Feasibility of capturing and converting industrial CO_2 in synthetic methane using Power-to-Gas

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

With the recent changes in the Earth's climate, especially the high level of CO_2 emissions, it has become more necessary than ever to discover and develop processes to tackle this issue. One way to do so is by substituting natural gas with biomethane, which is already a reality, since 17% of all gas consumed by the road transport sector in Europe is composed with it. One other alternative is to produce synthetic methane by using a technology that has brought much research attention in the last few years: Power-to-Gas, namely through carbon capture.

Therefore, this dissertation can be divided in two main sections: the first one is to provide a theoretical basis in order to discuss the feasibility of a possible implementation of Power-to-Gas in Portugal, by performing an economic-financial assessment. This is going to be achieved by initially presenting the *Audi* e-gas and *HELMETH* projects, which serve as basis to explain all the processes regarding Power-to-Gas implementation, as well as its economics, taking into consideration the Portuguese context, through understanding the regulation (EU ETS) and funding support (*Fundo Ambiental*). In order for Power-to-Gas to be a reality in Portugal, it is absolutely crucial to consider its economic and financial feasibility, which will be accomplished by analysing project appraisal criteria. Afterwards, a methodology based on the steps to perform an economic evaluation is going to be proposed, which can be applied in specific case studies.

The second main section of this dissertation is to present a specific case study regarding a Power-to-Gas implementation, based on the installation of photovoltaic panels and an electrolyser with 5 and 2.5 MW power, respectively. A technical model was created in order to determine all the technical flows of the project's implementation, with the results showing a prediction of production of around 310 tons of synthetic methane and the non-emission of around 850 tons of CO_2 yearly. The next step was to perform an economic and financial analysis of the project and perform sensitivity analysis on key variables which could affect the project. All these alternatives showed the non-feasibility of this project, which lead to proposing a possible solution that can help turning it (and similar ones) viable: the creation of a feed-in tariff.

Keywords: Climate change, decarbonisation, natural gas, Power-to-Gas, renewable gases, synthetic methane, economic analysis, financial analysis

Resumo

Devido às recentes mudanças climáticas da Terra, nomeadamente o elevado nível de emissões de CO_2, tem-se tornado mais necessário do que nunca descobrir e desenvolver processos para combater esta questão. Uma forma de o fazer é através da substituição de gás natural por biometano, o que já é uma realidade, uma vez que 17% de todo o gás consumido pelo sector do transporte rodoviário na Europa já o é feito dessa forma. Outra alternativa passa pela produção de metano sintético, usando uma tecnologia que tem atraído muita atenção de pesquisa nos últimos anos: o *Power-to-Gas*, nomeadamente através da captura de carbono.

Assim, esta dissertação pode ser dividida em duas secções principais: a primeira consiste em fornecer uma base teórica para discutir a viabilidade de uma eventual implementação do *Power-to-Gas* em Portugal, através da realização de uma avaliação económico-financeira. Para isso, serão apresentando numa primeira fase os projetos *Audi e-gas* e *HELMETH*, que servem de base para explicar todos os processos de implementação *Power-to-Gas*, bem como os seus aspetos económicos, tendo em consideração o contexto português, através de uma análise ao atual regulamento (CELE) e apoios financeiros (Fundo Ambiental). Para que o *Power-to-Gas* seja uma realidade em Portugal, é absolutamente fundamental considerar a sua viabilidade económica e financeira, o que se fará através da análise de critérios de avaliação dos projetos. Posteriormente, será proposta uma metodologia baseada nas etapas de realização de uma avaliação económica, que poderá ser aplicada em estudos de caso específicos.

A segunda principal secção desta dissertação passa por apresentar um estudo de caso específico sobre a implementação de um projeto *Power-to Gas*, baseado na instalação de painéis fotovoltaicos e eletrolisador com uma potência total de 5 e 2,5 MW, respetivamente. Foi criado um modelo técnico para determinar todos os fluxos técnicos relativos à implementação do projeto, com os resultados a mostrar uma previsão de produção de cerca de 310 toneladas de metano sintético e a não emissão de cerca de 850 toneladas de CO_2 anualmente. A próxima etapa foi realizar uma análise económica e financeira do projeto e efetuar uma análise de sensibilidade sobre as principais variáveis que poderiam afetar os resultados. Todas as alternativas apresentadas mostraram a inviabilidade deste projeto, o que levou a propor uma possível solução que pode ajudar a viabilizá-lo (e a outros semelhantes): a criação de uma tarifa *feed-in*.

Palavras-chave: Alterações climáticas, descarbonização, gás natural, *Power-to-Gas*, gases renováveis, metano sintético, análise económica, análise financeira

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Acronyms

AEC – Alkaline electrolysis

AW – Annual Worth

CAPEX – Capital expenditures

CCS – Carbon Capture and Storage

CNG – Compressed Natural Gas

DN – Do Nothing

ENEA – National Strategy for Environmental Education

EU – European Union

EU ETS - European Union Emissions Trading System

FW – Future Worth

GHG – Greenhouse Gases

HDV – Heavy-duty vehicles

IEA – International Energy Agency

IRR – Internal rate of return

LCC – Life-cycle Cost

LCM – Least Common Multiple

LNG – Liquified Natural Gas

MARR – Minimum Acceptable Rate of Return

NCF – Net Cash Flows

NGV – Natural Gas Vehicles

NPV – Net Present Value

OPEX – Operation Expenditures

PEMEC – Proton Exchanges Membrane Electrolysis

PtG - Power-to-Gas

PV - Photovoltaic

PW – Present Worth

RFNBO – Renewable fuels of non-biological origin

RNG – Renewable natural gas

ROR – Rate of Return

SNG – Substitute Natural Gas

SOEC – Solid Oxide Electrolysis

Chapter One – Introduction

The first chapter presents a contextualization in which the problem fits in, providing a bridge between the current situation and the case study to be analysed. In section 1.1, a briefly context is presented on energy, natural gas, and its presence in the transportation field. The objectives for this dissertation are described in section 1.2, with section 1.3 containing the structure of the document.

1.1 – Problem context

1.1.1 – Energy and the future

“Energy is ingrained in all aspects of human life: It is how we power our homes, schools, and hospitals, our businesses, factories, and transport.” (Mountford et al., 2018). Energy is everywhere, but at what cost?

The recent changes in Earth’s climate have had a great impact on human and natural systems. These changes have been hugely influenced by humans, specially due to the anthropogenic emission of greenhouse gases (GHG) (Jarraud & Steiner, 2012). In 2011, Fossil fuels (coal, fuel, oil, natural gas, diesel and gasoline) accounted for 82% of the total primary energy worldwide and, currently, are the ones which generate the majority of air pollution, due to its combustion (Perera, 2018), being responsible for around 75% of GHG emissions (IEA, 2016). However, a different paradigm is to be expected by 2050, with renewable energies (solar, wind, hydroelectric, geothermal, ocean, hydrogen and biomass) becoming the leading source of primary energy consumption (US Energy Information Administration, 2019).

For this change of paradigm to occur, there needs to be a transformation from a fossil-based energy supply, which is currently in place, to an efficient and sustainable energy system, a shift called “energy transition” (van Foreest, 2010).

One essential step to tackle the climate change problem is by addressing the currently high amount of GHG emissions, particularly the CO_2 ones, which are expected to be reduced up to 90% between 2040 and 2070 (Pourakbari-Kasmaei et al., 2020). Over the last few years, the European Union (EU) has increased its ambitions to turn Europe’s decarbonization into a reality. To do so, several measures were applied in order to control Europe’s energy consumption, to increase energy from renewable sources (RES) and energetic efficiency, with the expectation being that these actions continue to increase over the next years.

One of the measures taken was the creation of the Renewable Energy Directive (European Commission, 2008), with the main goal of promoting the reduction of GHG, in order to meet the goals outlined in the Kyoto Protocol and the Paris Agreement. This directive defined that by the end of 2020, 31% of the gross final energy consumption in Portugal must come from RES, with that value being of 10% for the transportation sector.

With the 2010-2020 decade ending, a plan for the decade that follows for the energy sector in Portugal has been outlined, the National Energy and Climate Plan 2021-2030 (PNEC 2030) (Governo de Portugal, 2019). Thus, the main goals for Portugal (figure 1) include a reduction in emissions in the range of 45% to 55%, when comparing with 2005, an increase in energy efficiency of at least 35%, the incorporation of RES in final energy consumption to be of no less than 47 %, a ratio that must be of 20% in the transportation sector. To finalize, 15% of the country's interconnections must be electrical.

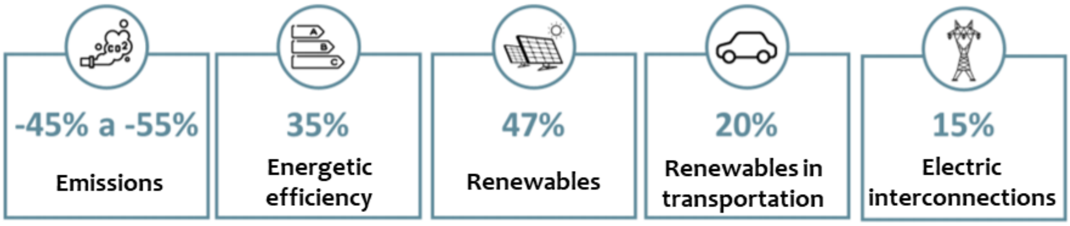

Figure 1 – Energy and climate goals in Portugal to 2030 (Governo de Portugal, 2019)

Integrated carbon capture and subsequent sequestration is seen as one of the most promising choices to tackle this issue (Jiang et al., 2010). The usage of this sequestrated CO_2 to produce biomethane is one possibility, aiding in this so-called "energy transition". Therefore, one of the today's greatest challenges is to find applications that offer a marketable concept of synthetic renewable gas coming from renewable sources with a high CO_2 reduction potential (Peters et al., 2019).

1.2 –Dissertation objectives

This master's dissertation has the main goal of analysing the feasibility of capturing CO_2 to transform it in synthetic methane, with the main objectives being the creation of a technical model regarding technical flows expectations and the study of the economic and financial viability of this implementation, as well as understanding the potential and limitations of this innovative technology.

To achieve these goals, several intermediate objectives in this dissertation are presented, which aim to support the main target:

- To provide a contextualization on natural gas: what it is and how it is used in today's world, namely for transportation; to present biomethane and renewable gases from non-biological origin as possible alternatives for natural gas.
- To generally describe base case studies similar to the one which is going to be presented and analysed;

- To explain how renewable natural gas (RNG) can be a substitute of natural gas through power-to-gas (PtG) techniques;
- To describe the PtG technology and all the steps that are related with its implementation, specifically: carbon capture and storage (CCS), electrolysis, methanation and its economics;
- To explain how the market emissions trading operates in Portugal and how the Portuguese government is acting to implement tools to assist the transition to a low carbon society;
- To discuss the different methods to evaluate project appraisal using engineering economy, trying to understand the best criteria to evaluate a PtG implementation and to propose a methodology for the case study to be presented;
- To present and explain the case study in hand, developing a model in order to determine all the technical flows necessary to evaluate its economic and financial feasibility;
- To evaluate the presented project both economic and financially in 2 base alternatives created, contemplating the use of the final product internally or as a fuel for mobility. This evaluation is going to include sensitivity analysis, namely through variation of single KPIs, but also by presenting: a best-case situation; a more favourable situation when comparing with base alternatives; a later start of the project with different conditions.
- To present a conclusion on this dissertation, by evaluating the results, presenting limitations and possible recommendations regarding the presented case study, but also trying to provide a point-of-view in terms of what the future can hold regarding this innovative technology.

1.3 –Dissertation structure

The structure of this dissertation is the following:

- Chapter One – Introduction: in this chapter, a brief contextualization on the theme is performed, the objectives are established, and the structure of the dissertation is indicated;
- Chapter Two – Natural gas: To start off, an overview on natural gas and its role in transportation is performed. Afterwards, biomethane and renewable gases of non-biological origin are presented and an overview of these is presented, showing how they can be substitutes of natural gas.

- Chapter Three – Case Study description: The *Audi e-gas* and *HELMETH* projects are presented and described in order to explain in what the project to be analysed consists of, since it possesses several similarities with those two.

- Chapter Four – PtG Technology: In this chapter, the Power-to-Gas technology is presented and all of the different processes (production of renewable electricity, carbon capture and storage, electrolysis and methanation) and its economics are explained. Following that, the carbon emissions trading and the Portuguese government strategic intervention to a low carbon society are explained.

- Chapter Five -: In this section of the dissertation, it is explained in what manner engineering economy is used to evaluate projects and how a life-cycle cost analysis is fit to be used in the implementation of PtG. Afterwards, the criteria to evaluate projects is described, namely present, future and annual worth, rate of return and payback analysis. In addition, a methodology for the case study which is going to be presented in chapter Seven will be presented.

- Chapter Six – Theoretical conclusions: A summary of the most important aspects of the theoretical up to that point presented are going to be discussed.

- Chapter Seven – This is the most important chapter of this dissertation and starts by explaining the case study to be analysed, followed by explaining its technical implementation, through describing a model to determine all the flows connected to its engineering, which allow for calculation of the project's annual revenues. Afterwards economic and financial analysis are performed, followed by a sensitivity analysis. To finalize, a discussion on the results is presented.

- Chapter Eight – Final Remarks – In the chapter that finalizes this master's dissertation, an overview on this dissertation is done, where recommendations and limitations and the future of the Power-to-Gas technology in Portugal is discussed.

Chapter Two – Natural Gas

2.1 – Natural Gas

Natural gas, or fossil gas, is a hydrocarbon gas mixture that consists mainly of methane (CH_4) and Ethane (C_2H_6), containing propane (C_3H_8), butane (C_4H_{10}), higher alkanes (C_5H_{12} and above), nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and, in some cases, helium (He) (Bakar & Ali, 2010). This gas is colourless, tasteless, odourless, and lighter than air, and its composition can vary among its production facilities, where the gas is liquefied by cooling it to -162ºC and at atmospheric pressure. Afterwards, the gas is refined, the resulting fuel is cleaned, containing, after that process, around 95% of methane (Eswara, 2013).

When compared with the remaining primary fossil fuels (coal and oil), natural gas is considered to be the most fit one to use in terms of emissions of pollutants into the atmosphere, since it emits fewer harmful pollutants when compared with the other two (Liang et al., 2012). As it is possible to observe on table 1, natural gas emits fewer pounds per billion of energy input of carbon and sulphur dioxide, nitrogen oxides, and mercury when compared with the other two primary fossil fuels, emits more carbon monoxide and less particulates than oil and more particulates and less carbon monoxide than coal (EIA, 1998). These values are still considered to be up to date since the conditions in which these GHG emissions estimations are performed remain the same.

Table 1 - Comparing the GHG emissions of several fossil fuels. (Source: EIA, 1998)

Pollutant (pounds per billion btu of energy input)	Natural Gas	Oil	Coal
Carbon dioxide	117,000	164,000	208,000
Carbon monoxide	40	33	208
Nitrogen oxides	92	448	457
Sulphur dioxide	1	1,112	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

Natural gas is used in a wide variety of fields, such as commerce, industry, residences, as a sourcing power or transportation (Bakar & Ali, 2010), and it currently represents 23% of European Union's (EU) total primary energy consumption (Mihnea et al., 2019). As shown in figure 2, worldwide natural gas consumption has been rising over the last 2 decades and in 2018 amounted to nearly 3.8 trillion cubic meters, an increase of over 59% when compared with the year of 2000, of around 2.4 trillion cubic meters (Statista, 2019).

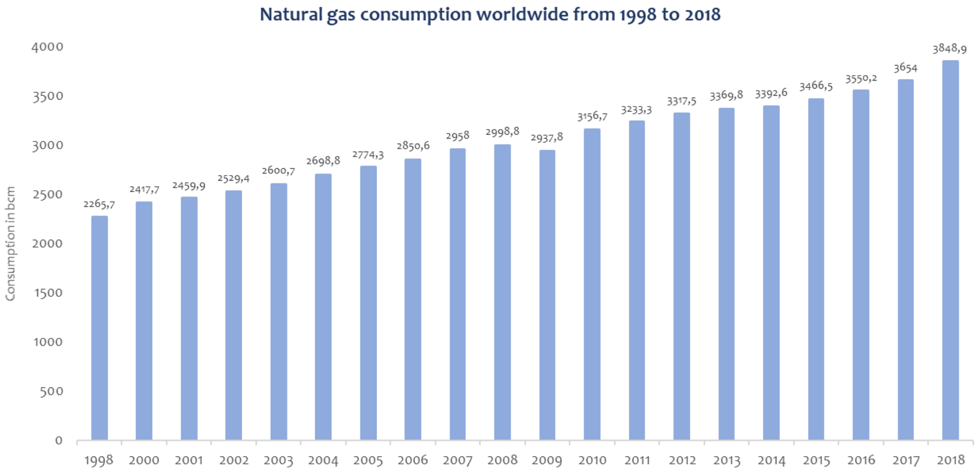

Figure 2 – Natural gas consumption worldwide from 1998 to 2008. (Source: Statista, 2019)

According to the IEA (2018), and represented in figure 3, which displays the past (2000) and current (2017) demands for natural gas in these areas, there has been a tendency for an increase of natural gas consumption in 3 of the 4 areas (electricity, buildings and transport), being the industry field the only one in which a decrease has taken place.

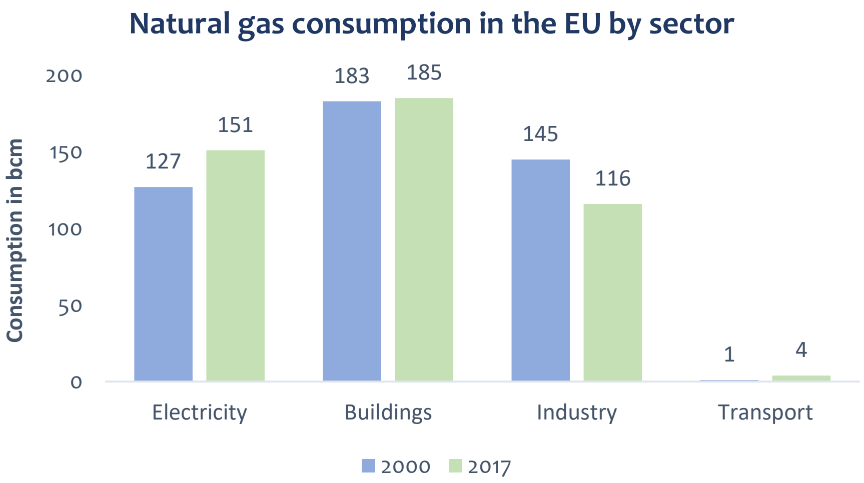

Figure 3 - Natural gas consumption in the EU by sector. (Source: IEA, 2018)

In Portugal, and as shown in figure 4, the consumption of natural gas was the highest ever recorded in the country in 2017, with a value of 6.3 billion cubic meters (Statista, 2018). This ranks the country 57th in the world regarding natural gas consumption, which accounts for around 0.2% of the world's total consumption, with 99% of the natural gas of the country being imported (BP, 2019).

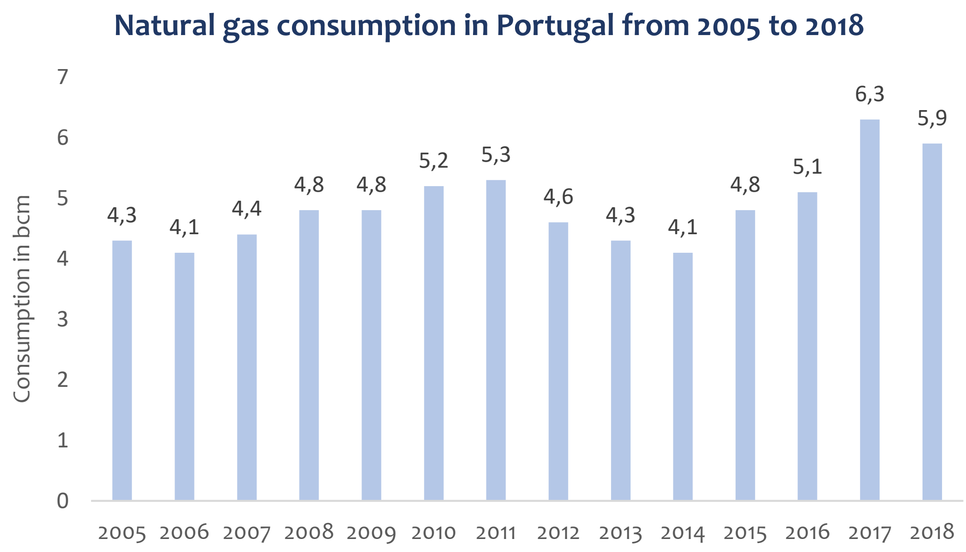

Figure 4 - Natural gas consumption in Portugal from 2005 to 2018. (Source: Statista, 2018)

2.1.1 - Natural Gas in Transportation

Transportation is one of the many areas in which natural gas has made its presence felt, namely as a fuel and, as previously stated, its importance has been increasing over the last few years in this field. Natural gas is often seen as a bridge fuel to an eventual use of hydrogen, in order to achieve zero emission fuel cell vehicles in the long term (Ogden et al., 2018).

As it possible to observe in figure 5, it is expected that natural gas demand increases over the next years, peaking in 2035. Thereafter, gas consumption is expected to go into moderate decline. One of the areas in which natural gas will rise its contribution is transportation, which even though is not expected to be significant in the overall demand, it is projected to be much higher when compared to the almost inexistent impact of natural gas in the field up until the 21st century (DNV GL, 2017).

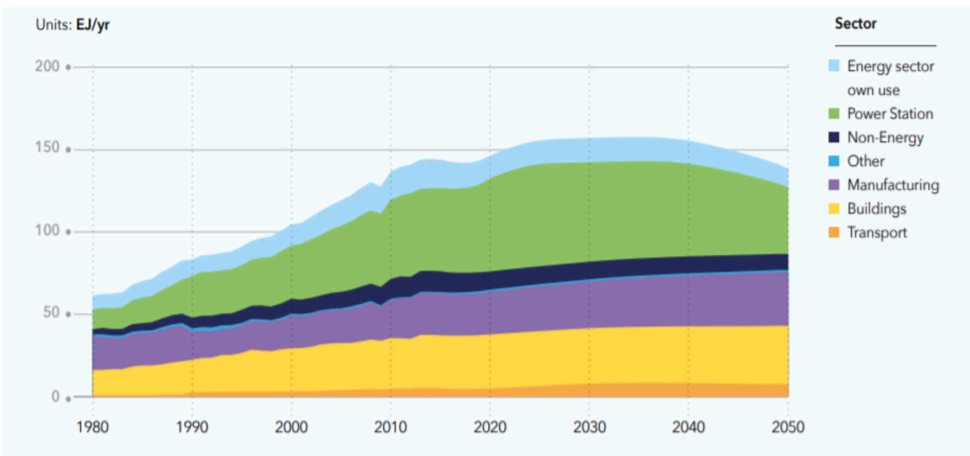

Figure 5 - World gas demand by sector. (Source: GL DNV, 2017)

Nowadays, natural gas is mainly used as a transportation fuel in two ways: CNG, which is compressed to between 200 and 250 bar; liquid natural gas (LNG), which is cooled to -162ºC, when it becomes a liquid. Generally, LNG is preferred for long distance HDV road applications and marine shipping, whereas CNG is preferable for short distances and public transport vehicles (Ogden et al., 2018).

Figure 6 shows the evolution on the number of natural gas vehicles (NGV) between 2000 and 2018. It is possible to observe that there has been a growth over the last two decades on the number of these vehicles, especially in Asia, contrasting with Latin America. In 2008, the number of NGVs was inferior to 10 million units, whereas in 2018 this number was over 26 million (Fevre, 2019).

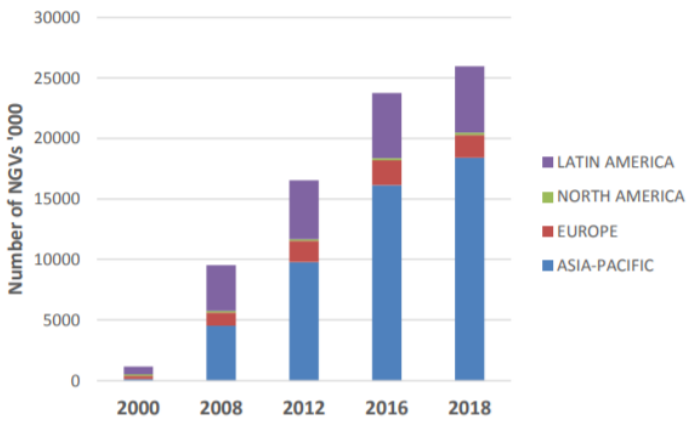

Figure 6 - Global NGV numbers by region, 2000 to 2018. (Source: Fevre, 2019)

The rise on the number of NGV has been matched by two other factors: firstly, the demand for LNG hit 359 million tons in 2019, an increase of 12.5% when compared with the previous year, being expected that the demand for this product doubles to 700 million tons by 2040 (Royal Dutch Shell, 2020); secondly, the number of CNG and LNG filling stations in the EU, which increased between 2015 and 2019 (figure 7), confirming that natural gas is starting to be more relevant in transportation (EAFO, 2019).

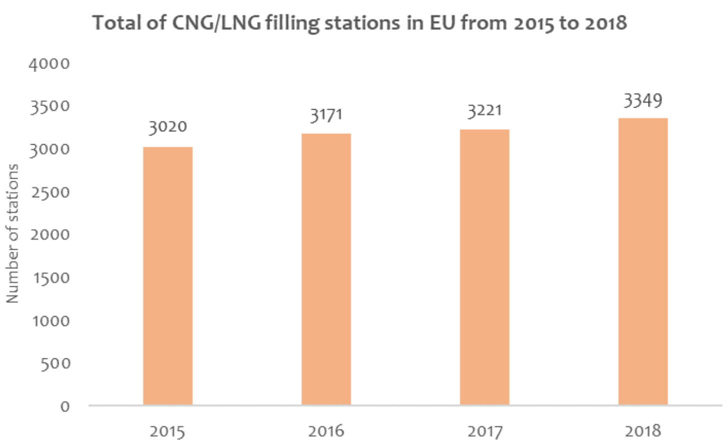

Figure 7 - Total number of CNG/LNG filling stations in EU from 2015 to 2019. (Source: EAFO, 2019)

In Portugal, this tendency is maintained, which can be observed through the 393 NGV registered in 2018 when compared with the 7 in 2012 (figure 8). In August 2020, the registered number of NGV vehicles in the country was of 871 (Cardial, 2020).

