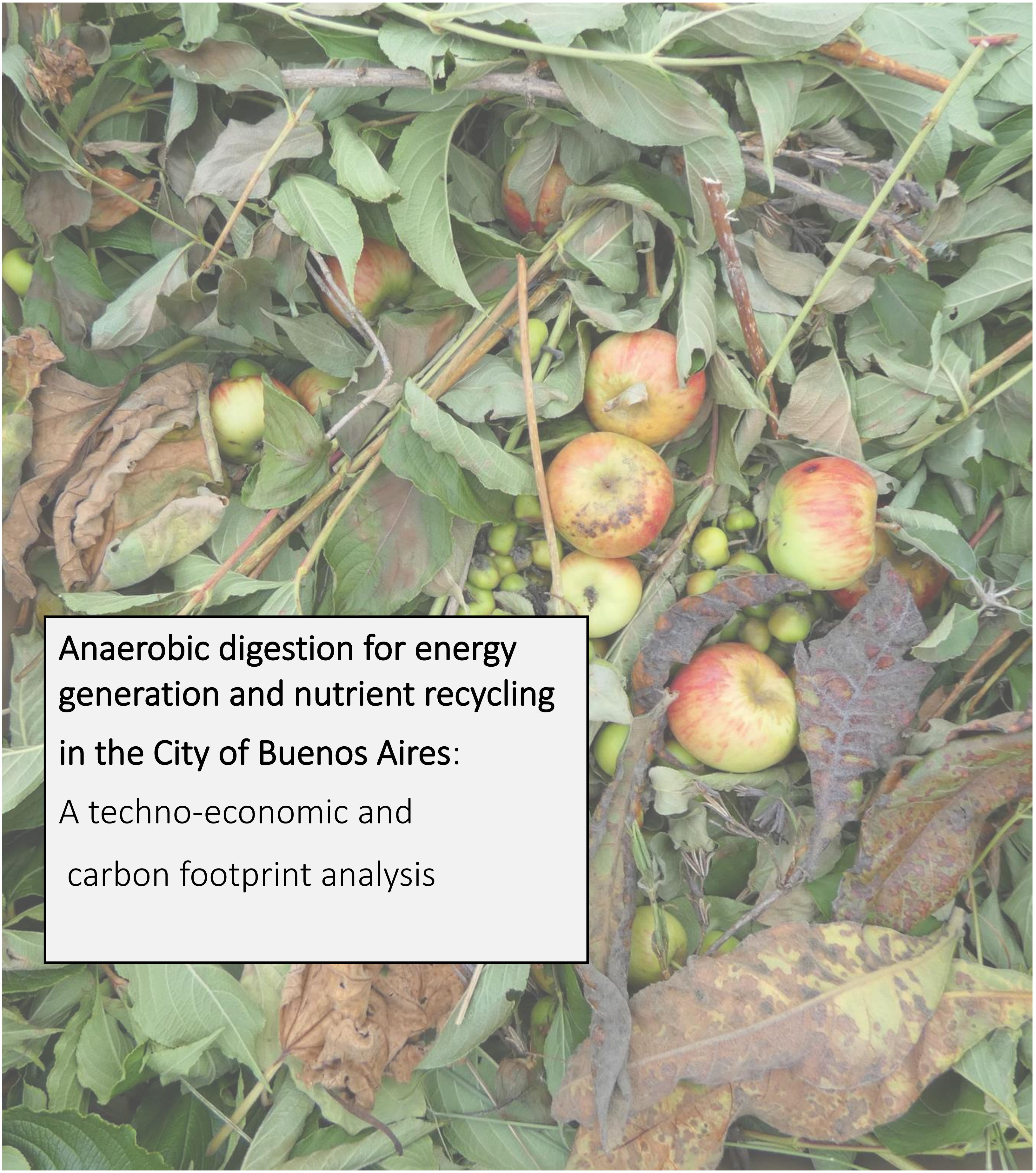

Anaerobic digestion for energy generation and nutrient recycling in the City of Buenos Aires:

A techno-economic and carbon footprint analysis

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Written by:

Malen Rocio Otero

Leiden University (s3022455) | TU Delft (5435390)

Supervised by:

Dr. José Mogollón (CML Leiden University)

Prof. Dr. Andrea Ramírez Ramírez (Engineering systems and services, TU Delft)

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Abstract

Organic waste is the largest domestic waste category in the City of Buenos Aires (CABA) and is currently landfilled together with other waste streams. Landfilling organic waste not only has a large impact on the environment, but also leads to the loss of the value embedded in organic waste, such as nutrients and energy. In this regard, anaerobic digestion emerges as a potential waste treatment alternative that supports energy generation and nutrient recycling, while avoiding landfilling emissions.

