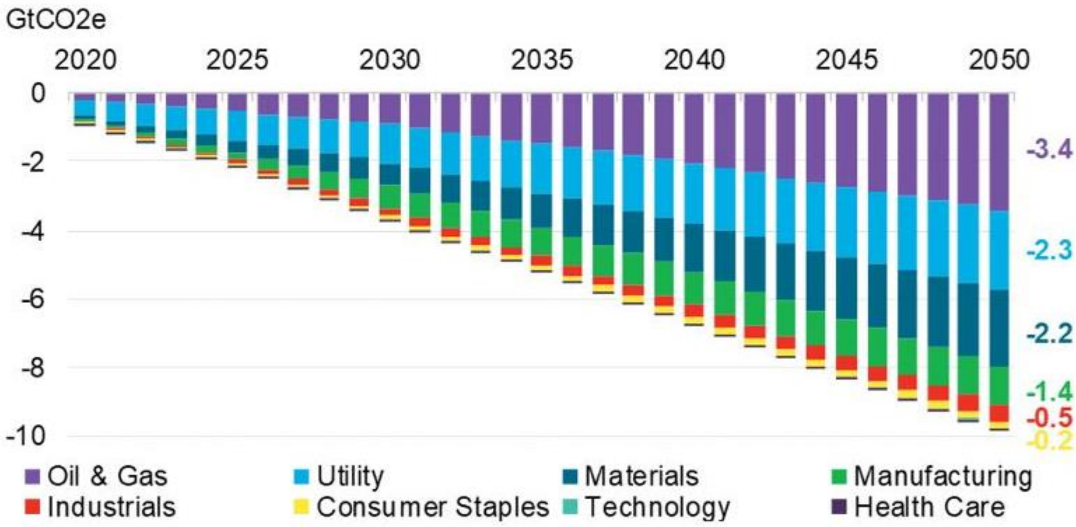

Figure 3. Emmission reductions for Cimate Action 100+ focus companies with Net-Zero goals [4]

Actually, there are many well-known industry players that are really pushing to make a change for a net zero world and that are committed to implement sustainable and climate-positive strategies. It is worth mentioning that the Oil & Gas industry is playing a crucial role because of its contribution to the global GHGs emissions.

One of the major drivers is The Climate Pledge, which brings the world's top companies together to reach net-zero carbon emissions by 2040. It was co-founded by Global Optimism, an organization that oversees the delivery of the Paris Agreement, and Amazon. Specifically, it is powered by 463 companies around the globe that involve 58 different kinds of industries. Around 30 % of the companies that take part in this organization are dedicated to engineering-related sectors, such as fossil fuels, infrastructure, manufacturing, materials, transportation services, power generation… Although the vast majority of these companies are established in the United States and the United Kingdom, the mission of the organization already covers the whole globe, reaching up to 41 countries.

The following *Figure 4* shows the first 24 companies to join the organization back to 2019.

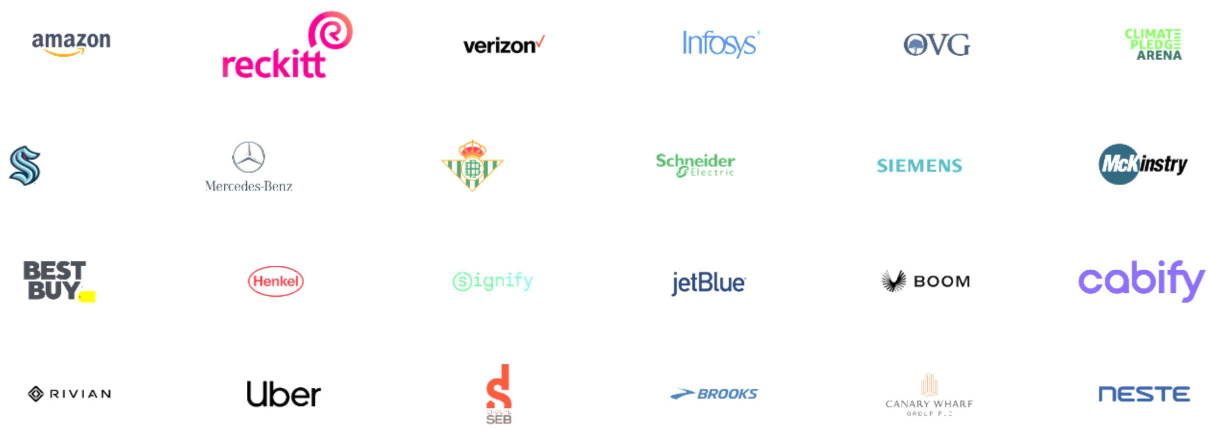

Figure 4. First 24 companies to join The Climate Pledge [5]

At the same time, this organization collaborates with several partners, such as Race to Zero or We Mean Business, which are aligned with its purpose and that are currently leading great actions in order to generate a big impact. These campaigns are dedicated to build a sustainable growth together with businesses, cities, regions, investors, educational and financial institutions… for a zero-carbon recovery.

Therefore, many initiatives are already launched and moving forward to achieve the global objective of reaching net-zero carbon emissions. Here are some of the most influential companies in this field, which are advancing and improving in leaps and bounds towards this objective and which are really making a difference, demonstrating their strength in their respective sectors.

- **CEMEX**
    - Industry: Cement
    - Headquarters: Mexico

Committed to reaching net-zero by 2050, it has increased its emissions reduction target from 30 to 35 % by 2030.

- **Coca-Cola HBC**
    - Industry: Beverage manufacturing
    - Headquarters: Switzerland

Coca-Cola HBC is currently working with suppliers to address 90% of emissions in scope 3 and intends to reach net-zero carbon emissions by 2040 through its plan, track record and partnership approach.

- **L'Oréal**
    - Industry: Personal care
    - Headquarters: France

It is a member of SBTi and Race to Zero, achieving an 87% reduction in CO_2 emissions since 2005 without carbon-offsetting. Furthermore, this company is targeting to use 100% renewable energy by 2025.

- **Maersk**
    - Industry: Shipping
    - Headquarters: Denmark

Since shipping accounts for a significant amount scope 3 emissions, this company is committed to reach net-zero GHGs emissions by 2040 and it states that "More than half of Maersk's top 200 customers have ambitious science-based or zero-carbon targets for their supply chain".

- **Microsoft**
    - Industry: Information Technology
    - Headquarters: United States

Microsoft already achieved carbon net zero in 2012 and aims to be carbon negative by 2030. Many initiatives are being taken by this company to do so, such as investing $1B in a climate innovation fund, transitioning to renewable energy, and focusing on water usage reduction and waste management. In addition, not only it is a member of The Climate Pledge, mentioned before, but it also recently shared that they will "expand our internal carbon fee to start charging not only our direct emissions but those from our supply and value chains".

- **Salesforce**
    - Industry: Software Technology
    - Headquarters: United States

Taking part in the signatories of The Climate Pledge and being a partner of Race To Zero, this company has launched a nature-positive strategy to reduce environmental impacts and to lead nature restoration, thus encouraging other companies to integrate nature into their climate strategies.

- **Sasol**
    - Industry: Oil & Gas
    - Headquarters: South Africa

Planning to reduce GHGs emissions by 30% in 2030 and reach net zero by 2050, Sasol has expanded their target to also address scope 3 emissions through the direct decarbonization of their existing assets.

- **Swire Properties**
    - Industry: Real Estate
    - Headquarters: Hong Kong

This company has pledged to reach net-zero emissions by 2050 and it starts to do so by signing for the campaign "Business Ambition for 1,5 ªC".

- **Unilever**
    - Industry: Consumer goods
    - Headquarters: United Kingdom

It is a member of The Climate Pledge and it aims to reduce by half the food waste by 2025. Unilever has already made great advances in GHGs emissions reduction and it is working for a deforestation-free supply chain, for regenerating land, forests and oceans, and with sustainable sourcing initiatives in order to reduce emissions in retail stores.

- **Vodafone**
    - Industry: Telecommunications
    - Headquarters: United Kingdom

This company joined the Race To Zero back in 2019, when it all started, and since then it has been working to reach the target of eliminating scope 3 emissions linked to its own operations by 2040.

It must be noted that they all offer a great variety in terms of industries to which they are dedicated and the countries where they are established, which gives quite a hopeful view in terms of decarbonization options around the world.

2. SCOPE OF THE PROJECT

Refineries are petrochemical industrial plants that refine crude oil extracted from wells to transform it into useable products for use as fuels for transportation, heating, paving roads, for generating electricity, as feedstocks for making chemicals... Specifically, the refining processes enable to purify crude (removal of impurities) and allow to obtain high-value products such as gasoline, diesel, asphalt, kerosene, liquefied gas, oils, fuels or even ethylene and propylene.

Nevertheless, before delving into the topic and in order to comprehend the complete picture of this sector, the different segments in which the oil and gas industry (including refineries) are distributed will be briefly described; upstream, midstream and downstream (see *Figure 5*).

Upstream processes entail anything having to do with the exploration and production of oil and natural gas. Geologic studies are usually carried out in order to identify potential areas where minerals are likely to be found. This sector also includes the steps involved in the actual drilling and the extraction of oil and natural gas resources to the surface.

The following procedures are encompassed in the so-called midstream processes, which in general terms include the transportation and storage of crude oil and natural gas after being extracted from the soil. In other words, midstream sector includes pipelines and all the infrastructure needed to move these resources long distances, such as pumping stations, tank trucks, rail tank cars and transcontinental tankers.

Finally, downstream processes are the most varied ones, since they involve any refining or processing procedure that converts crude and gas into thousands of final products, such as gasoline, diesel, kerosene, jet fuels, heating oils, asphalt for building roads, synthetic rubbers, fertilizers, preservatives, containers, and plastics.

Figure 5. Typical sectors of refining industry

Therefore, distillation processes, which are carried out in the downstream industry to transform heavy oils into lighter products, consist of heating up crude at different temperatures in order to obtain its derivatives. This fractional distillation emits polluting gases such as sulfur dioxide, nitrogen dioxide, carbon dioxide, carbon monoxide, methane, hydrogen fluoride, dioxins, chlorine among other gases.

In this way, as it is clearly exposed, refineries are significant contributors to GHGs emissions due to their operating processes, thus it is important to consider all the possible decarbonizing projects that may be implemented within them.

Hence, in accordance with the disclosed concepts, this Final Master Thesis will be dedicated to establishing a decarbonization plan for a refinery in Latin America; specifically, it will be focused on the study of some initiatives in order to assess and improve its performance. The project will provide the company with knowledge and expertise in what concerns the decarbonization of their 3 industrial complexes spread around the territory, taking scope 1 and 2 emissions as the basis (the concept of “scopes” is included in the “State of the art” section below).

Although the refinery owner company information is confidential, this project copes with realistic data which is coherently used to develop and implement the methodology taught by the Boston Consulting Group company (BCG) to work on the decarbonization options.

Moreover, an Excel model has been developed in order to deeply study the levers involved in what concerns their feasibility and economic impact on the company. It includes several data, from pertinent information regarding general and specific assumptions taken during its development, to diverse calculations related to the emissions from crude oil processed in the refinery or calculations used to obtain the abatement of each initiative and the economic balance of these.

3. ROLE IN THE COMPANY

Boston Consulting Group is a global consulting firm that combines leading and expertise capabilities to help and guide its partners to create value through strategic projects. Founded in 1963 by Bruce Henderson, BCG is now a company that is spread around the world, collaborating with great clients that rank among the world's largest corporations.

The purpose of this company is: "unlocking the potential of those who advance the world" by implementing traditional methodologies combined with new perspectives to solve complex issues. BCG collaborates closely with clients and drives business strategies to embrace and help develop their potential that will impact on their performance, according to their specific needs.

BCG's consulting projects reach a wide range of industries that include:

- Aerospace and Defense
- Automotive Industry
- Consumer Products Industry
- Education
- Energy
- Financial Institutions
- Health Care Industry
- Industrial Goods
- Insurance Industry
- Principal Investors and Private Equity
- Public Sector
- Retail Industry
- Technology, Media, and Telecommunications
- Transportation and Logistics
- Travel and Tourism

The opportunity to work with different sectors and developing such diverse capabilities, gives the company a broad expertise to transform nearly any organization in the world.

My work at BCG has consisted in supporting different strategic projects carried out in the Energy department. My role as solution analyst intern has been key to complete the consulting teams which I have worked with to deliver the clients' requirements or demands according to each project.

During my stay in BCG, aside from the Latin America project which this Final Thesis project is based on, I have had the pleasure to work for other clients in different regions, such as Saudi Arabia, Oman and Germany, which has contributed to my knowledge development concerning the cultural differences when establishing client-company relationships (or business to consumer relationship, B2C).

Even though most of the projects sold in the consultancy are international projects, my position in the company (intern) did not allow me to travel during the internship. Therefore, my stay in the company was based in the Barcelona office.

In all the projects I have taken part in, despite their objective or industry sector, my specific tasks have been to carry out different sorts of calculations and models definition in excel files, to prepare the information and design presentations to show to the clients, among other more project-related activities.

The first project I joined was a refinery decarbonization project in Karlsruhe, Germany. My job for one week was to do some research concerning the hydrogen market established in the zone. The objective was to propose, study and develop several strategic levers to contribute to the refinery's decarbonization. I was in charge of searching information regarding the hydrogen demand in Germany, the public and private projects already in operation in the region and other hydrogen production processes information.

Afterwards, I was set up for more than 2 months in a project that had the objective of implementing and enhancing best industry practices, in terms of process safety, in an important petrochemical industry player in Saudi Arabia.

The consulting team and I started by analyzing all the client data concerning the job profiles and their job roles in the company's facilities. After mapping and properly categorizing all the information, the team travelled to the site to make some interviews to the employees, including general managers, heads of sections, supervisors, superintendents, operators, technicians, and other positions among all departments. The objective of the interviews was to evaluate the competences they had and assessing them considering the regularized training requirements for each position in the petrochemical sector.

Some established models were used to do so, such as the CCPS Risk Based Process Safety methodology delivered by the Center for Chemical Process Safety. This model defines 5 pillars and 20 elements that englobe all the competences that any employee in the industry must acquire, according, of course, to their level of proficiency. In this way, the project involved studying the current client's situation with respect to this model and other process standards in order to prepare and build some matrices that allowed to measure the gap between its performance and the expected outcome.

The development of the competency and training matrices were key materials to define the company's requirements to reach the adequate and expected plant performance.

The third project in which I was involved in the consultancy was the one I am exposing in this Thesis report, which, as I have exposed previously, consisted in implementing several decarbonization levers to some refineries placed in Latin America. The work I was assigned was to do some research for the "Fuel Switch" lever and implementing it to the client's situation, regarding their emissions baseline.

The tasks that were included in this role were the following:

- To gain knowledge and perspective about fuel switching and the processes it involves.
- To search for information concerning related projects already in operation across the country where the client is established, in order to analyze the offer and demand of sustainable products.
- To acquire consciousness about the specific constraints and factors that the lever depends on in order to be introduced in a refinery.
- The more adequate technologies to carry out the lever and their requirements.
- The raw materials which are needed to implement the different technologies chosen.
- To identify the feedstock availability in the complexes' region and the acquiring options.
- To create and develop the excel model that includes all the calculations regarding the implementation of the lever to the refineries.
- To calculate the potential reduction of emissions due to natural gas through the introduction of fuel switch to the facilities.
- To generate Marginal Abatement Cost Curves from the data calculated and evaluate the viability of implementing the lever.
- To calculate the economic impact of carrying this fuel switch in the refineries.
- To prepare different kinds of slides to show the project progress in diverse client meetings.
- To create a user manual for the client to understand the organization and the functioning of the model in case some other initiative must be added or modified.

A more detailed description of the project will be shown in the following sections.

Finally, during the last month, I have participated in a benchmarking study for a company that possesses many assets across Oman. Due to the internship finalization, this is the first project in which I have had the opportunity to actively participate in the client meetings.

The client owns nine business units that include from upstream and downstream processes to commercial and supplying assets. They entail from the crude extraction and processing to the petrochemicals and special chemicals production and distribution.

The work itself consisted in studying all the data, which we requested to the client, related to the operational and capital expenses of the different facilities, the gross margin, the working capital, among other important information needed to compare the company's performance against the main competitors. In this way, the objective was to provide an insight of the existing opportunities to reduce the identified gap with the benchmark and thus, to enhance their activity and increase the profit of each asset.

The overall experience has given me a small overview of what the world of consulting is, and it has allowed me to enter the professional world in a very profitable way, being able to undertake projects of all kinds.