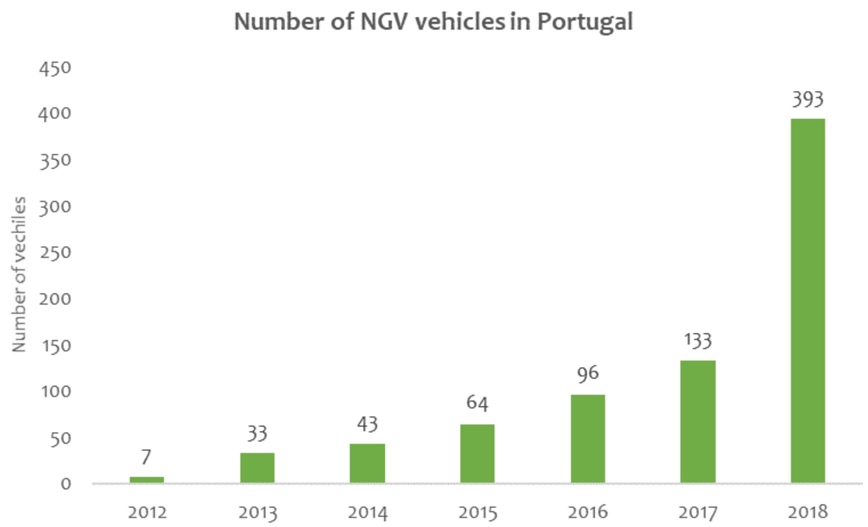

Figure 8 – Number of NGV vehicles in Portugal from 2012 to 2020 (Source: Cardial, 2020)

In terms of fill stations, there are currently 5 fill stations the sell solely CNG, 8 fill stations that sell both CNG and LNG, with 2 offering the option of LNG exclusively, thus resulting in a total of 17 fill stations in the country (table 2). There are also projects to expand this network to 21 stations (2 planned to sell solely CNG and 2 to sell both CNG and LNG) (GASNAM, 2020).

Table 2 – Number of CNG and LNG fill stations in Portugal (Source: GASNAM, 2020)

	Currently Open	In project	Total
CNG	5	2	**7**
CNG + LNG	8	2	**10**
LNG	2		**2**

2.2. – Biomethane and RFNBO

Substitute natural gas (SNG), or synthetic natural gas, is a fuel gas that can be produced from fossil fuels, such as coal, lignite, biomass, biofuels or even from captured carbon. Since natural gas is mainly made of methane, this chemical component can be synthesized to produce SNG, with several similarities with natural gas, meaning that SNG may be fed into the Natural Gas infrastructure (Walspurger et al., 2014).

Depending on the source fuel, SNG may be a low-carbon or even carbon free substitute for fossil fuels, which is the case when it is produced from biofuels or biogenic captured carbon. In this case, when this gas has more than 90% of methane in its composition, one is under the presence of renewable natural gas (RNG), also known as sustainable natural gas or, more commonly, biomethane (Al Mamun & Torii, 2017).

According to the European Biogas Association (2018), and as expressed in figure 9, there were 540 industrial plants of biomethane in Europe in the year of 2017, a rise of 8% when comparing to the 497 in 2016. The number of biomethane plants in Europe has increased 2.6 times since 2011.

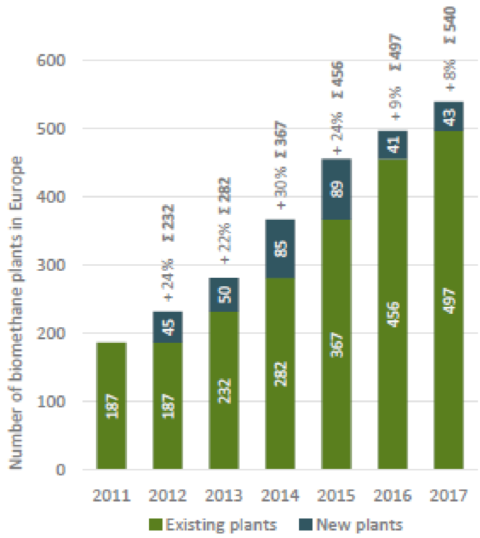

Figure 9 – Number of biomethane plants in Europe from 2011 to 2017 (Source: European Biogas Association, 2018)

In terms of European countries, Germany is the one with the most plants in the continent, with 195, which corresponds to 36.1% of the total (figure 10). When analysing the number of plants per million of inhabitants, with 7, followed by Iceland, with 5.9. In Portugal, no industrial plant of biomethane was registered in this year.

Figure 10 – Number of biomethane plants in European countries (left) and per million capita (right) (Source: European Biogas Association, 2018)

Currently, the most commonly used method for the production of biomethane is through the purification of biogas, which is a gas mixture composed of roughly 60% CH_4 and 40% CO_2, containing, in some cases, small amounts of other gases such as hydrogen sulphide or O_2. Nowadays, biogas is mainly used to generate electricity through cogeneration or power plants. However, its conversion into biomethane may prove to be not only more profitable, but also with a better environmental impact, since there is not only a higher energy retention if biomethane is injected into gas networks, but also due to the fact that methane leakage into the atmosphere when electricity is generated by combustion is avoided (Northern Gas Networks, n.d.).

It is generally accepted that the production of renewable gases is much more expensive than fossil ones, and biomethane as a substitute to natural gas is no exception. In order to incentive the production of biomethane, there are 5 different types of support schemes for its development in Europe (Eba et al., 2020):

- Feed-in tariff - Specific technology support scheme that provides a specific technology fee per unit of renewable energy, which public authorities define and guarantee for a specific period. Typical advantages are:
    - Long-term contract with the producer (usually 10 to 20 years);
    - Guaranteed access to the network;
    - Payment levels based on renewable energy production costs.
- Feed-in-Premium - A bonus feed-in premium to be paid above the reference price. It is specific subsidy of technology per unit of renewable energy at a pre-defined rate, (fixed or variable). This value can be calculated to estimate negative externalities avoided through the generation of renewable energy or to cover the cost of energy generation for the total payment.
- Quotas/green certificates system – In this system, the production of renewable energy is encouraged by a mandatory target that establishes a specific portion of renewable energy in the mix of producers, consumers or distributors. Renewable energy producers benefit from selling energy to the gas network at the market price, as well as selling green certificates on the market.
- Tax incentives - Tax exemptions or reductions are generally additional (and minor) support systems. Renewable energy producers receive certain tax exemptions (such as carbon taxes) as compensation for the competitiveness of the renewable energy market and its development. The impact of these incentives depends on the applicable tax rate.
- Investment support - Fixed amount received before, during or shortly after the construction phase of the industrial plant, regardless of the amount of renewable energy production.

Figure 11 shows the most impactful type of support in each European country. Currently, the feed-in tariff system is the most used in Europe.

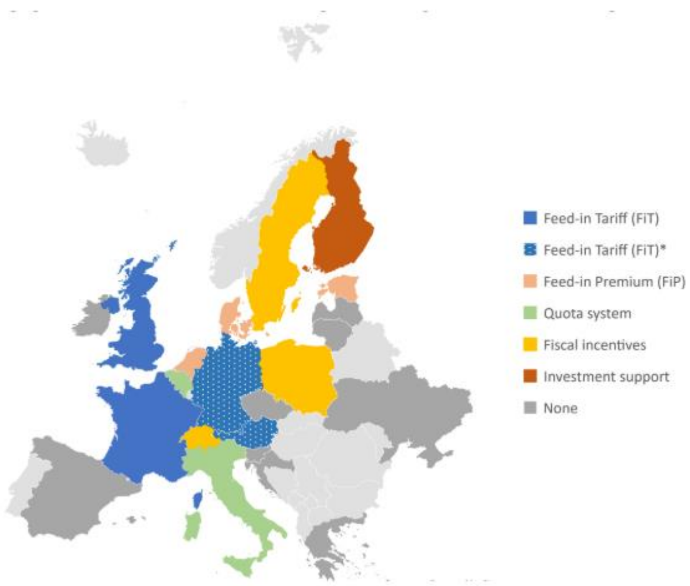

Figure 11 – Support schemes in place per country in Europe (Source: Eba et al., 2020)

Biomethane production is performed using waste with a biological origin. One possibility of doing so is by capturing carbon with such origin (for example, from biomass). However, this situation changes if carbon is captured from a non-biological source (when it is captured from the exhaust gases of natural gas burning, for example). In this case, one is dealing with a renewable fuel from a non-biological origin (RFNBO), if the energy content used to produce it is derived from renewable sources (IEA Bioenergy, 2020).

It is important to keep in mind that burning fossil fuels releases carbon that has been locked up in the ground for millions of years, while burning biomass emits carbon that is part of the biogenic carbon cycle (figure 12).

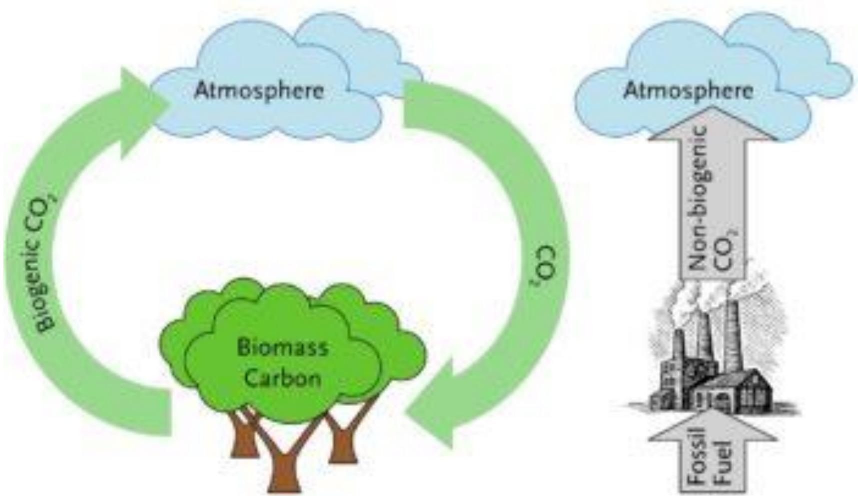

Figure 12 – Biogenic and non-biogenic CO_2. (Source: (IEA Bioenergy, 2020)

The uses for synthetic methane are the same as for natural gas itself. The difference between these two fuels is that natural gas has a variety of other hydrocarbons besides methane (as described previously), which gives it a higher calorific value when compared with pure methane (Materazzi & Foscolo, 2019). Currently, biomethane production is already a reality, with 17% of all gas consumed by the road transport sector in Europe being composed with it (NGVA Europe, 2020).The different applications for biomethane (which are the same for all synthetic methane), according to the CEN–TC 408 (European Commission, 2016), are as follows (figure 13):

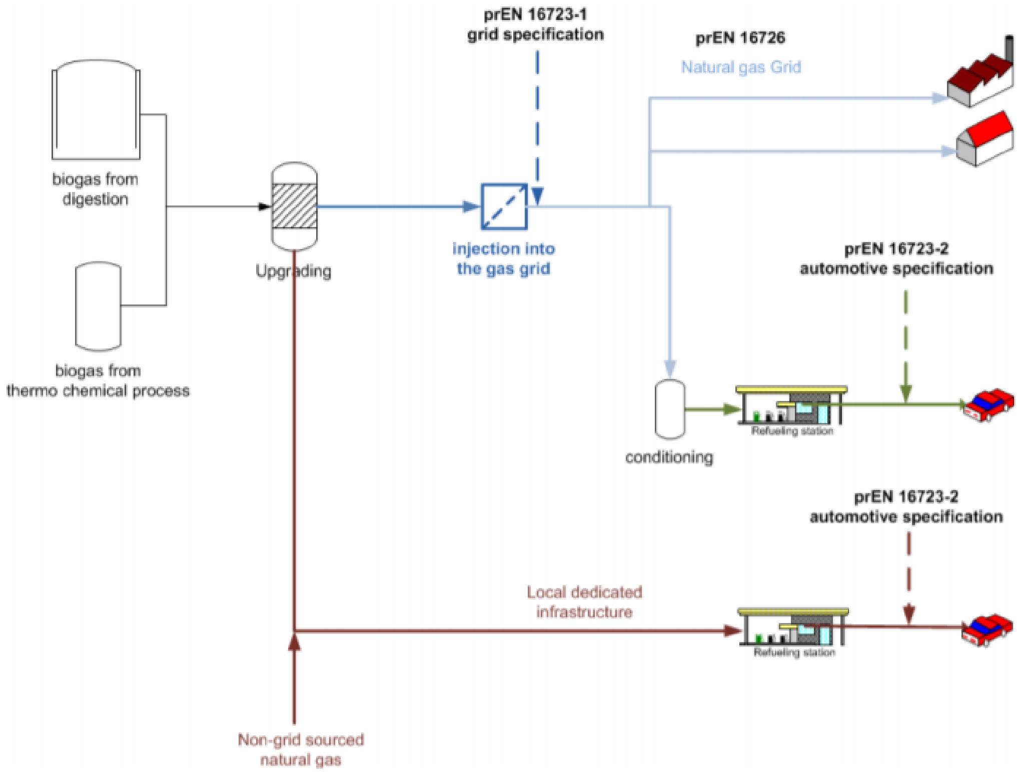

Figure 13 – Uses for Biomethane, according to CEN – TC 408 (Source: European Commission, 2016)

Synthetic methane may be considered a practical option to fulfil the role of renewable energy carries, but its production is still far from being developed enough to do so, especially in Portugal. In recent years, technologies to produce it through carbon capture have been developed, namely the power-to-gas (PtG) concept, via methanation (Tichler & Bauer, 2016). This means that instead of being considered an industrial waste product, CO_2 can be seen as a raw material to produce hydrocarbons, derived fuels or synthetic products, while at the same time mitigating the harmful environmental effect of excessive carbon dioxide in the atmosphere (Materazzi & Foscolo, 2019).

Chapter Three – Case study description

In June 2013, *Audi* launched the *Audi e-gas project* and opened its first e-gas plant in *Werlte*, in the *Emsland* district, in Germany, becoming the first car manufacturer to develop a sustainable energy production chain. The process starts with green electricity, water and carbon dioxide. The final products are hydrogen and synthetic methane: the *Audi* e-gas.

As shown in figure 14, this e-gas plant operates in two steps: electrolysis and methanization. In the first step, the plant uses surplus green electricity to separate the water atoms into oxygen and hydrogen. In the second phase, Hydrogen reacts with CO_2 to produce synthetic methane: the *Audi* e-gas. This product is similar to fossil natural gas and is distributed in Germany's CNG (compressed natural gas) stations through an existing infrastructure, the German natural gas network.

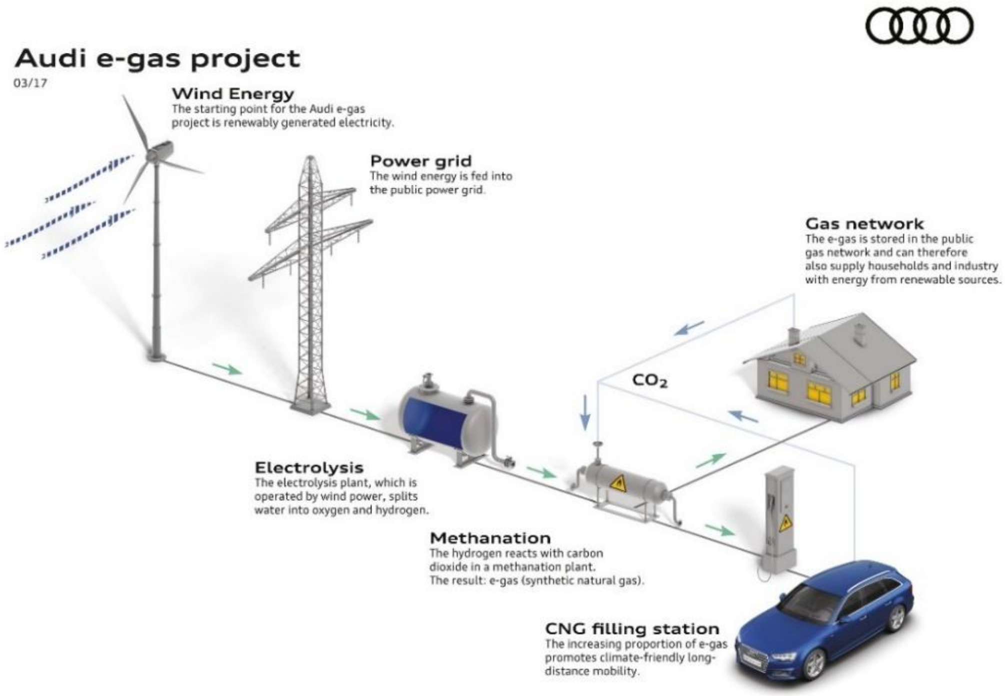

Figure 14 – Audi e-gas project scheme. (Source: Audi, 2017)

The factory started supplying the network with the *Audi* e-gas in the fall of 2013.According to *Audi* (n.d.), the factory produces about 1,000 metric tons of e-gas per year, saving about 2,800 metric tons of CO_2. This corresponds approximately to what a forest with more than 220 thousand trees can absorb in one year. The only by-products are water and oxygen.

Another example of a project which can fit in this category was the *HELMETH* (Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion) project. Its main goal was to be proof of concept of a highly efficient Power-to-Gas (P2G) technology with methane as a chemical storage and by thermally integrating high temperature electrolysis (SOEC technology) with methanation.

This thermal integration can be seen as an innovation with a high potential for a most energy-efficient storage solution for renewable electricity, since it provides SNG (Substitute Natural Gas) as a product, which is fully compatible with the existing pipeline network and storage infrastructure (HELMETH Consortioum, 2018). A representation of this project can be seen in figure 15 below.

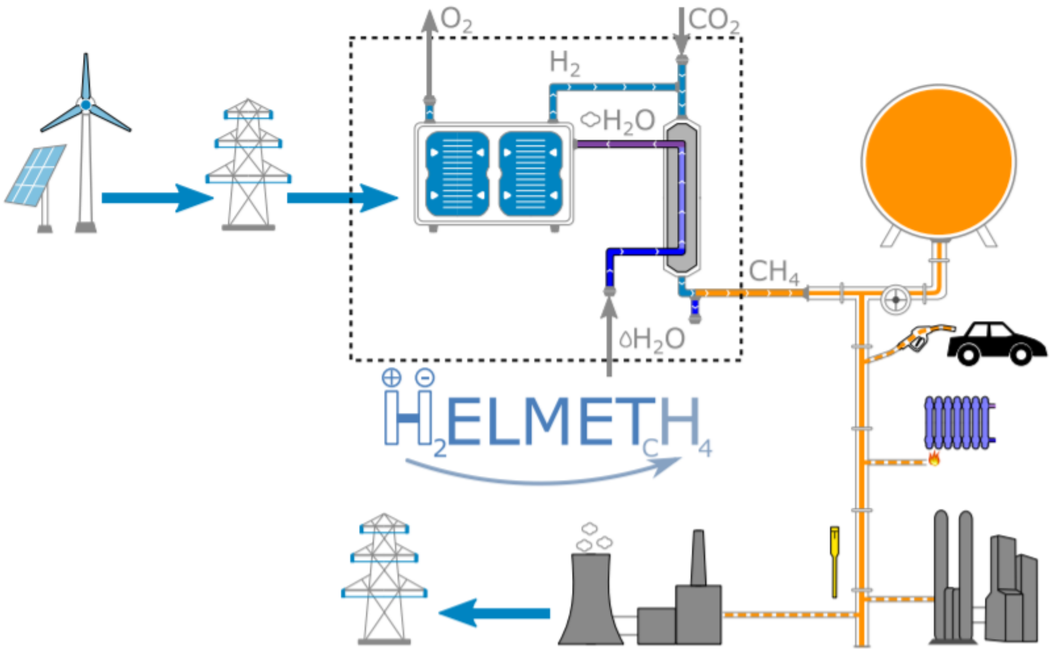

Figure 15 – HELMETH project scheme. (Source: HELMETH Consortioum, 2018)

In the following chapters of this dissertation, the technology of Power-to-Gas, behind the *Audi e-gas* and the *HELMETH* projects, is going to be described. Thereafter a specific case study is going to be presented, with the main goal of analysing the viability of implementing this process in a Portuguese context.

Chapter Four - Power-to-Gas (PtG)

Regarded as a long-term, large capacity energy storage solution, commercialized power-to-gas (PtG) technology has drawn much research attention in recent years (Liu et al., 2017). In PtG, as shown in figure 16, the hydrogen is acquired from an electrolysis plant, which uses excess electrical energy to split water into hydrogen and oxygen. After that, the hydrogen and captured CO_2 (that would be normally released to atmosphere) are fed into a methanation reactor. Finally, the gas Is sent to the gas distribution grid and is ready to be used.

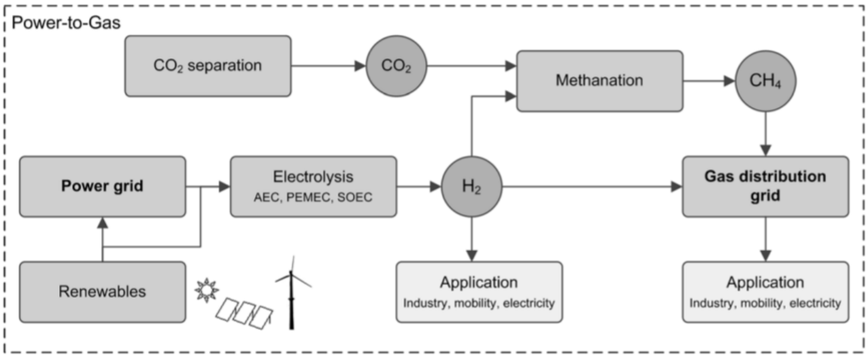

Figure 16 – Main process steps in a power-to-gas system. (Source: Reiter, 2016)

4.1 – PtG process

4.1.1 – Production of renewable electricity

In order for this process to be 100% renewable, the first step is to obtain the necessary electric energy to perform the water electrolysis, which will be achieved through the installation of photovoltaic (PV) panels.

The PV technology operates by catching the photons of light and manipulating them to produce electrons, which generate an electric current, through solar power panels or PV cells. A PV cell is a semi-conductor cell which is able to convert solar rays into electrical power. This system is composed by three different elements, represented in figure 17:

- Cell - the unit where the photon-electron energy transfer occurs.
- Module or panel - The combination of several cells. The calculation of the main energy characteristics of these systems is usually referred to as the panel.
- Array - The combination of various panels.

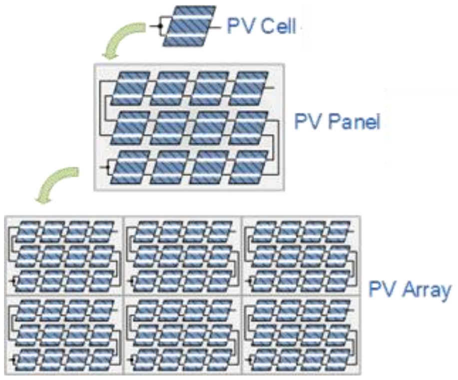

Figure 17 – PV solar system (Source: Prashant, 2018)

There are a variety of solar panels based on semiconductor materials and manufacturing methods. Additionally, they can be classified according to their final shape. The most common types of solar panels that can be found on the market, related to the materials and manufactured process used are (Eldin et al., 2015; Prashant, 2018):

- Mono crystalline panels - These panels are sections of a silicon bar in one piece crystallized perfectly, with an efficiency of around 24.7% in laboratory and 16% for commercial use. The expected lifespan of these cells is typically 25-30 years.
- Polycrystalline panels - Similar to the previous type but in this case the panels possess a granulated surface and are formed by pieces of a silicon bar that have been structured as disordered crystals. A lower efficiency than mono crystalline (18-23% laboratory 14-17% in commercial modules) is provided by these panels, resulting in a lower price.
- Amorphous panels – These are one of the most developed and widely known thin-film solar cells. Amorphous silicon can be deposited on cheap and very large substrates based on continuous deposition techniques, thus considerably reducing manufacturing costs. These panels have lower efficiencies when comparing with the previous ones (up to 12.2% in laboratory and 4-8% in commercial modules)
- Tandem panels – These panels combine two different types of semiconductor materials. Each type of material absorbs only a part of the electromagnetic spectrum of solar radiation and can be used to collect more than one of the electromagnetic spectrums. This type of panel may reach an efficiency up until 35%.

The power incident on a PV module is dependent on the sunlight's power and the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight. However, one needs to take into account that this angle is continuously changing, which means that the actual power density of the panel is smaller than the incident sunlight (Honsberg & Bowden, n.d.).

Figure 18 shows how to determine the radiation incident on a tilted surface (S_{module}) given either the solar radiation measured on horizontal surface (S_{horiz}) or the solar radiation measured perpendicular to the sun ($S_{incident}$).

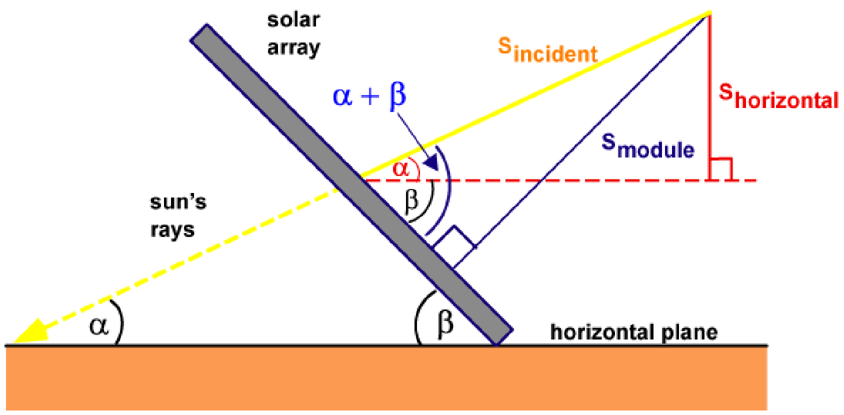

Figure 18 – Radiation on a tilted surface (Honsberg & Bowden, n.d.)