Although AD is a relative mature and widely applied technology for the treatment of a variety of feedstocks (e.g., sewage sludge and animal manure), urban AD systems using biowaste are still in a preliminary stage. Therefore, the present research aims to evaluate the economic performance and the carbon footprint of this technology in CABA in the context of two case studies, where biogas is used to produce bioelectricity (C-1) and bio-CNG (C-2).

The case studies were assessed using a plant design which consisted of a biogas facility treating 23 thousand t/y of substrate, a mixture of OFMSW and recycled liquid fraction. Once biogas is produced as a result of the digestion process, a CHP and a membrane unit are used to produce bioelectricity and bio-CNG, respectively. Moreover, digestate, the material remaining after anaerobic digestion, is pasteurized for its utilization as biofertilizer on land.

The results of the economic analysis suggest that, under defined conditions, a positive NPV, IRR, and payback period can be obtained for both case studies. Nevertheless, there are high chances that the economic performance becomes negative, especially when changes are simulated that directly impact the amount of revenue the project makes.

The results of the carbon footprint indicate that both case studies could lead to substantial carbon savings, given that the avoided GHG emissions are substantially higher than the emitted ones. Large savings are obtained from avoiding the landfilling of organic waste, and replacing conventional energy, fuel, and fertilizers. The results of the carbon footprint are less sensitive to simulations performed, given the margin of avoided emissions over the emitted ones.

The analysis concluded that while both case studies are very likely to present environmental benefits, the economic constraints might impose a drawback for its implementation. Therefore, the support of the

government is crucial to promote the adoption of AD, considering all the benefits that are associated with this technology.

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AD	Anaerobic Digestion
CABA	Autonomous City of Buenos Aires
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
C&D	Construction and Demolition
OWTP	Organic Waste Treatment Plant
CE	Circular Economy
CADER	Argentinian Chamber of Renewable Energy
TS	Total Solids
VS	Volatile Solids
DM	Dry Matter
HRT	Hydraulic Retention Time

C-1	Case Study 1
C-2	Case Study 2
TEA	Techno-economic analysis
GWP	Global Warming Potential
FU	Functional Unit
IRR	Internal Rate of Return
NPV	Net Present Value
OPEX	Operational Costs
CAPEX	Capital Costs
WWTP	Wastewater Treatment Plant

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1. Introduction

1.1. MSW in the City of Buenos Aires, a problem

One of the major problems that mega cities are facing, including the Autonomous City of Buenos Aires (hereafter CABA), is the management of municipal solid waste (MSW). CABA produced around 1,229,700 tonnes of domestic MSW in the year 2019 (López de Munai, et al., 2021), half of which approximately (48%) corresponded to the organic fraction of MSW (OFMSW), or 1,617 tons daily (Ceamse, 2018). Despite the efforts to recycle the OFMSW, only 0.01 % of the it is daily recycled, while the remaining is sent to sanitary landfill (Buenos Aires Ciudad, 2022).

There are numerous environmental and social consequences from discarding MSW in landfills, yet there are three that are prevalent. First, the methane emissions to air generated from the decomposition of organic matter. Emissions from landfill sites represents 10% of the global anthropogenic methane emissions (Ishii & Furuichi, 2013), a significant number considering that the global warming potential of methane is equivalent to 25 times that of carbon dioxide (Derwent, 2020). Second, the contamination of soil and water bodies, particularly groundwater, as a consequence of heavy metals and excess of nutrients that are present in leachates (Jayawardhana, et al., 2016) (Ramakrishnan, et al., 2015). Last, the occupation of large land surfaces for sanitary landfill has a negative impact on the environmental services of the soil, among which are: production of biomass, filtration and purification of water, regulation of erosion and regulation of climate (Mukherjee, et al., 2014). In the case of CABA, the Northern Environmental Complex III, where the city disposes most of its MSW (López de Munai, et al., 2021), is located on the most fertile area of the country and has expanded more than 40% over the last 20 years due to the increase of the population and the amount of waste disposed (Caprile, 2015).

The local government recently expressed their concern about the increasing quantities of waste generated, and the large negative impacts associated with their disposal (Instituto IDEAS, 2020). In this regard, technical measures are being implemented to limit the impact of landfills, for example, with the use of impermeable liners underneath the landfill to avoid leaching, and the use of covers and pipes to capture some of the gases that are generated (Poulsen, 2014). Nonetheless, these technical interventions do not alleviate the issues related to the use of land, which are particularly of concern in urban areas where land is becoming scarce due to growing population and rapid urbanisation (Poulsen, 2014) (Letcher & Vallero, 2019).