At the same time, BCG has given me the tools and has taught me how to deliver value to any project. Therefore, these internships provide BCG with new talents that are built in the company and that will grow inside of it, giving worth to the whole corporation and the projects it is involved in. The fact of training interns within the company allows BCG to standardize the working method and to acquire employees who will become experts after a few years of joining.

4. STATE OF THE ART

Before delving into the main topic some theoretical context should be considered and exposed, as they will gain importance in this report, such as they have been the basis of the project.

As it has been stated before, the process of decarbonizing a refinery plant consists of reducing the CO_2 emissions that it produces throughout its processes.

However, companies are responsible for different sorts of emissions which are classified within 3 categories called *scopes* (see *Figure 6*). This terminology was given by the Greenhouse Gas Protocol, which is the go-to standard for tracking GHGs emissions globally and it intends to help companies understand all emissions and thus see the complete picture of their impact; not only what they directly produce, but also the emissions linked to their suppliers and customers (the so-called 'value chain'). This also helps companies to target their efforts when it comes to reducing or cutting emissions.

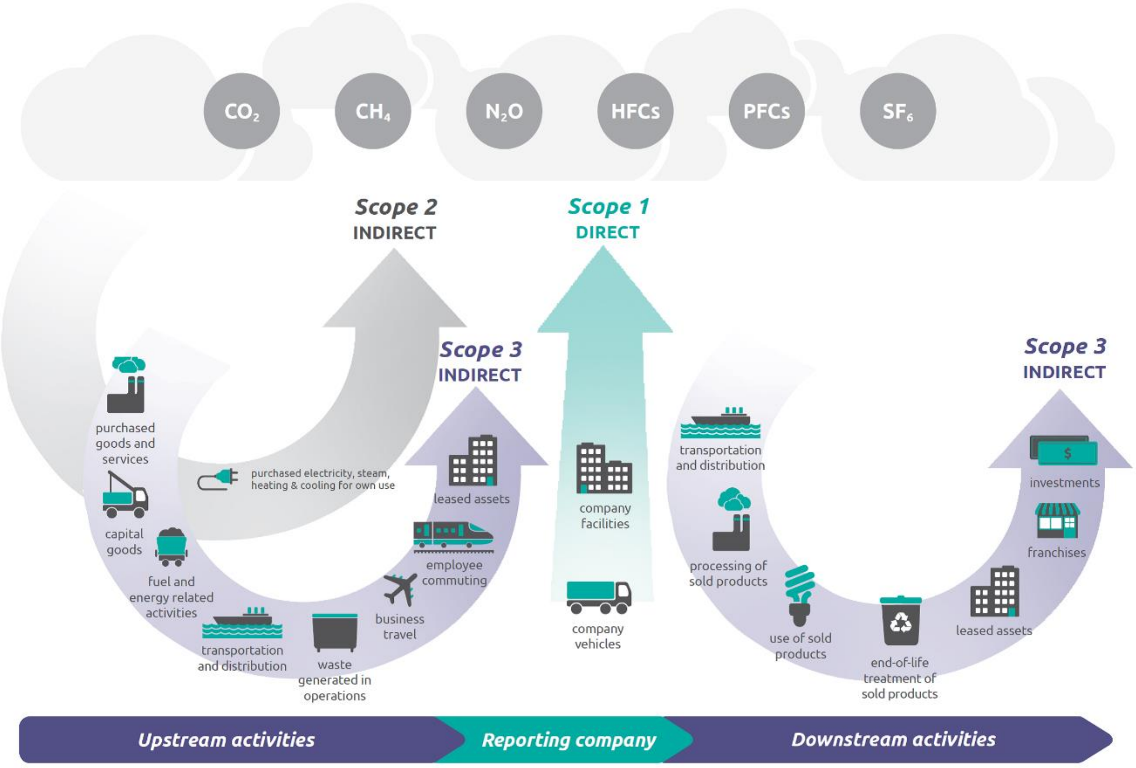

Figure 6. Overview of GHG Protocol scopes and emissions across the value chain [6]

In general terms, scope 1 emissions are direct emissions linked to sources owned by the company while scope 2 emissions are indirect emissions that come from the generation of purchased energy. That is, the first category englobes all the emissions from sources that the organization owns and controls directly, such as the ones emitted from space heating or from burning fuel in the company's vehicles. Alternatively, the second group involves emissions that come from where the energy that the company uses or purchases is produced, like for instance the emissions produced by the generation of electricity that is used in the facilities.

On the other hand, emissions involved in indirect upstream and downstream activities such as transportation services among others, are not considered in this study. Although these value chain emissions, also known as scope 3 emissions, hold the majority of the GHGs produced by a company, trying to decarbonize it implies a lot more resources and complexity, hence they will not be involved in the project.

Based on the current recorded emissions, a future projection of the refinery's emissions has been estimated, according to the criteria considered by the BCG team:

- The calculation has been based on the projection of processed crude oil, which has been estimated from the expected performance of each complex according to the client.
- Emissions up to 2026 will increase due to the increase in processed crude, which is required to meet the need to reduce imports of fuels in the country.
- The fall in demand for fossil fuels will reduce the use of refineries from 2026 onwards.
- At the same time, the lower use of refineries will consequently mean a reduction in CO_2 emissions within 2040 and 2050.
- The calculations used to approximate this future projection have considered the current and future projects the company is working on.
- The intensity of emissions of scope 1 and 2 has been calculated from the refinery throughput recorded.
- Aside from the different scopes where emissions have been included in, they have also been classified according to the emitting source in the refinery, based on the information provided by the client.
- An automatic coding has been generated that allows to distinguish and classify the equipment of the different complexes according to the emission source that applies to each one.

4.1. Levers proposed to implement the decarbonization plan

Although there exist several levers to carry out the decarbonization of these emissions, this study has been focused on the ones that are more appropriate to be applied within the refining assets:

- Energetic Efficiency
- Electrification of boilers
- Renewable Energy
- Green Hydrogen
- CCUS
- Fuel Switch
- Offsetting

It is important to understand what these levers above imply, why they are important and what they can provide the refinery with. Nevertheless, this Final Thesis will only cope with the implementation of *Fuel switch*, in order to reduce content and to adapt to the specifications of it.

4.1.1. Fuel Switch

Fuel switch is a sustainable lever that consists of using sustainable biogas or syngas instead of natural gas in boilers and furnaces; in other words, replacing fossil fuels with low-emission fuels. In this way, the usage of biofuels helps reduce the carbon footprint of the refinery equipment.

4.1.1.1. Composition of biogas

Biogas is a fuel gas that is mainly composed by methane, ranging from 50 to 75 %; its exact final content highly depends on the feedstock and the treatment technology used to obtain it. This substance is usually produced by Anaerobic Digestion of waste (traditional waste like crop residues, animal manure, industrial residues, wastewater…), although alternative feedstock options are currently being developed, such as microalgae and seaweed, or methanation of hydrogen. This topic will be covered afterwards in more detail.

The following *Table 1* contains information about the usual composition of biogas, according to the data base of the BCG Energy Department.

Table 1. Composition of biogas.

Compound	Concentration (Vol. %)
CH_4	50 – 75
CO_2	25 – 45
CO	Traces
N_2	< 2
O_2	< 2
H_2	< 1
H_2S	20 – 20.000 ppm
NH_3	< 1
Steam	2 – 7
Volatile Organic Compounds (VOCs)	5 ppm

4.1.1.2. Uses of biogas

Despite the fact that biogas can be used for many purposes, the most common end-use application is Combined Heat and Power (CHP) generation (see *Figure 7*). The main advantage of using biogas in this way is the fact that it can be used directly, that is, there is no need to upgrade it, which would lead to economic and operational implications. Therefore, biogas is useful for power and heat generation for turbines and boilers due to its high energetic content (because of the methane content).

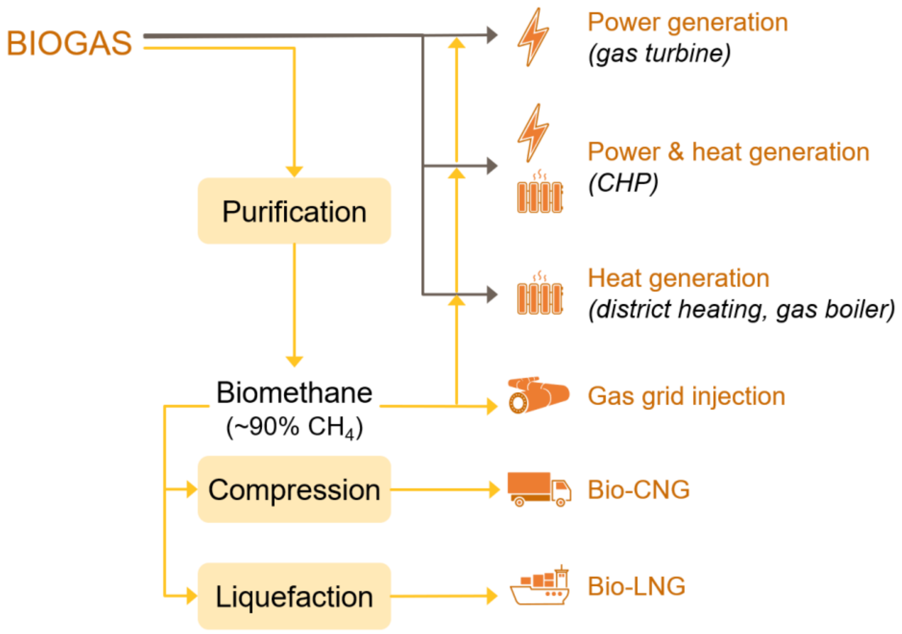

Figure 7. Biogas energetic functions

On the other hand, it is important to note that although biogas can be directly used for many interesting applications, upgrading this product to biomethane can be beneficial when a higher purity of methane is required, such as for injection into natural gas grids or for use as a vehicle fuel.

4.1.1.3. Archetypes for Fuel Switch implementation

Several archetypes have been proposed in order to implement the Fuel Switch lever to the refining complexes and purchase the required biogas.

- Gas Purchase Agreement:

The first option is to purchase de biogas produced by a third-party plant already in operation.

- On-site biogas production:

The second possibility is to produce the biogas in a facility built in close proximity to the client's refinery; that is to produce the biogas required to feed the refining complex, according to the current natural gas consumption.

- Gas pipeline connection:

The last option considered is to acquire the raw material (waste) and to produce the biogas nearby key access points to gas pipelines hence, to distribute the produced biogas from high-biomass-availability locations to the refining complexes through the pipelines.

Analyzing these implementation options is key to check the weak points and the advantages that each one implies in order to select the most appropriate one.

The following *Table 2* sums up the main key points for the concepts exposed above.

Table 2. Advantages and disadvantages of scenarios proposed

	Gas Purchase Agreement	On-site biogas production	Gas pipeline connection
Advantages	- No need for plant construction - No need for raw material acquisition	- Own production - Savings in transportation costs	- Strategic point for raw material availability - Potential for agreements and market opening depending on the production area
Disadvantages	- Higher cost due to the intervention of an intermediary - Transportation costs may apply, depending on the pipeline used	- CAPEX and OPEX investment required - Limited availability of raw materials	- CAPEX and OPEX investment required - Transportation costs

Gas pipeline connection archetype will be prioritized due to the limitation of biomass availability, which is an important constraint of the project. Not all kinds of waste are adequate for biogas production, nor this biomass is available throughout the whole territory comprised by Latin America. Therefore, the last archetype proposed, combined with the on-site biogas production (if client's complexes are located nearby high-biomass-availability locations) is a perfect combination to implement and acquire the required biogas.

4.1.1.4. <u>Types of biomass for biogas production</u>

As it has already been mentioned, a certain type of waste is optimal to produce biogas because of their carbon composition and energy content.

The following scheme (*Figure 8*) shows different types of waste and the final product for which they are more adequate, depending on their characteristics and their performance.

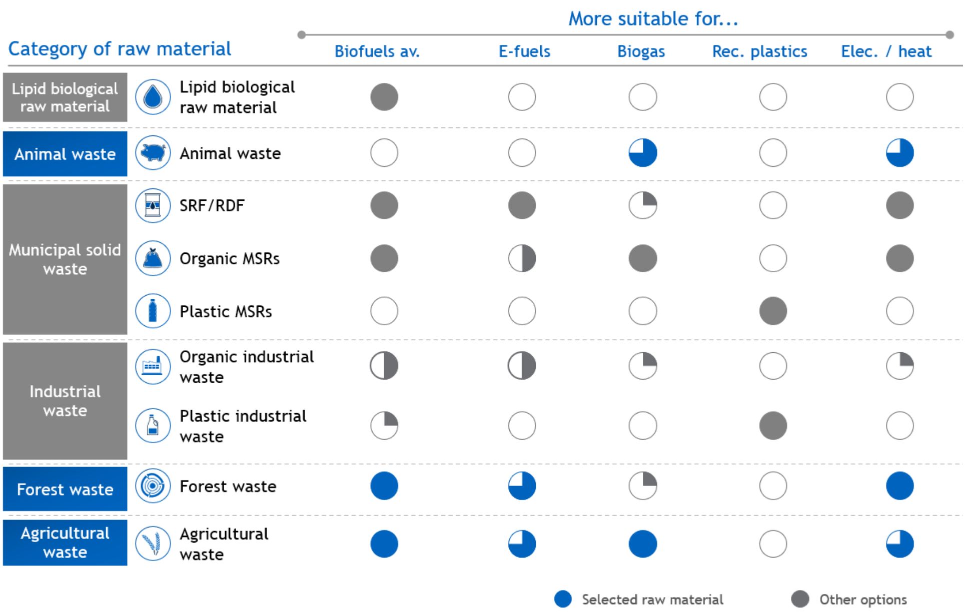

Figure 8. Feedstock adequacy for final products [7]

Three types of waste have been selected for this project, according to the criteria explained above: animal waste, agricultural and wood residues. Aside from being easily available residues as by-products of farming, forestry, and livestock rearing activities, using this type of waste is a sustainable option because it does not compete with food supply, a debate that is common nowadays.

Here are some data regarding the composition of some of the organic biomass identified as the optimal to produce biogas. As it can be appreciated (see *Table 3*), carbon is the most dominant element in the composition of these residues, which offers them a high potential for biodegradability and methane yield. In fact, biomass energy content is highly dependent on feedstock type. Animal manure, for instance, is rich in organic matter that can produce significant amounts of methane, which at the end is the key component of biogas.

Table 3. Feedstock composition and other properties

	Wood and wood residues		**Agricultural residues**		**Construction residues**	**Energy crops**	**Units**
	Clean wood	**Bark from spruce**	**Straw from wheat**	**Grass Red canary**	**Waste/demolition wood**	**Salix**	
Moisture	50	55 - 65	55	60	15 - 20	50	Wt % of wet fuel
Ash	1,3	2,34	4,71	8,85	0,9	1,18	Wt % of dry fuel
Fixed C	13,2	22,46	17,59	17,65	-	18,92	Wt % of dry fuel
HHV	19,2	19,83	18,94	18,37	15,4	19,75	MJ/kg
LHV	15,4	18,54	17,65	17,13	13,9	18,42	MJ/kg
Composition							
C	49,1	51,1	49,6	49,4	48,8	50,3	Wt % (daf)
H	6,00	6,04	6,16	6,25	5,25	6,17	Wt % (daf)
O	44,3	42,4	43,5	42,7	45,6	43,1	Wt % (daf)
N	0,48	0,41	0,61	1,54	0,15	0,40	Wt % (daf)
S	0,01	0,03	0,07	0,15	0,03	0,03	Wt % (daf)
Cl	0,10	0,03	0,18	0,07	0,08	0,004	Wt % (daf)

4.1.1.5. <u>Biogas production</u>

Having exposed the main key factors to implement biogas production, the only remaining concept is, how can these sustainable fuels be obtained?

In general terms, biomass typical use is burning feedstock directly in a boiler to produce steam, which can be used for power and/or for heat generation. Therefore, although it is not a complex process, several steps can be stated (see *Figure 9*) to wholly describe it, which comprise the following:

1. <u>Feedstock reception:</u> When biomass, which refers to waste usually with more than 60% of moisture content, is received, weight and moisture content measures are carried out, as well as random visual inspections in order to control its general quality.

2. Management and storage: Afterwards, the feedstock is stored in a yard, whose volume will significantly influence the project CapEx.
3. Waste preparation: Before entering the boiler unit, biomass can be pre-treated with drying and grinding techniques, in order to fulfil the size requirements. Nevertheless, pre-treatment may not be needed depending on the type of boiler and the quality of the feedstock.
4. Combustion: The burning of the biomass can be carried out through 2 main combustion techniques: with fixed bed boilers or fluidized bed combustion boilers.
5. Power and/or heat generation: The steam obtained from the combustion can directly be used for heating purposes. It also can be directed to a steam turbine for power generation. On the other hand, the heat produced can also be extracted from exhaust steam out of the turbine.