Having the data of radiation, it is possible to calculate S_{module}. To do so, the first step involves determining the elevation angle (α), using Eq.1, with ϕ being the latitude and δ the declination angle:

$$\alpha = 90 - \phi + \delta \tag{1}$$

The δ of each day of the year can be estimated using Eq.2, where d represents the day of the year:

$$\delta = 23.45 * \sin\left(\frac{360}{365} * (284 + d\right) \tag{2}$$

It is now possible to determine S_{module} through Eq.3, where β is the tilt angle of the module measured from the horizontal:

$$S_{module} = \frac{S_{horizontal} * \sin(\alpha + \beta)}{\sin(\alpha)} \tag{3}$$

Module temperature is a parameter that has great influence in the behaviour of a PV system, as it modifies system efficiency and output energy, depending on the material used, its thermal dissipation and absorption properties, the working point of the module, the atmospheric parameters such as irradiance level, ambient temperature and wind speed and the particular installing conditions. It is common to use Normal Operative Cell temperature (NOCT) as an indicative of the module temperature, which is defined as the mean solar cell junction temperature within an open-rack mounted module in Standard Reference Environment (SRE): tilt angle at normal incidence to the direct solar beam at local solar noon; total irradiance of 800 W/m2; ambient temperature of 20ºC; wind speed of 1 m/s and nil electrical load. Thus, the panel temperature (T_{PV}) can be estimated using Eq.4. T_{amb} represents the ambient temperature and NOCT the normal operative cell temperature.

$$T_{PV} = T_{amb} + (NOCT - 20)\frac{S_{module}}{800} \tag{4}$$

Panel manufacturer firms usually provide the electrical values of the PV panel under Standard Test Conditions (STC): 1000 W/m² solar radiation level, 25 ºC cell temperature and A.M. 1,5 air mass rate. With all the information described previously, it is possible to calculate the power for a certain point in time with Eq.5. In this case, $P_{máx}$ represents the power generated by the panel, $P_{máx}(\ @STC\ )$ the panel's nominal power in STC conditions and K_I the temperature coefficient

$$P_{máx} = P_{máx}(\ @STC\ ) * (1 - K_I * (T_{PV} - T_{amb})) * \frac{S_{module}}{1000} \qquad 5$$

Finally, it is now possible to estimate the electrical energy generated by 1 panel through Eq.6, where E is the energy generated by the panel and ΔT the time interval.

$$E = P_{máx} * \Delta T \qquad 6$$

4.1.2 – Carbon capture and Storage

One important aspect of the production of SNG (and consequently RNG) is the fact that using CO_2 helps delaying its release to the atmosphere (Vandewalle et al., 2015). Nowadays, it is clear that CO_2 reduction is seen as the path to go, with different approaches being studied by different countries, such as: improve energy efficiency and promote energy conservation; increase usage of low carbon fuels, such as natural gas, hydrogen or nuclear power; increase the usage of renewable energy, such as solar, wind, hydropower and bioenergy; apply geoengineering approaches, like reforestation and afforestation; CO_2 capture and storage (CCS) (Leung et al., 2014).

To be used in the PtG process, CCS is seen as the way to go. In order to do so, CO_2 must be firstly captured and separated afterwards, being then ready to be transported or stored. To do that, different processes and techniques are required (Leung et al., 2014; Mazza et al., 2018; Reiter, 2016; Reiter & Lindorfer, 2015).

The necessary CO_2 for the PtG process can be obtained from different sources:

- CO_2 from combustion processes – Combustion processes in power plants emit a considerable amount of CO_2, meaning that there is a potential source of CO_2 which may be used in PtG. There are three types of combustion processes in order to obtain CO_2: post-combustion, where CO_2 is obtained from the flue gas of a power plant; pre-combustion, in which there is a separation of CO_2 before the fuel combustion; oxyfuel process, which consists of burning fuel using pure oxygen instead of air.
- CO_2 as by product from industrial processes – There are several industries from where CO_2 can be obtained from: biotechnological processes, such as biogas upgrading, fermentation or production of bioethanol; in the chemical industry, as a by-product of refineries or the production of ethylene or ammonia; in industrial production processes, for instance production of cement or steel.
- CO_2 from the atmosphere – It is also possible to obtain CO_2 from atmosphere. However, air's extremely low concentration of this component makes the process extremely complex and expensive.

As shown in figure 19, most CO_2 sources contain concentrations below 15%. On the other hand, there are cases where this concentration can go up to almost 100%, which would be extremely important to the efficiency of CCS, since the higher the concentration of CO2 in the original source, the easier and more economically feasible becomes its implementation (Metz et al., 2005).

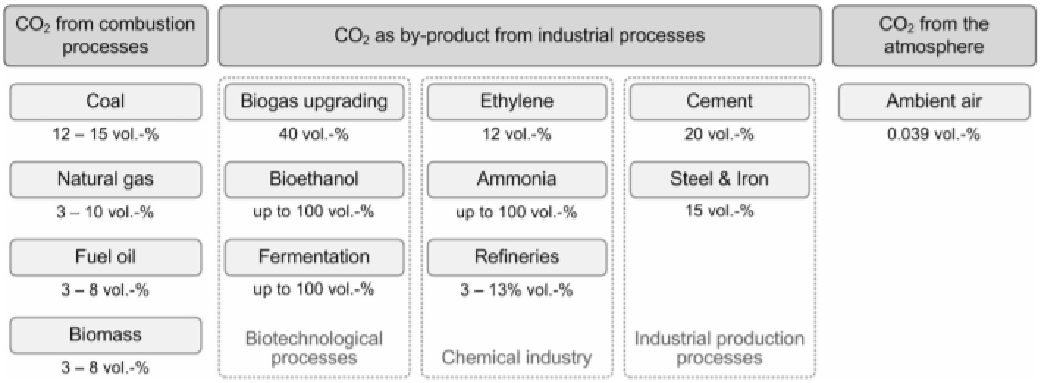

Figure 19 – Overview of potential CO_2 sources and related CO_2 concentrations (Source: Reiter, 2016)

In order to separate the CO_2 from its source, there are already several separation technologies in use up until this point:

- Absorption – This technique is state of the art and can be easily integrated at an industrial level. In this process, a liquid sorbent is used to separate CO_2 from the fuel gas. There are two distinct absorption techniques: chemical absorption, which usually involves amine-based solvents like monoethanolamide; physical absorption, that uses organic solvents such as selexol or rectisol.

- Adsorption – unlike absorption, solid sorbent is used rather than a liquid one. In this case, CO_2 is absorbed on the surface of a solid adsorbent at a high pressure, which swings to low pressure to desorb the adsorbent and release CO_2 for transport.

- Membrane separation – This method has also been used to separate O_2 and N_2 from natural gas and involves the use of a membrane that allows that only CO_2 passes through it.

- Cryogenic distillation – This gas separation process occurs at a very low temperature and high pressure, using distillation to separate the components of a gaseous mixture. In the case of CO_2, a flue gas containing it is cooled until CO_2 is solidified. Afterwards, CO_2 is separated from other light gases and compressed to a high pressure of 100-200 atmospheric pressure.

- Chemical looping combustion – In this technique, a metal oxide is used as an oxygen carrier rather than using pure oxygen directly for the combustion. In this process, the metal oxide is reduced to metal while the fuel is being oxidized to CO_2 and water.

- Hydrate-based separation – This technology is an innovative one, in which the exhaust gas containing CO_2 is exposed to water under high pressure to form hydrate, where it is possible to separate the CO_2.

If this captured CO_2 cannot be stored or applied directly, it needs to be transported, with the transportation of compressed or liquified CO_2 being nowadays performed via truck or pipeline.

4.1.3 – Electrolysis

Nowadays, hydrogen is mainly obtained industrially through steam reformation using natural gas as a raw material. However, it is possible to obtain it through an electrolysis process. The electrolysis of water is a process in which electric power is used to split water into hydrogen and oxygen, as described in Eq.7.

$$2\ H_2O\ (\mathrm{l}) + energy\ \rightarrow\ 2\ \mathrm{H_2} + \mathrm{O_2}\ (g) \qquad 7$$

According to different authors (Peters et al., 2019; Reiter, 2016; Vartiainen, 2016), there are three main ways in which electrolysis can be performed: alkaline electrolysis (AEC), proton exchanges membrane electrolysis (PEMEC) and solid oxide electrolysis (SOEC).

AEC is currently state of the art and its process is characterized by the existence of two electrodes operating in a water-based solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH), with a membrane being placed to separate the hydrogen and oxygen product gases with a hydroxide ion (OH-) being passed through the membrane to transport the electric charge and to close the circuit.

Unlike the previous method, PEMEC uses solid polymer electrolytes instead of a liquid one and, in this case, the proton (H+) is the ion that is transported from the anode to the cathode, passing through the membrane.

The SOEC technology is the most recent one and it is not used as much as the two previous ones yet. For this process, the water is in steam form and oxygen ions carry the charge through a solid oxide membrane which acts as the electrolyte.

4.1.4 – Methanation

Methane is an energy carrier of great importance to the industry, transportation and energy sectors worldwide and has a significant impact on modern economies, with its major industrial use coming from fossil natural gas resources. With the recent debate on climate change and the impact of fossil fuels, methane production from carbon oxide-rich gases (methanation) has become an important point of focus over the last few years (Rönsch et al., 2016).

CO and CO_2 methanation processes were first discovered by Sabatier and Senderens in 1902 and have been investigated and developed for over 100 years. These processes have the goal of producing methane from hydrogen and carbon dioxide, with these processes focusing on two different options (Rönsch et al., 2016):

- CO methanation – A process that uses carbon monoxide and hydrogen for the catalytic production of methane and water, represented in Eq.8.

$$CO + 3\,H_2 \leftrightharpoons CH_4 + H_2O\,(g) \qquad -206\,kJ\,mol^{-1}\,(at\,298\,K) \tag{8}$$

- CO_2 methanation – In this case, the carbon monoxide is replaced by carbon dioxide to produce the same products (Eq.9).

$$CO_2 + 4\,H_2 \leftrightharpoons CH_4 + 2\,H_2O\,(g) \qquad -164\,kJ\,mol^{-1}\,(at\,298\,K) \tag{9}$$

Both reactions are exothermic, i.e., release energy, which, in this case, is heat. In Eq.8, the conversion of carbon monoxide releases 206 kJ heat per mole, whereas the conversion of carbon dioxide releases 164 kJ heat per mole (Eq.(9)), which means that for each m^3 of methane produced per hour, 2.3 and 1.8 kW heat, respectively, are released. In addition, a significant volume contraction occurs in this reaction, which is of 50% for CO methanation and 40% for the CO_2 one.

In thermodynamic equilibrium, high pressures favour the production of methane, whereas high temperatures limit its formation. The efficiency methanation processes are limited by the Sabatier reaction to a maximum of 80% (Benjaminsson et al., 2013).

Methanation is an important step in the creation of synthetic or substitute natural gas (SNG) (Kopyscinski et al., 2010) and has been considered since the 1970s (Rönsch et al., 2016).

4.1.4.1 – Types of methanation in power-to-gas

According to several authors (Götz et al., 2014, 2016; Kopyscinski et al., 2010; Rönsch et al., 2016; Vartiainen, 2016), there are two different types of PtG methanation process: biological and thermochemical methanation.

Biological Methanation

Biological methanation is one of the options for the PtG process chain, where a microorganism is used as biocatalyst, turning the hydrogen and carbon dioxide into methane. This reaction occurs at low temperatures (40-70ºC) and at atmospheric pressure, which makes it a simple process. There are two main types of biological methanation:

- *in situ* digester (figure 20), where the digesters of biogas plants can be used for the PtG process chain, with the hydrogen being fed directly to the biogas digester. Afterwards, a part of the CO2 produced is *in situ* converted to CH_4. Depending on its pureness, the gas may be cleaned before being fed to the gas grid.

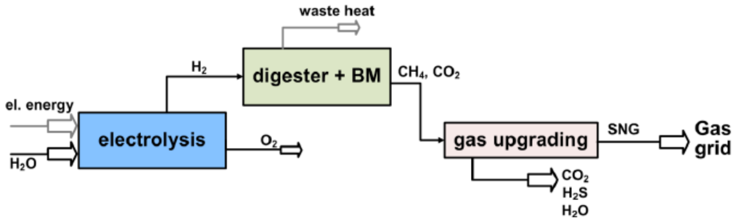

Figure 20 - Process flow diagram for in situ variation of biological methanation (Source*:* Götz et al., 2014)

- in a separate reactor (*ex situ*) (figure 21) – in this case, the CO_2 is converted into methane in a separate methanation plant, by adding hydrogen. After that process, the gas is cleaned and fed to the gas grid.

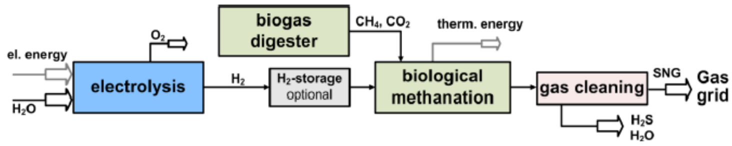

Figure 21 - Process flow diagram for biological methanation with a separate reactor (extern) (Source*:* Götz et al., 2014)

Thermochemical methanation

Thermochemical methanation, or catalytic methanation, is defined as the conversion of CO or CO_2 and H_2 in the presence of a catalyst (several metals can be used, but it is usually nickel-based), due to its relatively high activity, good CH_4 selectivity and low prices. This type of methanation takes place with temperatures in a range of 300-550ºC and pressures of 1-100 bar. There are different types of thermochemical methanation: fixed bed, fluidized bed, three phase and structured reactors methanations.

Fixed bed methanation

Nowadays, fixed bed state methanation is state of the art and the most used method of thermochemical methanation. This technique is used to remove small concentrations of CO in hydrogen-rich streams, with the reactor being packed with the catalyst. In this process, either adiabatic or isothermal reactors can be used, with the first ones being the most common. This method relies on a series of reactors, generally 2-5, with intercooling and gas recycle. The highest challenge of this type of process is the temperature control inside the reactor since methane conversion occurs above 300ºC and temperatures above 550ºC can cause catalyst deactivation. To tackle this issue, several methanation reactors are connected with intermediate cooling or recycle of product gas. Different types of fixed bed methanation processes have been developed over the years, and a few are used industrially, like the Air *Liquide* (former Lurgi process), which was used in the first commercial methanation plant in North Dakota, or the TREMP process, used in coal-to-gas plants in China and biomass-to-gas plant *GoBiGas* in Sweden.

Fluidized bed methanation

As an alternative to the previous process, fluidized bed methanation is another method that is used nowadays in industrial methanation, where fine catalyst particles are fluidized by the reactants. This process only requires a single reactor with a simple design, since the mixing of fluidized solids leads to almost isothermal conditions, providing a better control of heat removal. On the other hand, the CO_2 conversion may be incomplete due to bubbling and the reactor is limited by the gas velocity in the reactor, since it cannot to be too low, in order to assure a minimum fluidization, but also not too high, so that a breakage of the catalyst does not occur.

Three phase methanation

Fluidized bed methanation is another type of thermochemical methanation, which is based on the use of three-phase reactors for methanation. In this process, the catalyst is suspended in an inert liquid phase (such as dibenzyl toluene), enabling a better heat removal and temperature control capacity, which results in an almost isothermal reactor, thus leading to a simple design. Unlike the previous two processes, this one is still not performed at an industrial level.

4.2 – PtG Economics

Up until today, the number and scale of pilot and demonstration projects for the PtG technology are quite small, which means that there remains considerable uncertainty regarding its costs, which are mainly split amongst the four phases described previously: solar production of electricity, electrolysis, CCS and methanation.

Renewable electricity costs have dropped significantly over the past decade (figure 22), driven by improving technologies, economies of scale, increasingly competitive supply chains and growing developer experience. Solar PV has fallen 82% since 2010, with electricity costs reaching value of 0.068 $/kWh (IRENA, 2019).

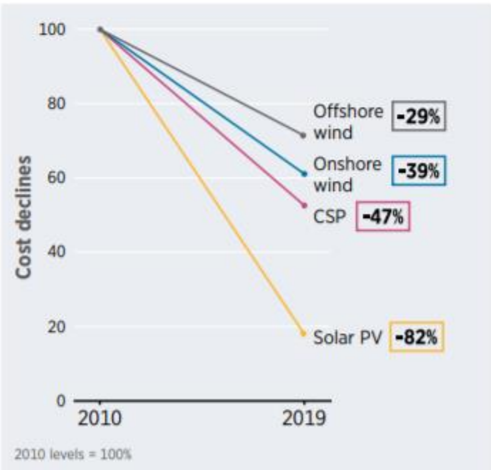

Figure 22 - Renewable power technologies: Cost decreases since 2010 (Source: IRENA, 2019)

For the CCS, the values for the carbon capture vary amongst the different existing industries. According to Budinis et al. (2018), and represented in table 3, the costs in 2015 for CCS varied according to the industry and capture technology implemented, with these values being in a range of 20-110 $/t_{CO2}$. In a different study, (Peters et al., 2019) state that the prices for CCS vary between 23-34 $/t_{CO2}$ for coal power plants and 58-112 $/t_{CO2}$ for natural gas power plants, adding that the costs are in a range of 20-260 $/t_{CO2}$ in the literature.

Table 3 - Cost of captured CO2 for different process plants, capture technologies and storage solutions. (Source: Budinis et al, 2018)

	Cost ($2015/tCO$_2$)	
	Min	Max
Process plant		
Coal-fired power	41	62
Gas-fired power	52	100
Iron and steel	57	69
Refineries and natural gas processing	20	79
Cement production	35	110
Natural gas combined cycle	75	95
Oxyfuel combustion	45	50
Capture technology		
Post-combustion (amine)	50	110
Chemical looping	35	52
Oxy-combustion	45	66
Storage		
CCS	20	110
EOR/EGR	52	62

In terms of electrolysis, according to a study performed by Bertuccioli et al. (2014), the first important aspect to consider is the efficiency of an electrolyser system, i.e., the energy input in kWh per kg of hydrogen output, that has a theoretical value of at least 39.4 kWh/kg$_{H2}$, which would be the value for a 100%-efficient electrolyser. According to the same study, the amount of electrical input required to produce 1 kg of H_2 in 2014 for the AEC system was in the range of 50-78 kWh/kg$_{H2}$, whereas for the PEMEC systems was of 50-80 kWh/kg$_{H2}$, with the value on a central case being lower for the AEC system when compared with the PEMEC one (54 vs 58 kWh/kg$_{H2}$). However, by 2030, it is expected that the efficiency of a PEMEC system is higher than an AEC one, with ranges of 44-53 kWh/kg$_{H2}$ and 48-63 kWh/kg$_{H2}$ and central case values of 47 and 50 kWh/kg$_{H2}$, respectively. This evolution is graphically represented in figure 23.

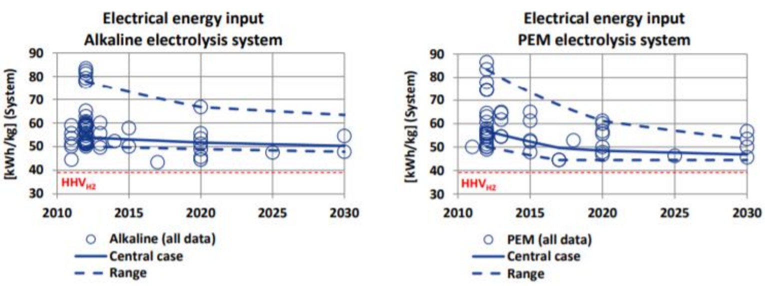

Figure 23 – Electrical energy input for AEC and PEMEC electrolysis. (Source: Bertuccioli et al., 2014)

In this same study, as graphically shown in figure 24, capital costs were also considered, showing that the price for AEC electrolysis was in a range of 1,000-1,200 €/kW and a central value of 1,100 €/kW in 2014 and suggested a price of 370-800 €/kW with a central value of 580 by 2030. In terms of the PEMEC electrolysis, the price was of 1,860-2,320 €/kW and a central value of 2,090 in 2014 and expected to be of 250-1,270 €/kW with a central value of 760 by 2030.

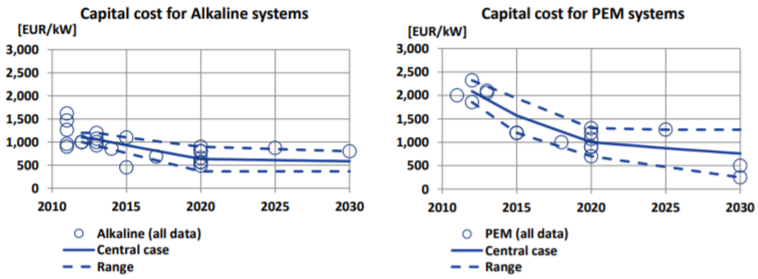

Figure 24 – Capital cost for AEC and PEMEC electrolysis. (Source: Bertuccioli et al., 2014)

Another study performed by industry experts (Schmidt et al., 2017) showed that the capital costs for the AEC systems lie in the range of 800-1,300 €/kW of electrical input, whereas the costs for the PEMEC systems are of 1000-1,950 €/kW. In terms of the SOEC technology, the prices were of 3,000-5,000 €/kW. According to this study, it is expected that by 2030, PEMEC systems take over and replace the AEC ones, which are currently the most used ones. For the AEC systems, a small reduction in the price is expected, thus leading to a cost of around 750 €/kW, whereas the PEMEC systems are expected to have a price in the range of 850-1,650 €/kW. In terms of the SOEC electrolysis, there is an extremely high uncertainty, with a cost of 1,050-4,250 €/kW to be predicted.

Even though there might be a considerable level of uncertainty in some of these values, it is worth noting that both these studies have similar conclusions, and that the electrolysis cost is likely to continue to drop over the next years.

Regarding methanation, there is not much literature regarding its investment. According to Graf et al. (2014), in a study performed by Outotec GmbH, the investments costs were of 400 €/kW for a 5 MW plant and 130 €/kW for a 110 MW plant, both operating at a pressure of 20 bar. In another study performed by Lehner et al. (2014), in which different reports and articles were compared, the cost for methanation is in a range of 300-500 €/kW. Gassner & Maréchal (2009) investigated the Biomass-toGas process chain for a 14.8 MW CO methanation that operated at a pressure of 15 bar, obtaining similar results.

A comprehensive study by ENEA Consulting (2016), shown in figure 25, that analyses the feasibility of PtG technology evaluated the potential costs of power-to-hydrogen and power-to-methane, where different scenarios were assumed. In the lowest cost case, where low cost (15 €/MWh) electricity would be available for around 75 per cent of the time, the cost of power-to-hydrogen is of 50 €/MWh. In other scenarios, where low-cost electricity would be only available for around 10 per cent of the year or electricity costs averaged around 40 €/MWh, the cost of power-to-methane could reach values of 150-200 €/MWh. In all scenarios, methanation adds an additional 40-50 €/MWh to the cost. The lowest resulting cost of power-to-methane of around 100

€/MWh is achieved for biomethane production. The cost of all power-to-gas alternatives remains higher than the cost of fossil-derived natural even assuming a cost of 100 €/t CO_2 carbon price.

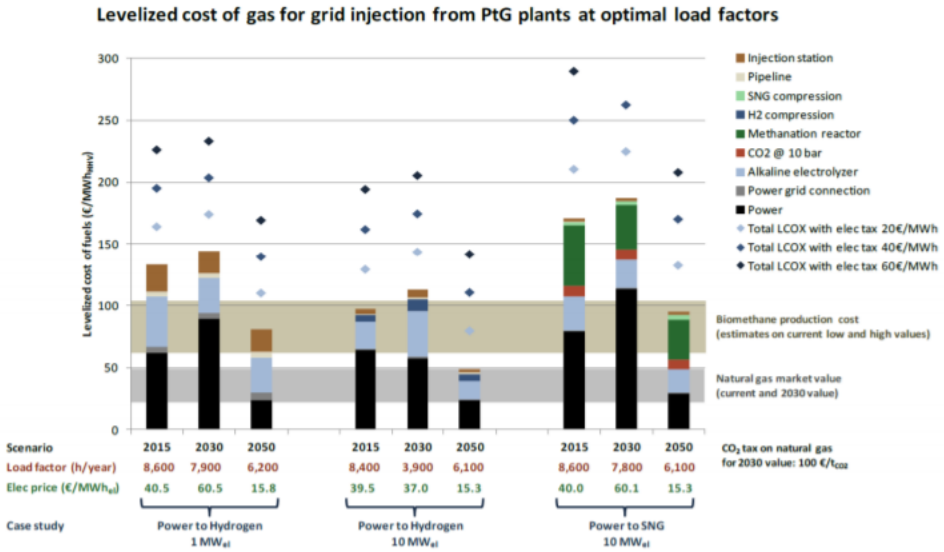

Figure 25 - Costs for PtG under different scenarios. (Source: ENEA Consulting, 2016*)*

It is worth noting that this study emphasizes an assumption in which decarbonisation must be the primary driver to implement PtG, needing to be driven by government policies, at least for this moment in time (Lambert, 2018).

4.3 – Carbon emissions trading market

An important aspect connected with capturing carbon and using it in the PtG technology in a Portuguese context is understanding how the CO_2 market works in the country. This carbon emissions market is described by the European Commission (n.d.), being applied in the same manner in all the EU, including Portugal.

In 1997, the Kyoto Protocol set for the first-time emissions reduction targets, or caps, which led to the need of policy instruments to ensure its implementation. Later, in March 2000, the European Commission presented a green paper with first suggestions on the design of the EU Emissions Trading System (EU ETS). In 2003, the EU ETS Directive was adopted and in 2005 this system was launched. The EU ETS operates in all EU countries plus Iceland Liechtenstein and Norway and limits emissions from more than 11,000 heavy energy-using power stations and industrial plants, covering 45% of the EU's greenhouse gas emissions.

EU ETS works based on a cap-and-trade principle, where a certain cap is set on the total amount of GHG emitted by the facilities covered by this system. The companies receive or buy emission allowances to emit CO_2 or CO_2 equivalent, which they can trade with one another as needed. Another alternative is to purchase limited amounts of international credits from emission-saving projects around the world. There is a limit on the allowances available, which guarantees its value, and, at the end of every year, companies must have enough allowances to cover all its emissions, being heavily fined if that does not occur. If a company has spare allowances, it is possible to sell them to others who need them.

The system covers the following sectors and gases, focusing on emissions that can be measured, reported and verified with a high level of accuracy:

- Carbon dioxide (CO_2) from: power and heat generation; energy-intensive industry sectors including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals; commercial aviation;
- Nitrous oxide (N_2O) from production of nitric, adipic and glyoxylic acids;
- Glyoxal perfluorocarbons (PFCs) from aluminium production.

Companies in these sectors are obliged to be part of the EU ETS. However, there are sectors where only plants above a certain size are included, with certain small installations being able to be excluded if governments apply measures to cut their emissions by an equivalent amount. In terms of the aviation sector, the EU ETS will be applied only to flights in the European Economic Area (EEA) until 31 December 2023. It is expected that by the end of 2020 and 2030, emissions from the sectors covered by this system will be 21% and 43% lower than in 2005, respectively.

EU ETS has worked through phases since it was launched, with 2030 marking the end of phase 4. These stages are:

- Phase 1 occurred between 2005 and 2008, covering only CO_2 emissions from power generators and energy-intensive industries, with almost all allowances being given for free and a penalty of 40 €/ton. The most successful aspects of this stage were establishing: a price for carbon; free trade in emission allowances in the EU; infrastructure required to monitor, report and verify emissions. At that time, no reliable emissions data were available, which meant caps were set based on estimates, resulting in an excessive number of caps and the price of allowances dropping to 0 in 2007.
- Phase 2 took place from 2008 to 2012 and in this stage, allowances' cap was reduced based on actual emissions. In addition, nitrous oxide emissions from the production of nitric acid were included by some countries and the proportion of free allocation dropped to around 90%. Furthermore, the penalty for non-compliance was increased to 100 €/ton.
- The EU ETS is currently in phase 3, from 2013 until the end of 2020, with significant changes when comparing with the previous phases. The main changes were: a single EU-wide cap on emissions was chosen as a new system instead of one of national caps; Auctioning was selected now the default method for allocating allowances, rather than free allocation, but with free allowances still being provided; 300 million € were set aside to fund the deployment of innovative, renewable energy technologies

and CCS through the NER 300 programme. During this stage, an annual reduction factor of 1.74% was set.