Due to the mentioned reasons, landfilling is no longer considered by the government as the prevalent solution for treating municipal waste. In this regard, the Climate Action Plan highlights that landfills will not be allowed to dispose any recyclable and usable materials by the year 2028, equivalent to 80% of the total MSW landfilled (Gobierno de la Ciudad de Buenos Aires, 2020). Therefore, it is pertinent to search for alternatives to manage MSW that are economically and less environmentally harmful.

1.2. The City of Buenos Aires and its current waste management system

The study area of the present research is the capital of Argentina, CABA. It is the most populated and largest city of the country, with around 3 million inhabitants in the year 2019 and an area of 203km2 (DGEC-GCBA, 2019). Like any of the Argentinian provinces, without CABA being one, it has a head of government, legislature, and judiciary competences (Gómez Ramírez, 2021), which means that the city has the capacity to, among other things, decide on its own waste management system.

In the year 2019, CABA generated around 6.793 daily tons of MSW (López de Munai, et al., 2021). MSW can be classified into domestic, pruning and landscaping, construction and demolition (C&D), and special generators' waste, which corresponds to waste generated by public and private organizations that have to manage it independently from the state (López de Munai, et al., 2021). Domestic waste stream represents the largest waste stream of the city (48%), followed by the construction and demolition stream (46%). The special generators (3%), on the other side, represent lower values compared to the other two, given that much of the material generated by this sector is treated in the other two circuits. Lastly, pruning activities represent 2% of the total solid waste of the city (López de Munai, 2021).

In line with the Zero Waste Regulation, the City of Buenos Aires reduced by more than 50% the waste sent to landfill by the year 2019, compared to 2012 values. This reduction was possible due to the construction of a C&D Waste Treatment Plant in the year 2013, which recycles 87% of the waste coming from C&D; a Forestry Waste Treatment Plant in the year 2015, which composts 80% of waste generated from pruning activities; and an Organic Waste Treatment Plant (OWTP) which composts 8% of the organic waste from special generators and 10% from public pruning activities (López de Munai, et al., 2021).

Domestic waste is separated into two flows that are disposed in containers located on public roads. The wet fraction corresponds to organic and non-recyclable waste (76%) (López de Munain, 2021). The heterogeneity of the materials that make up this waste stream affects its recovery, and consequently is landfilled. The dry fraction is the potentially recyclable waste (24%) and is composed of paper, glass, plastics, and metals, of which 23% is recycled in Green Centres and by urban recuperators (López de Munai, 2021).

Given that the source separation of municipal waste is not regulated, the government has been promoting the voluntary separation of it. Depending on the type of waste, different waste streams can be disposed in bell-shaped green bins on the streets and other public spaces, or they can be brought directly to the so-called Green Points located in squares and parks. At the moment (Sept-2022), there are 19 of them distributed across CABA. The OFMSW can be also brought to the Green Points, where it is collected and sent to the OWTP to be composted for its utilization as soil improvement in parks (Buenos Aires Ciudad, 2022).

According to official estimations, the amount of the OFMSW that is collected with this program is on average 0.2 tons daily, which corresponds to only 0.01% of the total organic waste produced daily in CABA (Buenos Aires Ciudad, 2022). Although this solution is not meant to be scaled up at the moment, as the OWTP has a very limited capacity (30 tons/d), neither is it practical for people to transport their organic waste to the Green Points. Nevertheless, this recycling program aims to raise citizens' awareness on understanding the OFMSW as a resource and not as waste, and to create the habit of source-separation (Buenos Aires Ciudad, 2022). Therefore, even though the government has not officially expressed it, everything indicates that this is a temporary solution, while further alternatives are explored.

1.3. Reduction targets in line with the CE principles

In this context, in the year 2018, the Law 5966 was enacted, which modified the Law 1854/2005 by setting some updated goals for the reduction of MSW disposed in landfills, namely 65% in the year 2025 and 80% in the year 2030, compared to 2012 values (López de Munai, et al., 2021). For organic waste specifically, the Climate Action Plan set a reduction target of 80% by the year 2040, compared to 2015 values. Not only does this measure aim to reduce the amounts of waste going to landfill, but also to reduce the environmental costs associated with the extraction of virgin materials, as well as the impacts related to the transportation and the disposal in sanitary landfills (Gobierno de la Ciudad de Buenos Aires, 2020).