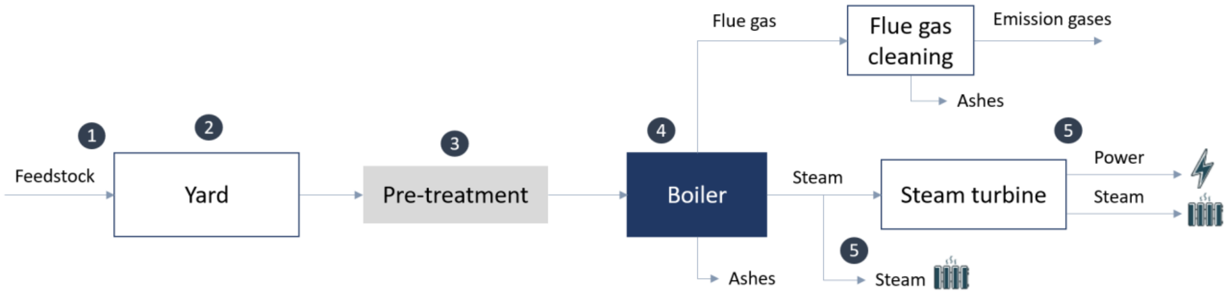

Figure 9. Usual biomass processing

Various waste recovery technologies are based on this general process outlined above. Their level of maturity will play a crucial role in selecting the most appropriate technology for implementing the Fuel Switch lever in the client's refineries.

This concept, known as Technology Readiness Level (TRL), corresponds to the current state of the technology in terms of development and utilization at a given point in time, which is categorized among 9 levels (see *Figure 10* below):

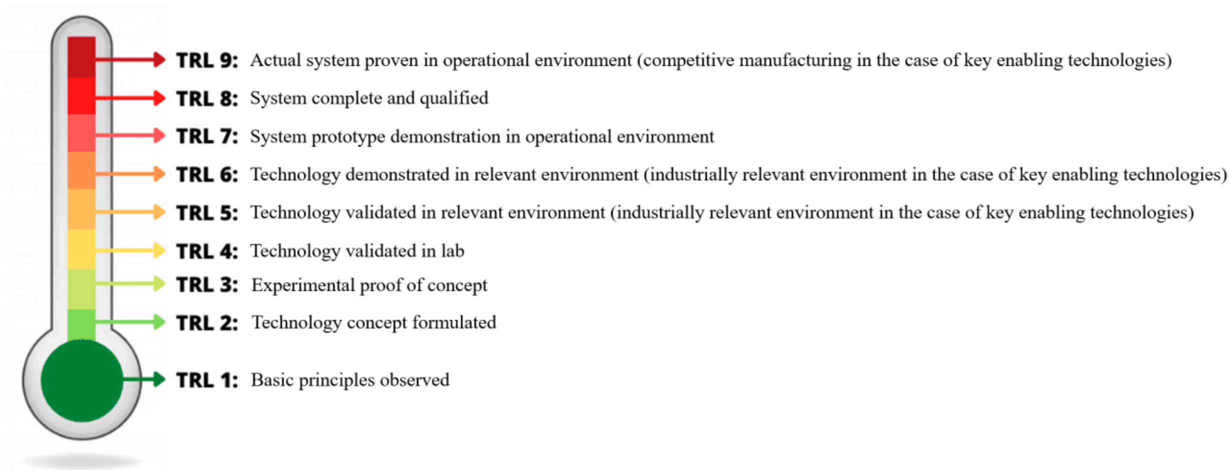

Figure 10. Technology Readiness Level (TRL) established tiers

In this way, the following scheme (*Figure 11*) shows the TRL of the waste recovery technologies previously mentioned that consist of producing biogas or syngas.

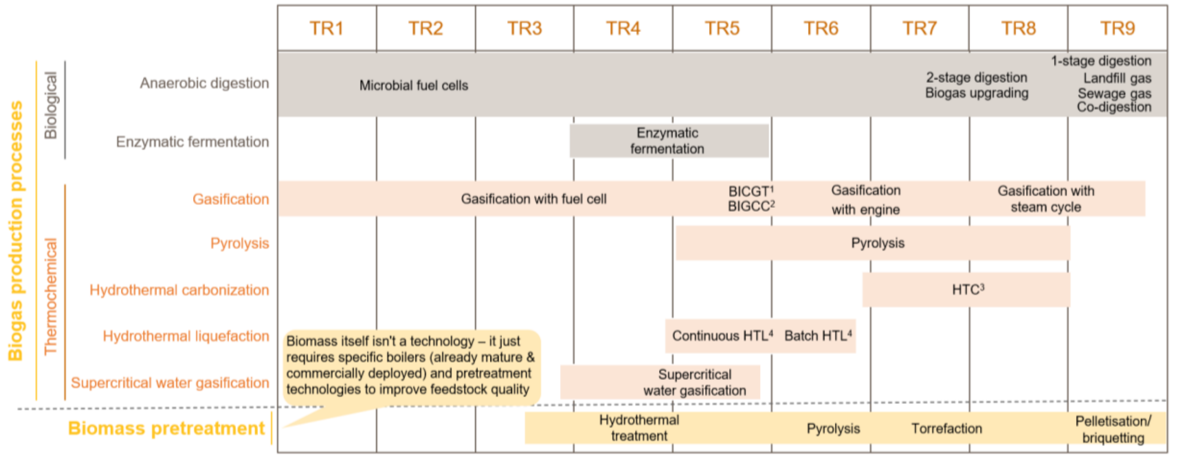

Figure 11. Overview of waste valorization technologies and their TRL status [7]

Three technologies will be key in this project, which have been selected because of their industrial maturity and their efficiency when transforming biomass into sustainable fuels.

1. Anaerobic digestion

Anaerobic digestion is a biological process that takes place inside a closed digester and consists of transforming organic materials into biogas (see *Figure 12*). The key principle that drives the process is the organic matter decomposition that microorganisms (bacteria) carry out in absence of oxygen, which is called fermentation.

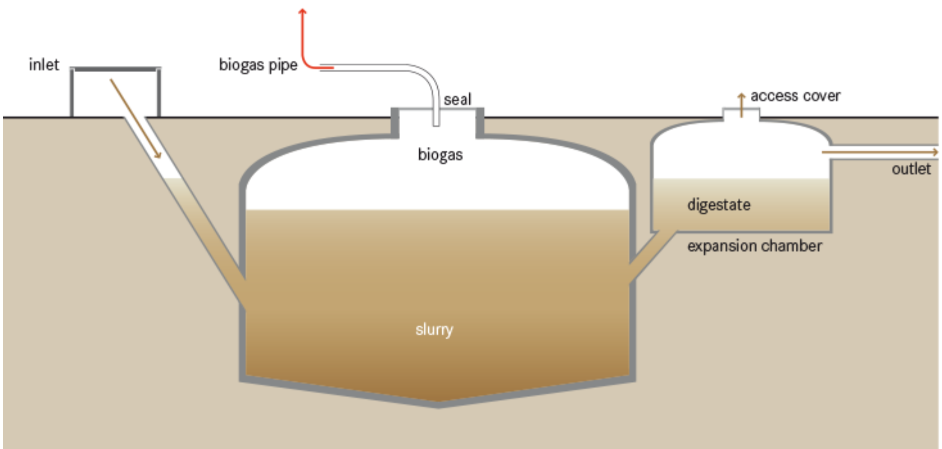

Figure 12. Anaerobic digestion process scheme

During this process, the organic matter is broken down into simpler compounds, which are transformed into volatile fatty acids. Simultaneously, these acids are consumed by methanogenic microorganisms, producing methane and carbon dioxide, which compose the final biogas generated. It is worth mentioning that the three of the selected residues are useful for this technology.

This process takes place at around 35 - 50 ºC and part of the energy obtained from the biogas produced is used to maintain this thermal condition.

On the other hand, aside from the biofuel, a solid biogenic residue is also obtained during the fermentation, which is called digestate. Specifically, it is solid left-over indigestible material and dead microorganisms from the digestion. Its density depends on the operating temperature and the type of feedstock used and it presents an alkaline pH. Its production rate will be specified later on together with the biogas obtention, when exposing the specific calculations carried out to create the model.

Leveraging this product is viable, considering its substantial utility as a fertilizer due to its composition; it presents high moisture retention properties and high content of nutrients. Therefore, great selling potential or business opportunities are expected from this residue. Agreements with agricultural partners can be established in order to exchange their residues as feedstock and digestate as fertilizer for their activities.

Capital expenditures linked to biodigesters' acquisition strongly depends on their capacity and the feedstock composition. As it is shown in *Figure 13* and according to ETSAP [8], the animal residues (manure) content in biomass input directly affects the CapEx of this technology. More detail will be exposed in the Model description section.

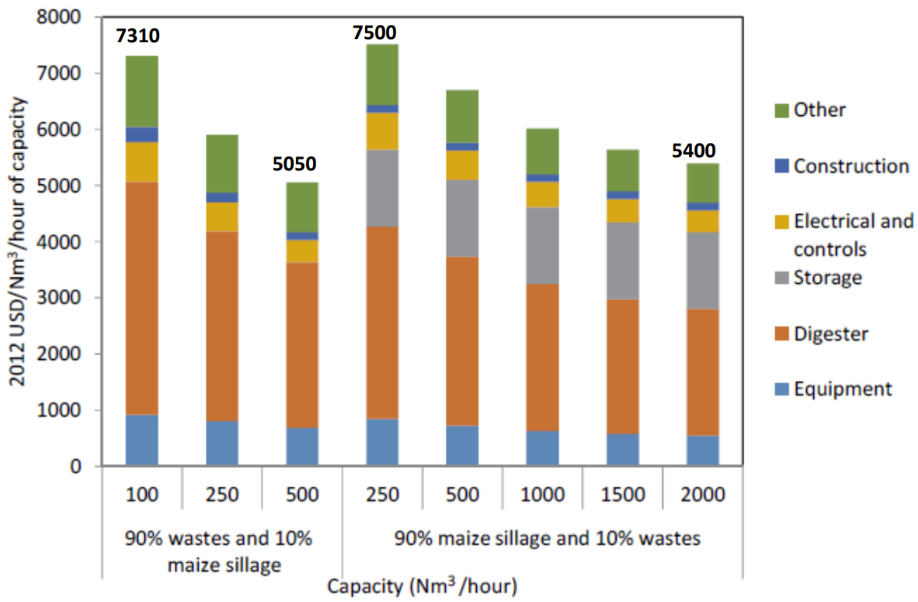

Figure 13. Capital Cost of Anaerobic Digestion Systems [8]

In addition, upgrading to biomethane can be considered, which also contributes to the costs' increase. This biogas transformation is important because biofuels transportation through gas pipelines is critically conditioned by the gas properties; that is, certain conditions must be fulfilled by gases content and purity when entering the pipelines that take them from the production plant to the consumer facilities.

Although biogas presents a slightly high methane content, natural gas infrastructures are prepared to transport methane, which makes biogas unsuitable for travelling through them. In other words, biogas upgrading to biomethane is an essential requirement to meet the established quality standards and regulations applicable to all gaseous fuels. Not only security reasons drive this transformation, but also quality and environmental compliance. Hence, biomethane compatibility with existing transport infrastructures contributes beneficially to the product distribution. *Figure 14* shown below represents the capital expenditures associated to both Anaerobic Digestion system and the pertinent upgrading process from biogas to biomethane.

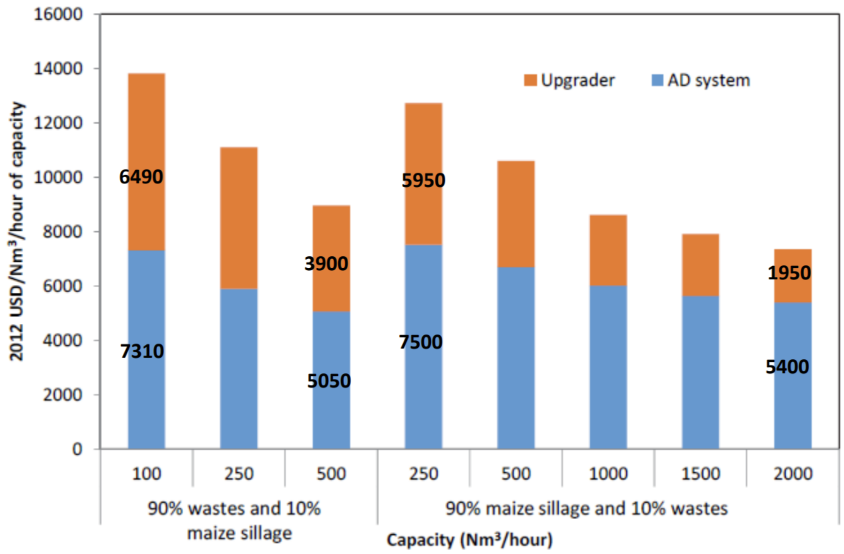

Figure 14. Capital Cost of Anaerobic Digestion systems and biogas upgrading [8]

2. Gasification

Gasification is a thermochemical process in which the reactions between biomass and the gasification agent take place at high temperatures and syngas (also known as synthesis gas) is produced.

Syngas is a biofuel with different composition to biogas (see *Table 4*), that is also usable as fuel either for electric or thermal energy generation. Nevertheless, it cannot be used directly, nor it can be poured into gas pipelines. Therefore, an essential requirement for projects based on this technology is to be implemented in the surroundings of the consumer complex.

Table 4. Syngas composition

Compound	Concentration (Vol. %)
N_2	50
CO	20
H_2	20
CO_2	8
CH_4	2

Actually, the composition of syngas is very dependent on the source fuel (i.e. biomass) fed into the gasifier, and it is also dependent on the type and technology of the gasifier and its design. For this reason, several yields can be associated with it.

Depending on the gasification agent that is used to convert the organic waste into syngas, there exist different types of gasification processes: oxygen, air, steam, carbon dioxide gasification… Even though air gasification is the simpler and cheaper one, steam gasification has been considered for this study because it results in higher LHV of syngas.

It is important to mention that only agricultural and wood residues are applicable to this technology since densities lower than 250 kg/m^3 create problems in the management of biomass in vertical ducts.

This endothermic process consists of several steps (see *Figure 15*):

1. Once biomass has been pre-treated in order to reach the targeted scale, it is dosed through the top part of the reactor and the gasification agent (in this case steam) is blown through the sides.
2. The following phase consists of combusting part of the biomass in the middle section of the reactor, also called combustion chamber, at higher temperatures (between 800 and 1 200 ºC). Natural gas is provided in order to start the partial combustion, however, in the calculations, this amount is negligible when accounting it to the gas consumption of the refining complexes.

$$C + 0_2 \rightarrow CO_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

3. Meanwhile, the generated heat goes upwards, which dries the feedstock and eliminates the vast amount of humidity. This phase takes place in the drying zone, and it can reach temperatures of 100 – 150 ºC.
4. The zone located just above the combustion chamber is characterized by the increased temperature (around 200 – 500 ºC) and lack of oxygen, which are the perfect combination for the pyrolysis of biomass to take place in. The resulting products are tar and steam.
5. The thermal degradation of biomass leads to the formation of more gasification agents due to the volatile compounds' detachment. On the other hand, the degraded matter flows downwards to the reduction chamber, also called gasification zone.

$$C + C0_2 \rightarrow 2CO$$

$$C + H_2O \rightarrow H_2 + CO$$

$$C + 2H_2 \rightarrow CH_4$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

6. The tar's cracking and the non-combusted gases form the fuel gas flow (syngas). Moreover, the residual char (also called biochar) is accumulated in the bottom part of the reactor, which can also be leveraged; it is actually a great candidate as a fertilizer.