- Phase 4 is going to start in 2021 until the end of 2030. In the revision performed by EU, the goal is to strengthen the EU ETS as an investment driver by reducing allowances 2.2% annually starting in 2021, with free allocation of allowances still given, focusing on technological progress and creating low-carbon funding mechanisms to aid industry and power sector.

The EU ETS is one of many emissions trading systems that currently exist. Carbon pricing initiatives are expanding across national and state lines, with increased cooperation among jurisdictions to align their carbon markets. There are currently 61 carbon pricing initiatives in place or scheduled for implementation, consisting of 31 ETSs and 30 carbon taxes, covering 12 gigatons of carbon dioxide equivalent ($GtCO_{2eq}$), around 22% of global GHG emissions (World Bank Group, 2020).

The High-Level Commission on Carbon Prices estimated that carbon prices of at least 40–80 $/tCO2 by 2020 and 50–100 $/tCO2 by 2030 are required to cost-effectively reduce emissions which can cope with the temperature goals of the Paris Agreement. As of today, less than 5% of GHG emissions currently covered by a carbon price are within this range, with about half of covered emissions being priced at less than 10$/tCO2e (CPLC, 2017). At the moment, the global average carbon price is only of 2 $/tCO2 (Parry, 2019). A map of carbon capture schemes in the world is presented in Appendix A and the share of global emissions covered by each scheme in Appendix B.

A PtG implementation through carbon capture will allow companies to reduce their carbon emissions, thus leading to a potential profit through the allowances that will not be used.

4.4 – Portuguese Government Strategic Intervention

Governments have an extremely important role on the development of renewable energies, having the power to establish strategic plans and implementing the necessary mechanisms to ensure its execution. These defined policies may affect the price of conventional and renewable energies through taxes or dedicated funds, for example (Abdmouleh et al., 2015). Thus, these aspects need to be taken into account when promoting the production of biomethane via PtG technology.

According to the *Ministério do Ambiente e Ação Climática* (n.d.), on June of 2017, the Portuguese Government approved the National Strategy for Environmental Education (ENEA 2020), for the period 2017-2020, with the goal of promoting a sustainable development and the construction of a low carbon society. ENEA has three essential pillars: decarbonizing society, build a circular economy and valuing the territory.

In order to achieve a higher effectiveness on environmental policies and to aid achieving ENEA's purpose, a single Environmental Fund was created in Portugal, named *Fundo Ambiental*, which was created through the Decree-Law no. 42-A / 2016, of 12 August, extinguishing, for this purpose, the Portuguese Carbon Fund, the Environmental Intervention Fund, the Protection of Water Resources and the Fund for the Conservation of Nature and Biodiversity. This way, all the resources of the existing funds were aggregated in order to obtain an instrument with greater financial capacity and adaptability to the challenges posed.

Therefore, this fund financially supports environmental policies with the aim of pursuing sustainable development objectives, contributing to the fulfilment of national and international goals. The fund reimburses projects at a maximum of 70%, except in the case of non-governmental environmental organizations, which are financed up to 95%. Due to the nature of PtG technology, there is potential for allocation of funds to implement it, through *Fundo Ambiental*.

In February 2020, the order No. 2269-A / 2020 determined a budget of over 469 million € for *Fundo Ambiental*, the highest ever recorded for this fund, corresponding to an increase of 12% when comparing to the previous year. In this document, it is also referred that it is estimated that *Fundo Ambiental* will have around 38.89 million € available to distribute to new projects, having the following allocation: Direct support to projects defined by this order in the amount of 30.09 million €; submission of applications worth 8.8 million €.

Another relevant measure introduced by the Portuguese government was the expansion of the renewable energy Guarantees of Origin (GO) in Portugal, for the production of renewable and low carbon gases, through the Decree Law no. 60/2020, in August of 2020. GO are electronic documents which provide end consumers with proof that a given amount of power was produced using a certain type of technology, which means they have an associated value.

Up until this point, this GO system only covered the electricity produced from renewable energy sources, the power for heating and cooling produced from renewable energy sources and the electricity produced at cogeneration facilities with an efficient or highly efficient operating regime.

Therefore, this decree-law provides for the growing recognition of renewable gases as a modern, clean and versatile energy carrier, thus promoting an energy change that invests in national economic development, coupled with competitiveness and sustainability.

Even though some steps have been taken into the path of decarbonisation, there is still plenty left to do. Currently, there is no regulation for biofuels for the next decade nor for grid injection of renewable gases. However, this regulation is expected to be appear in the year of 2021.

Chapter Five – Economic and financial Feasibility

5.1 – Engineering economy for project appraisal

It is well-recognised that money makes money, and time value of money explains the change in the amount of money over time for funds that are owned or owed, being the most valuable concept in engineering economy (Blank & Tarquin, 2017). Identifying and selecting good investment projects is essential to develop a sustainable successful future for a company and the decision of choosing a good or a bad project not only impacts its economic profile but, more than that, tends to have an impact in its long term profitability (Mota, 2015).

Blank & Tarquin (2017) state that it is possible to perform an engineering economic analysis on future estimated amounts or past cash flows to determine if a specific measure of worth was achieved. To perform an engineering economy study, there are several steps that need to be performed, as shown in figure 26:

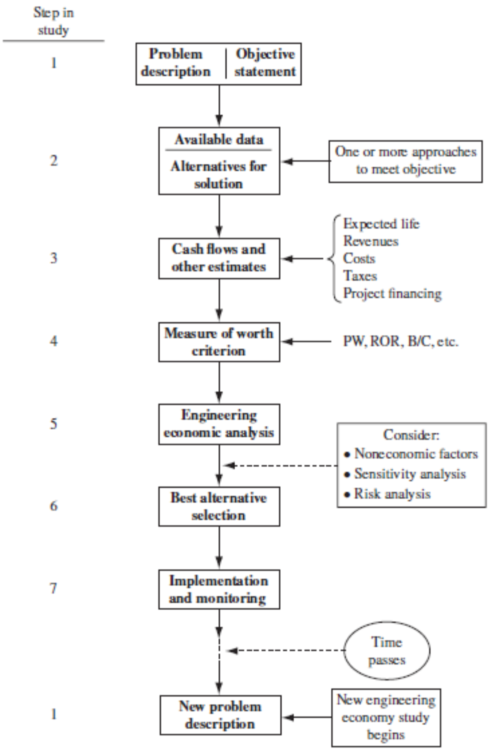

Figure 26 – Steps in an engineering economy study (Source: Blank & Tarquin, 2017)

- Problem description and objective statement – This is the very first step, which is essential for the study since it is crucial to identify, understand the problem and define the objective of the project before trying to formulate a solution.

- Alternatives – It is necessary to collect relevant and available data, as well as describe the viable solutions to the problems that can meet the objectives when implementing a PtG technology.

- Cash flows – All cash flows must be estimated for each alternative. For PtG, besides the direct cash flows that are associated with the production of RNG itself, it is important to consider possible funding and environmental benefits.
- Identify an economic measure of worth criterion for decision making.
- Engineering economic analysis – Evaluate each alternative considering the measures chosen for the analysis.
- Best alternative selection – The measure of worth is a primary basis for selecting the best economic alternative. According to the evaluation performed, the best alternative must be chosen.
- Implementing and monitoring – It is necessary to implement the solution and monitor the results. This step is not part of the economy study but is needed to meet the project objective.

5.2 – Life-cycle cost analysis (LCC)

Life-cycle cost (LCC) analysis evaluates cost estimates for the entire life cycle of a certain project. The estimates cover the costs from the conceptual stage, through design, development, and operating phases up to phaseout and disposal stages. In this type of analysis, not only both direct and indirect costs, but also revenue and saving projections between alternatives are included.

LCC analysis is most effectively applied when a great percentage of the costs will be expended in direct and indirect costs when compared with the initial investment. The direct costs include material, human labour, equipment, supplies or other costs directly related to a product, system or process, whereas the indirect costs are those that are not directly related to it, such as taxes, management, legal, human resources, insurance, software, among others.

In most cases, LCC analysis can be categorized into three major phases:

- Acquisition– All the activities prior to the delivery of products or services, such as:
    - requirements definition stage, which includes the user needs, as well as preparation such as documentation;
    - preliminary design stage, which includes a feasibility study and conceptual/early-stage plans;
    - Detailed design stage – Comprises detailed resources and plans, namely capital, facilities, human resources, marketing, etc.
- Operation – In this phase, all the activities are operational, and products or services are already available. There are two types of costs in this stage:

- Construction and implementation – Purchase, construction, implementation or preparation activities are included;
- Usage stage – These are the costs of the already implemented and operational system.

- Phaseout and disposal – Contains all the activities that transition to a new system, in the end of the life cycle of the product/service implemented.

Typical LCC applications occur in military or commercial aircraft, new manufacturing plants, automobile models or fresh product lines. Due to the characteristics of the PtG technology, it is possible to use the LCC analysis to study its implementation.

To evaluate a project, Blank & Tarquin (2017) defined several criteria that can be used to measure worth when evaluating a project. The most important ones for this study are present worth (PW), future worth (FW) and annual worth (AW) analysis. The LCC analysis mostly uses the AW method, especially when only one alternative is studied. However, if there are expected revenues or other benefits, the PW analysis is the recommended one. In addition to the mentioned metrics, rate of return (ROR) and payback time analysis may be used together with the previous ones, to provide a more complete analysis.

LCC analysis has been used to evaluate different types of projects throughout the years, and projects related with renewable energy are no different. The measures of worth which are hereafter going to be presented were also presented by Owens (2002) for the United States Agency International Development (USAID) regarding "Economic & Financial Evaluation of Renewable Energy Projects". These metrics were used, for example, by Jun et al. (2011) regarding "Gas Power Generation Projects Considering Carbon Emission Reduction" or Espinoza & Rojo (2015), concerning a case study evaluation of a solar project. In terms of actual PtG projects in Portugal, there are no references which can be used, since there is no project of this kind in the country.

5.3 – Present worth (PW) and future worth (FW) analysis

Nowadays, net present value (NPV) is possibly the most popular economic valuation technique and consists in summing all the discounted future cash flows ((in and out flows) resulting from a certain project (Eq.10), with NCF_t being the net cash flow of period t, i the discount rate and n the project's lifetime.

$$NPV = \sum_{n=o}^{t} \frac{NCF_t}{(1+i)^n} \qquad 10$$

In engineering economy, NPV is known as present worth (PW) (Blank & Tarquin, 2017). This approach is based on the principle that a risky euro tomorrow is less valuable than it is today, which is the reason for the cash flows being discounted every year. The minimum acceptable rate of return (MARR) reflects the opportunity of capital and is higher the riskier the project is since riskier projects are expected to result in higher returns if successful. Typical MARR used for corporate projects range from 10-15%, whereas in high tech start-ups it is usually of 25-30% (Žižlavský, 2014).

The second principle of this method is to consider all the future net cash flows connected with the project, unlike metrics such as payback period or investments that only consider the initial cash flow.

. For one alternative or independent projects, a positive PW (>0) represents today the amount of value generated by the project when compared with the initial investment, considering a certain rate of return, meaning it is viable to invest on the project. On the other hand, a negative PW (<0) indicates that the project does not meet the required return that makes it worth on, which means that a DN (do nothing) alternative is preferred. When the PW equals 0, there is no gain or loss for the investor. For two or more alternatives, one should select the one with the most positive PW.

The future worth (FW) analysis is very similar to the one described previously. In the PW analysis, the calculations are estimated in terms of the equivalent present costs and benefits. However, this analysis is suited to be performed in the past, present or future time. An analysis based on a certain future point in time is the FW analysis.

FW is usually used if the asset might be sold or traded at some time before its expected life is reached. Another application for this analysis is for projects that will only start at the end of a multiyear investment period (such as airports).

The selection of the projects using FW is the same as for the PW analysis. If FW is zero or positive, it means that the MARR is met or exceeded, respectively. In the case of two or more mutually exclusive projects, one should select the one with the highest positive FW value.

There are some cases where the alternatives do not have the same time lives. However, the PW of the alternatives must be compared over the same number of time periods and must end at the same time to satisfy the equal service requirement. For cost alternatives, if this is not considered, the shorter-lived mutually exclusive alternative is favoured.

The equal-service requirement is satisfied comparing the PW of the alternatives over a period equal to the least common multiple (LCM) of their estimated lives. For example, if two alternatives have lives of 3 and 5 years, they are compared for a 15-year period. The first cost of an alternative is reinvested at the beginning of each life cycle, with the salvage value being accounted for at the end of each life cycle. There are some assumptions that need to be made for the following life cycles:

- The service provided will be needed over the entire LCM years or more.
- The selected alternative can be repeated in the same conditions for each life cycle of the LCM.
- For each life cycle, the same cash flow estimates must be considered.

5.4 – Annual worth (AW) analysis

For several engineering economic studies, the annual worth (AW) is a better choice when comparing with PW, FW or ROR. This analysis is the equivalent uniform annual worth of all estimated receipts and costs during the life cycle of a project or alternative. There is a direct relation between AW and PW or FW (Eq.11 and Eq.12):

$$AW = PW\ (A/P, i, n) \ = \ FW\ (A/F, i, n) \tag{11}$$

$$AW = PW\ \frac{i(1+i)^n}{(1+i)^n-1} = \ FW\ \frac{i}{(1+i)^n-1} \tag{12}$$

The AW method has the advantage of having calculations performed for only one life cycle, with the value for one life cycle being the same for the remaining ones. For this reason, it is not necessary to use the LCM to satisfy the equal service requirement.

The selection guidelines for projects in AW are the same as PW and FW: for one alternative, or independent projects, if AW $\geq$ 0, the requested MARR is met or exceeded, and it is viable to invest on that project. For two or more alternatives, one should select the option with the most positive AW. If AW $<$ 0, the DN option is the best one.

AW analysis is many times preferable when comparing PW or FW due to the easiness in its calculation. In addition, its measure (monetary units per year) is understood by most individuals when compared with PW.

5.5 – Rate of return

According to Blank & Tarquin (2017), the rate of return (ROR or i*) “is the rate paid on the unpaid balance of borrowed money, or the rate earned on the uncovered balance of an investment, so that the final payment or receipt brings the balance to exactly zero with interest considered”. In other words, i* is the interest rate that makes de PW or AW of a cash flows series equal to zero (Eq.13).

$$0 = PW = AW \tag{13}$$

For one alternative or independent projects, if the i* $\geq$ MARR, the project should be accepted as economically viable. Otherwise, if i* $<$ MARR, the project is not economically viable.

When two or more mutually exclusive alternatives are evaluated, engineering economy can identify which one is best economically. The project i* values do not provide the same ranking of alternative as the PW and AW analysis and when the i* values of several alternatives exceed the MARR, an incremental ROR analysis must be performed. If performed correctly, the ROR analysis will result in the same selection as the PW and AW analysis.

This analysis is based on PW or AW relations for incremental cash flows between two alternatives at a time and requires a comparison for equal service, meaning that the incremental cash flows must be evaluated over the LCM of lives. In this case, the terms defender and challenger are brought up and correspond to the alternative that is currently selected and the one that is challenging it based on Δi*. The steps to apply this method are as follows:

1. Order the alternatives from the smallest to the largest initial investment, stating the annual cash flows for each equal-life alternative.
2. Calculate the i* for the first alternative. In this case, the DN option is the defender and the first alternative the challenger. If i* $<$ MARR, this alternative is eliminated and the next one is analysed. This process is repeated until i* $\geq$ MARR, defining that alternative as the new defender and the following alternative to be analysed as the new challenger.
3. Compute the incremental cash flow between the challenger and the defender, using Eq.14:

$$Incremental\ cash\ flow = challenger\ cash\ flow - defender\ cash\ flow \qquad 14$$

4. Measure Δi* for the incremental cash flows using the AW or PW relation based.
5. If i* $\geq$ MARR, the challenger becomes the defender, and the previous defender is eliminated. Otherwise, if i* $<$ MARR, the defender remains the same and this alternative is eliminated.
6. Repeat steps 3-5 until only one alternative remains, with that one being selected.

The i* of these specific projects should be of 4%, in accordance with paragraph 3 of article 19 of Delegated Regulation (EU) No. 480/2014 (The European Commission, 2014), considering that in this way the neutrality of the assumed base year is ensured. This is the rate which is going to be used in the case study to be presented in chapter seven. This tax is fit to be used on projects of such kind, especially due to the fact that these types of projects are competing for incentives and need to be equally evaluated. It is, however, worth trying to understand the factors which may influence a possible discount rate taking into account both the country and the sector in which this type of project fits in. When analysing discount rate, two components need to be analysed: risk-free rate and a premium for risk. Regarding risk-free rate, the 10-year treasury hold for Portugal has been decreasing over the last decade, reaching values of 1.8% for 2018 and 0.8% for 2019 (PORDATA, 2019). In terms of the risk for the sector, there is not much information regarding the Beta of PtG projects (this technology is not even used in the country). In terms of overall sector, and according to Damodaran (2020), the Beta used for renewable energy projects has been decreasing in the last decades, having a value of 0.59 in the United States for the year of 2020. For these reasons, the rate of 4% is a good choice regarding economic and financial evaluations with these characteristics.

5.6 – Payback period analysis

The payback period (n_p) is an estimated time for the revenues or other monetary benefits to completely recover the initial investment (P0) added to a state of return i*. There are two types of payback analysis:

- No return (i* = 0%) – also referred as simple payback, indicates the recovery of only the initial investment. There are two possible ways of obtaining it, presented in Eq.15 and Eq.16 below:
  - Annual uniform NCF: $$n_p = \frac{P_0}{NCF} \quad (15)$$
  - NCF varies annually: $$0 = -P_0 + \sum_{t=1}^{t=n_p} NCF_t \quad (16)$$
- Discounted payback (i* ≥ 0) – The rate is considered in addition to recovering the initial investment, as Eq.17 and Eq.18 show.
  - Annual uniform NCF: $$0 = -P_0 + \sum_{t=1}^{t=n_p} NCF_t\,(P/F, i, t) \quad (17)$$
  - NCF varies annually $$0 = -P_0 + NCF_t(P/A, i, n_p) \quad (18)$$

The payback analysis uses a different approach when comparing with the methods described previously. The information provided by this procedure can be very useful in terms of the risk involved in choosing a certain alternative. On the other hand, payback time disregards all the cash flows occurring after the payback period. In addition, when comparing two alternatives using this analysis, the short-lived assets will be favoured when comparing with longer-lived ones. In these cases, PW or AW analysis should be the primary selection method.

5.7 – Sensitivity analysis

Economic analysis uses estimates of a certain parameter's (which can be the first costs, estimated life, the product rate or cost of materials) future value to aid decision makers. It is known that there is an associated inaccuracy in this type of assessments, meaning that future estimates are never completely correct. To study the impact of the variation of these parameters on the methods previously described, one can use sensitivity analysis.

Sensitivity analysis determines how a measure of worth – PW, FW, AW, ROR or payback time – changes when one or more parameters are changed over a selected range of values. In most cases, one parameter at a time is varied, considering that all the parameters are independent from each other. This approach is considered to be an oversimplification of real-world situations, but since the dependencies are usually difficult to model, the results are usually accurate.

Sensitivity analysis is mostly used on the variation of estimates of initial investment, MARR, unit costs and revenues, time life and similar parameters.

To conduct a sensitivity analysis, the general procedure is as follows:

1. Decide the parameter(s) of interest are fit to be used;
2. Choose the probable range and an increment of variation for each parameter;
3. Select the measure of worth;
4. Compute the results for each parameter;
5. Graphically display the parameter versus the measure of worth.

This sensitivity analysis process should indicate the parameters that justify closer analysis or require additional information, which is going to be presented more specifically in the chapter 7.5.

It is possible to evaluate the economic advantages and disadvantages between two or more alternatives when performing a sensitivity analysis, by making three estimates for each parameter: a pessimistic, a most likely and an optimistic estimate. In most cases, a single parameter is analysed within a range (between pessimistic and more optimistic values), with the most likely estimate being used for all other parameters. For PtG implementation, these scenarios are mainly dependent on future market conditions and global, EU or even Portuguese environmental policies.

5.8 – Proposed methodology for the case study

Throughout this dissertation, the whole PtG technology has been described, with the goal of providing a solid foundation to perform an economic and a financial analysis of a specific case studies. To do so, the methodology proposed is based on the steps previously described to perform an economic evaluation by Blank & Tarquin, (2017), being shown on figure 27. This methodology is going to be followed for both financial and economic analysis that are going to be performed.

Figure 27 – Proposed methodology

This methodology is, therefore, split in six different stages:

1. Description of the problem and objectives of the case studies – After a generalized description of the case study was made, through the *Audi e-gas* and *HELMETH* projects, a specific description of the case study will be provided, with the goal of implementing the PtG technology in Portugal.

2. Description of every alternative – In the second phase, and with the goal of implementing the best solution, the alternatives will be presented and described. These alternatives are going to differ on the use of the final product and are going to be explained with more detail in the case study itself, in Chapter Seven.

3. Cash flow estimates for every alternative – In the third step, all the cash flows will be estimated. It is important to considerate possible funds, carbon allowances and the production of synthetic natural gas as positive cash flows. On the other hand, negative cash flows will mainly come from the initial investment in plants, CCS, electrolysis, methanation and operational costs.

4. Select the measure of worth – In the previous sections, several criteria were mentioned when evaluating a project. In the case of PtG technology, PW is the most fit choice for an LCC application. In addition, IRR and payback period should be used as complementary evaluation techniques to provide a more complete analysis.

5. Perform an economic and financial analysis – After the selection on the measures of worth, it is necessary to evaluate each alternative. In addition, a sensitivity analysis will be performed.

6. Select the best alternative and conclude – Finally, after analysing each of the alternatives, the best one must be chosen, if there is one. Otherwise, if no alternative is to be chosen, the project is not feasible. In this step, a sensitivity analysis is also performed, with the addition of possible optimistic and pessimistic regarding values for the most important key performance indicators (KPIs), which will be presented in the case study to be analysed.

Chapter Six – Theoretical Conclusions

Nowadays, fossil fuels are still the most used source of energy but are also the ones which cause most harm to the environment. With that in mind, a shift called “energy transition” has been proposed over the past few years in order to prevent the recent climate changes, mainly through the reduction of CO_2 emissions, in order to switch to an efficient and sustainable energy system.

With the 2010-2020 decade ending, a plan for the decade that follows for the energy sector in Portugal has been outlined, the National Energy and Climate Plan 2021-2030 (PNEC 2030) (Governo de Portugal, 2019). The main goals for Portugal include a reduction in emissions in the range of 45% to 55%, when comparing with 2005, an increase in energy efficiency of at least 35%, the incorporation of RES in final energy consumption to be of no less than 47 %, a ratio that must be of 20% in the transportation sector. To finalize, 15% of the country’s interconnections must be electrical.

It is a well-known fact that natural gas is the less pollutant fossil fuel of all, and its consumption has risen over the last two decades. One of the areas in which natural gas has made its presence felt is in transportation, coinciding with the appearance and increase of NGV vehicles, which are expected to continue to grow in number in the future. Due to the characteristics of natural gas, it is possible to produce a renewable gas with similar characteristics, the biomethane. Besides biomethane, RFNBO is also starting to become revevant, appearing in the form of synthetic methane as a direct substitute of fossil NG. One way to produce synthetic methane is through the PtG technology, allowing CO_2 to be considered a raw material with value rather than an industrial waste product.

Two examples of a PtG implementation are the *Audi e-gas project* the *HELMETH* project, serving as a starting point to present this technology, which is split in three main sections:

- CCS, that has the objective of capturing carbon, being possible to obtain it from combustion processes, as a by-product from industrial processes or from the atmosphere, with the techniques used to separate the CO_2 being absorption, adsorption, membrane separation, cryogenic distillation, chemical looping combustion and hydrate-based separation.
- Electrolysis, where hydrogen is obtained in a process in which electric power is used to split water into hydrogen and oxygen, with AEC, PEMEC and SOEC being the technologies to do so.
- Methanation, a process in which CO_2 reacts with H_2 to produce methane (CH_4). There are two types of methanation: biological methanation, where a microorganism is used as a biocatalyst and can occur *in situ* digester or in a separate reactor, taking place at temperatures of 40-70ºC and atmospheric pressure; thermochemical methanation, in which a catalyst, usually nickel-based, is used to produce the CH_4, occurring

through the processes of fixed bed methanation, fluidized bed methanation or three phase methanation, at temperatures of 300-500ºC and pressures of 1-100 bar.

In terms of PtG economics, there are not many studies in this matter and there is the idea that at the current moment, decarbonisation must be the primary driver to implement this technology. However, a drop in CCS, electrolysis and methanation prices in the next years may change this current outcome.

Another very important aspect of the PtG technology in EU and Portugal is the carbon emissions trading market, which is regulated through the EU ETS. This market works based on a cap-and-trade principle, which means companies may buy or receive allowances to emit CO_2 or CO_2 equivalent. At the end of each year, a company must have a sufficient number of allowances to cover all the emissions, with companies being allowed to purchase or sell allowances, if they do not have the required amount, or in case they have spare allowances, respectively. This is extremely important in the case of PtG technology through CCS, since companies will capture carbon, thus being able to profit from spare allowances.

The Portuguese government has acted in order to put in practice this “energy transition” and, with the goal of promoting a sustainable development and construction of a low carbon society, approved ENEA 2020, which is based on three pillars: decarbonizing society, build a circular economy and valuing the territory. To help achieving these goals, an Environmental Fund was created, the *Fundo Ambiental*, which financially supports environmental policies and projects that pursue these sustainable objectives. Due to the characteristics of the PtG technology, which were explained throughout the previous chapters, there is a chance that this fund supports projects related with its implementation.

It is possible to perform an engineering economic analysis to determine the feasibility of a PtG implementation, through an LCC analysis, since this is a case of industrial plants. To perform this assessment, the most accurate metric is PW, with IRR and payback time analysis also being suited to provide a more robust evaluation.

A methodology based on engineering economy was proposed to analyse the specific case study is which is going to be presented in the next chapter, with the goal of evaluating the feasibility of its implementation and its sensitivity to the change of critical key performance indicators (KPIs), in order to select the best alternative and the underlying base conditions.

Chapter Seven – Case Study

7.1 – Case study description

The following case study to be presented is an attempt to implement the PtG technology in an industrial unit of a Portuguese company, located in Almeirim, which is expected to be the first of its kind in Portugal. This industrial plant is covered by EU ETS, since it is a combustion plant that has a nominal thermal power greater than 20 MW, meaning that currently, the emitted CO_2 by this factory, in addition to the negative environmental impact, has a monetary cost associated.

Thus, the main goal is to modify one of the current processes which takes place in this industrial unit. The current process is composed of two steam boilers: a first one, with a power of 4.5 MW, an annual operating time of 6135 hours and a production of 2 million Nm^3/year; a second one, with a power of 8.4 MW, an annual operating time of 6360 hours and a production of 0.6 million Nm^3/year. Both these steam boilers are powered by natural gas and have an efficiency of 92%. This process rises the following final products to highlight: steam at a temperature of 54ºC and pressure of 11 bar; hot water at 55ºC and atmospheric pressure. However, as a consequence, a harmful by-product to the environment is generated: fossil carbon dioxide (CO_2). This current process is illustrated in figure 28.

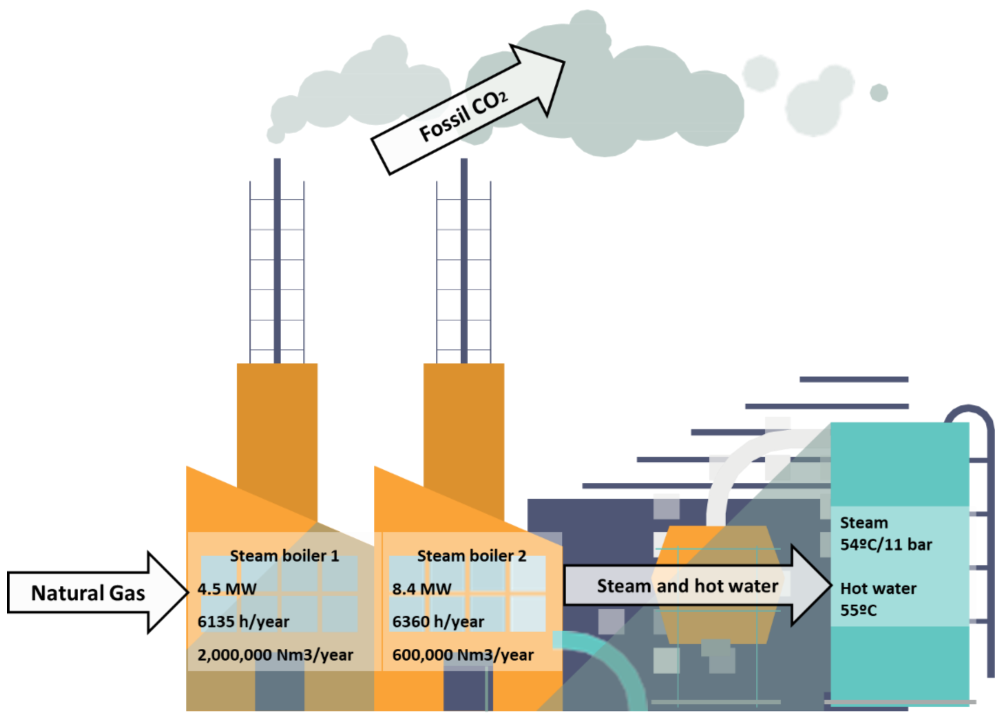

Figure 28 – Current process of the industrial unit

Therefore, in order to integrate the currently emitted CO_2 in the process and create value, something that does not occur at the moment, 4 main equipment are going to be installed:

- Photovoltaic panels with a total nominal power of 5 MW;
- Electrolyser with a power of 2.5 MW and an efficiency of 78.8%;
- Equipment for the capture of emitted CO_2 from the steam boilers;
- Reactors for the methanation reaction.

As explained in previous chapters, the CH_4 produced is very similar to fossil natural gas, which means it can be used for the same purposes. In this case study, two different base alternatives are going to be analysed: the use of CH_4 for the internal process of the industrial unit and the use of CH_4 as a fuel for vehicles.

7.2 – Technical implementation

7.2.1 – Methodology description

In order to study the feasibility of this project, one must estimate all the aspects connected with its implementation, namely the technical flows which are obtained throughout each one of the stages.

The methodology of analysis which is going to be presented allows for an estimation of the hourly flows. The reason behind it is that by estimating the energy produced by the PV panels for every hour of a year, it is also possible to estimate the production flow of H_2 for the same periods of time. Assuming H_2 as the limiting reactant for the methanation, since it depends on the generated electricity, one can not only estimate the necessary amount of CO_2 to capture from the factory chimneys, but also the production flows of CH_4, H_2O and heat released in the process.

Bearing this in mind, the first step is to estimate the electrical energy produced by the PV panels, taking into account the radiation in the Almeirim area. The information regarding this radiation was obtained using the hourly data solar radiation tool of the Photovoltaic Geographical Information System (PVGIS), which provides, among other information, the horizontal radiation of every hour of a chosen time range. For this case study, the data year of 2015 was collected for the latitude of 39.198 and longitude of -8.642.

Adapting Eq.1-6 from sub-chapter 4.1.1, along with the information regarding the horizontal radiation obtained, it is now possible to estimate the radiation incident on a tilted surface of a certain hour of a certain day ($S_{module_{d,h}}$). To do so, the first step is to determine the declination angle of the sun (δ_d) in a certain day of the year, through Eq.19, where d represents the day of the year:

$$\delta_d = 23.45 * \sin\left(\frac{360}{365} * (284 + d)\right) \qquad 19$$

It is also required to calculate the elevation angle of the sun (α_d), which is based on δ_d and the latitude (ϕ), through Eq.20:

$$\alpha_d = 90 - \phi + \delta_d \qquad (20)$$

With this, it is now possible to calculate $S_{module_{d,h}}$, using Eq.21, where $S_{horizontal_{d,h}}$ represents the solar radiation measured on horizontal surface and β_{panel} the tilt angle of the module measured from the horizontal:

$$S_{module_{d,h}} = \frac{S_{horizontal_{d,h}} * \sin\ (\alpha_d + \beta_{panel})}{\sin\ (\alpha_d)} \qquad (21)$$

In order to estimate the module temperature of the panel and the power for a certain point in time, the first step is to choose a reference panel. For this case study, the chosen reference panel was the SunPower E18/300 Solar Panel (Sun Power, n.d.), which has the following characteristics (table 4):

Table 4 – Characteristics of the SunPower E18/300 Solar Panel (Sun Power, n.d.)

Panel information

Nominal Power (STC)	NOCT	Ambient Temperature	Power temperature coefficient (K_I)
300 W	46ºC	20 ºC	0,38%

The first information that one is able to obtain is the number of panels to install, based on the chosen reference panel. Since the total nominal power ($P_{nom\_AllPanels}$) to be installed is of 5 MW and the reference panel has a nominal power of 300 W at STC conditions ($P_{máx\_}(@STC)$), the number of panels to be installed, using Eq.22 is:

$$Number\ of\ Panels = \frac{P_{nom\_AllPanels}}{P_{máx\_}(@STC)} = \frac{5 * 10^6\ W}{300\ W} = 16666,(6) \cong 16667 \qquad (22)$$

It is also possible to determine the module temperature for a certain hour of a certain day of the year ($T_{PV_{d,h}}$), using with Eq.23, based on the ambient temperature (T_{amb}), the NOCT and $S_{module_{d,h}}$:

$$T_{PV_{d,h}} = T_{amb} + (NOCT - 20)\ \frac{S_{module_{d,h}}}{800} \qquad (23)$$

With this, one may now determine the real power generated by 1 panel ($P_{máx\_1Panel_{d,h}}$), taking into account $P_{máx}(@STC)$, the power temperature coefficient (K_I), $T_{PV_{d,h}}$, T_{amb}, and $S_{module_{d,h}}$, with Eq.24.

$$P_{máx\_1Panel_{d,h}} = P_{máx}(@STC) * (1 - K_I * (T_{PV_{d,h}} - T_{amb})) * \frac{S_{module_{d,h}}}{1000} \qquad (24)$$

The electrical energy generated by 1 panel at a certain hour of a day of the year ($E_{1Panel_{d,h}}$) is achieved through Eq.25, based on $P_{máx\_1Panel_{d,h}}$ and time interval (ΔT). With this hourly methodology, ΔT is always equal to 1 hour.

$$E_{1Panel_{d,h}} = P_{máx\_1Panel_{d,h}} * \Delta T \qquad 25$$

Finally, the electrical energy generated by all the reference panels at a given hour of a certain day of the year ($E_{AllPanels_{d,h}}$) is obtained by multiplying $E_{1Panel_{d,h}}$ per the number of panels (Eq.26).

$$E_{AllPanels_{d,h}} = E_{1Panel_{d,h}} * Number\ of\ Panels = E_{1Panel_{d,h}} * 16667 \qquad 26$$

With the information on the generated electricity, it is now possible to estimate the amount of H_2 produced in the electrolyser, as well as the self-sufficient electricity obtained.

As stated in the case study description, and represented in Eq.27, when $E_{AllPanels_{d,h}}$ is lower or equal than 2,5 MW, all of that energy is used in the electrolyser ($E_{electrolyser_{d,h}}$) to produce H_2. On the other hand, if it exceeds that value, 2,5 MW are used to produce H_2, with the remaining energy being used for the factory's self-sustainability ($E_{self-sufficient_{d,h}}$).

$$E_{electrolyser_{d,h}} = \begin{cases} E_{AllPanels_{d,h}}, & E_{AllPanels_{d,h}} \leq 2{,}5 \\ 2{,}5, & E_{AllPanels_{d,h}} > 2{,}5 \end{cases}$$

$$E_{self-sufficient_{d,h}} = \begin{cases} 0, & E_{AllPanels_{d,h}} \leq 2{,}5 \\ E_{AllPanels_{d,h}} - 2{,}5\ MW, & E_{AllPanels_{d,h}} > 2{,}5 \end{cases} \qquad 27$$

It is expected that the equipment installed to perform the electrolysis and methanation operates in all the hours when there is electrical energy used in the electrolyser. Therefore, a binary equation (Eq.28) is created, where :

$$Operating\ hour_{d,h} = \begin{cases} 1, & E_{electrolyser_{d,h}} \neq 0 \\ 0, & E_{electrolyser_{d,h}} = 0 \end{cases} \qquad 28$$

It has also been expressed that the amount of energy required to produce 1 kg of H_2 in an ideal case ($E_{1kg\_H2\_ideal}$), i.e., in the presence of an electrolysis process with an efficiency of 100% is of 39.4 kWh/kgH_2. For this case study, the efficiency for this process is of 78.8%, resulting in the following necessary electrical energy to produce 1 kg of H_2 (E_{1kg_H2}), using Eq 29.

$$E_{1kg\_H2} = \frac{E_{1kg\_H2\_ideal}}{Electrolysis\ efficiency} = \frac{39.4}{0.788} = 50\ \mathrm{kWh/kgH_2} \qquad 29$$

It is now possible to determine the amount of H_2 produced in a certain hour of a certain day ($H_2\ Produced_{d,h}$), using Eq.30, based on the $E_{electrolyser_{d,h}}$ and E_{1kg_H2}:

$$H_2\ Produced_{d,h} = \frac{E_{electrolyser_{d,h}}}{E_{1kg\_H2}} = \frac{E_{electrolyser_{d,h}}}{50\ \mathrm{kWh/kgH_2}} \qquad 30$$

Recalling Eq.7, the stoichiometry of the electrolysis of H_2O equation makes it possible to determine the amount of H_2O necessary based on the H_2 produced, as well as the O_2 produced.

The H_2 has a molar mass of 2 g/mol, which means that to produce 1 kg of H_2, 500 moles are required (Eq.31).

$$\frac{1\,kg\,H_2}{2\,g/mol} = \frac{1000\,g\,H_2}{2\,g/mol} = 500\,moles\,H_2 \qquad 31$$

For each mole of H_2 produced, 1 mole of H_2O is needed, which means 500 moles of H_2O are needed to produce 1 kg of H_2. The H_2O has a molar mass of 18.015 g/mol, which results in (Eq.32):

$$H_2O_{needed} = \frac{500\,moles\,H_2O\,*\,18{,}015\,g/mol}{1000} = 9{,}001\,kg\,H_2O/kg\,H_2 \qquad 32$$

Therefore, the amount of H_2O necessary in a certain hour of a certain day of the year ($H_2O\ needed_{d,h}$), shown in Eq.33, is:

$$H_2O\ needed_{d,h} = H_2\ Produced_{d,h}\,*\,9.001\,kg\,H_2O/kg\,H_2 \qquad 33$$

The same thought process can be put into the O_2 production. For every mole produced of H_2, 0.5 moles of O_2 are produced, which means that to produce 1 kg of hydrogen, 250 moles of O_2 are produced as well. O_2 has a molar mass of 32 g/mol, which means that the mass of O_2 produced per kg of H_2 ($O_{2_{produced}}$), represented in Eq.34, is:

$$O_{2_{produced}} = \frac{250\,moles\,O_2\,*\,32\,g/mol}{1000} = 8\,kg\,O_2/kg\,H_2 \qquad 34$$

Therefore, the amount of O_2 produced in a certain hour of a certain day ($O_2\ Produced_{d,h}$), determined with Eq.35, is:

$$O_2\ Produced_{d,h} = H_2\ Produced_{d,h}\,*\,8\,kg\,O_2/kg\,H_2 \qquad 35$$

For the methanation, using the stoichiometry of the reaction, represented in Eq.9, it is possible to determine the amount of CO_2 to capture ($CO_{2_{captured}}$), the production of CH_4 ($CH_{4_{produced}}$) and H_2O ($H_2O_{produced}$) and the heat released, per kg of H_2.

The CO_2 and CH_4 have a molar mass of 44.01 g/mol and 16.04 g/mol, respectively. Therefore, for each kg of H_2 (500 moles) acting as a reactant, 125 moles of CO_2 are required and 125 and 250 moles of CH_4 and H_2O are produced, respectively. Since the methanation reaction is exothermic, it releases heat with an associated value since it can be used internally in this industrial unit. 164 kJ being released for every 4 moles of H_2 means that for every mole of hydrogen, 41 kJ are released. With this, Eq.36-39 result in:

$$CO_{2_{captured}} = \frac{125\,moles\,CO_2\,*\,44.01\,g/mol}{1000} = 5.501\,kg\,CO_2/kg\,H_2 \qquad 36$$

$$CH_{4_{produced}} = \frac{125\,moles\,CH_4\,*\,16.04\,g/mol}{1000} = 2.005\,kg\,CH_4/kg\,H_2 \qquad 37$$

$$H_2O_{produced} = \frac{250\,moles\,H_2O\,*\,18.015\,g/mol}{1000} = 4.504\,kg\,H_2O/kg\,H_2 \qquad 38$$

$$Heat = -41\,kJ/mol\,*\,500 = -20500\,kJ/kg\,H_2 = -5.69\,kWh/kg\,H_2 \qquad 39$$

Therefore, the amount of CO_2 to capture, the CH_4 and H_2O to produce and heat released in a certain hour of a certain day ($CO_2\ captured_{d,h}$, $CH_4\ Produced_{d,h}$ and $H_2O\ Produced_{d,h}$, and $Heat_{met\,d,h}$, respectively), depending on the hourly production of H_2 ($H_2\ Produced_{d,h}$), are (Eq.40-43):

$$CO_2\ captured_{d,h}\ =\ H_2\ Produced_{d,h}\ *\ 5.501\ kg\ CO_2/kg\ H_2 \qquad 40$$

$$CH_4\ Produced_{d,h}\ =\ H_2\ Produced_{d,h}\ *\ 2.005\ kg\ CH_4/kg\ H_2 \qquad 41$$

$$H_2O\ Produced_{d,h}\ =\ H_2\ Produced_{d,h}\ *\ 4.504\ kg\ H_2O/kg\ H_2 \qquad 42$$

$$Heat_{met\,d,h}\ =\ H_2\ Produced_{d,h}\ *\ (-5.69)\ kWh/kg\ H_2 \qquad 43$$

An overall preview of the previously described process and its correspondent flows are represented in figure 29:

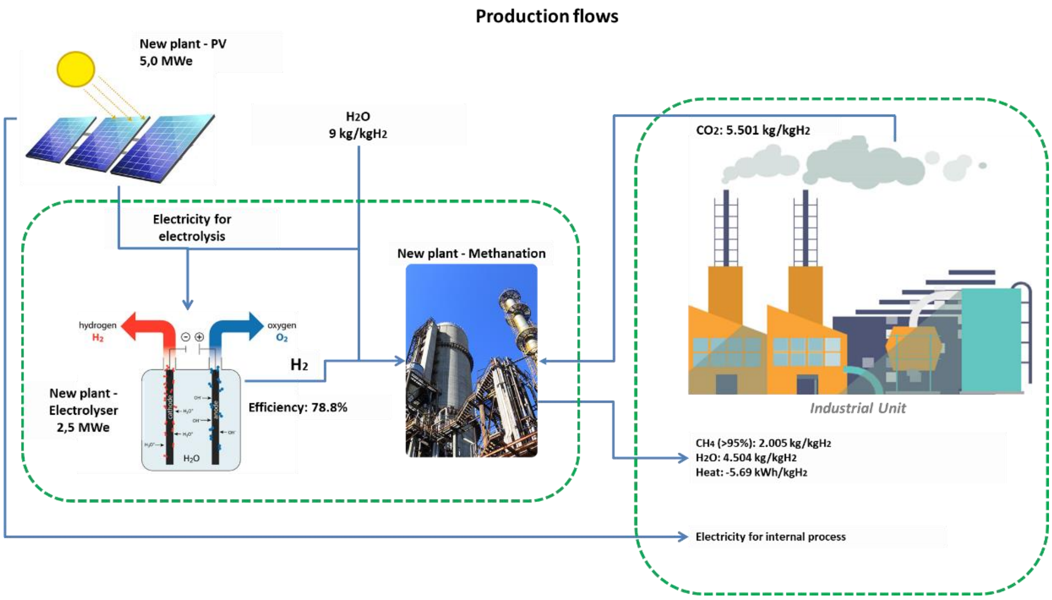

Figure 29 – Technical flows of the project

All the information is now gathered to estimate the technical annual flows of the project (number of operating hours, electricity for the electrolyser, electricity for the self-sufficiency of the factory, water needs and H_2 and O_2 production in electrolysis, CO_2 needs for methanation, CH_4 and water production and heat released in methanation). In all the equations (Eq.44-52 presented below, d represents the day of the year (1 to 365, with leap years being discarded) and h the hour of the day (1 to 24).

$$Number\ of\ operating\ hours = \sum_{d=1}^{365}\sum_{h=1}^{24} Operating\ hour_{d,h} \qquad 44$$

$$Annual\ electricity\ produced = \sum_{d=1}^{365}\sum_{h=1}^{24} E_{AllPanels\,d,h} \qquad 45$$

$$Annual\ self-sufficient\ electricity\ produced\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} E_{self-sufficient_{d,h}} \quad 46$$

$$Annual\ H_2O\ needed\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} H_2O\ needed_{d,h} \quad 47$$

$$Annual\ H_2\ produced\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} H_2\ Produced_{d,h} \quad 48$$

$$Annual\ O_2\ produced\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} O_2\ Produced_{d,h} \quad 49$$

$$Annual\ CO_2\ captured\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} CO_2\ captured_{d,h} \quad 50$$

$$Annual\ H_2O\ produced\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} H_2O\ Produced_{d,h} \quad 51$$

$$Annual\ CH_4\ produced\ =\ \sum_{d=1}^{365}\sum_{h=1}^{24} CH_4\ Produced_{d,h} \quad 52$$

Regarding the final products resulting from the methanation, 3 of them have an associated economic value: the produced CH_4, the produced water (may be reused for the electrolysis process) and heat. Due to its low calorific power, it was considered that the O_2 produced in the electrolysis has no value and can, therefore, be discarded. Regarding the use of these products, 2 different base alternatives were defined, which are described hereafter.

Base alternative 1 – CH_4 for internal process

For this first alternative, it is considered that all 3 final products are fit to be used internally. Thus, the water is going to be used in the electrolysis (same for base alternative 2), whereas both the CH_4 and heat from methanation are going to be used in the steam boilers to replace the natural gas.

In order for the CH_4 to be used as heat for the internal process, one must consider its calorific value, which is of 13.9 kWh/kg (also 13.9 MWh/ton). With this, it is possible to estimate the heat generated by the CH_4 in this project ($Heat_{CH_4{}_{d,h}}$), using Eq.53:

$$Heat_{CH_4{}_{d,h}}\ =\ CH_4\ Produced_{d,h}\ *\ 13.9\ kWh/kg\ CH_4 \quad 53$$

Therefore, and also considering the annual produced heat in the methanation process itself ($Heat_{met_{d,h}}$), the total annual heat generated (Eq.54) are:

$$Total\ Annual\ heat\ _{Scenario\_1} =\ \sum_{d=1}^{365}\sum_{h=1}^{24} Heat_{CH_4{}_{d,h}}\ +\sum_{d=1}^{365}\sum_{h=1}^{24} Heat_{met_{d,h}} \quad 54$$

Alternative 2 – CH_4 for mobility

In the second alternative, the water and heat from methanation will remain with the goal of being used in the internal process of the industrial unit. However, the produced CH_4 is going to be used as fuel for vehicles. Therefore, the heat produced by the CH_4 is now irrelevant for the internal process, meaning that the only heat to be used by the factory is the one produced directly from the methanation process. Thus, Eq.55 is applied:

$$Total\ Annual\ heat\ _{Scenario\_2} = \sum_{d=1}^{365}\sum_{h=1}^{24} Heat_{met\,d,h} \qquad 55$$

7.2.2 – Example of implementation

In order to provide a more complete explanation regarding the implementation, a specific example is going to be provided. To do so, the hour of 12 to 1pm on the July 15th was chosen, which represents hour 13 (h = 13) of day 196 of the year (d = 196), with the corresponding ϕ for the Almeirim area being of 39.198.

In order to estimate $S_{module_{196,13}}$, the first step is to determine δ_{196}, using Eq.19:

$$\delta_{196} = 23.45 * \sin\left(\frac{360}{365} * (284 + 196)\right) = 21.517º$$

Naturally, the next step is to calculate α_{196}, through Eq.20.

$$\alpha_{196} = 90 - 39.198 + 21.517 = 72.3$$

At this time, the registered $S_{horizontal_{196,13}}$ was of 972.01 W/m^2, with the chosen β_{panel} being of 37.51º (obtained using the Excel solver tool to maximize the value of $S_{module_{d,h}}$). Applying Eq.21:

$$S_{module_{196,13}} = \frac{972.01 * sin\,(72.3 + 37.51)}{\sin\,(72.3)} = 959.72$$

The $T_{PV_{196,13}}$ is estimated through Eq.23, using the information on table 4:

$$T_{PV_{196,13}} = 20 + (46 - 20)\,\frac{959.72}{800} = 51.2ºC$$

It is now possible to determine $P_{máx\_1Panel_{196,13}}$, using, one more time, the information on table 4 along with the already determined data, and applying Eq.24.

$$P_{máx\_1Panel_{196,13}} = 300 * (1 - 0.0038 * (51.2 - 20)) * \frac{959.72}{1000} = 259.3\,W$$

Therefore, $E_{1Panel_{196,13}}$, determined using Eq.25, is:

$$E_{1Panel_{196,13}} = 259.3 * 1 = 259.3\,Wh$$

Finally, taking into account the 16667 panels to be installed, $E_{AllPanels_{196,13}}$ is (Eq.26):

$$E_{AllPanels_{196,13}} = 259.3 * 16667 = 4\,321\,121.3\,Wh = 4.321\,MWh$$

Since $E_{AllPanels_{196,13}} > 2{,}5$, applying Eq.27:

$$E_{electrolyser_{196,13}} = 2.5\,MWh$$

$$E_{self-sufficient_{196,13}} = 4.321 - 2.5 = 1.82\,MWh$$

Since $E_{electrolyser_{196,13}} \neq 0$, an operating hour of the equipment must be added, using Eq.28:

$$Operating\ hour_{196,13} = 1$$

It is now possible to estimate the $H_2\ Produced_{196,13}$, using Eq.30:

$$H_2\ Produced_{196,13} = \frac{2{,}5\,MWh}{50\ \mathrm{kWh/kgH_2}} = \frac{2\,500\,kWh}{50\,kWh/\mathrm{kgH_2}} = 50\ \mathrm{kgH_2}$$

Finally, it is possible to determine the remaining flows, namely $H_2O\ needed_{196,13}$, $O_2\ Produced_{196,13}$, $CO_2\ captured_{196,13}$, $CH_4\ Produced_{196,13}$, $H_2O\ Produced_{196,13}$, $Heat_{met_{196,13}}$ and $Heat_{CH_{4_{196,13}}}$, through Eq.32, Eq.34, Eq.40-43 and Eq.54, respectively:

$$H_2O\ needed_{196,13} = 50\ kg\ H_2 * 9.001\ kg\ H_2O/kg\ H_2 = 450.05\ 50\ kg\ H_2$$

$$O_2\ Produced_{196,13} = 50\ kg\ H_2 * 8\ kg\ O_2/kg\ H_2 = 40\ kg\ O_2$$

$$CO_2\ captured_{196,13} = 50\ kg\ H_2 * 5.501\ kg\ CO_2/kg\ H_2 = 275.05\ kg\ CO_2$$

$$CH_4\ Produced_{196,13} = 50\ kg\ H_2 * 2.005\ kg\ CH_4/kg\ H_2 = 100.25\ kg\ CH_4$$

$$H_2O\ Produced_{196,13} = 50\ kg\ H_2 * 4.504\ kg\ H_2O/kg\ H_2 = 225.20\ kg\ H_2O$$

$$Heat_{met_{196,13}} = 50\ kg\ H_2 * (-5.69)\ kWh/kg\ H_2 = -284.50\ kWh$$

$$Heat_{CH_{4_{196,13}}} = -100.25\ kg\ CH_4 * 13.9\ kWh/kg\ CH_4 = -1393.475\ kWh$$

This process was repeated for all the hours of all the days for a year, in order to determine all the necessary annual flows.

7.2.3 – Production flows

With the implementation previously described, it is possible to predict the production flows of the project. Considering the location of this industrial unit, around 10180.90 MWh/year of electricity are expected to be generated by the PV panels. Of those, about 2432.98 MWh/year, corresponding to 24% of the total, are expected to be used for this factory's self-consumption, which means the remaining 76% will be utilized in the electrolyser, for the production of H_2.

The production flows for the total and self-consumption generated energy, for each month of the year, are represented in table 5 and graphically in figure 30.