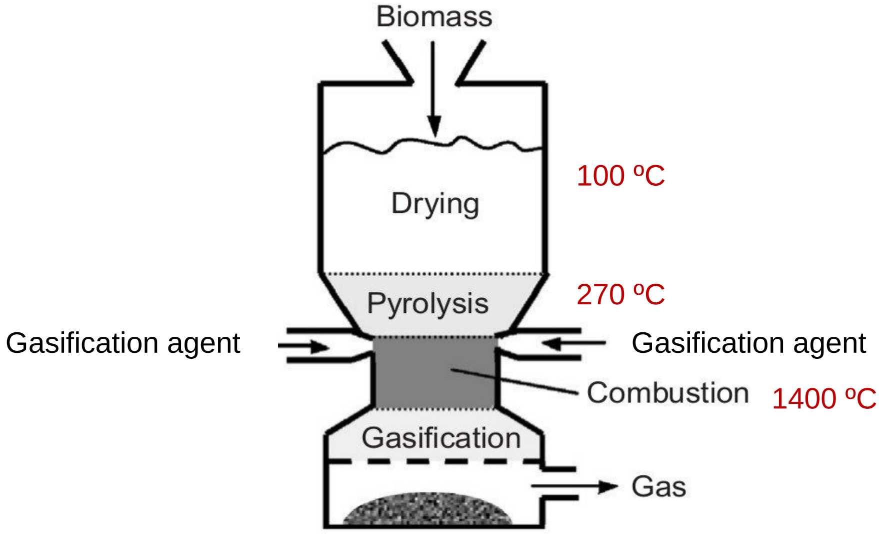

Figure 15. Gasification process scheme

Each product's rate will also be specified later on together with the syngas yield, when exposing the specific calculations carried out to create the model.

Capital expenses required for implementing this process reach significantly higher values than the anaerobic digestion related costs because of the additional complexity and imposed operational conditions, being the estimated range from 2 400 – 3 000 \$/tpy of biomass.

3. Pyrolysis

Pyrolysis is also a thermochemical process that consists of an anaerobic degradation of biomass through heating it, to obtain syngas as well. Organic matter decomposes because of the high temperatures applied (around 200 – 1 000 ºC), which are reached thanks to the heat supply through natural gas combustion.

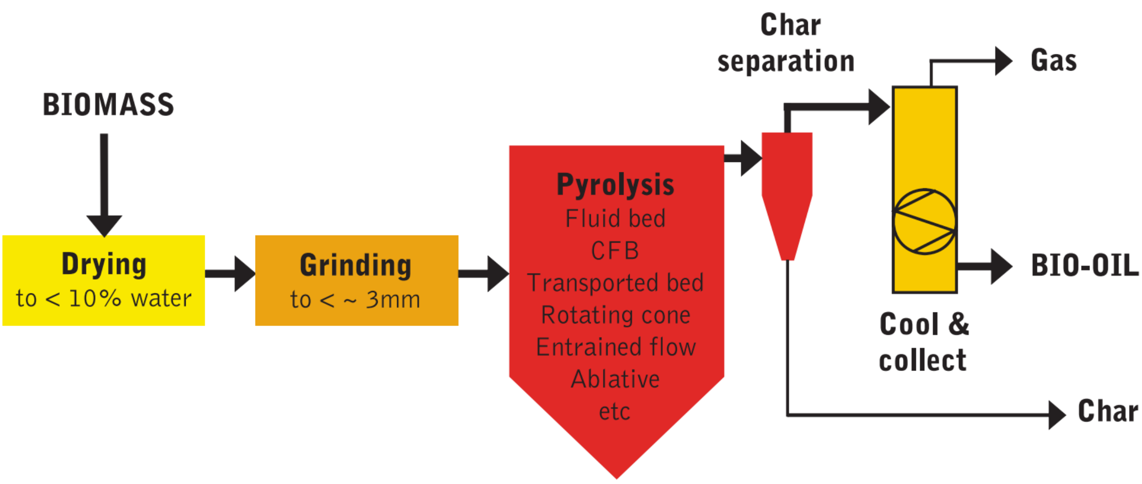

Figure 16. Pyrolysis process scheme

In this case, the reactor, unlike gasification process, is composed by a unique chamber, where all stages take place (see *Figure 16*).

To begin with, pre-treated biomass (previous grinding is required in order to introduce pellets into the reactor) is fed into the unit. After providing the required heat, humidity evaporates, and organic matter starts to decompose; several products in different phases are obtained.

On the one hand, hydrogen and oxygen molecules ascend through the reactor and are cooled down:

- Bio-oil obtention: The heaviest substances condensate at room temperature, such as water, tar and other heavy hydrocarbons.
- Syngas obtention: The lightest substances remain in gaseous phase at room temperature, like carbon monoxide, carbon dioxide, methane, ethane…)

On the other hand, the solid residue obtained (carbon, also called biochar) is accumulated at the bottom of the reactor. Despite being lighter than the original biomass, it is characterized by a higher heating value.

Despite the fact that the obtained products proportion is highly dependent on feedstock type, heat input velocity and operating temperature reached, an estimated yield has been considered for each one, which will be exposed in the following model description's section. Moreover, pyrolysis optimal performance is reached due to the utilization of agricultural and wood residues kind of biomass. As well as in gasification, other types of biomass such as municipal solid waste, may require extensive processing before conversion.

In this case, capital expenses associated with this technology reach slightly lower values than in gasification because of the equipment simplification, being the estimated range from 1 200 – 1 500 $/tpy of biomass.

Table 5 below exposes some advantages and disadvantages related to implementing each one of the technologies proposed.

Table 5. Main advantages and disadvantages of technologies proposed

	Anaerobic digestion	**Gasification**	**Pyrolysis**
Advantages	- Co-digestion of manure with agricultural residues boosts biogas production	- It can handle a wide range of biomass with high efficiency, including high S content and high viscosity	- Process parameters' optimization allows to modify the syngas and bio-oil distribution, compared to other thermochemical processes
Disadvantages	- If it is run inefficiently, odor nuisance is generated - Management of digestate	- Biomass needs to be very homogeneous	- Efficiency is highly dependent on feedstock

4.1.1.6. Latin America biomass availability

In this way, before implementing a project of these characteristics and dimensions, a biomass availability study must be carried out in the areas where the industrial complexes are placed.

Wood residues

As it is appreciated in *Figure 17* below, it is worth mentioning that Latin America comprises huge land extensions and thus, great number of trees can be found nearly in each point in the map.

Figure 17. Latin America surfaces covered by forests and crops

However, there is a significant difference between the existing forests and the biomassic wood availability; the latter is limited compared to the actual existing wood since many forests in Latin America are protected forest plantations for environmental reasons. Therefore, biomassic potential is more reduced than the expected.

The following chart (*Figure 18*) represents the total wood biomass potentially available, which corresponds to wood and other forest residues that are considered useful as biomass. Different provinces have been studied according to refinery complexes' location.

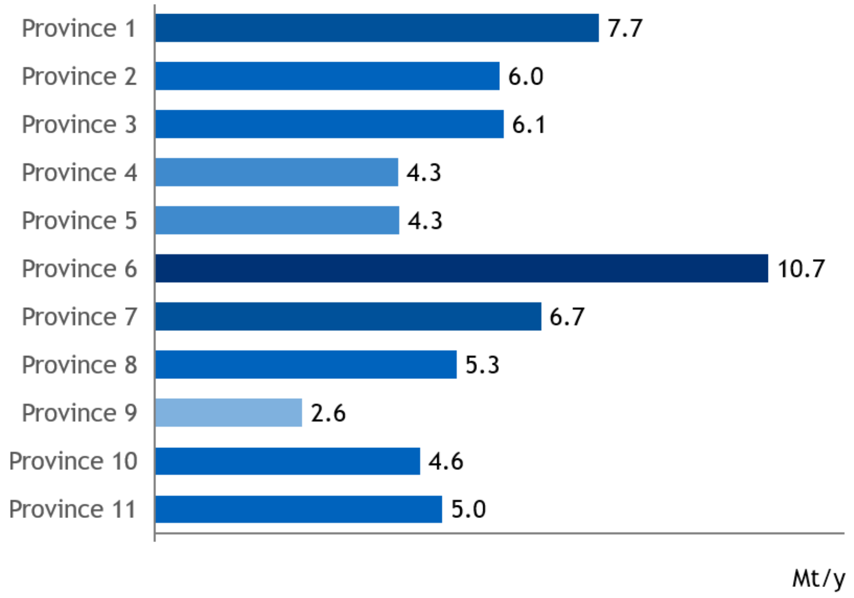

Figure 18. Total potentially available wood biomass per province (Mtpy) [9]

In this way, more than 63 Mt of wood biomass can be extracted annually from Latin America forests and can be leveraged to produce biofuels and thus reduce GHGs emissions.

Nevertheless, aside from the environmental restrictions, other physical limitations exist when it comes to this biomass acquisition. Accessibility to this kind of residues is reduced mainly because of transportation factors. That is, even though there exist accessible forests by foot, reaching those locations by trucks or other vehicles used to move biomass to the destination place is very complicated. Therefore, it has been considered that only 10% of the available biomass is actually accessible.

The total biomass used in each biogas plant will strictly depend on the location where each refinery is placed.

Animal waste

With respect to animal waste residues, also called manure, some previous research about pig and cattle breeding has been carried out to ensemble the availability data.

In the following graphics (*Figure 19* and *Figure 20*), the total number of heads of both kinds of animals considered for this project (pigs and cows) that are annually produced in the region where the client refineries are placed, are represented respectively.

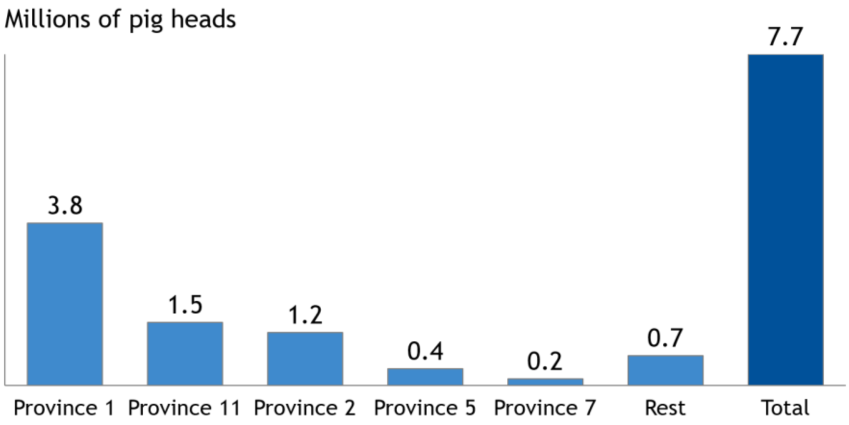

Figure 19. Annual pig slaughter distribution per province (M heads) [10]

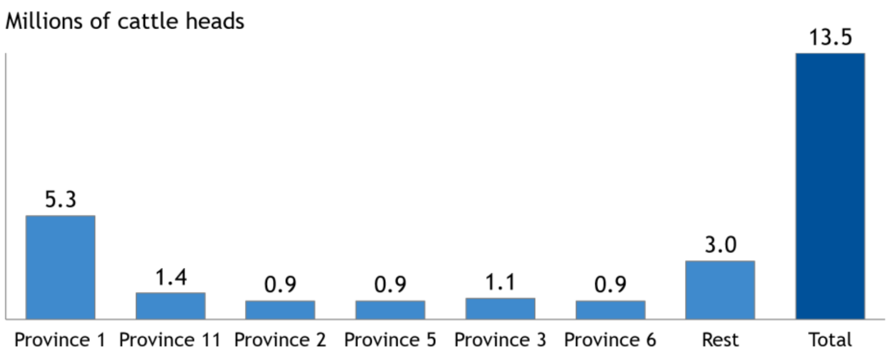

Figure 20. Annual cattle slaughter distribution per province (M heads) [10]

As it can be appreciated, cattle production abounds significantly more than pig production, which will be useful in terms of manure generation.

In this way, more than 7 M pig heads and 13 M cattle heads are produced annually across the studied zone, which can be translated into manure residues through some assumed factors. Regarding pig waste, it is possible to estimate that 1 kg/y is approximately generated per each animal, whereas in case of cattle, much more amount is generated per head, which reaches up to 18 kg/y. Therefore, simple mathematics allow to determine the approximated quantity of animal residue that the identified livestock production generates annually (see *Table 6* below).

Table 6. Annual manure generation calculation

	Annual pig production (heads)	**Annual cattle production (heads)**	**Manure generation per pig (kg/y)**	**Manure generation per cow (kg/y)**	**Annual pig waste (t/y)**	**Annual cattle waste (t/y)**
Province 1	3.773.000	5.265.000	1.095	18.250	4.131.435	96.086.250
Province 11	1.463.000	1.350.000			1.601.985	24.637.500
Province 2	1.232.000	945.000			1.349.040	17.246.250
Province 5	385.000	945.000			421.575	17.246.250
Province 3	-	1.080.000			-	19.710.000
Province 6	-	945.000			-	17.246.250
Province 7	154.000	-			168.630	-
TOTAL	**7.700.000**	**13.500.000**			**7.672.665**	**192.172.500**

This analysis enables to estimate the total manure production per year, which accounts for nearly 200 Mt.

Agricultural residues

Finally, agricultural residues also abound in Latin America, since agriculture it is a fundamental and strategic sector of the national economy, which is mainly based on cereals and oilseeds production.

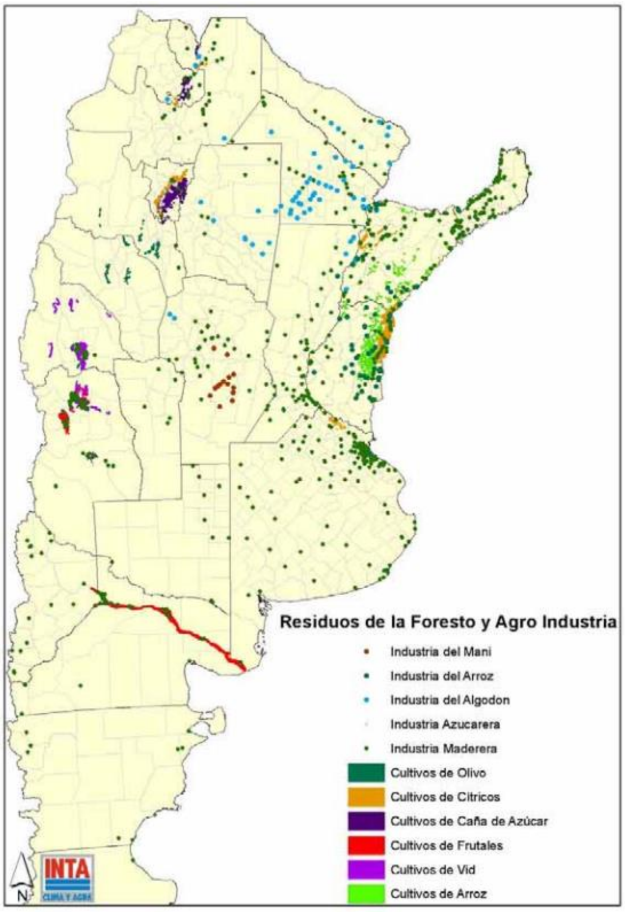

Figure 21. Agricultural residues distribution [9]

As it is detailed in the matrix below (*Figure 22*), a wide variety of agricultural residues that are attainable to be used as feedstock for biogas obtention can be found in the studied regions.

(ktpy)	Citrus pruning residues	Vineyard pruning waste	Fruit pruning residues	Olive tree pruning residues	Rice field residues	Sugar agricultural residues	Unused bagasse residues	Peanut husk residues	Rice industry waste	Cotton waste	Olive pomace residues
Yield (t BG/t biomass)	0,160	0,160	0,160	0,160	0,181	0,160	0,208	0,208	0,181	0,160	0,160
Province 1	16,3		37,7						5,4		
Province 4			2,2								
Province 2	0,2	0,7	6,4					180,0		0,3	
Province 3	73,7		0,7		173,6				29,0	5,9	
Province 5	141,9		2,3		144,6				84,5		
Province 6		0,3	2,7								
Province 7		361,5	296,6	35,8							114,4
Province 8	24,9		1,1		0,8		2,7		2,6		
Province 9		2,1	46,8								
Province 10			0,2							6,3	
Province 11	1,6		3,7		46,9		19,8		6,1	2,0	

Figure 22. Agricutural residues generation per province (ktpy) [9]

The plugged data represent thousands of tonnes of residues generated annually per each kind of agricultural product, and the values in grey indicated below each product's name correspond to the specific yield that has been considered to produce biogas, according to IEA.

In this way, nearly 2 Mt/y of agricultural residues have been identified in the regions nearby the refinery complexes of the client, which will also be distributed according to each plant exact location.

However, as it has been explained before, identifying optimal biomass availability locations is key to establish the biogas plants, as well as to evaluate the proximity to gas pipelines connections. That is, despite all the biomass potential of Latin America, its accessibility and geographical concentration are crucial factors that will drive/limit the feedstock acquisition and the plants' construction processes.

Thus, searching for these geographical points has been the key to set all the projects that have been proposed to produce the required biogas hence, to provide the client's refineries with the necessary fuel to substitute natural gas.

Taking into account the refineries' location, 7 access points to gas pipelines have been selected as the optimal ones with respect to the nearby animal, agricultural and wood waste disposal. *Selected locations will be kept confidential to protect client's information.*

The following *Table 7* sums up the available quantity of each type of biomass, according to the identified locations.