Table 5 – Monthly generated and self-sufficient electricity generated

	Electricity (MWh)	
	Generated electricity	**Self-sufficient electricity**
January	662.92	144.02
February	629.26	131.13
March	907.87	247.63
April	837.98	187.86
May	1076.92	278.77
June	999.14	231.69
July	1113.26	282.45
August	1064.48	276.77
September	952.30	264.79
October	682.53	132.99
November	692.85	163.44
December	561.39	91.42
Total	**10180.90**	**2432.98**

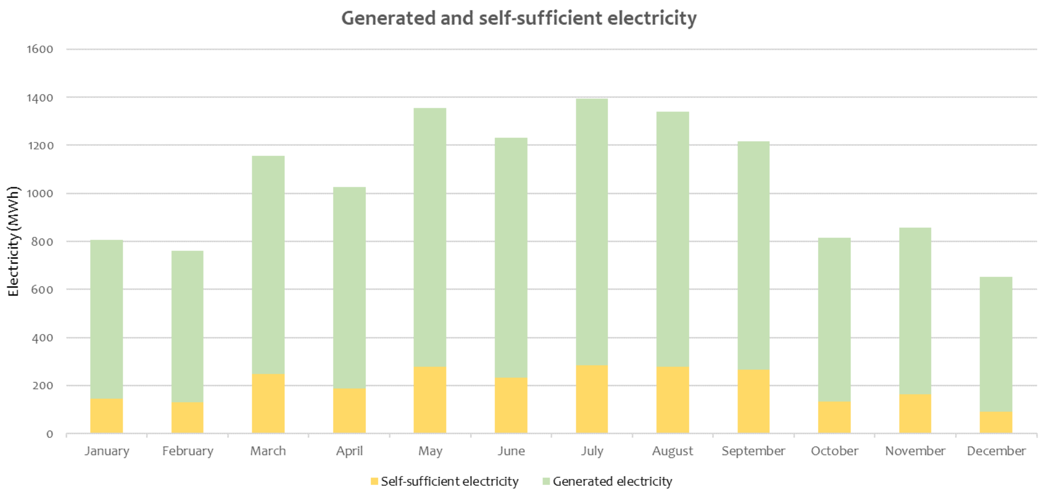

Figure 30 – Monthly self-sufficient and generated electricity flows

The electricity generated for the process of electrolysis will naturally be directed into the electrolyser, which is expected to have around 4200 hours of operating time annually (4239 in this case). In this process, the expectation for the production of H_2 is of about 154.96 tons, which corresponds to a necessity of around 1395.81 tons of water and a production of 1239.67 tons of O_2. Expectations for monthly water needs and H_2 and O_2 production are shown in table 6 and figure 31.

Table 6 – Monthly flows of electrolysis

	Electrolysis (ton)		
	H_2O needed	O_2 produced	H_2 produced
January	93.48	83.02	10.38
February	89.74	79.70	9.96
March	118.94	105.64	13.20
April	117.12	104.02	13.00
May	143.79	127.70	15.96
June	138.26	122.79	15.35
July	149.67	132.93	16.62
August	141.91	126.03	15.75
September	123.86	110.00	13.75
October	99.00	87.93	10.99
November	95.37	84.71	10.59
December	84.67	75.20	9.40
Total	**1395.81**	**1239.67**	**154.96**

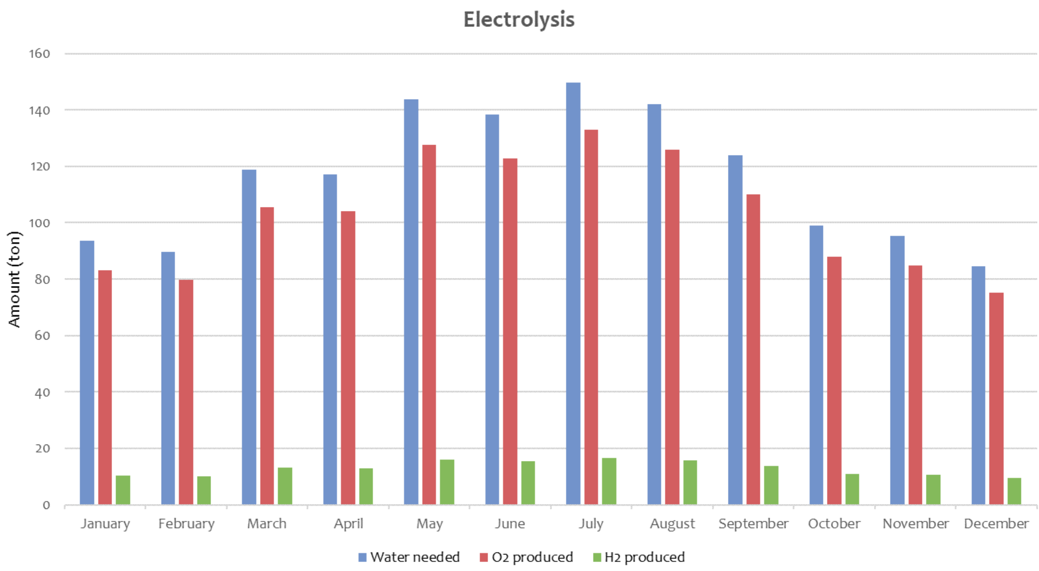

Figure 31 – Monthly representation of electrolysis' flows

Regarding methanation, the 154.96 tons of H_2 produced in the electrolysis process represent an annual need of 852.47 tons of CO_2, which is the annual amount of CO_2 captured from the steam boilers in this industrial unit. With this, the methanation process allows for the production of 310.69 tons of CH_4 and 697.90 tons of water, as well as 882.40 MWh/year of heat. The expected monthly flows for the methanation process are shown in table 7 and figure 32.

Table 7 – Monthly flows of methanation

	Methanation (ton)			
	H_2 needed	**CO_2 needed**	**H_2O produced**	**CH_4 produced**
January	10.38	57.09	46.74	20.81
February	9.96	54.81	44.87	19.98
March	13.20	72.64	59.47	26.48
April	13.00	71.53	58.56	26.07
May	15.96	87.82	71.89	32.01
June	15.35	84.44	69.13	30.77
July	16.62	91.41	74.84	33.32
August	15.75	86.67	70.95	31.59
September	13.75	75.64	61.93	27.57
October	10.99	60.46	49.50	22.04
November	10.59	58.25	47.69	21.23
December	9.40	51.71	42.33	18.85
Total	**154.96**	**852.47**	**697.90**	**310.69**

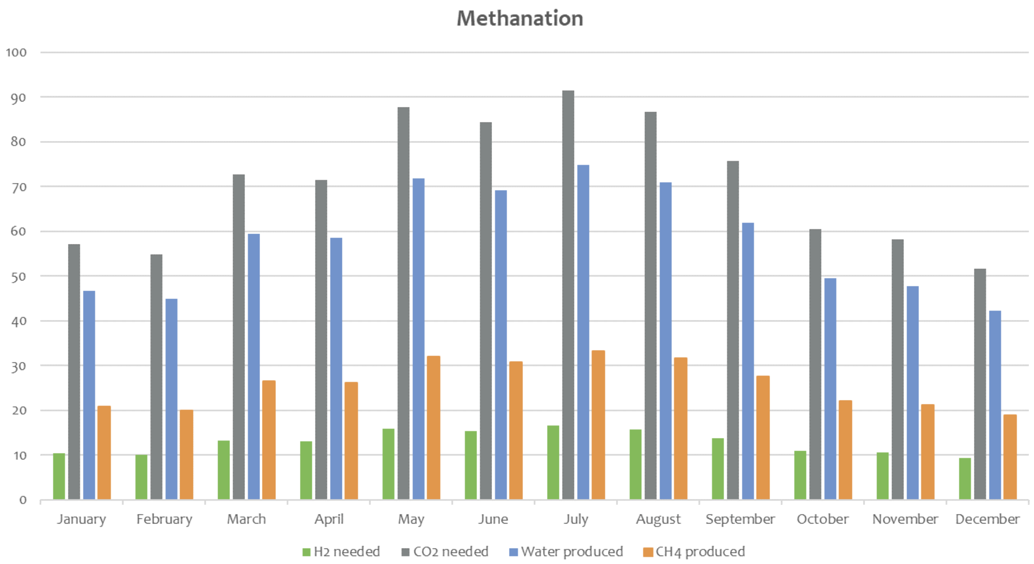

Figure 32 - Monthly representation of methanation's flows

In alternative 1, the 310.69 tons of CH_4 result in a total of 4318.61 MWh of heat, with the heat released in the methanation process being of 882.40 MWh., resulting in a total of 5201.02 MWh of heat generated for the internal process of the factory. The values for the generated heat for every month of the year are represented in table 8 and figure 33.

Table 8 - Monthly flows of generated heat

	Generated heat (MWh)	
	CH_4	**Released in methanation**
January	289.23	59.10
February	277.65	56.73
March	368.01	75.19
April	362.37	74.04
May	444.88	90.90
June	427.77	87.40
July	463.09	94.62
August	439.06	89.71
September	383.21	78.30
October	306.31	62.59
November	295.09	60.29
December	261.96	53.52
Total	**4318.61**	**882.40**

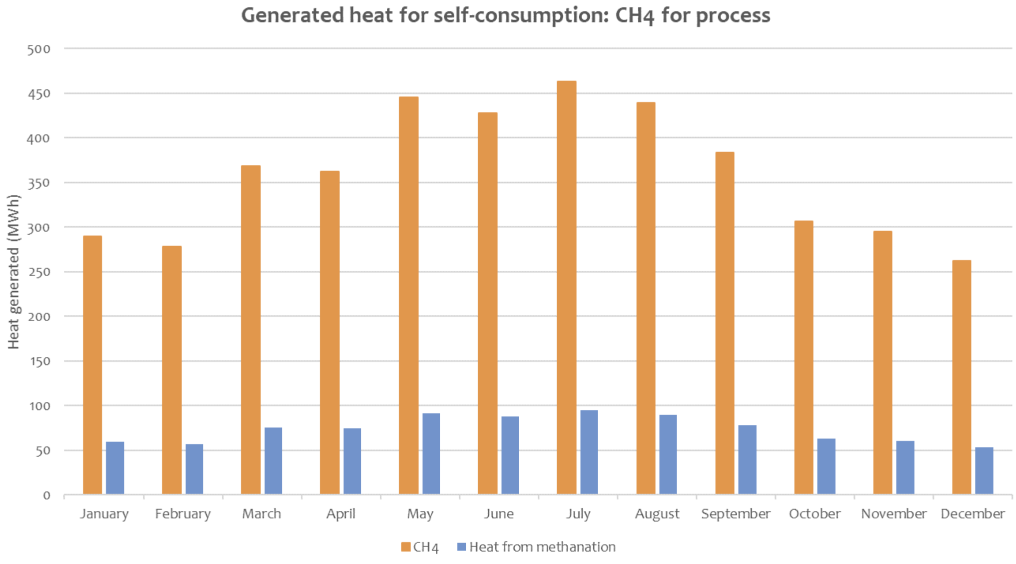

Figure 33 - Monthly representation of generated heat flows (alternative 1)

For base alternative 2, the 882.40 MWh of generated heat in the methanation presented in table 8 represent the total heat to be used in the internal process of the industrial unit (monthly production shown in figure 34).

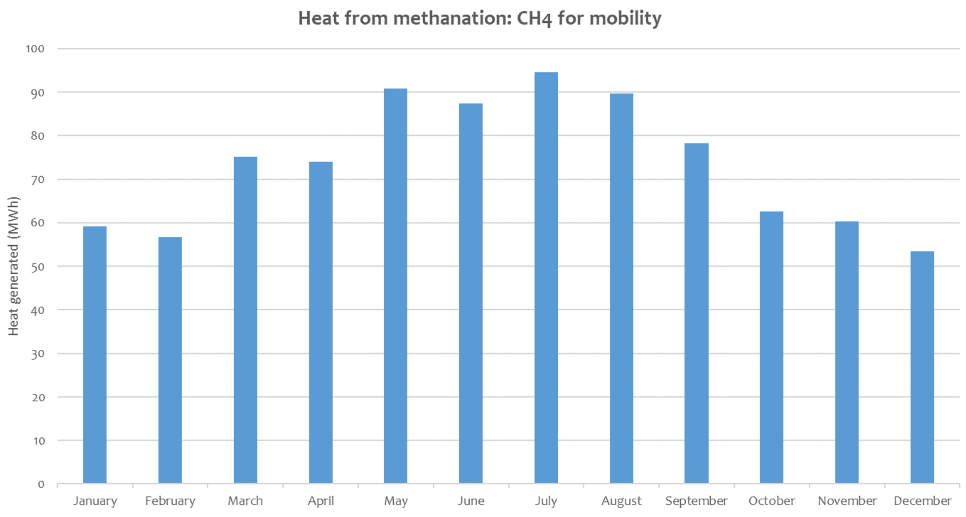

Figure 34 - - Monthly representation of generated heat flows (alternative 2)

The monthly renewable CH_4 produced in the methanation reaction, which is represented in table 6, is graphically shown in figure 35.

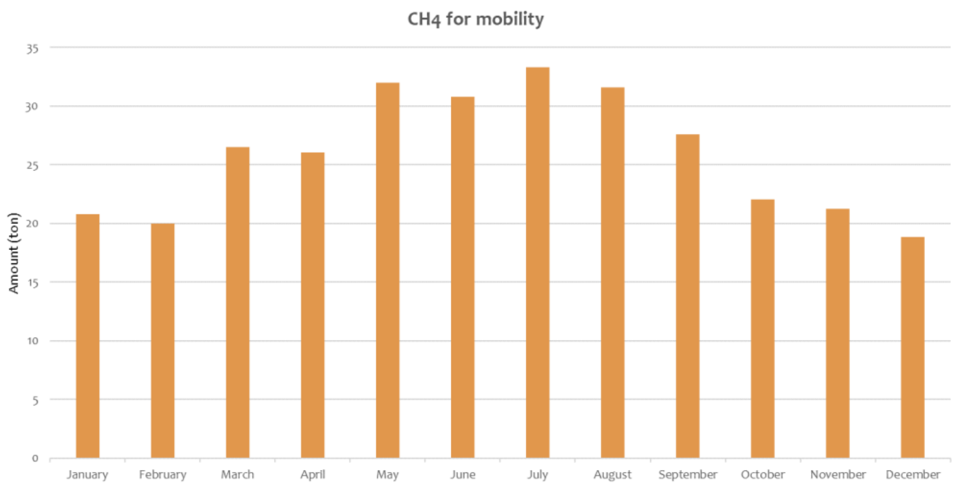

Figure 35 – Monthly representation of CH_4 production

Another relevant aspect has to do with the H_2O in the process. There is the expectation that the H_2O produced in this reaction can be reused in the electrolysis, which would diminish the total H_2O required to be acquired by the industrial unit and, thus, diminishing its cost. As previously expressed, the total H_2O necessities for electrolysis and production in methanation are of 1395.81 and 697.90, respectively (tables 5 and 6). This indicates that 50% of the H_2O needed for the electrolysis may be acquired in the methanation process. The monthly H_2O necessities and production are represented in figure 36.

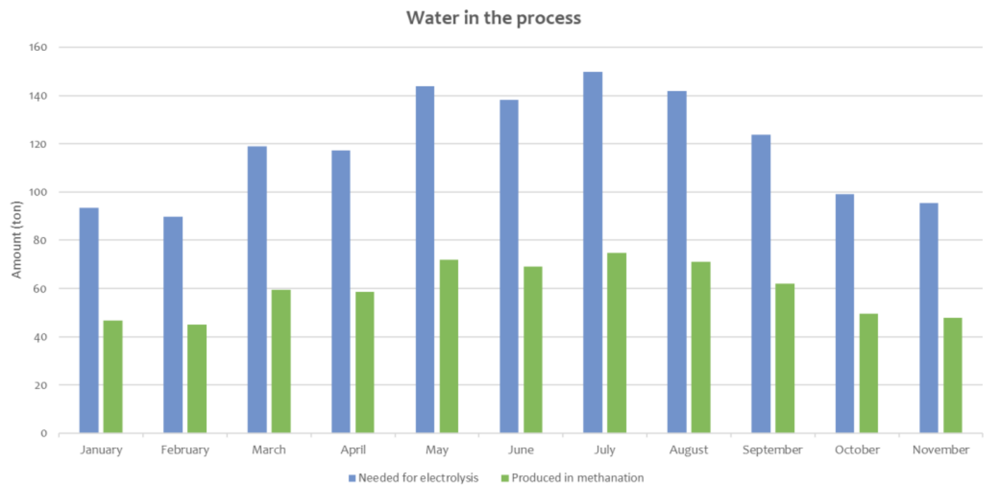

Figure 36 – Monthly representation of water required for electrolysis and produced in methanation

Since the electricity generated depends on solar radiation, it is expected that months with a higher production of electricity correspond to those in which there is higher radiation in the Almeirim area, which occurs in the Spring and Summer months in Portugal. In this case, it is expected that the production of electricity between the months of March and September corresponds to 68.28% of the total produced, increasing to 72.75% for the energy that will be used for the factory's self-consumption.

It has been expressed that the PtG technology refers to the transformation of electricity to gas. In this case, the production of H_2 depends solely on the energy that it used in the electrolyser. In the same way, the methanation reaction depends on the H_2 produced, which means that both electrolysis and methanation are limited to the generated electricity which is used in the electrolyser. Therefore, all the remaining percentages (necessity of H_2O and production of H_2 and O_2 in electrolysis, CO_2 to be captured, production of H_2O, CH_4 and heat released in methanation) are the same, with a value of 66.88%. All of these ratios are represented in figure 37.

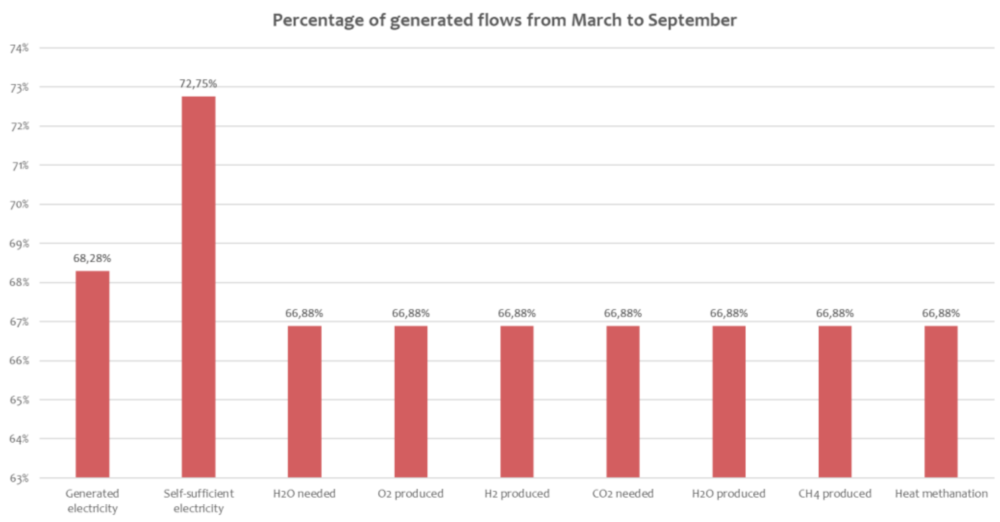

Figure 37 – Percentage of generated flows in the months between March and September

7.3 – Annual Revenues

With the estimation of all the production flows connected with the project, one is now capable to start performing an economic and financial feasibility. To do so, the first step is to estimate the current costs, associated with this industrial unit's process which can be converted into potential revenues with the project in hand.

The costs per unit of measure associated with this project are the same for both alternatives. To start off, it has been defined that the fuel used in these boilers is NG. To estimate the current heat provided by NG, the higher heating value (HHV) is going to be considered. For Portugal, the NG HHV is of 11.9 kWh/m^3.

Therefore, the necessities of NG for steam boilers 1 ($Boiler1\_NG\_necessity$) and 2 ($Boiler2\_NG\_necessity$) are (Eq.56 and Eq.57, respectively):

$$Boiler1\_NG\_necessity = \frac{2.000.000\ m^3/year * 11.9\ kWh/m^3}{1000} = 23\ 800\ MWh/year \qquad 56$$

$$Boiler2\_NG\_necessity = \frac{600.000\ m^3/year * 11.9\ kWh/m^3}{1000} = 7\ 140\ MWh/year \qquad 57$$

Thus, the total necessity of NG for steam boilers 1 and 2 combined ($Total\_NG\_necessity$) is (Eq.58):

$$Total\_NG\_necessity = Boiler1\_NG\_necessity + Boiler2\_NG\_necessity \qquad 58$$

$$Total\_NG\_necessity = 23.800 + 7.140 = 30.940\ MWh$$

This NG necessity of NG is higher than the synthetic methane produced, which means the latter can all be used in this industrial unit, if alternative 1 is to be chosen.

The price to acquire NG by this industrial unit is of 25 €/MWh. Since the boiler has an efficiency of 92%, it is now possible to estimate the cost of steam produced by NG, with Eq.59:

$$Cost\ of\ steam\ produced\ (NG) = \frac{NG\ Price}{Boiler\ efficiency} = \frac{25\ €/\mathrm{MWh}}{0.92} = 27.174\ €/\mathrm{MWh} \qquad 59$$

There is a CO_2 factor associated with the emission of NG, which is of 56.1 kgCO_2/GJ (ADB, 2017b), corresponding to 202.0 kgCO_2/MWh. Since the price to emit 1 ton of CO_2 in Portugal is of 23.619 €, the emission price of NG is (Eq.60):

$$Cost\ of\ CO_2\ emission\ (NG) = \frac{23.619€/\mathrm{ton} * 202.0\ kgCO_2/MWh}{1000} = 4.770\ €/\mathrm{MWh} \qquad 60$$

The cost of electricity for this industrial unit was defined to be of 125 €/MWh. Table 9 represents all the relevant energy costs described.

Table 9 – Cost per unit of measure

Parameter	Cost (€/MWh)
Steam produced (NG)	27.174
CO_2 emission (NG)	4.770
Electricity	125

These costs per unit of measure are crucial when estimating the revenues of the project. The electricity, CH_4 and heat produced for self-consumption of the industrial unit turn into revenues, since there is no need to purchase them in the market any longer. In addition, the non-emission of CO_2 turns into a profit since there is no need to keep on paying for these certificates. These revenues depend on the two base alternatives that were set.

Revenues of Alternative 1 – CH_4 for internal process

As it was previously mentioned, this 1st alternative contains the use of both CH_4 and heat in the form of steam from the methanation in the internal process of the industrial unit, to substitute the NG. As shown in table 8, the CH4 and heat production result in 4318.61 MWh and 882.40 MWh, respectively. In addition, as represented in table 5, 2432.98 MWh of electricity are generated for self-consumption. The estimation of revenues for this alternative is performed using Eq.61-63 and is represented in table 10:

$$Revenue\_Steam\_S1 = (4318.61 + 882.40)\, MWh * 27.174\ €/\mathrm{MWh} = 141\,331.96\ € \tag{61}$$

$$Revenue\_Certificates\_S1 = (4318.61 * 882.40)\, MWh * 4.770\ €/\mathrm{MWh} = 24\,809.33\ € \tag{62}$$

$$Revenue\_Electricity\_S1 = 2432.98\, MWh * 125\ €/\mathrm{MWh} = 304\,122.01\ € \tag{63}$$

Table 10 – Annual revenues for Alternative 1 – CH_4 for internal process

Parameter	Revenues (€/year)
Steam	141 331.96
Certificates	24 809.33
Electricity	304 122.133
Total	**470 263,30**

In this 1st alternative, 65% of the total revenues comes from the self-consumption electricity produced, 30% from the generated heat of both CH_4 and steam produced in methanation and the remaining 5% are related to the non-emission of CO_2. The total revenues and its relative impact are graphically represented in figure 38.

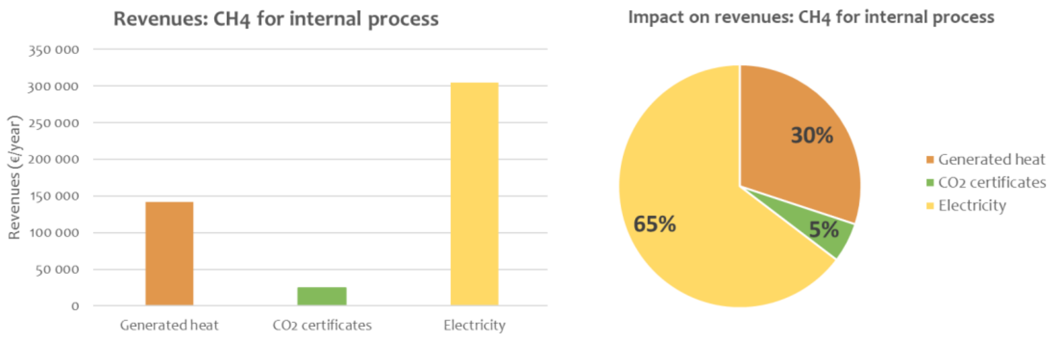

Figure 38 - Revenues and its impact for alternative 1 - CH_4 for internal process

Revenues of Alternative 2 – CH_4 for mobility

In this 2nd alternative, the only difference lies in the fact that the CH_4 is to be used as a fuel for transportation. Therefore, all the revenues associated with heat ($Revenue\_Steam\_S2$), certificates ($Revenue\_Certificates\_S2$) and electricity ($Revenue\_Certificates\_S2$) remain the same, being represented in Eq.64-66:

$$Revenue\_Steam\_S2 \ = \ 882.40 \ MWh \ * \ 27.174 \ \text{€/MWh} = 23\,978.32 \ \text{€} \tag{64}$$

$$Revenue\_Certificates\_S2 \ = \ (4318.61 \ + \ 882.40) \ MWh \ * \ 4.770 \ \text{€/MWh} = 24\,809.33 \ \text{€} \tag{65}$$

$$Revenue\_Electricity\_S2 \ = \ 2432.98 \ MWh \ * \ 140.9 \ \text{€/MWh} = 304\,122.01 \ \text{€} \tag{66}$$

In order to estimate the revenue associated with the use of CH_4 as fuel, the price of 45 €/MWh was considered. Therefore, the revenue for the produced CH_4 to be used as a fuel ($Revenue\_Fuel\_S2$) is (Eq.67):

$$Revenue\_Fuel\_S2 \ = \ 4318.61 \ MWh \ * \ 45 \ \text{€/MWh} = 194\,337.63 \ \text{€} \tag{67}$$

There is an extra revenue associated with this alternative, related with the fact that there is a save in the tax in transportation to be paid ($Revenue\_Tax\_Saved\_S2$), due to the use of biomethane instead of NG. Currently, this cost is of 1.33 €/GJ, which is 4.778 €/MWh. This revenue is determined with Eq.68:

$$Revenue\_Tax\_Saved\_S2 \ = \ 4318.61 \ MWh \ * \ 4.778 \ \text{€/MWh} = 20\,677.52 \ \text{€} \tag{68}$$

The estimation of revenues for alternative 2 is represented in table 11 and figure 39.

Table 11 – Annual revenues for alternative 2 – CH_4 for mobility

Parameter	Revenues (€)
Steam	23 978.32
Certificates	24 809.33
Electricity	304 122.01
Fuel	194 337.63
Tax saved	20 677.52
Total	**567 924.81**

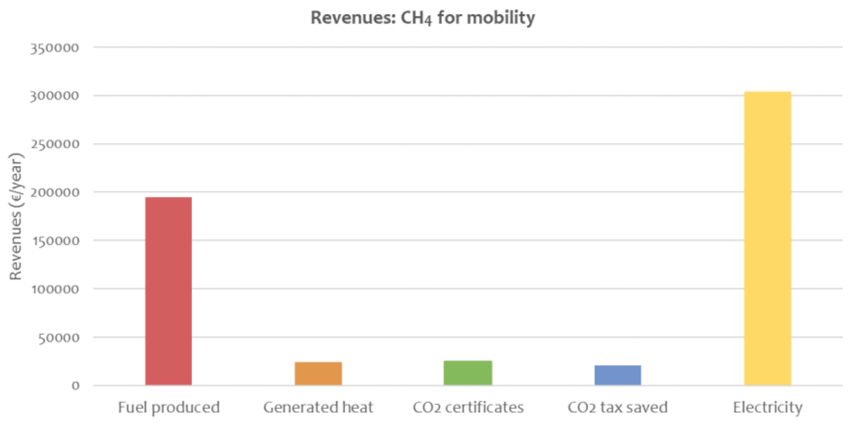

Figure 39 - Revenues for alternative 2 - CH_4 for mobility

In this 2nd alternative, 54% of the total revenues come from the electricity produced for self-consumption, 34% from the produced CH_4 as fuel, 4% from the generated heat from the steam produced in methanation, 4% from the non-emission of CO_2 and the remaining 4% from the CO_2 tax saved in the transportation sector. The relative impact of each type of revenue is graphically represented in figure 40.

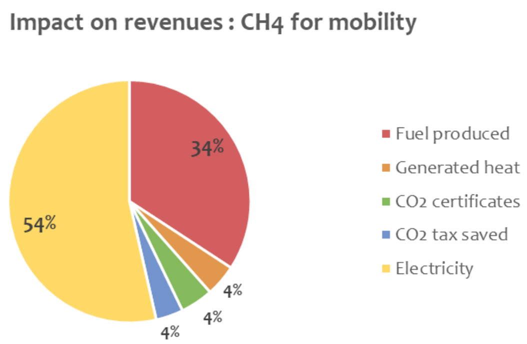

Figure 40 - Relative impact of each type of revenue for alternative 2 - CH_4 for mobility

7.5 – Economic evaluation

An economic analysis is carried out from the perspective of the entire economy, and it assesses the overall impact of a project on the welfare of all the citizens of the country concerned. The purpose of project economic analysis is to assess whether a project is economically viable for the country, which means it needs to consider society's economic perspective, to apply economic prices excluding taxes, tariffs and subsidies, in order to reflect the value of the project to society (ADB, 2017a).

If possible, externalities (positive and negative) need to be included and quantified in monetary terms (such as reduction in GHG emissions). For this specific project, externalities are extremely difficult to quantify in numbers, which means they are not going to be accounted for monetarily, since a much more detailed study on this matter would need to be performed. However, it is important to recognize their existence and explain them, as it follows:

- Aiding to accomplish national climate goals – Portugal has defined its national goals for energy until 2030, where renewable gases can have a major impact on. For Portugal, achieving these goals is not only important environmentally, but also to assure the country fulfils its obligations defined at European level, in order to ensure the country receives European monetary funds and avoids possible sanctions.
- Decrease of foreign dependence on NG - Portugal imports all the NG that is consumed in the country. The innovative production of this renewable gas will allow the reduction of NG imports and, consequently, the existing foreign dependence.
- Valuation of gas networks - Currently, gas networks play a fundamental role in the supply of national energy. However, a decarbonisation plan that does not include these infrastructures means the devaluation of a very expensive asset. This synthetic methane, having very similar characteristics to NG, allows for the current national gas system to be valued.
- Turning waste into profit – Nowadays, CO_2 is not only seen as waste, but also harms the environment. This project can be the beginning of a change, with what now is seen as waste being used as raw materials for another product, using the concept of circular economy.
- Job creation – A new renewable gases industry in Portugal could have a major impact in terms of employability, allowing the creation of up to 500 thousand new jobs in the country (Silva, 2019).

Typically, the equipment used in PtG projects such as this one has a lifetime of 20 years. In both base alternatives, the production is set to start on year 3 of analysis, meaning there are no revenues and operational costs (OPEX) in the first 2 years of the project. The i*, as explained in subchapter 5.5, is of 4%.

In the 2 base alternatives considered, the initial investment, which corresponds to the acquisition phase (CAPEX), and OPEX are the same. The total CAPEX of the project is considered to be of 11.2 M€. In terms of OPEX, a percentage of 3% of the total CAPEX was considered for all the equipment, resulting in expenses of 0.336 M€/year after production begins, i.e., in year 2. The revenues are going to be the same for all years of analysis after production starts (with values of around 0.470 M€/year for alternative 1 and 0.568 M€/year for alternative 2). For depreciation, a 12.5% rate was considered, which results in a yearly depreciation of 1.4 M€ for 8 years, starting in year 2 of the project (which is when the equipment is completely installed and ready for production) up to year 9. All of these parameters belong to the operation phase of LCC analysis.

For the phaseout and disposal phase, it was defined that the residual value was of 0, since the disassembly of the equipment would cost the same than of what it can be sold after the project is completed. These parameters are presented in table 12.

Table 12 – Parameters of the project for economic feasibility - base alternatives

Parameter	Value	Unit	Year of project
CAPEX	11.2	M€	0
OPEX (excluding depreciation)	0.336	M€/year	2-19
Depreciation	1.05	M€/year	2-9
Revenues (alternative 1)	0.470	M€/year	2-19
Revenues (alternative 2)	0.568	M€/year	2-19
i*	4	%	0-19

After the model for the base alternatives has been developed, the economic feasibility of the project can now be calculated, taking into account the mentioned indicators. The cash-flows of the project are presented in figures 41 and 42, for alternatives 1 and 2, respectively. In Appendix C, a more detailed cash-flow estimation of the economic analysis is shown for base alternative 2.

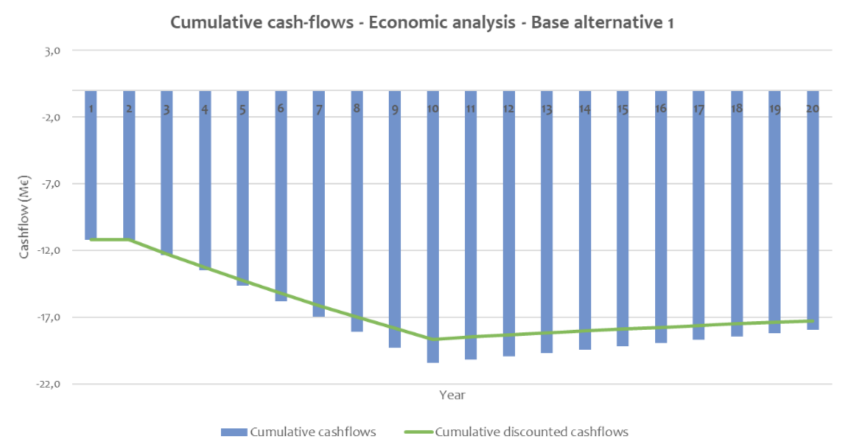

Figure 41 – Cumulative cash-flows – Economic analysis – Base alternative 1

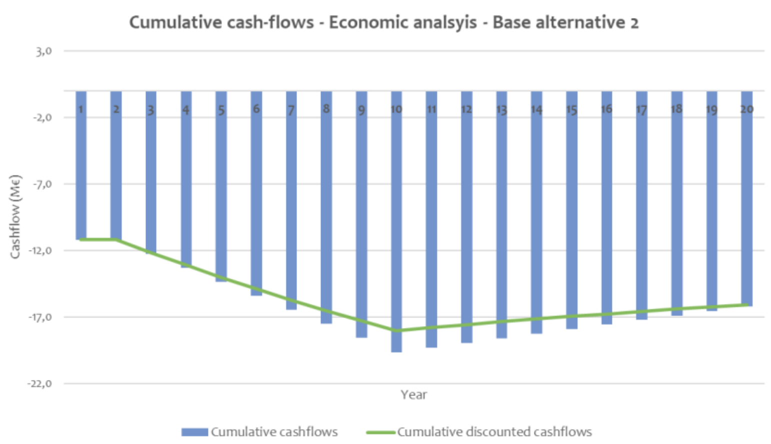

Figure 42 - Cumulative cash-flows – Economic analysis – Base alternative 2

The results for a 20-year economic analysis are presented in table 13 and show that the PW/NPV of this project is < 0 for both alternatives, which means this project is not feasible from an economic perspective for a 20-year period.

Table 13 - 20-year economic feasibility analysis - base alternatives

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-17.27	M€	-16.01	M€

7.6 – Financial evaluation

Financial analysis is the process of evaluating businesses, projects, budgets, and other finance-related transactions to determine their performance and suitability. Typically, financial analysis is used to analyse whether an entity is stable, solvent, liquid, or profitable enough to warrant a monetary investment (Tuovila, 2020). The main differences between financial and the economic analysis which was just performed are that financial analysis: represents the investor's perspective; is based on market prices; includes taxes, tariffs or subsidies; does not include externalities.

In this case study, the real differences lay on considering a CAPEX subsidy in which this project fits in, which is going to be of 70% (the maximum reimbursement allowed by *Fundo Ambiental*). With this, the CAPEX of the project from the company's perspective decreases to 3.36 M€.

For this dissertation, it was considered that the company is going to require financing all of the necessary CAPEX. To do so, a 10-year loan of 3.36 M€ is going to be considered, with a 2-year grace period, resulting in an investment of 0.42 M€/year form years 2-9. Regarding interest, the chosen rate was of 1.7%, which was the rate defined by Banco de Portugal (2020) for loans over 1 M€ in October of 2020. Regarding depreciation, it decreases to 0.42 M€/year. These costs belong to the operation phase of the LCC analysis. The revenues and OPEX for both alternatives are considered to be the same as the ones use in the economic analysis. The tax rate in Portugal is of 23%. It is worth noting that in the years when the project is not profitable, there is no need to pay taxes, but if the company promoting the project has other ongoing projects that are profitable, they can reduce the amount of tax to be paid regarding income from other projects. This fact will not, however, be considered for this analysis. These values are represented in table 14 below.

Table 14 – Parameters of the project for economic feasibility - base alternatives

Parameter	Value	Unit	Year of project
CAPEX	0.42	M€	2-9
Revenues (alternative 1)	0.470	M€/year	2-19
Revenues (alternative 2)	0.568	M€/year	2-19
OPEX (excluding depreciation)	0.336	M€/year	2-19
Depreciation	0.42	M€/year	2-19
Interest	Variable	M€/year	0-9
Tax	23	%	0-19
i*	4	%	0-19

With all the necessary information gathered, the cash-flows of the project were estimated, being shown with more details for base alternative 2 in Appendix D. The cash-flows and discounted cash-flows of the project are presented in figures 43 and 44 for base alternatives 1 and 2, respectively.

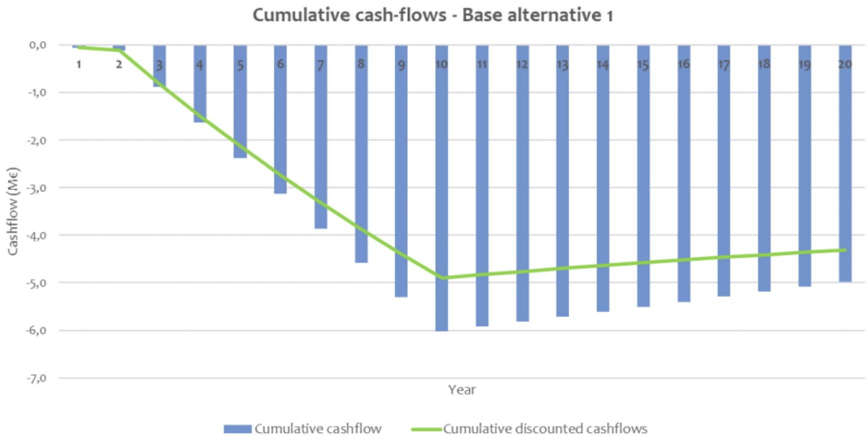

Figure 43 - Cumulative cash-flows – Financial analysis – Base alternative 1

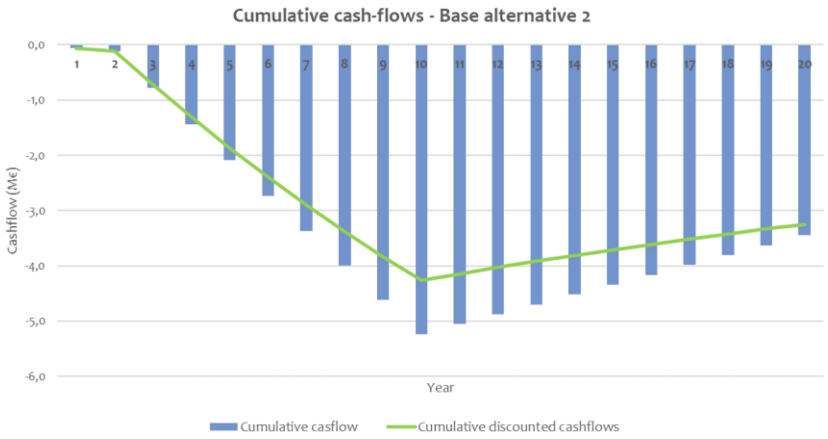

Figure 44 – Cumulative cash-flows – Financial analysis – Base alternative 2

The financial indicators for both base alternatives are shown in table 15. As it is possible to observe, the resulting PW/NPV of the project is negative for both alternatives, meaning that the project is not feasible in any of the base alternatives.

Table 15 - 20-year financial feasibility analysis - base alternatives

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-4.309	M€	-3.248	M€

7.7 – Sensitivity analysis

7.7.1 – KPI research

In the project discussed, economic and financial analysis were both performed according to parameters defined to set base alternatives. However, in order to perform a sensitivity analysis, the following variables were chosen to be subject to variations in order to provide a more robust assessment of the project and to determine possible KPIs which can influence the result:

- Price of CO_2 emission – Currently, factories included in the EU ETS, which is the case, have to pay for the emitted CO_2. At this time, the price in Portugal is set in 23.619 €/ton and it is considered to remain the same in the base alternative throughout the whole project lifetime. However, this CO_2 emission price has been growing in the last years and it is expected to do so, in order to penalize fossil fuels usage. For this project, a yearly increase up to 10% in this CO_2 emission tax is going to be considered throughout the whole project. A 10% increase would result in a CO_2 emission tax value of around 144 €/ton in the year of 2040.
- Synthetic methane selling price – The selling price of the final product is also a variable which is going to be varied, in order to evaluate its impact on annual revenues. A variation between 0 and 15% and be considered, since a premium price could be assumed due to the renewable factor associated with this product.
- Electricity price – Even though electricity is not the main final product in this project, it is possible to observe that it has a major impact on annual revenues. This happens due to the fact that a lot of electrical energy produced cannot be used directly in the electrolyser for hydrogen produced, which means it can be sold either directly to the industrial unit or to the grid. According to PORDATA (2020), the price of electricity for industrial users in Portugal is of 137.1 €/MWh. Therefore, an increase of up to 10% (maximum of 137.5 €/MWh) can be considered.
- CAPEX– The initial investment is an indicative estimation, since its exact values are not completely known yet, meaning its accuracy is not the best one. For that effect, a variation is going to be applied to this variable, which is going to directly affect the OPEX. In this case, a positive impact, which in this case is a decrease, of up to 15% (lowest value of 9.53 M€) can be estimated to still provide a realistic value for sensitivity purposes.

For a 20-year economic analysis for base alternative 1, the performed sensitivity analysis resulted in the following results (figure 45):

- PW between -17.27 M€ (0%) and -16.72 M€ (+10%) when CO_2 annual growth is changed;
- PW between -17.27 M€ (0%) and -16.90 M€ (+10%) when electricity price is varied;
- PW between -17.27 M€ (0%) and -13.18 M€ (-15%) when varying CAPEX;

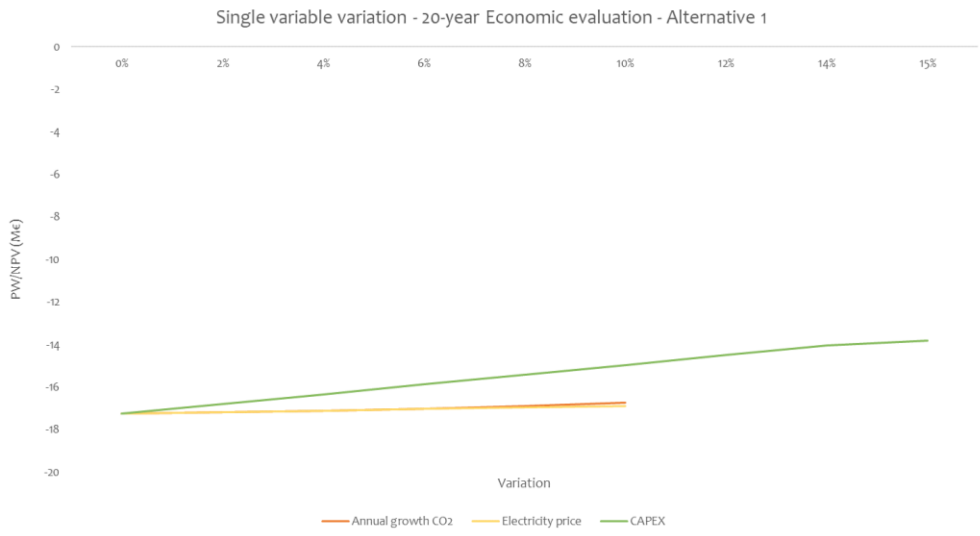

Figure 45 - Single variable variation - 20-year Economic evaluation - alternative 1

As it is possible to observe, a single variable variation also does not make the project feasible in any circumstances for alternative 1 in a 20-year economic analysis.

For a 20-year economic analysis for base alternative 2, these variations resulted in (figure 46):

- PW between -16.07 M€ (0%) and -15.54 M€ (+10%) when CO_2 annual growth is changed;
- PW between -16.07 M€ (0%) and -15.72 M€ (+15%) when synthetic methane selling price for mobility is modified;
- PW between -16.07 M€ (0%) and -15.71 M€ (+10%) when electricity price is varied;
- PW between -16.07 M€ (0%) and -12.63 M€ (-15%) when varying CAPEX.

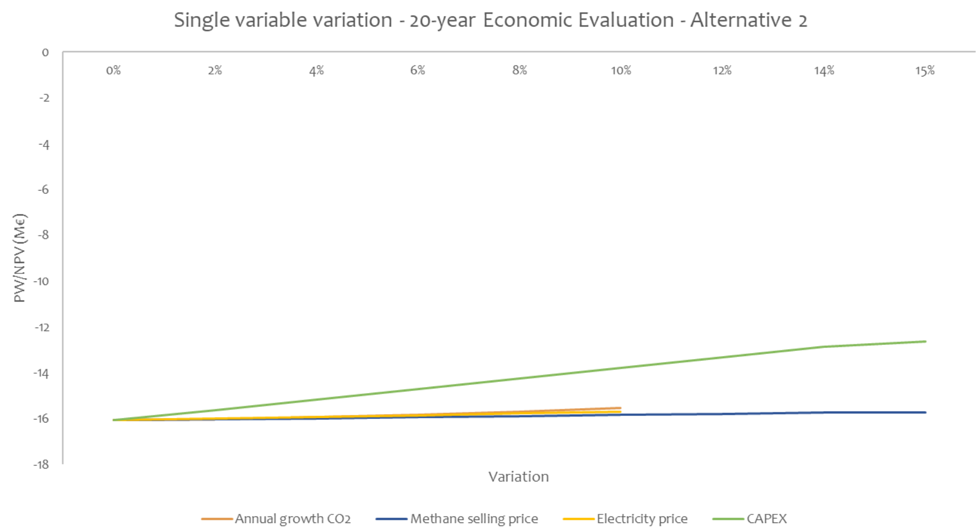

Figure 46 - Single variable variation - 20-year Economic evaluation - alternative 2

A single variable variation in the selected range does not make the project feasible in any circumstance for alternative 2. Therefore, in all base alternatives, the project is not feasible economically for both lifetimes considered by varying 1 single varibale within defined ranges.

For a 20-year financial analysis for alternative 1, the sensitivity analysis performed resulted in the following results (figure 47):

- PW between -4.30 M€ (0%) and -3.87 M€ (+10%) when CO_2 annual growth is modified;
- PW between -4.30 M€ (0%) and -3.97 M€ (+10%) when electricity price is varied;
- PW between -4.30 M€ (0%) and -2.90 M€ (-15%) when varying CAPEX;

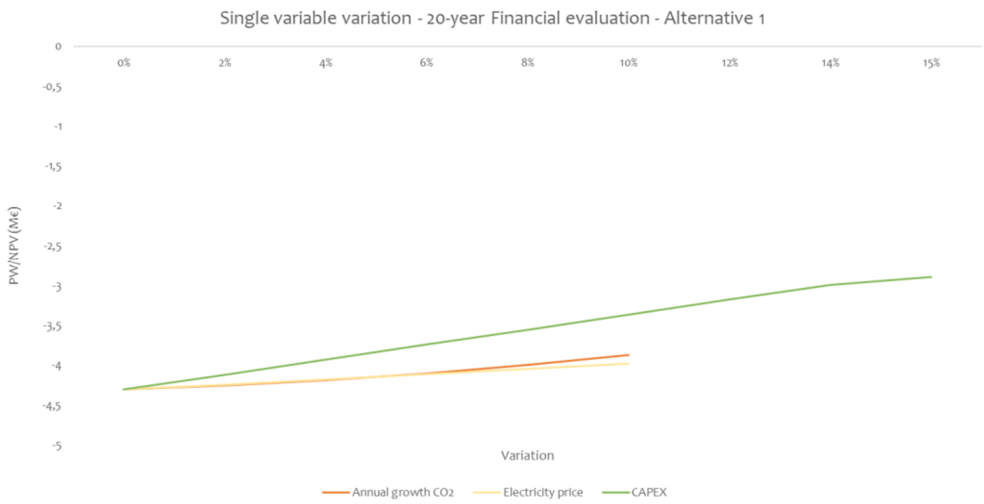

Figure 47 - Single variable variation - 20-year Financial evaluation - alternative 1

In a 20-year financial analysis for alternative 2, these variations resulted in (figure 48):

- PW between -3.25 M€ (0%) and -2.81M€ (+10%) when CO_2 annual growth is changed;
- PW between -3.25 M€ (0%) and -2.93 M€ (+15%) when synthetic methane selling price for mobility is modified;
- PW between -3.25 M€ (0%) and -2.92 M€ (+10%) when electricity price is varied;
- PW between -3.25 M€ (0%) and -1.84 M€ (-15%) when varying CAPEX.

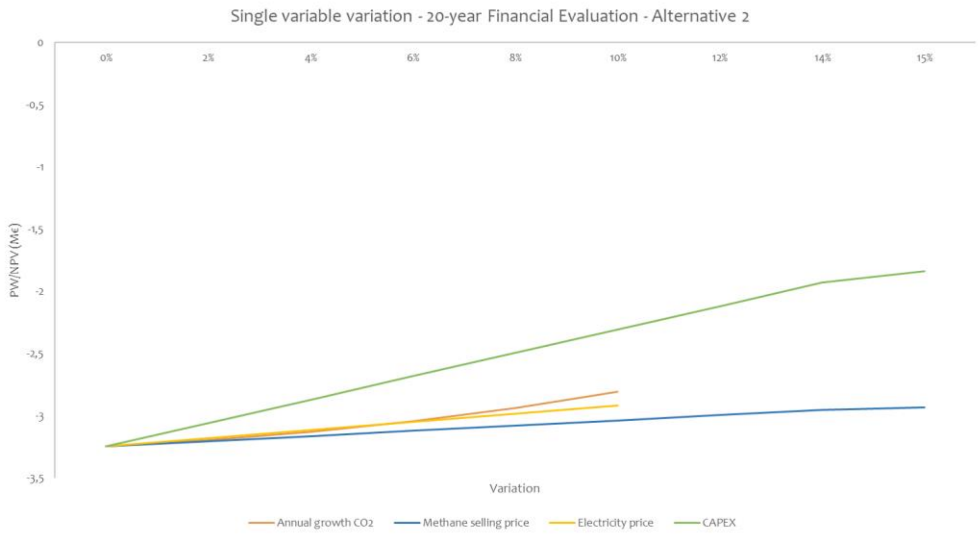

Figure 48 - Single variable variation - 20-year Financial evaluation - alternative 2

From the presented results, it is possible to observe that the project does not become feasible when varying 1 single variable within the defined range for any of these variables, both economic and financially. Regarding variable research, there is no variable that actually changes the results using realistic values for today's market.

7.7.2 – Best case alternatives

Besides single variable variation, different alternatives are going to be presented in this project's evaluation. The first one is best case alternatives, where variables' values are defined in order to pursue what would be an ideal case for these variables within the range defined in subchapter 7.7.1, which are shown in table 16:

Table 16 – variable values – best case alternatives

Variable	Variation	Value	Unit
CO_2 annual growth	10%	10	%
Synthetic methane price	15%	51.75	€/MWh
Electricity Price	10%	137.5	€/MWh
CAPEX (economic)	-15%	9.52	M€
CAPEX (financial)	-15%	2.856	M€

The results for a 20-year economic and financial analysis are presented in tables 17 and 18, respectively:

Table 17 – 20-year economic feasibility analysis – best-case alternatives

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-12.91	M€	-11.37	M€

Table 18 - 20-year financial feasibility analysis – best-case alternatives

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-0.935	M€	-0.751	M€
IRR	-6.2	%	0.3	%

In both cases, PW < 0, meaning the project is still not feasible, even with an ideal alternative regarding variables variation.

7.7.3 – Later start & lower CAPEX

In this alternative, the project is only set to begin 5 years later (with the production only starting in year 3 after that), reducing its lifetime to 15 years. However, the CAPEX for all the technologies is considered to be reduced in 35%, from 11.2 M€ to 7.28 M€, for economic analysis, which results in 2.184 M€ regarding financial analysis (70% is reimbursed). In addition, a 5% growth in CO_2 tax is going to be considered (due to its trend to increase), with the other variables remaining the same as in the base alternatives (table 19).

Table 19 – Variables values – Later start & lower capex alternative

Variable	Value	Unit
CO2 annual growth	3	%
Synthetic methane price	45	€/MWh
Electricity Price	125	€/MWh
CAPEX (economic)	8.4	M€
CAPEX (financial)	2.52	M€

Regarding OPEX, a percentage of 3% of the total CAPEX was maintained for all the equipment, resulting in expenses of 0.2184 M€/year after production begins. The revenues are going to change for this alternative, due to increase in CO_2 tax, and are going to increase every year: from 0.480 M€ in year 1 to 0.508 M€ in year 15 when synthetic methane is used for internal process; from 0.578 M€ in year 1 to 0.605 M€ in year 15 when synthetic methane is used for mobility;

Regarding depreciation, it decreased to 0.6825 1 M€ for 8 years, starting in year 3 of the project (8 years from now) (which is when the equipment is completely installed and ready for production) up to year 10 (15 years from now). The rate of return is naturally maintained at 4%. All these monetary values are represented in table 20.