Table 7. Available biomass identified per location (ktpy)

Gas pipeline access point	Wood biomass (kt/y)	Animal biomass (kt/y)	Agricultural biomass (kt/y)
1	0,8	10 200	6
2	0,9	-	16
3	1,4	40	170
4	2,2	7 000	100
5	1,2	6 300	45
6	1,1	4 500	36
7	0,7	-	7

5. MODEL DESCRIPTION

As it has been exposed before, this study copes with the creation and optimization of an excel model that calculates the abatement cost of each initiative proposed, hence allows to compare them with respect their CO_2-reduction potential.

5.1. Main concepts' definition

There are several variables and parameters that will be commonly used during this project, which will be briefly described within the following lines in order to facilitate and ensure a complete understanding.

- Emission: Quantity of CO_2 gases emitted by any polluting source, usually expressed in kilo tonnes per year (ktpy).
- Abatement potential or CO_2-reduction potential: Quantity of CO_2 gases reduced with the proposed levers, usually expressed in kilo tonnes per year (ktpy).
- Emissions' NPV: It corresponds to the Net Present Value of the emissions accounted for the refinery, which represents the present value of the cost associated with the refinery's emissions over a specified period (the useful life of each initiative).
- Initiative's NPV: It corresponds to the Net Present Value of the proposed initiative, which represents the present value of the cost associated with it over its useful life.
- Abatement cost: It refers to all costs associated with the implementation of a certain decarbonization initiative, including from operational to capital costs. It is the ratio between the initiative's NPV and the emissions' NPV and it is expressed in dollars per each tonne of CO_2 reduced ($/t).
- CAPEX: It states for "Capital Expenditures" and it englobes the required investment (fuds) to acquire the physical assets needed to start implementing a project or initiative which will be used for long periods of time.
- Opex: It states for "Operational Expenditures" and it accounts for all the costs associated with day-to-day operations when running a plant or a project. Operational and maintenance expenses are incurred in these short-term costs.
- Unitary opex: It corresponds to the part of the total OpEx which is destinated to reducing each tonne of CO_2; in other words, it can be estimated through the ratio between the operational costs and the abatement potential of the initiatives.
- Incremental opex: This variable is the equivalent to EBITDA; it corresponds to the opposite value. That is, EBITDA represents the earnings obtained through the initiative (Revenues – OpEx), whereas Incremental OpEx are the costs associated to it (OpEx – Revenues).
- EBITDA: It stands for "Earnings Before Interests, Taxes, Depreciation and Amortization" and, as its name indicates, it gives information regarding the overall financial performance by extracting the operating costs of the project from the revenues obtained with it.
- NOPLAT: It stands for "Net Operating Profit Less Adjusted Taxes" and it is a measure of profit that includes all operating expenses and taxes that are related to the operation but excludes financial expenses and income taxes. It represents the total profit a company would make if it had no debt and held no financial assets.
- Revenues: Corresponds to all the economic inputs or money generated from the business operations, including savings and earnings.

- Free Cash Flow: The FCF parameter shows the cash generated by the correspondent initiative after accounting for the capital expenditures required to implement it, and considering also any other non-cash expenses such as depreciation and amortization.
- CAPEX distribution: It entails the investment required to run each correspondent initiative distributed into a certain number of years right before the startup year.
- WACC: Stands for "Weighted Average Cost of Capital" and it is a discount rate which considers costs from all capital sources. It is used to deduct the future cash flows when valuing an investing project.
- Location Factor: Factor applied to the total investment in order to evaluate relative cost difference between two geographic locations (taking one of them as the reference, and being the other one the client's position).
- MACC: It states for "Marginal Abatement Cost Curve", and it is a tool used to determine optimal cost paths to net zero using underlying initiatives, inputs, scenarios and assumptions incorporated in the model.

5.2. Main tabs

To begin with the model description, a tab hierarchy has been established in order to maintain certain organization within the model, which is shown in the following descriptions:

- **Cover**: The first tab in the model corresponds to the cover, which includes the basic information concerning the model itself and it gives rise to the main control sheet.
- **Outputs**: This section collects all the relevant data and results regarding the initiatives studied for all levers, such as the emissions base line projected to future, the expected OpEx and CapEx, the Revenues, among other relevant parameters recap.
- **Inputs**: The inputs section englobes all the necessary data collected from the client that will be useful for any calculation in the model. That is, general assumptions, raw materials and fuel prices, emissions base line, emitting sources, refineries' performance scenarios and relevant information regarding other future projects are included in this collection of tabs.
- **Analysis**: The following part of the model includes the general analysis of the initiatives studied, bringing all the significant information calculated for each one. Moreover, an "Initiatives selection" tab is also ensembled in order to differentiate the ones that will specifically be implemented in each refinery.
- **Initiatives definition**: Finally, the last and most extended section of the Excel model involves the description, approach, calculations, and summary of each initiative proposed for all levers in detail.

Focusing on the Fuel Switch lever, 7 initiatives have been created in order to fulfil the constraints of the project, that is, each gas pipeline access with significant nearby available biomass that has been identified must have a particular biogas production plant (individual calculation sheets). The large area covered in this study and the large amount of biomass identified implies the need to select its distribution for each of the refinery complexes, since its transportation over long distances (more than 100 km) entails high costs.

In this way, 7 biogas production projects have been proposed in accordance with the 7 gas pipeline access points that have been considered.

Two excel tabs have been developed for each one of these initiatives; a summary sheet called FS_Xx – Sum, which englobes all the data required to carry out all the calculations (inputs, assumptions, mass balance, energy balance, yields, operational and capital expenses…) and a sheet called FS_Xx – FCF, which contains the Free Cash Flow calculations that provide the initiative's economic impact overview. *Being "Xx" the numeration assigned to each initiative included in the Fuel Switch lever.*

Thus, there exist a total of 14 tabs which encompass the whole Fuel Switch lever. The following sections will delve into the specific calculations exposed in these tabs.

5.3. Main assumptions

- The emissions produced by the refinery have been calculated from the tons of crude that are annually processed.
- Pig waste, bovine waste, forest waste and agricultural waste are the processable raw materials that have been considered for the projects.
- Organic fraction of municipal solid waste has not been considered because the client is not enabled to process this type of waste.
- To maximize the potential of these initiatives, some research regarding pipeline passage zones has been carried out in order to identify the possibility to pour the produced biogas into the pipeline and to account for the emission reduction through credits without having to physically consume it in the complexes (applicable for regions where there are no client operations).
- For the regions where the complexes are located, the production of fuel next to the complex has been prioritized to minimize transport costs by pipeline while allowing flexibility to produce biogas or syngas (H_2 + CO).
- For projects involving the discharge of gas into the national pipeline, an upgrading plant has been included to increase gas purity to a methane content greater than 90% to meet the minimum quality specifications.
- For projects next to complexes, upgrading has not been considered as fuel volumes allow it to be injected into the refinery network without having a significant impact on the network's calorific power or furnace performance.
- The calculation of the savings associated with the displacement of natural gas consumption has been made on an energy basis, that is, the energy delivered by the bio/syngas (mass x LHV) has been calculated and it has been converted through the price of natural gas (on an energy basis).
- The Capex curves used have been adapted taking into account the mix of residues available in each region, as well as the expected yields based on the type of waste and its distribution in the mix.
- Depending on the fossil fuel used, different emissions are accounted for, as they depend on the emission factor of each type.
- As a base case, it has been considered that 10% of the raw material available in the different regions can be processed.

- A location factor of 1,35 has been applied to all investment costs in order to compensate the geographical reference (United States).
- Steam utilities consumed during gasification processes have been valued to natural gas price.
- 6% of the total CapEx has been valued as the operational expenditures (OpEx) for each initiative.
- Biomass transport by road and fuel gas transportation through national gas pipelines associated costs have been considered null due to possible agreements with external providers or governmental bodies.

5.4. Calculations

Despite the fact that several initiatives have been prepared according to each zone conditions and adequacy, the calculations specified in this section will be only exposed once, since all of them follow the same pattern. Nevertheless, anaerobic digestion will be specially defined deeper (case base) since it is the most commonly used and the most complex one.

5.4.1. Summary tab

Mass balance

The first input in the excel file is the usable organic matter, found in the previous biomass availability research; depending on the zone it is being considered, this will change.

Let's consider a total of 10 000 kt/y as the basis of the calculation for one zone (case base), which, considering a 10% of accessibility, includes the following amounts of each type of biomass:

Table 8. Total usable biomass for the base case (ktpy)

Total biomass input (kt/y)	10 000	
Total usable biomass (kt/y)	1 000	
Pig waste	4,1%	41 kt/y
Bovine waste	95,8%	958 kt/y
Agricultural residues	0,06%	0,59 kt/y
Wood residues	0,01%	0,08 kt/y

However, the different energy content of the various feedstocks is a key factor in the productivity of biogas production facilities, hence the next step is to adjust the biogas production yield depending on the type of biomass that is being used (see *Figure 23*). The International Energy Agency (IEA) [11] states that, in general terms, agricultural waste is the one with more energy content among the three selected types of biomass.

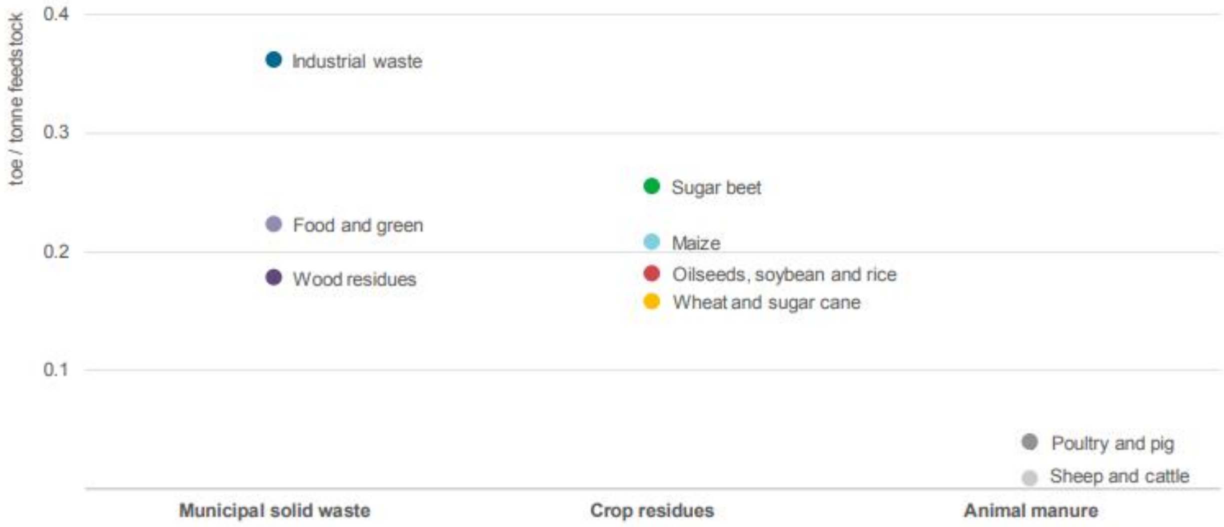

Figure 23. Average biogas production yield by tonne of feedstock type (toe BG/tonne biomass) [11]

Therefore, considering the data above, biogas production potential can be calculated for the biomass in this zone. The conversion from toe to tonnes is calculated through the following calculation:

$$Biomass\ yield\ \left[\frac{t\ BG}{t\ biomass}\right] = \frac{Biomass\ yield\ \left[\frac{toe\ BG}{t\ biomass}\right] \cdot 41{,}87\ \left[\frac{GJ}{toe}\right]}{16{,}4\ \left[\frac{GJ}{t}\right]}$$

Where 41,87 GJ/toe is a conversion factor, and the divisor corresponds to the biogas low heating value (LHV).

The biogas that can be obtained from the biomass identified is calculated multiplying that value with each biomass type yield.

Table 9. Biogas potential calculation per biomass type (tpy)

	Yield (toe biogas/tonne feedstock)	**Yield (t biogas/t feedstock)**	**Biogas potential (t/y)**
Pig waste	0,039	0,10	4 100
Bovine waste	0,008	0,02	19 600
Agricultural residues	0,183	0,47	280
Wood residues	0,178	0,45	35
Total biogas produced (t/y)			**24 000**

As it has been exposed before, in the anaerobic digestion case, the rest of feedstock is transformed into a usable residue called digestate; that is, more than 970 000 t of digestate can be sold or exchanged for agricultural residues.

Leaving the base case aside, during the gasification and pyrolysis processes, however, syngas is produced which corresponds to different energy conversions, as shown in the *Table 10* below. It must be noted that agricultural and wood residues are the only type of biomass considered for the calculations and they pelletized before being fed into the reactor, hence they are both considered as dry biomass as a whole.

Table 10. Syngas potential calculation for gasification and pyrolysis technologies (tpy)

Gasification			
Dry biomass yield (t syngas/ t feedstock)	2,4	**Syngas potential (t/y)**	1 600
Pyrolysis			
Dry biomass yield (wt. %)	30	**Syngas potential (t/y)**	200

Aside from the biofuel (syngas), two more products are obtained when implementing both technologies, which, in the gasification case are biochar (15 % in weight of the biomass fed) and tar (the rest), and in the pyrolysis case are biochar (20 % of the feedstock) and bio-oil (50 % of it).

Some other considerations must be taken into account when implementing these other technologies.

Gasification:

As it has been explained in the "State of the art" section, steam is required to carry out the thermochemical process. The necessary amount of steam for each gasification process accounts for 1,5 moles per each mole of biomass:

$$670\ tpy_{dry\ biomass} \cdot \frac{1{,}5\ mole\ steam}{mole\ biomass} \cdot \frac{18\ g\ steam}{1\ mole\ steam} \cdot \frac{1\ mole\ dry\ biomass}{13{,}1\ g\ dry\ biomass} = \mathbf{1\ 380\ tpy\ steam}$$

Pyrolysis:

Following similar combustion process as gasification, in pyrolysis, a notable amount of natural gas is required to start the degradation of biomass.

$$Required\ heat = 670\ 000\ kg\ py \cdot (600 - 25)ºC \cdot \left(11{,}5\ \%_{wood} \cdot \frac{0{,}5\ kcal}{kg_{wood} \cdot ºC} + 88{,}5\ \%_{agric.} \cdot \frac{0{,}3\ kcal}{kg_{agric.} \cdot ºC}\right) \cdot 4{,}18 \cdot \frac{10^{-3} MJ}{kcal} = \ 500\ 000\ MJ\ py$$

Where 600 ºC is the required heat to reach degradation (pyrolysis temperature) and 25 ºC is the usual biomass temperature, 11,5 % and 88,5 % correspond to the proportion of wood and agricultural residues in the dry biomass identified in the base case respectively, and 0,5 kcal/kg·ºC and 0,3 kcal/kg·ºC are the respective specific heat of these wastes.

$$Required\ NG = 500\ 000\ MJp\ y \cdot \frac{1\ kg}{6\ MJ} \cdot \frac{1\ t}{1000\ kg} = \mathbf{83\ tpy\ of\ NG}$$

Where 6 MJ/kg corresponds to syngas LHV in the pyrolysis defined. This consumption is accounted together with the current gas consumption of the corresponding refinery studied.

Energy balance

Once the mass balance has been performed, it is key to identify the energetic potential of the obtained products. Taking a gas natural consumption of 50 kt/y as the basis for the refinery complex where it is intended to be applied this initiative, it is possible to calculate the corresponding energy potential when using the biogas production.

$$Biogas\ energetic\ potential = \frac{24\ 000\ t\ BG\ produced}{y} \cdot \frac{16{,}4\ GJ}{t\ BG} = 393\ 600\ GJ/y$$

Where 16,4 GJ/t corresponds to the biogas low heating value (LHV).

In case of producing syngas, its LHV will be multiplied by the amount of syngas obtained from the biomass. 12 GJ/t will be considered for using steam during gasification, and 6 GJ/t will be used in case of implementing pyrolysis.

$$Natural\ Gas\ energetic\ potential = \frac{50\ 000\ t\ NG\ consumed}{y} \cdot \frac{47\ GJ}{t\ NG} = 2\ 350\ 000\ GJ/y$$

$$\boldsymbol{Natural\ Gas\ replaced} = \frac{50\ 000\ t\ NG\ consumed}{y} \cdot \frac{393\ 600 \frac{GJ}{y} (BG)}{2\ 350\ 000 \frac{GJ}{y} (NG)} = \boldsymbol{8\ 400\ t\ NG/y}$$

Just in order to comprehend the real scope of it, the calculations regarding the linked emissions have been carried out. Considering 2,63 t CO_2/t NG as the emission factor for the fossil fuel, the following emissions can be reduced:

$$Natural\ Gas\ emissions = \frac{50\ 000\ t\ NG\ consumed}{y} \cdot \frac{2{,}63\ t\ CO_2}{t\ NG} = 130\ 000\ t\ CO_2/y$$

$$\boldsymbol{Reduced\ emissions} = \frac{8\ 400\ t\ NG\ replaced}{y} \cdot \frac{2{,}63\ t\ CO_2}{t\ NG} = \boldsymbol{22\ 000\ t\ CO_2/y}$$

Which corresponds to 17% of the current refinery's emissions. At the end, despite the fact that the Fuel Switch lever is not as powerful as CCUS can be, for instance, the individual contribution of each initiative proposed, together with the rest of levers, can make a difference.

Investment and operational expenses

Once the reduction potential has been defined, it is important to estimate the costs required to implement it.

To begin with the capital expenditures (CapEx), as it has been explained in the previous section, anaerobic digestion processes significantly depend on feedstock quality and quantity. Therefore, considerations assumed regarding CAPEX of anaerobic digestion are distinguished between high and low content of processed animal waste (see *Figure 24 below).*

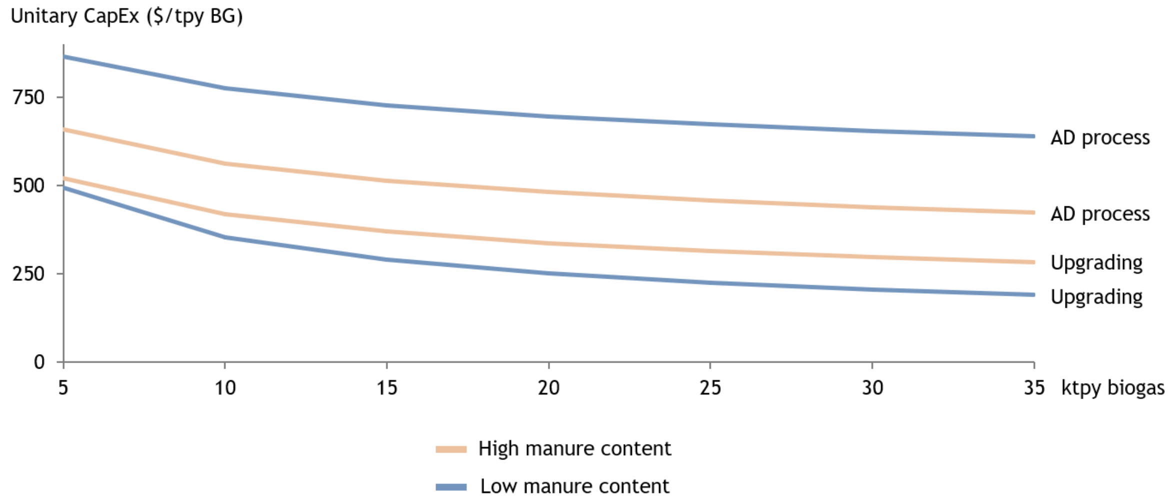

Figure 24. Unitary CAPEX for high and low percentage of animal waste processing ($/tpy biogas)

Other factors, such as additional CapEx regarding the gas pipeline which will distribute the product, have not been taken into account because each individual project has been proposed to be established nearby already built national pipelines or directly in the client's sites.

Therefore, CapEx for an anaerobic digestion plant located in the surroundings of the client's refinery (which does not require upgrading to biomethane to be fed into a gas pipeline) attains to the following calculation:

$$CapEx\ (M\$) = m_{BG} \cdot \left(CapEx_{equipment} + CapEx_{upgrading}\right) \cdot LF \cdot 10^{-6}$$

Where m_{BG} is the amount of biogas produced through this initiative (24 000 tpy BG), CapEx equipment corresponds to the unitary CapEx of the digestion $_{\text{equipment}}$ for processing biomass with high percentage of animal waste, depending on the production of biogas (460 $/tpy BG), CapEx $_{\text{upgrading}}$ is the unitary CapEx of the upgrading equipment for processing biomass with high percentage of animal waste, depending on the production of biogas (0 $/tpy BG), and LF represents the location factor applied to the investment to correct the geographical cost differences (1,35).

Hence,

$$CapEx\ (M\$) = 24\ 000\ \text{tpy BG} \cdot 460\frac{\$}{\text{tpy}}\text{BG} \cdot 1{,}35 \cdot 10^{-6} = 14{,}90\ M\$$$

giving a total of **15 M$** for the considered biogas plant project.

On the other hand, if gasification or pyrolysis techniques are implemented instead of anaerobic digestion, capital expenses comprehend the following:

Table 11. Gasification and pyrolysis CapEx ($/tpy biomass)

CapEx gasification ($/tpy biomass)	2 700
CapEx pyrolysis ($/tpy biomass)	1 350

Moving forward, some operational expenses (OpEx) must also be reflected for the general economic impact to be estimated. As it has previously been mentioned, it accounts for 6 % of the CapEx calculated, which enables to obtain the OpEx per unit of each project proposed, regardless of the technology selected. Taking the base case as an example:

$$Opex\ per\ unit\ (M\$) = 6\% \cdot 14{,}90\ M\$ = 0{,}89\ M\$$$

In addition, other operational costs are reported during the implementation and performance of these biofuel plants, which are represented below (*Table 12*). It is important to highlight that no biomass acquisition or transport costs have been considered nor biofuel transportation through national pipelines, as mentioned in the assumptions. This is the reason why anaerobic digestion does not have additional operational costs.

Table 12. Gasification and pyrolysis operational costs ($/t)

Gasification	
Wood pellets ($/t)	60
Steam (utilities cost based on NG price) ($/t)	150
Biomass pre-treatment ($/t)	6
Pyrolysis	
Wood pellets ($/t)	60
Biomass pre-treatment ($/t)	15

Pyrolysis pre-treatment is more expensive than gasification pre-treatment because of the required sizing of the pellets, which is stricter for the former one.

The prices stated above must be multiplied by each corresponding amount of biomass, or steam, as convenient.

5.4.2. FCF tab

The first section of the Free Cash Flow tab contains a recap of the essential parameters and variables calculated in the Summary tab.

The following section of the sheet presents some key calculations in order to obtain the economic impact of each initiative, concerning the previous analysis. It must be noted that, in general terms, this tab is a future projection of the variables calculated, since it entails annual values for each calculated term from 2022 to 2075. This is because the decarbonization levers involve long-term initiatives.

Income sources

To begin with, all the revenues generated by the initiative and all the money saved with it are listed down.

For anaerobic digestion projects, digestate is not accounted as a revenue source since, as it has been exposed above, establishing alliances with the agriculture or horticulture sector to ensure the exchange of this residue obtained by usable biomass can be beneficious for the client. Nevertheless, natural gas saving is the key variable in this technology's income sources. All the biogas that is produced from the identified biomass potential replaces the existing fossil fuel currently utilized in all refineries. Hence, considering a natural gas price of 150 $/t and taking into account its variation throughout the years, the associated revenues can be calculated. The following formula exemplifies the case base calculation for 2024:

$$8\,400\ tpy\ NG\ replaced \cdot \frac{150\ \$}{t} \cdot 10^{-6} = 1{,}26\ M\$\ /y$$

This computation is compatible with all 3 technologies studied. However, for gasification and pyrolysis, residues selling can be accounted for additional revenues.

In case of gasification, the obtained tar can be sold. For this, a price estimation has been proposed based on the crude price:

$$Tar\ price = \frac{80\ \$}{bbl} \cdot \frac{1\ bbl}{0{,}14\ t} - \frac{10\ \$}{t} = 560\ \$/t$$

Where 80 $/bbl is a standard and constant price estimated for the crude processed.

Therefore, multiplying the tar obtained annually through the gasification project per this assumed price, the revenues associated with selling this product can be computed:

$$340\ tpy\ tar \cdot \frac{560\ \$}{t} \cdot 10^{-6} = 0{,}2\ M\$\ /y$$

The same approach stands for pyrolysis products, however in this case, both residues obtained from the process are expected to be sold hence, to receive income from them. The following equations summarize the price used for each product.

$$330\ tpy\ bio-oil \cdot \frac{580\ \$}{t} \cdot 10^{-6} = 0{,}2\ M\$\ /y$$

$$130\ tpy\ tar \cdot \frac{100\ \$}{t} \cdot 10^{-6} = 0{,}01\ M\$\ /y$$

Again, the bio-oil price is based on the crude price.

OpEx and other operational costs

This section comprises more complex parameters, since it includes financial metrics used to assess the initiative's performance and profitability. It is worth mentioning that negative values usually correspond to costs whereas positive values account for revenues or incomes for the client.

Furthermore, this section is equally applicable for each type of technology studied, simply modifying the operational expenses exposed above.

Thus, it starts with all the operational costs related to the initiative exposed (the case base will continue to be taken as reference), which have already been explained above. They are all added to bring the total outcome and they are then extracted from the revenues to obtain the EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization), which gives information regarding the overall financial performance.

$$EBITDA = Revenues - Operating\ costs = 1{,}26\ M\$\ /y - 0{,}89\ M\$\ /y = 0{,}37\ M\$\ /y$$

Assuming that a positive EBITDA attains to the generation of profit, it is possible to state that the base case is beneficial for the client, since income exceeds the operational costs.

As the own parameter indicates, adding back depreciation and amortization (which is a non-back accounting charge) to the EBITDA is a must in order to provide a clearer picture of the cash-generating ability of the initiatives. Taking 2029 as the starting year for the implementation of the base case (anaerobic digestion of 1 000 tpy biomass), and estimating a useful life of 25 years, the following mathematics can be used.

$$Depreciation = \frac{Total\ initiative's\ CapEx\ M\$}{Initiative's\ useful\ life} = \frac{-\ 25{,}3\ M\$}{25\ years} = -\ 1\ M\$\ /y$$

This additional expense is annually added in equal parts during the project lifetime.

Hence,

$$EBIT = EBITDA + Depreciation\ \&\ amortization = 0{,}37\ M\$\ py - 1\ M\$\ py = -\ 0{,}53\ M\$/y$$

As it can be appreciated, this added cost significantly contributes to the company's profit (becoming a negative earning translates into an expense).

Furthermore, considering a tax rate of 35 %, taxes reach an annual value of:

$$Taxes = -EBIT \cdot Tax\ rate = 0{,}53\ M\$\ py \cdot 0{,}35 = 0{,}19 M\$\ /y$$

Therefore, the net operating profit (NOPLAT) is calculated by adding taxes to the previously calculated earnings:

$$NOPLAT = EBIT + Taxes = -\ 0{,}53\ M\$\ /y + 0{,}19\ M\$\ /y = -\ 0{,}34\ M\$\ /y$$

Finally, the free cash flow can be obtained through the summation of the NOPLAT, the depreciation calculated before and the CapEx distribution.

The latter concept entails the investment required to run the initiative distributed into a certain number of years (to be chosen as convenient for the client) right before the start-up year, which in the base case corresponds to the 5 previous years to 2029. Even though the optimal CapEx distribution is within 3 years, this selection was made as per client's request. In this way, a certain proportion of the total CapEx is included in each of these 5 years, which in this case 50 %, 40 %, 5 %, 4 % and 1 % have been chosen respectively, as it is represented in *Figure 25*.

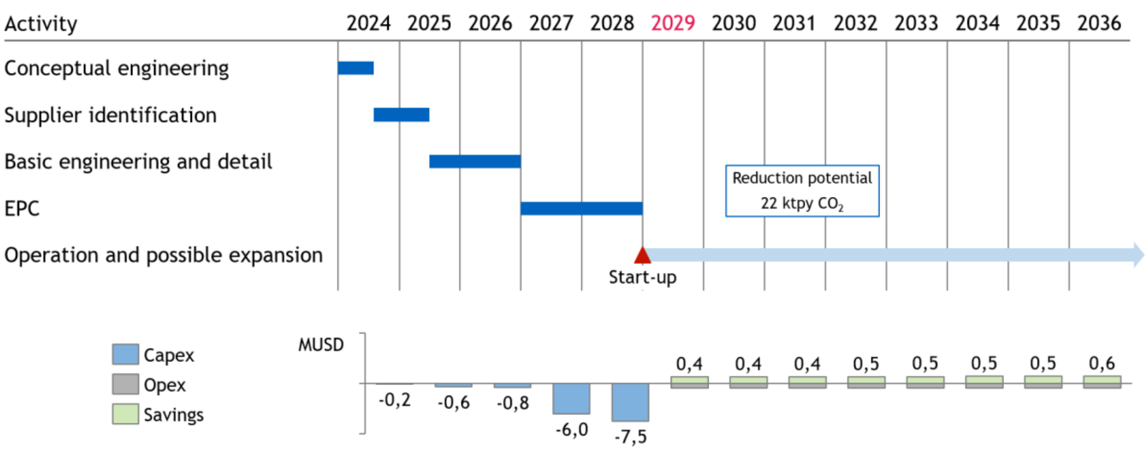

Figure 25. Execution plan timeline for the base case initiative and CapEx distribution

The following equation shows the free cash flow calculation previously mentioned, for the previous year to the startup, that is, 2028 (adding 50 % of the CapEx):

$$FCF = NOPLAT - Depreciation\ \&\ amortization + CapEx\ distribution =$$

$$0\ M\$\ py - 0\ M\$\ py + \left(0{,}5 \cdot (-15\ M\$)\right) = -\ 7{,}5\ M\$\ py$$

It is important to mention that all calculations exposed above are applicable for operation years. In other words, as long as the 5 implementation years' period has not come to an end, all these parameters will be null except for the CapEx distribution.

Therefore, the FCF in 2029 would be computed the following way:

$$FCF = -\ 0{,}34\ M\$\ py + 1\ M\$\ py + \left(0 \cdot (-15\ M\$)\right) = 0{,}7\ M\$\ py$$

After accounting for all cash outflows, the FCF shows the cash generated by the initiative, which is negative before the start-up year due to the CapEx contribution, and it is positive afterwards, when capital expenses have been already settled.

The last parameter left to be computed in this section is the net present value (NPV) for this free cash flow. This metric shows the difference between the present value (each year in operation) of cash inflows and cash outflows over a period of time (the useful life of the initiative studied). That is, the estimated cash flows must be discounted back to their present value using a discount rate that reflects a required rate of return, which in this case is 13 % (also called WACC, "Weighted Average Cost of Capital").

The pertinent equation to calculate this parameter entails more complexity than the ones computed above:

$$NPV = \sum_{t=0}^{n} \frac{Cash\ Flow_t}{(1 + WACC)^t}$$

Where n is the total number of years, t corresponds to the specific year in which cash flows are being evaluated, and Cash Flow $_t$ is the estimated incomes and outcomes (FCF) of the initiative in a specific year.

In this way, a positive NPV indicates that the projected earnings exceed the anticipated costs, as it happens in 2029, whereas a negative NPV suggests that the project may not be financially viable, as in 2028, for instance. Otherwise, if the value is zero, it means that cash flows are exactly sufficient to repay the invested capital and provide the required rate of return.

Reducted emissions

This section aims to state all the emissions associated to using the proposed fuel sources, which in this case are considered null. This is because, aside from generating a sustainable fuel from natural resources, implementing this kind of initiatives (Fuel Switch) contributes to avoiding emissions associated with agriculture and livestock farming. Thus, it is possible to state that switching natural gas by biofuels (biogas or syngas in this case), allows to close de CO_2 cycle.

It is worth mentioning that, just as the previous section, this one is equally applicable for each type of technology studied. It is dedicated to calculating the NPV of the emissions linked to the project outcome, which will be useful to calculate the abatement cost of the initiative afterwards. To do so, it is imperative to know the net reduced emissions, which in this case it is equivalent to the emissions avoided by substituting natural gas by biogas or syngas. That is, the result of implementing a biofuel in the facilities does not imply any additional emission.

$$\begin{aligned}&Net\ reduced\ emissions\\&= Emissions\ reduced\ due\ to\ implementing\ a\ decarbonization\ initiative\\&- Emissins\ emitted\ associated\ with\ the\ solution\ (after\ decarbonization)\end{aligned}$$

Taking into consideration the base case, net reduced emissions correspond to 22 000 t CO_2/y.

Thus, the NPV is obtained through the calculation exposed before. This value will not be indicated since it accounts for different values according to the year considered.