Table 20 - Parameters for economic feasibility – Later start & lower CAPEX alternatives

Parameter	Value	Unit	Year of project
CAPEX	7.28	M€	0
OPEX (excluding depreciation)	0.2184	M€/year	0-14
Depreciation	0.91	M€/year	2-9
Revenues (1st year - alternative 1)	0.480	M€/year	Increases every year
Revenues (1st year - alternative 2)	0.605	M€/year	Increases every year
i*	4	%	0-14

In this case, an economic feasibility for a 15-year lifetime project starting 5 years from now is presented in table 21 below.

Table 21 - 20-year economic feasibility analysis – Later start & lower CAPEX alternative

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-8.668	M€	-7.898	M€

Regarding economic feasibility, the PW < 0 for both alternatives. Thus, the project is still not feasible in this dimension considering the defined characteristics for this alternative.

For the financial analysis for this alternative, a 10-year loan with a 2-year grace period was once again considered, but this time of 2.184 M€, resulting in an investment of 0.42 M€/year from years 2-9, with the same interest rate of 1.7%. These parameters are shown in table 22 below.

Table 22 - Parameters for financial feasibility – Later start & lower CAPEX alternatives

Parameter	Value	Unit	Year of project
CAPEX	0.273	M€	2-9
Revenues (1st year - alternative 1)	0.480	M€/year	Increases every year
Revenues (1st year - alternative 2)	0.605	M€/year	Increases every year
OPEX (excluding depreciation)	0.2184	M€/year	2-14
Depreciation	0.273	M€/year	2-9
Interest	Variable	M€/year	0-9
Tax	23	%	0-14
i*	4	%	0-14

With this information, a financial analysis was performed for this alternative, with results being shown in table 23. In a financial dimension, PW < 0 for both alternatives, indicating that this alternative is also not feasible.

Table 23 - 20-year financial feasibility analysis – Later start & lower CAPEX alternative

Parameter	Alternative 1		Alternative 2	
	Value	Unit	Value	Unit
PW/NPV @4%	-1.237	M€	-0.465	M€
IRR	-13.9	%	-3.0	%

7.7.4 – Search for feasible solution

Up to this point, all the alternatives analysed showed the same results: the non-feasibility of the project, both economic and financially; using CH_4 for mobility is always a better alternative than using it for the industrial unit's internal process, since using synthetic CH_4 for mobility is more valuable than for the process (45 MWh vs 25 MWh in this project). As stated in subchapter 2.2, there are currently several funding-schemes in Europe which aid the production of biomethane. In addition, as represented in subchapter 4.2, the cost of all power-to-gas alternatives remains higher than the cost of fossil-derived natural even assuming a cost of 100 €/t CO_2 carbon price, and that governmental policies are needed in order for projects of PtG to be feasible.

Bearing this in mind, it is necessary to define possible parameters which provide an alternative that can be considered feasible, providing a realistic overview for the future. To do so, only the alternative where synthetic CH_4 is to be used for mobility is going to be subject to analysis in this case. Regarding variables definition, the total CAPEX and electricity price are going to remain the same.

One of the biggest issues regarding this project's feasibility lies on the fact that annual revenues are extremely low when comparing with OPEX and also initial investment, since equipment which has an extremely high value is not producing a valuable product monetarily, a fact that is confirmed when electricity has the most impact on revenues, rather than selling the synthetic CH_4. Therefore, one possible solution is the creation of a feed-in tariff for the production of synthetic methane and to estimate the NPV of the project considering these 2 variables. Table 24 shows the NPV values when varying these two variables simultaneously.

Table 24 – NPV values (M€) when varying CO_2 annual growth and feed-in tariff values

		Feed-in tariff value (€/MWh)							
	Values	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**
CO_2 Annual Growth	**0%**	-0.910	-0.694	-0.490	-0.287	-0.085	0.117	0.320	0.522
	2%	-0.859	-0.644	-0.440	-0.238	-0.036	0.167	0.369	0.572
	4%	-0.795	-0.582	-0.378	-0.176	0.026	0.229	0.431	0.634
	6%	-0.716	-0.504	-0.300	-0.098	0.105	0.307	0.509	0.712
	8%	-0.616	-0.404	-0.201	0.001	0.203	0.406	0.608	0.811
	10%	-0.489	-0.279	-0.076	0.126	0.329	0.531	0.734	0.936
	12%	-0.329	-0.120	0.083	0.285	0.488	0.690	0.893	1.095
	14%	-0.126	0.083	0.285	0.488	0.690	0.892	1.095	1.297

As it is possible to observe, in most situations, the minimum feed-in tariff is only possible with values between 60 and 70 €/MWh of synthetic methane produced. In order to estimate more accurate values, one can determine the breakeven values necessary for this feed-in tariff when varying CO_2 annual growth for the following rates: 0% (23.619 €/ton in 2040), 5% (59.68 €/ton in 2040), 8% (101.93 €/ton in 2040) and 10% (144.45 €/ton in 2040). These breakeven values for a feed-in-tariff mark the minimum value required for this tariff in order for the project to become feasible and are represented in table 25 below.

Table 25 – Breakeven values for feed-in tariff with different CO_2 tax annual growth

CO_2 annual growth	Feed-in tariff breakeven value (€/MWh)
0%	72.10
5%	68.44
8%	64.97
10%	61.88

Another important variable regarding this project is the CAPEX, which has extremely high values when comparing with annual revenues. Therefore, and considering a 5% CO2 annual growth, one can also determine feasible values for feed-in tariffs with CAPEX variation, in order to determine what could be realistic necessary values for the project to be feasible. Table 26 shows the NPV values when varying CAPEX and feed-in tariff simultaneously.

Table 26 - NPV values (M€) when varying CAPEX and feed-in tariff values

		Feed-in tariff value (€/MWh)							
	Values	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**
CAPEX (M€)	**11.2**	-1.682	-1.447	-1.213	-0.981	-0.758	-0.545	-0.342	-0.139
	10.64	-1.211	-0.978	-0.753	-0.538	-0.334	-0.132	0.070	0.273
	10.08	-0.748	-0.532	-0.327	-0.125	0.078	0.280	0.483	0.685
	9.52	-0.320	-0.117	0.085	0.287	0.490	0.692	0.895	1.097
	8.96	0.092	0.295	0.497	0.700	0.902	1.104	1.307	1.509
	8.4	0.504	0.707	0.909	1.112	1.314	1.516	1.719	1.921

Results show that if a 10% decrease in CAPEX is achieved, to 10.08 M€, the feed-in tariffs need to be valued between 45 and 50 €/MWh. However, if a 15% reduction occurs, to 9.52 M€ this feed-in tariff would need to be between 35 and 40 €/MWh. If CAPEX can be decreased in at least 20%, feed-in tariffs below 30 €/MWh would also turn the project into a feasible one.

7.8 – Discussion

This chapter as a whole can be split into two main sections: a first one, where a model was applied in order to estimate all the production flows related with the presented case study; a second one, regarding its economic and financial feasibility.

As explained in sub-chapter 7.1, this project comprises 4 different elements:

- The production of solar renewable electricity, resulting in the production of 10.18 GWh/year of electricity. Of those, 76% can be used for the production of green hydrogen, whereas the remaining 24% are to be utilized for the factory's self-consumption.
- The production of green hydrogen through water electrolysis. With the produced electricity, the expectation for the production of H_2 is of about 154.96 tons, which corresponds to a necessity of around 1395.81 tons of water and a production of 1239.67 tons of O_2.

- The capture of 852.47 tons of CO_2, which is the annual amount of CO_2 captured from the steam boilers in this industrial unit.
- The production of 310.69 tons of synthetic methane and 697.90 tons of water, as well as 882.40 MWh/year of heat.

As expected, since all the project is based on electricity dependency, months with more radiation correspond to periods of higher production, which occurs in Spring and Summer. Generally, around 2/3 of the production occurs in the months between March and September. These production flows allowed for the estimation of annual revenues for this project, with the creation of 2 base alternatives:

- The use of the produced CH_4 for this industrial unit's process, which includes 3 different sources of revenue: steam to be used in the process (30% of total revenues), saved money from certificates which no longer have to be paid (5% of total revenues) and the selling of electricity which was produced but not used for electrolysis (65% of total revenues). This income is estimated to be of ~0.470 M€/year.
- The use of CH_4 as a fuel for mobility, namely in NGV vehicles. In this case, there are now 5 different sources of income: steam to be used in the process (4% of total revenues), certificates which no longer have to be paid (4% of total revenues), electricity which was not used in electrolysis being sold (54% of total revenues), the synthetic CH_4 being sold as fuel for vehicles (34% of total revenues) and the tax which does not have to be paid (4% of total revenues). This income is estimated to be of ~0.568 M€/year.

The CAPEX was projected to be of 11.2 M€ and OPEX being estimated to be 3% of this value, 0.336 M€. Depreciation was defined to be of 12.5% and the rate of return for this project was of 4%. For the financial analysis, a 70% reimbursement of CAPEX was considered, becoming of 3.36 M€ and a 10-year loan with a yearly interest tax rate of 1.7% was contemplated. With all these parameters, it was possible to perform 20-year economic and financial analysis of the project. For the defined base-alternatives, results showed that the project was not feasible in all the analysis, since PW < 0 on all occasions. For this project, since PW was always extremely negative, no IRR and payback period were presented.

The next step was to perform a sensitivity analysis. In order to do so, 4 main variables were defined to be varied: price of CO_2 emissions, synthetic methane selling price, electricity price and CAPEX. This analysis was executed in 3 different dimensions:

- KPIs research – in this first case, each one of the variables was varied individually, in order to determine its impact on the feasibility results. All the variables were subject to variations, with results showing that this project is never feasible economical and financially in both alternatives, by varying 1 single variable.
- Best case alternatives – In this alternative, all the variables were varied to the value that would most benefit the results, within the ranged presented KPI research. Once

again, results showed that even when assuming the best possible values for all variables within the defined ranges, this project does not become feasible.

- Later start & lower CAPEX – This alternative was analysed in order to provide an overview on what would happen if the project is set to start 5 years later, but with a CAPEX (and consequently OPEX) reduction of 35%, due to the evolution of technologies, which are expected to result in a price decrease in the next years. In this alternative, the results remained the same, i.e., determining a non-feasibility for this project.

A first conclusion that can be achieved from this analysis up to this point is the fact that this project is never feasible in any of the described alternatives, mainly due to the high CAPEX involved to install all the necessary equipment, which generates low annual revenues, especially because of the fact that there are currently no incentives in order for this synthetic methane to become more profitable. This, along with the current low price for CO_2 emissions, explains the fact that even though production of electricity is not the main goal of this project, it has, by far, the highest impact on total revenues.

In order to search for a solution that can turn this project feasible, it was considered that CAPEX, electricity price and methane selling price would not be changing from the base alternatives. On the other hand, CO_2 annual growth could be subject to change and a feed-in tariff could be created, in order to value synthetic methane's production. Results showed that in most cases, this feed-in tariff has to be valued between 60 and 70 €/MWh in order for the project to be profitable. The breakeven points found for this tariff for specific increase on the price of CO_2 emission were the following: 72.10 €/MWh with no CO_2 tax annual increase; 68.44 €/MWh with a 5% increase; 64.97 €/MWh with an 8% increase; 61.88 €/MWh with a 10% increase.

Besides CO_2 annual increase, CAPEX is also an extremely important variable on this project's feasibility. Therefore, considering a 5% annual increase on CO2 emission tax, it was also possible to estimate the necessary values for feed-in tariffs. In this case, if: a 10% decrease in CAPEX the feed-in tariffs need to be valued between 45 and 50 €/MWh. However, if a 15% reduction occurs, this feed-in tariff would need to be between 35 and 40 €/MWh. If CAPEX can be decreased in at least 20%, feed-in tariffs below 30 €/MWh would also turn the project into a feasible one.

At the time being, there are currently no funding schemes and benefits apart from certain aid regarding initial investment for the production of renewable gases or carbon capture. However, and as expected, PtG projects can only become feasible through government policies which can allow for these renewable gases to be competitive with fossil fuels. One way to do so is through the creation of feed-in tariffs and the increase of CO_2 emission tax. However, and even though these possibilities were not presented for this specific case study, tax incentives and green certificates with monetary value can also help in the development of production of synthetic methane through PtG.

Chapter Eight – Final Remarks

8.1 – Conclusions

Several conclusions can be drawn regarding the implementation of the Power-to-Gas technology throughout this dissertation. The first and more obvious one is the fact that this technology is clearly far from being competitive when comparing to what already exists in today's world: fossil natural gas. Results showed that the production of synthetic methane requires an extremely high CAPEX, but the annual revenues generated by that production are extremely low in comparison.

The second conclusion achieved from the analysis conducted is the fact that there are 3 key points which are essential when discussing the feasibility of PtG:

- the first one being cost of technologies, which is currently extremely high, and can only realistically decrease with a global support for R&D into its development;
- secondly, the cost of CO_2 emissions, which is extremely important in order to punish the current production of fossil fuels, needs to keep its tendency of grow in the following decades;
- thirdly, the production of synthetic methane must be valued when comparing to the current fossil fuels price, since it contributes for the decarbonisation of society, namely industry and transportation, if used as a fuel for mobility. This last point could be achieved with tax exemptions and the creation of feed-in tariffs or green-certificates with monetary value.

As the worlds progresses, so does Energy: prior to the industrial revolution, energy sources were extremely scarce: for heat, sun, wood and straw; for transportation, horses and wind; for work, animals. Industrial revolution allowed mankind to start using coal and, shortly after, petroleum and natural gas, followed by nuclear and renewable energies in the 20th century.

In recent years, the production of electricity using renewable sources (solar, wind, hydro, tidal, geothermal and biomass) has suffered significant advances. In addition to these, the production of renewable gases, namely green hydrogen, biomethane and synthetic methane can contribute decisively for a successful energy transition to a decarbonised society.

Regarding renewable gases, in which synthetic methane, which was the focus of this dissertation, is included, its production is highly dependent on Governmental support and a global cooperation into the development of more efficient and cheap technologies. However, one thing is certain: this is the path for a more sustainable future and to leave a better world for current and future generations.

8.2 – Future work

The work developed in this dissertation can still be improved in different dimensions, in what concerns the approximation of the presented case study with a real one. One of the biggest issues regarding this project analysis was the fact that there is no similar one in Portugal to serve as comparison. In addition, the literature regarding the implementation of this technology is also not much extensive, making it difficult to search for evaluation of similar projects.

Regarding the technical implementation of the project, the chemical flows were determined purely based stoichiometry and no faults in production or margin of error was considered, with results may showing some differences regarding the obtained values, if applicable in a real case. Besides that, it was considered that the heat produced could be used to replace natural gas in the current process of the company, thus generating profit, a fact that may not be entirely accurate. In addition, oxygen was considered to not have any value for the project, since there is no information regarding its purity and utility in this context. However, the production of this gas could bring some added value to the project.

In terms of the economic analysis, one clear limitation in this dissertation was the lack of information regarding the monetary value of externalities, which should be accounted for. In this case, even though they were mentioned, no value was put into them, resulting in worse results in economic analysis, since the mentioned externalities were generally positive. Therefore, some research on this matter would aid immensely in presenting more accurate results.

Concerning both economic and financial analysis, the first limitation was the lack of exact values regarding the CAPEX of the project, since the presented investment was an indicative one. In addition, since there was no information regarding this matter, all of its value was put into assets value (which is reflected in depreciation), which may not be entirely accurate, since a part of the investment could be allocated into transportation or civil works regarding the equipment implementation and the connection to the gas grid, for example.

To finalize this dissertation, it is worth noting the lack of regulation and incentives regarding the production of synthetic methane in Portugal, which is a crucial step in order for the PtG technology to be implemented in Portugal successfully. With information regarding this issue, a much more accurate analysis could be performed.

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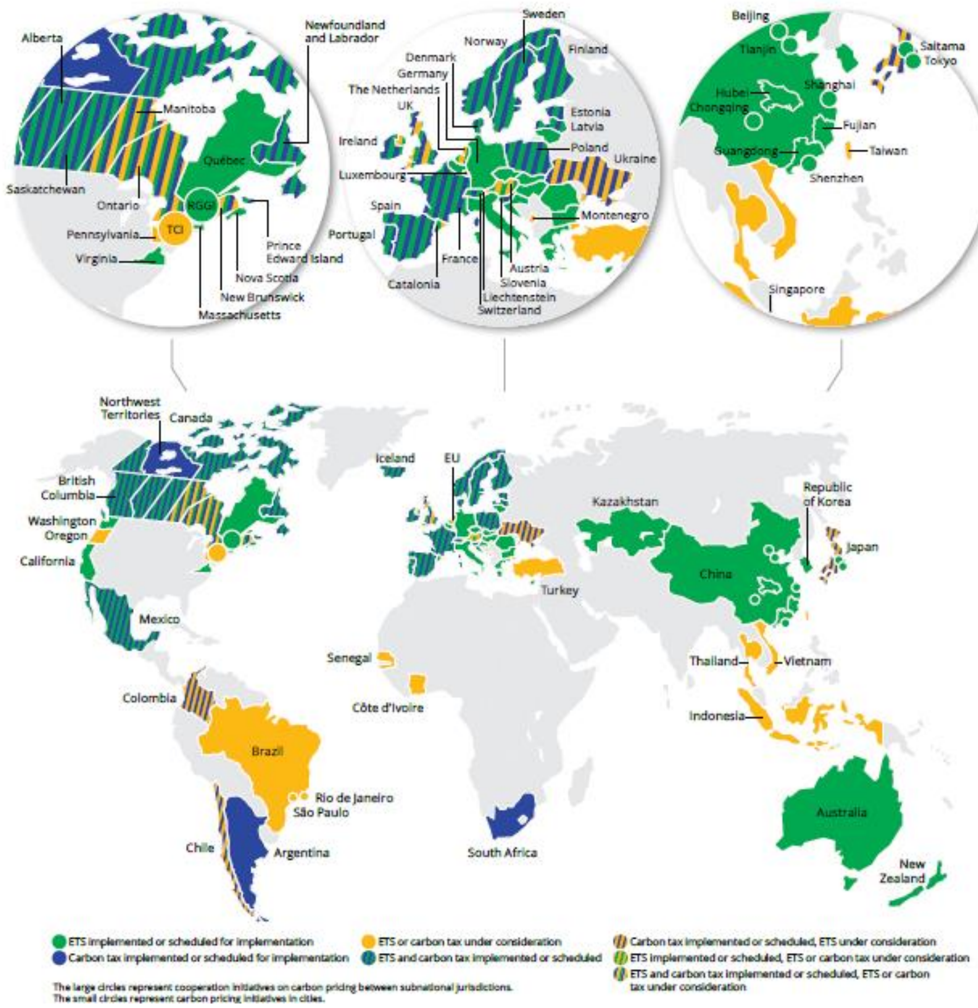
Appendix A

A map of the carbon pricing initiatives implemented, scheduled for implementation and under consideration is shown in Appendix A.

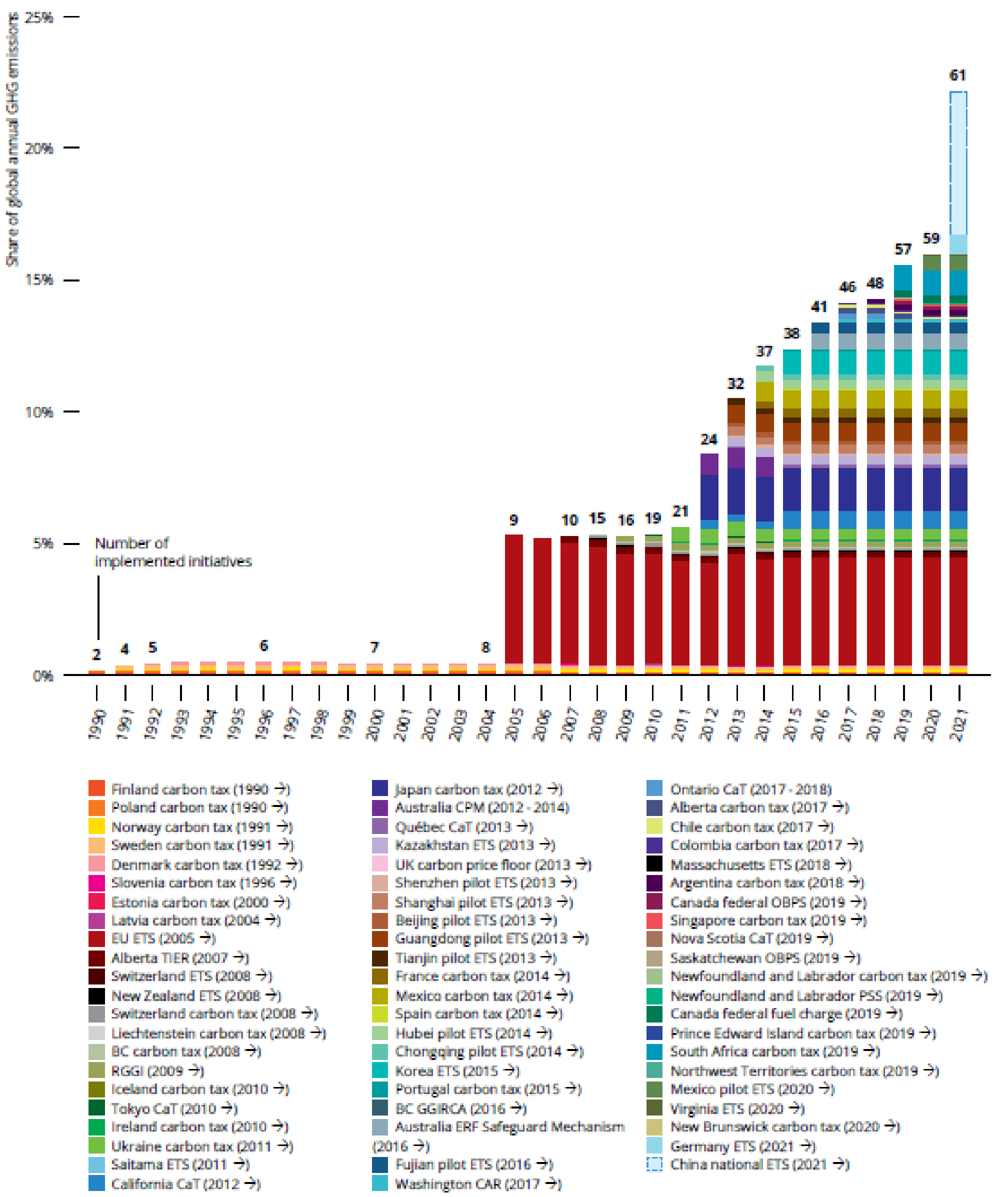


Appendix A - Carbon pricing initiatives implemented, scheduled for implementation and under consideration (Source: World Bank Group, 2020)

Appendix B

Appendix B represents the share of global emissions covered by ETS and carbon taxes from 1990 to 2020.

T



Appendix B - Share of global emissions covered by carbon pricing initiatives (ETS and carbon taxes)
(Source: World Bank Group, 2020)

Appendix C

Appendix C shows the cash flows of the project for the economic analysis of base alternative 2. The same procedure was followed for base alternative 1 and when performing sensitivity analysis of the project.

Appendix C - Cash flows of the project – Economic evaluation – Base alternative 2

	Year									
	0	1	2	3	4	5	6	7	8	9
- Investment	11.2	0	0	0	0	0	0	0	0	0
+ Revenues	0	0	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570
- COGS	0	0	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
- Depreciations	0	0	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Total CF	-11,20	0,000	-1,056	-1,056	-1,056	-1,056	-1,056	-1,056	-1,056	-1,056
Accum. CF	-11,20	-11,20	-12,26	-13,31	-14,37	-15,42	-16,48	-17,54	-18,59	-19,65
Disc. CF	-11,20	0,00	-0,98	-0,94	-0,90	-0,87	-0,83	-0,80	-0,77	-0,74
Ac. Disc. CF	-11,20	-11,20	-12,18	-13,12	-14,02	-14,89	-15,72	-16,52	-17,29	-18,04
	Year									
	10	11	12	13	14	15	16	17	18	19
- Investment	0	0	0	0	0	0	0	0	0	0
+ Revenues	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570
- COGS	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
- Depreciations	0	0	0	0	0	0	0	0	0	0
Total CF	0.344	0.344	0.344	0.344	0.344	0.344	0.344	0.344	0.344	0.344
Accum. CF	-19.30	-18.96	-18.62	-18.27	-17.93	-17.59	-17.24	-16.90	-16.55	-16.21
Disc. CF	-17.80	-17.58	-17.37	-17.16	-16.96	-16.77	-16.59	-16.41	-16.24	-16.08
Ac. Disc. CF	-4.145	-4.029	-3.918	-3.811	-3.708	-3.608	-3.513	-3.421	-3.333	-3.248

Appendix D

Appendix D shows the cash flows of the project for the financial analysis of base alternative 2. The same procedure was followed for base alternative 1 and when performing sensitivity analysis of the project.

Appendix D - Cash flows of the project – Financial evaluation – Base alternative 2

	Year									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
- Investment	0	0	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
+ Revenues	0	-0	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570
- COGS	0	0	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
- Depreciations	0	0	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
- Interest	0.057	0.057	0.057	0.500	0.428	0.357	0.286	0.214	0.143	0.071
EBT	-0,057	-0,057	-0,245	-0,238	-0,231	-0,224	-0,217	-0,209	-0,202	-0,195
- Taxes	0	0	0	0	0	0	0	0	0	0
Total CF	-0,057	-0,057	-0,665	-0,658	-0,651	-0,644	-0,637	-0,629	-0,622	-0,615
Accum. CF	-0,057	-0,114	-0,779	-1,437	-2,088	-2,732	-3,369	-3,998	-4,621	-5,236
Disc. CF	-0,057	-0,055	-0,615	-0,585	-0,556	-0,529	-0,503	-0,478	-0,455	-0,432
Ac. Disc. CF	-0,057	-0,112	-0,727	-1,312	-1,868	-2,398	-2,901	-3,379	-3,834	-4,266

	Year									
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
- Investment	0	0	0	0	0	0	0	0	0	0
+ Revenues	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570	0.570
- COGS	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
- Depreciations	0	0	0	0	0	0	0	0	0	0
- Interest	0	0	0	0	0	0	0	0	0	0
EBT	0.232	0.232	0.232	0.232	0.232	0.232	0.232	0.232	0.232	0.232
- Taxes	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053	-0.053
Total CF	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179
Accum. CF	-5.057	-4.879	-4.700	-4.522	-4.343	-4.164	-3.986	-3.807	-3.629	-3.450
Disc. CF	0.121	0.116	0.112	0.107	0.103	0.099	0.095	0.092	0.088	0.085
Ac. Disc. CF	-4.145	-4.029	-3.918	-3.811	-3.708	-3.608	-3.513	-3.421	-3.333	-3.248