Outputs

The final section of each FCF sheet in the project entails the summary of all the relevant parameters calculated across the tab in order to assess the comparative study of the different levers and initiatives proposed:

- Total CapEx
- Abatement potential (in 2030)
- Total emissions
- Iniciative's NPV (in the start-up year)
- Emissions' NPV (in the start-up year)
- Abatement cost (in the start-up year)

All the concepts are previously computed in some section of the Excel model. With respect to the last parameter, the abatement cost, as it has been defined previously, indicates the total associated cost to reduce each tonne of CO_2 through the initiative studied. The calculation carried out is the following:

$$Abatement\ cost = \frac{-\ Initiative's\ NPV\ (\$)}{Emissions'NPV\ (t\ CO_2)} = \frac{-\ (-\ 9\ 000\ 000\ \$)}{110\ 000\ t\ CO_2}\ = 80\ \$/t$$

As its name indicates, this parameter depicts a cost, hence, a positive abatement cost indicates that the initiative implementation implies expenses while a negative cost would indicate that the project carries savings for reducing emissions.

6. DATA ANALYSIS & RESULTS

Taking the data calculated above, it is possible to analyze diverse parameters which allow the assessment of each initiative's potential and economic impact.

6.1. CapEx analysis

To begin with the most relevant parameter for any company, even if it is not the most important one, the CapEx required to implement each of the initiatives proposed is represented below:

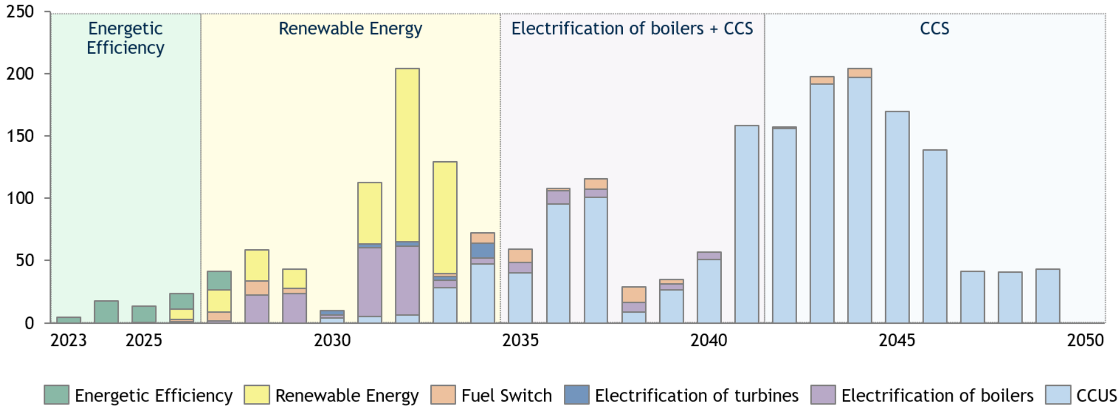

Figure 26. Projected annual CapEx (M$)

As it can be appreciated in *Figure 26* above, Carbon Capture and Storage require the most capital expenditures, due to necessary equipment and geotechnical studies.

It is usual to find very expensive initiatives that are able to abate immense quantities of O2 and initiatives with low CapEx associated that contribute substantially to GHGs emissions reduction. In this way, these terms are correlated among them. Therefore, it is logical to implement the latter ones at the earliest convenience.

6.2. OpEx analysis

Another factor that is important to check in order to carry out the complete analysis is the operational expenses required to implement each lever.

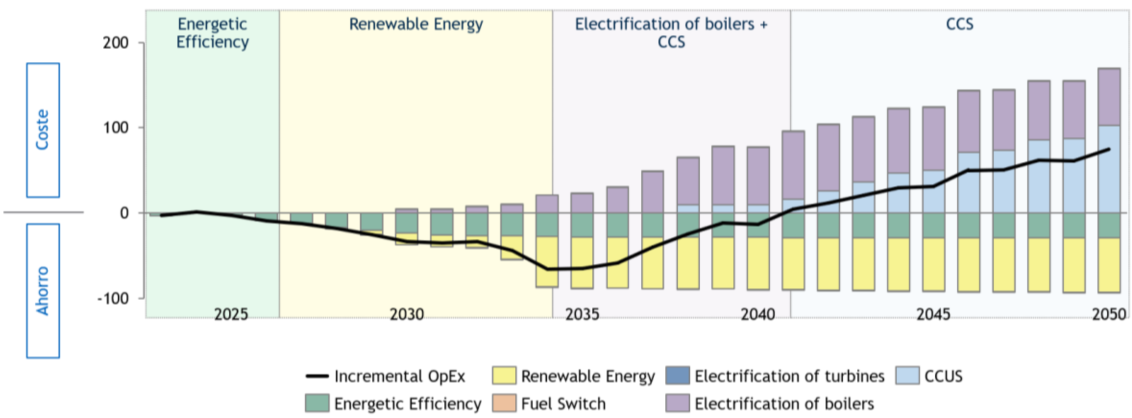

Figure 27. Projected incremental OpEx (M$/y)

In *Figure 27* above it is possible to observe that operational expenses associated with Fuel Switch initiatives are inappreciable compared to the rest of decarbonizing levers. Despite having reduced operational costs, they are able to provide the refineries studied with certain reduction potential, which is scale-comparable with other levers.

More detail will be exposed in the conclusions.

Moreover, it is also appreciable that the costs that electrification and CCUS initiatives require are compensated by the savings associated with Renewable Energy and Energetic Efficiency projects.

6.3. CO_2 reduction potential analysis

On the other hand, the following graphic (*Figure 28*) shows the abatement potential of each one of the Fuel Switch initiatives studied in this project, which is a parameter of significant importance for the comparative analysis carried out in this project. Multiple technologies have been considered for the same region, in order to assess the most suitable one according to the available biomass.

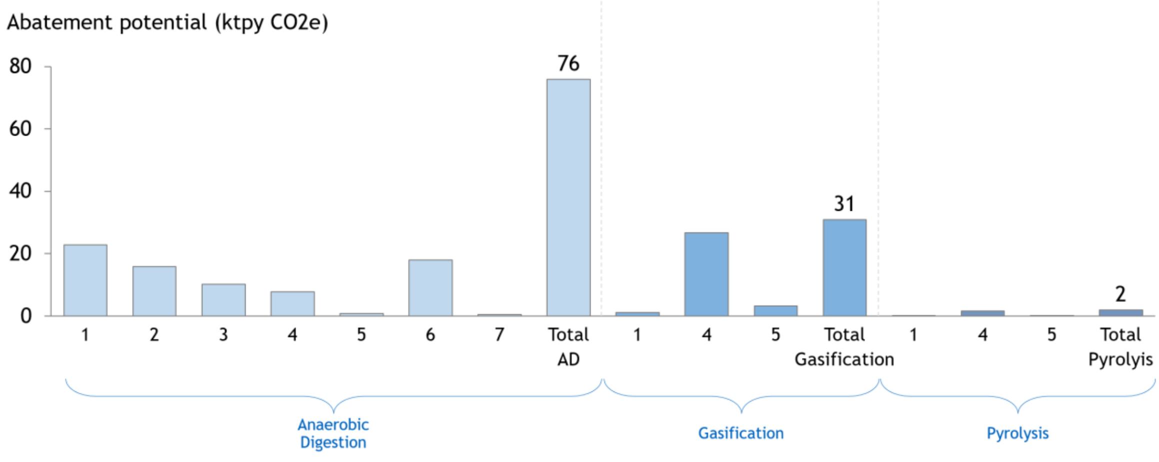

Figure 28. Abatement potential for all FS initiatives considered (ktpy CO2e)

As mentioned earlier, it must be highlighted that gasification and pyrolysis technologies have only been proposed for locations 1, 4 and 5, which correspond to the client refineries' placement. This is because syngas cannot be poured into gas pipelines due to its CO and CO_2 content, nor it can be upgraded, hence it must be directly produced nearby the final consumer (refining complex).

After analyzing the abatement potential of all the possibilities, it is clearly seen that Anaerobic Digestion is the technology that provides the opportunity to reduce the most emissions.

Furthermore, it is important to note that some initiatives stand out from the rest, such as gasification in location 4. The reason is that in that zone, agricultural and wood residues abound extremely more than in location 1, for instance. Therefore, gasification, which uses exactly these kinds of biomass to produce syngas, may be the technology to prioritize in location 4, depending on the associated abatement cost.

In this way, certain initiatives have been prioritized, which are summarized in *Figure 29* below. Regarding each gas pipeline access point, the selection of the most adequate technology has been based on the balance between higher potential and reduced cost, which will be exposed afterwards.

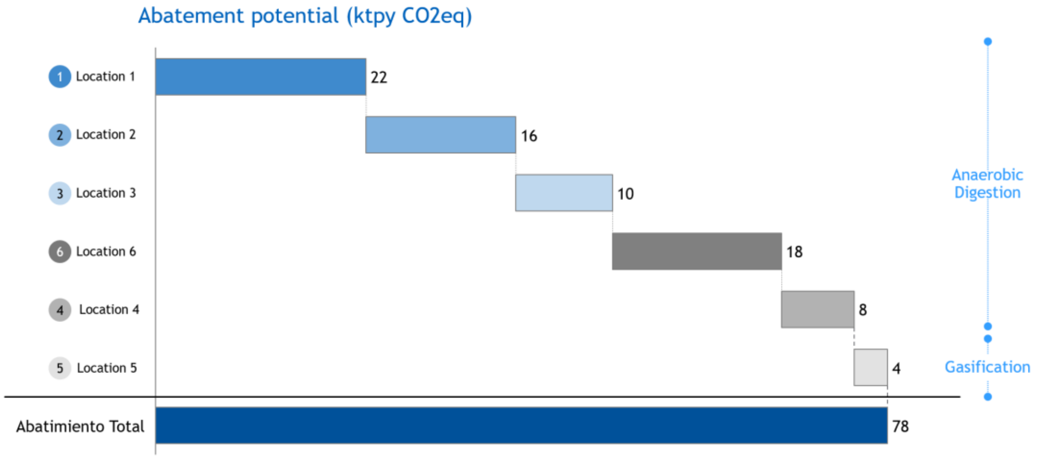

Figure 29. Abatement potential for FS initiatives selected according to each location (ktpy CO2e)

The first 4 initiatives are applicable to the most important refinery complex since the points selected are close enough to the facilities. The rest correspond to projects that will be implemented in the other 2 refinery complexes that the client owns, respectively.

Pyrolysis has not been prioritized for any refinery because of the extremely reduced syngas production potential.

6.4. Abatement cost analysis

With respect to abatement cost, it is also a key parameter to take into account when comparing different CO_2 reduction levers (see *Figure 30*).

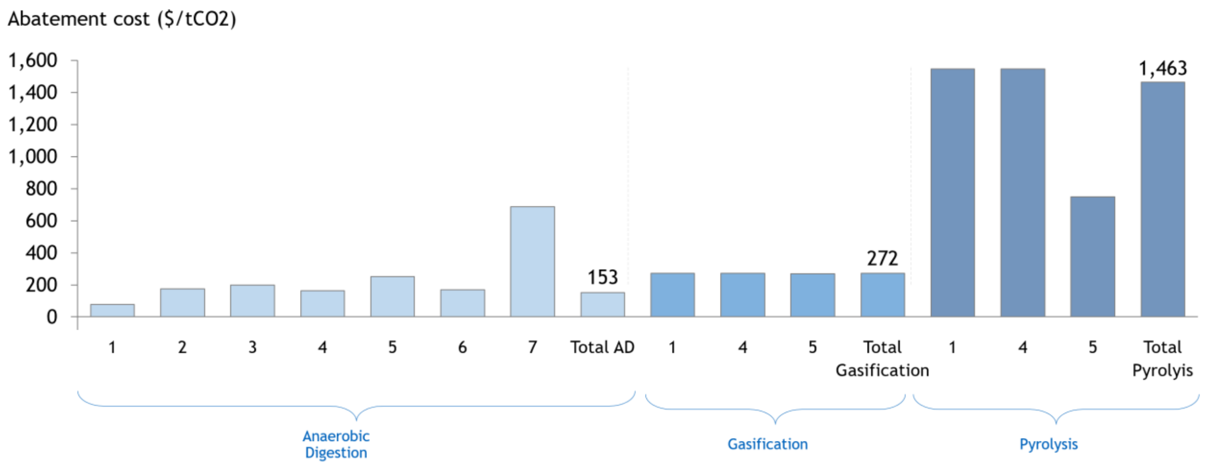

Figure 30. Abatement cost for all FS initiatives considered ($/ t CO2)

The selecting criteria will be led by the lower abatement cost, if possible. That is, for each project possibility, both abatement potential and cost should be considered and balanced whether if one accounts more than the other.

The total abatement cost for each technology is calculated through the weighted average of the individual costs, taking into account each abatement potential.

Furthermore, cost abatement breakdown exercise has been carried out for all initiatives in order to know which factors contribute the most to it. The following chart (*Figure 31*) shows the cost breakdown for one of the initiatives implemented in the most important refinery complex owned by the client, where upgrading was not required.

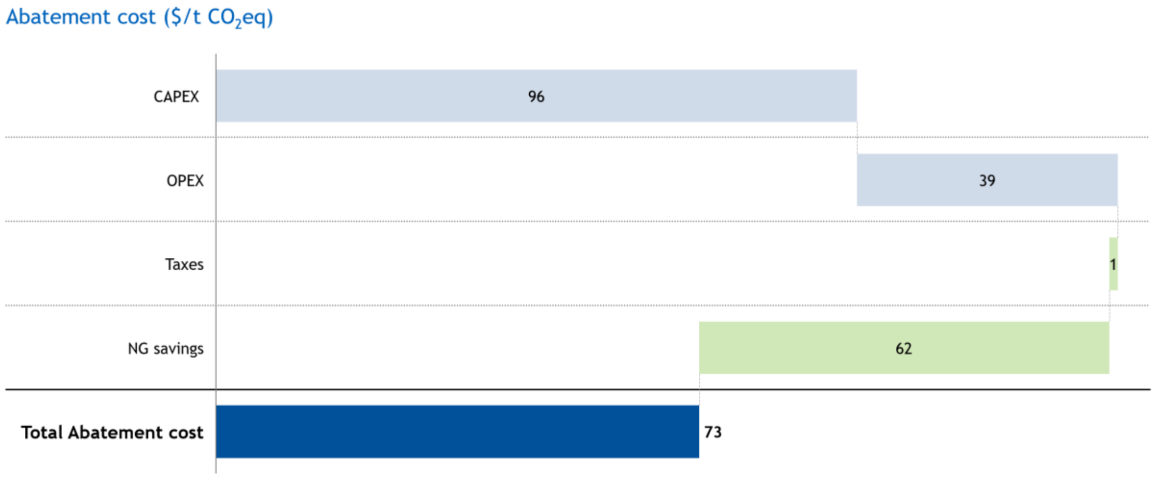

Figure 31. Abatement cost breakdown example ($/t CO2e)

As it is clearly seen and as it was expected, CapEx is the most significative factor. It must also be noted that both, taxes and Natural Gas savings contribute positively to it.

6.5.MACC analysis

As defined in the previous "5.1. Main concepts' definition" section, a MACC (Marginal Abatement Cost Curve) is a very effective tool that allows to compare the abatement performance of multiple levers. This curve entails a general analysis of the complete view of the refining decarbonization plan.

The following *Figure 32* shows an example of a MAC curve, which shows the reduction potential (x axis) and the abatement cost (y axis) of several projects; they are arranged in ascending order of abatement cost to see which ones are most cost efficient. In other words, two main sections can always be appreciated in this graphics. On the one hand, there are the economically beneficious projects, which imply savings (negative abatement cost) and on the other hand, the initiatives that have costs associated.

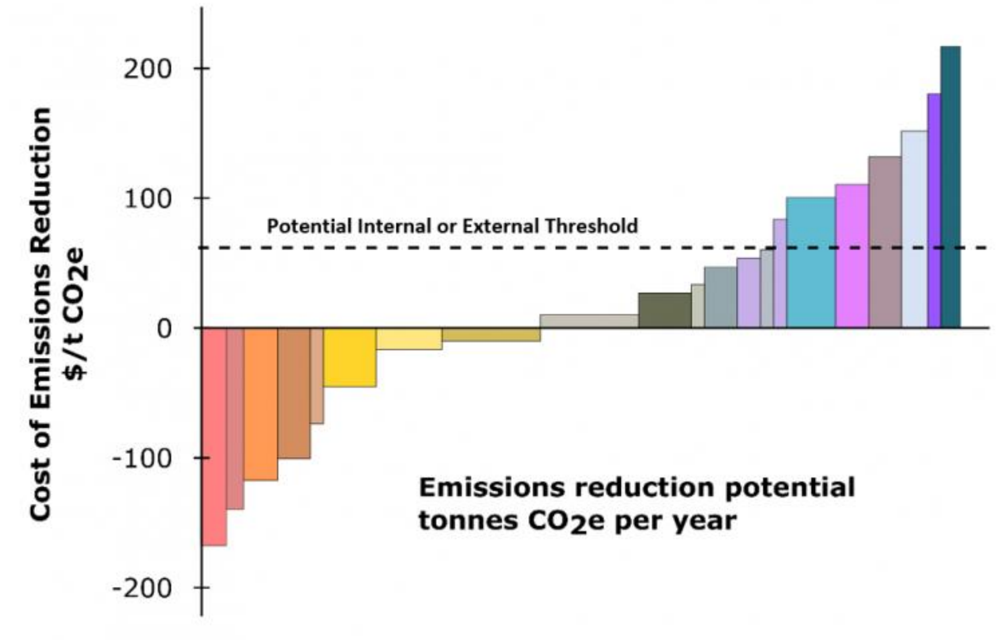

Figure 32. Marginal Abatement Cost Curve (MACC) example

The priority of implementation should follow the order of appearance, since the ones in the left are simpler and cheaper to be introduced in an already operative refinery, whilst the ones in the right are more expensive and involve many more factors.

Therefore, after having computed all required parameters for each Fuel Switch initiative (one for each gas-pipeline access point nearby available biomass), a MACC sample can be generated in order to compare Fuel Switch initiatives' impact against other levers such as CCUS, Energetic Efficiency, among others (*Figure 33* below).

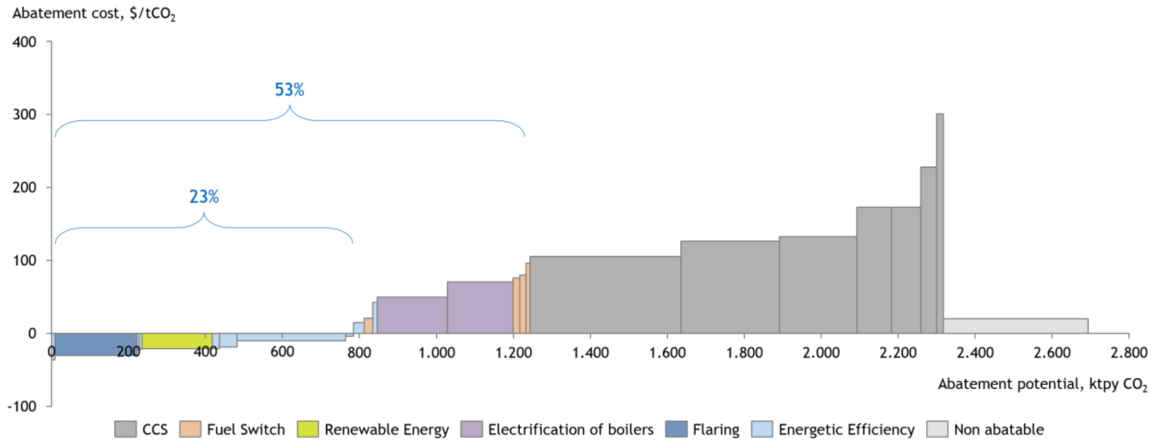

Figure 33. MACC for all levers proposed in the most important client's refinery

In general terms, depending on the zone selected, biomass availability varies, and thus operational costs change. This is the main reason why initiatives using the same technology can lead to different energetic and economic impact.

Focusing only on the Fuel Switch initiatives (the orange ones), it can be observed that they all follow the same pattern and remain in similar abatement scales. However, there is one initiative that stands out of the rest (with the lower abatement cost) due to the fact that it corresponds to the Anaerobic Digestion biogas plant project located next to one of the client's sites, hence no upgrading to biomethane is required to pour it into any gas pipeline. This contributes to the reduction of CapEx and consequently, to the reduction of the abatement cost.

Moreover, the last FS initiative (the orange one placed to the right) consists of syngas production through gasification process, which also implies higher CapEx, as it can be appreciated in comparison to both initiatives placed in its immediate left.

As it is possible to state, there is a significant difference between Fuel Switch and the rest of the levers when it comes to abatement potential. The main reason is that Fuel Switch is specially limited by biomass availability and usability, whereas other levers do not depend on external factors; they simply are operative implementations in the refineries which help reduce a proportion of the current GHGs emissions.

Additional information can be extracted from this MACC, such as the fact that, 23% of emissions associated to this specific refining complex represented, could be reduced only through Energetic Efficiency and Best practices implementation before 2030, with a negative abatement cost associated (which indicates profitability regardless of the cost of CO_2). This means that decarbonization plans can be easily implemented, even generating savings rather than implying costs.

In addition, 53% % of abatable emissions can be reduced with a negative average abatement cost through the proposed initiatives, which also gives a really positive overall decarbonization performance.

7. CONCLUSIONS:

This project was set out to study and propose some decarbonization levers, aiming to provide a future insight into the performance of several refinery facilities in Latin America.

After analyzing diverse initiatives regarding the Fuel Switch lever and studying their economic and energetic suitability, some conclusions have been made.

Although alternative fuels require major investment and infrastructural upgrades, they can substantially reduce carbon emissions. They also take advantage of natural resources to generate non-harmful fuels for the environment.

Through this study, it has been proved how important it is to have market incentives and stable agreements in place to help with this transition. An effective and practical method should be identified and studied for obtaining vast amounts of biomass of all types indefinitely. Despite that, Fuel Switch initiatives would still not be particularly effective to reduce GHGs emitted by one refinery of considerable scale. In order to make a big difference in reducing emissions, this lever needs to be used in conjunction with other levers, such as CCUS for instance.

Nevertheless, certain assumptions taken have been limiting for these initiatives' reduction potential estimation. That is, 10% of available biomass has been considered as usable feedstock to run anaerobic digestion, gasification and pyrolysis projects. During the project, several scenarios were analyzed to present certain sensibility studies to the client hence providing a wider understanding and vision of the strategic approach proposed. In doing so, it was estimated that the CO_2-reduction potential of Fuel Switch initiatives increased significantly when a biomass utilization of 40% was considered instead of 10%.

To sum up, even though multiple factors contribute to the limitation of Fuel Switch competency, it provides an essential contribution to GHGs emissions reduction in a simple and sustainable way, which thousands of facilities around the world are already implementing.

8. **REFERENCES:**

1. (Hannah Ritchie, 2023) **:** https://ourworldindata.org/co2-and-greenhouse-gas-emissions
2. (TWI, n.d.)**:** https://www.twi-global.com/technical-knowledge/faqs/what-is-decarbonisation
3. (New Climate Institute, June 2019)
4. (Roca, 2021)**:** https://elperiodicodelaenergia.com/dos-tercios-de-los-mayores-emisores-%E2%80%8B%E2%80%8Bdel-mundo-han-establecido-un-objetivo-neto-cero/
5. (The Climate Pledge, 2023) **:**https://www.theclimatepledge.com/us/en/Signatories?industry=Fossil+Fuels&industry=Industries&industry=Infrastructure&industry=Manufacturing&industry=Materials&industry=Power+generation
6. (World Resources Institute, 2011) :https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf
7. BCG Analysis
8. (ETSAP) : https://iea-etsap.org/E-TechDS/PDF/P11_BiogasProd_ML_Dec2013_GSOK.pdf
9. (WISDOM)
10. (BOLSA DE COMERCIO DE ROSARIO)
11. (IEA, 2020): https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

Other references:

12. (Ministerio de Economía)
13. (INTA)
14. (Suárez, Pérez, & Barrera, 2016)
15. (Mustafa, Calay, & Mustafa, 2016)
16. (Balat, Balat, Kırtay, & Balat, 2009)
17. Net Zero timeline: https://eciu.net/analysis/infographics/net-zero-history
18. Race To Zero campaign: https://unfccc.int/climate-action/race-to-zero-campaign
19. Net Zero leading companies: https://us.anteagroup.com/news-events/blog/low-carbon-companies-net-zero-energy
20. Climate Change causes: https://climate.ec.europa.eu/climate-change/causes-climate-change_es#:~:text=Influyen%20cada%20vez%20m%C3%A1s%20en,invernadero%20y%20el%20calentamiento%20global.
21. Climate Change: https://www.un.org/es/climatechange/what-is-climate-change
22. Greenhouse effect: https://www.iberdrola.com/sostenibilidad/consecuencias-efecto-invernadero
23. Emissions scopes: https://www.nationalgrid.com/stories/energy-explained/what-are-scope-1-2-3-carbon-emissions#:~:text=Definitions%20of%20scope%201%2C%202,owned%20or%20controlled%20by%20it.
24. Factores de emisión: https://www.miteco.gob.es/content/dam/miteco/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/factoresemision_tcm30-479095.pdf
25. World Biogas Association: https://www.worldbiogasassociation.org/wp-content/uploads/2019/09/WBA-globalreport-56ppa4_digital-Sept-2019.pdf
26. Gasification: https://munin.uit.no/bitstream/handle/10037/12515/article.pdf?sequence=2#:~:text=The%20density%20of%20syngas%20is,each%20kg%20of%20wood%20biomass
27. Biogas: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane

9. APPENDIX:

9.1. Appendix 1. Self-evaluation Questionnaire

a) Evaluate the acquired **competences** according to the **tasks** you have carried out.

Degree Competences		**Task in which you have observed the competence**	**Self evaluation [Rank 1 to 10]**	**Aspects to be improved**
SPECIFIC COMPETENCES				
A1.1	Effectively apply knowledge of basic, scientific and technological materials pertaining to engineering.	During the execution of the Excel models for biogas and syngas production projects, specifically for the mass and energy balance calculations	9	None
A1.2	Design, execute and analyze experiments related to engineering	N/A	N/A	N/A
A1.3	Be able to analyze and synthesize the continuous progress of products, processes, systems and services, whilst applying criteria of safety, economic viability, quality and environmental management. (G6)	N/A	N/A	N/A
A1.4	Know how to establish and develop mathematical models by using the appropriate software in order to provide the scientific and technological basis for the design of new products, processes, systems and services and for the optimization of existing ones. (G5)	During the execution of the Excel models for biogas and syngas production projects	9	None
A2.1	Be able to apply the scientific method and the principles of engineering and economics to formulate and solve complex problems that arise in processes, equipment, installations and services, in which the material undergoes changes to its composition, state or energy content, these changes being characteristic of industrial chemistry and other related sectors such as pharmacology, biotechnology, materials sciences, energy, food and the environment. (G1)	N/A	N/A	N/A
A2.2	Conceive, project, calculate and design processes, equipment, industrial installations and services in the field of chemical engineering and related industrial sectors in terms of quality, safety, economics, the rational and efficient use of natural resources and the conservation of the environment. (G2)	During the execution of the Excel models for biogas and syngas production projects, specifically for the mass and energy balance calculations	8	None
A2.3	Lead and technically and economically manage projects, installations, plants, companies and technological centres in the ambit of chemical engineering and related industrial sectors. (G3)	N/A	N/A	N/A

A3.1	Apply knowledge of mathematics, physics, chemistry, biology and other natural sciences by means of study, experience, practice and critical reasoning in order to establish economically viable solutions for technical problems (I1).	During the execution of the Excel models for biogas and syngas production projects, specifically during the research for technologies to obtain biofuels, and for the mass and energy balance calculations	9	None
A3.2	Design and optimize products, processes, systems and services for the chemical industry on the basis of various areas of chemical engineering, including processes, transport, separation operations, and chemical, nuclear, elctrochemical and biochemical reactions engineering (I2).	During the execution of the Excel models for biogas and syngas production projects	8	None
A3.3	Conceptualize engineering models and apply innovative problems solving methods and appropriate IT applications to the design, simulation, optimization and control of processes and systems (I3).	N/A	N/A	N/A
A3.4	Be able to solve unfamiliar and ill-defined problems by taking into account all possible solutions and selecting the most innovative. (I4)	During the execution of the Excel models for biogas and syngas production projects	7	To approach the model conceptualization all by myself, with no guidance at all
A3.5	Lead and supervise all types of installation, process, system and service in the different industrial areas related to chemical engineering (I5).	N/A	N/A	N/A
A3.6	Design, construct and implement methods, processes and installations for the integrated management of waste, solids, liquids and gases, whilst also taking into account the impacts and risks of these products (I6).	During the execution of the Excel models for biogas and syngas production projects, specifically during the design of different technologies (with different feedstock requirements) to obtain biofuels, and for the mass and energy balance calculations	8	Being able to help with the rea implementation of the initiatives and construct the proposed biofuels plants
A4.1	Lead and organize companies and production and service systems by applying knowledge and abilities regarding industrial organization, commercial strategy, planning and logistics, mercantile and labour legislation, and financial and costs accounting (P1).	During the execution of the Excel models for biogas and syngas production projects, specifically during the design of different technologies (with different feedstock requirements) to obtain biofuels, and for the mass and energy balance calculations	8	Leading the process (I was not actually leading it, but working together with other team members to fulfil the project approach)
A4.2	Lead and manage the organization of work and human resources by applying criteria regarding industrial safety, quality management, occupation risk prevention, sustainability and environmental management (P2).	N/A	N/A	N/A
A4.3	Manage research, development and technological innovation whilst ensuring the transfer of technology and taking into account property and patent rights (P3).	N/A	N/A	N/A
A4.4	Adapt to structural changes in society caused by economic, energy or natural	During the design phase, when analyzing the	7	None

	factors so as to be able to solve any resulting problems and to contribute technological solutions with a high commitment to sustainability (P4).	emissions' data provided by the client and when projecting them to the future to propose adequate decarbonization strategies		
A4.5	Lead and monitor the control of installations, processes, products, certification, auditing, verification, testing and reports (P5).	N/A	N/A	N/A
A5.1	Carry out, present and defend (once all the curriculum credits have been obtained) an original individually produced piece of work before a university panel. The work will consist of a professional integrated Chemical Engineering project that synthesizes (TFM1)	All done; to be defended on 9th February 2024	N/A	N/A
TRANSVERSAL COMPETENCES				
B1.1	Communicate and discuss proposals and conclusions in a clear and unambiguous manner in specialized and non-specialized multilingual forums (G9).	During daily team meetings, to expose the progress, doubts and approach proposals of individual project tasks	7	To be more concise and determined
B1.2	Adapt to changes and be able to apply new and advanced technologies and other important developments with initiative and entrepreneurial spirit. (G10)	During daily routine, when changing from project and working with different teams in different places…	9	None
B2.1	Lead and define multidisciplinary teams that are able to make technical changes and address management needs in national and international contexts. (G8)	N/A	N/A	N/A
B3.1	Work in a team with responsibilities shared among multidisciplinary, multilingual and multicultural teams	During daily routine, when changing from project and working with different teams in different places…	9	None
B4.1	Be able to learn autonomously in order to maintain and improve the competences pertaining to chemical engineering that enable continuous professional development. (G11)	During daily work, in order to meet individual expectations of my corresponding part of the project	8	To have more self-trust when delivering individual work
B5.1	Carry out and lead the appropriate research, design and development of engineering solutions in new or little understood areas, whilst applying criteria of creativity, originality, innovation and technology transfer. (G4)	During the execution of the Excel models for biogas and syngas production projects, specifically during the design of different technologies to obtain biofuels, and for the mass and energy balance calculations	8	Leading the process (I was not actually leading it, but working together with other team members to fulfil the project approach)
B5.2	Bring together knowledge, make judgements and take decisions on the basis of incomplete or limited knowledge whilst taking into account the social and ethical responsibilities of professional practice. (G7)	During the execution of the Excel models for biogas and syngas production projects, specifically during the research of different technologies to obtain biofuels, and for the mass and energy balance calculations	7	To have more self-trust when taking decisions
NUCLEAR COMPETENCES				

C1.1	Have an intermediate mastery of a foreign language, preferably English	During working periods for clients in Saudi Arabia and Oman	8	Be more participative in client meetings
C1.2	Be advanced users of the information and communication technologies	All internship scope	7	Get confident with technologic sources
C1.3	Be able to manage information and knowledge	All internship scope	8	None
C1.4	Be able to express themselves correctly both orally and in writing in one of the two official languages of the URV	All internship scope	9	None
C2.1	Be committed to ethics and social responsibility as citizens and professionals	All internship scope	10	None
C2.2	Be able to define and develop their academic and professional project	Master Thesis development	9	None

b) Evaluate the final master project and suggest improvements.

Key steps	**Evaluation** **[Mark 1 to 10]**	**Improvement proposed**
Selection/assignment of the project (dissemination, communication, assignment requirements...)	10	None
Stay (welcome, length, relationship, follow-up made by the company...)	10	None
Follow-up made by URV tutor	9	None
Other aspects to be considered (which ones...)		