The reduction targets that were defined by the government go in line with the concept of the circular economy (CE), one that shifts away from the linear economy of "take, make, dispose" model and moves towards an economic system where, in the case of organic waste, the value of the materials and nutrients is maintained for as long as possible, and the generation of waste is minimised (Eurostat, n.d.). Moreover, the CE treats waste as a secondary resource (Ellen MacArthur Foundation, 2013), and therefore employs multiple methods to maintain, or regain the value of materials and goods that are considered as waste in a closed cycle (Ghisellini, et al., 2016). Figure 1 aims to show a simplified way of how such a co-digestion biogas plant fits into the circular economy.

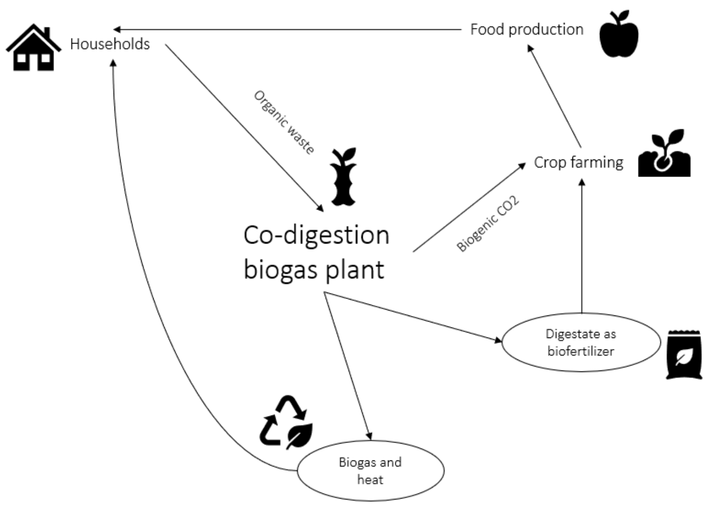

Figure 1 Example of how co-generation biogas plant fits into a circular economy

1.4. Anaerobic digestion as a potential solution

As it was mentioned, waste reduction legislation encourages a shift from linear to circular waste management systems, moving away from waste that ends in landfill and prioritising resource recovery during waste processing. On this note, AD has been proved to be especially effective for the treatment of organic waste streams, supporting the generation of renewable energy, while avoiding the risks of uncontrolled GHG emissions resulting from landfilling (Papageorgiou, et al., 2009).

Compared to other biological treatment processes for food waste valorisation, AD can accommodate to a much wider range of substrates, even those with high moisture content and impurities, which is not the case for vermicomposting and fermentation (Lohri, et al., 2017). On the other side, AD is substantially slower compared to thermochemical valorisation streams, such as pyrolysis, liquefaction and gasification.

Also, higher value products, such as bio-oil, glycerol and biodiesel can be produced via the transesterification and densification valorisation technologies, compared to the products obtained from AD. Nevertheless, the mentioned treatment technologies are typically associated with higher investment costs and energy consumption (Lohri, et al., 2017).

Additionally, while landfilling, incineration, and composting of food waste are a more economical option than AD, they have a bigger environmental impact (Lin, et al., 2013) (Posmanik, et al., 2017). Moreover, AD can produce two main products from AD, namely biogas and digestate, while from the others, only compost is obtained from composting.

Due to the mentioned reasons, the interest of CABA's government to look into the AD valorisation technology, and the fact that the urban AD system with biowaste as feedstock is still in its preliminary stage (Xu, et al., 2018), the present study will focus on the analysis of this technology in the context of CABA.

1.4.1. Trade-offs of treating the OFMSW with AD in CABA

The OFMSW is abundant and readily available, at low or no extra cost given that AD can be easily incorporated to the current waste management system (Kigozi, et al., 2014). Moreover, food waste has a higher CH4 yield compared to agricultural waste and animal waste. The reason is that the OFMSW has high total solids (TS) and volatile solids (VS) compared to the feedstocks (Kigozi, et al., 2014), which is equivalent to a higher energy content, which in the case of food waste ranges between 445-475 (mL/gVS) (Kigozi, et al., 2014).

Nevertheless, while abundant and with a high energy potential, the efficiency of an AD process primarily depends on the composition of the feedstock, which in the case of OFMSW is highly unpredictable. OFMSW can contain contaminants like plastics, metals, glass, and others, which can lead to low biogas production. Thus, a thorough sorting procedure must be set up, which can go from source sorting to the utilization of hydro-mechanical equipment, which can substantially increase the investment costs of a project (Kigozi, et al., 2014).

Additionally, economic analyses have revealed that the high investment and operational costs of AD, limit the economic feasibility of its implementation. The major point of concern for investors are long breakeven periods, and the competition with existing fossil fuel energy sources (Gebrezgabher, et al., 2010).

Nevertheless, the use of the OFMSW for biogas production can help to solve the problem of growing quantities of solid waste disposed in landfills. Additionally, AD can produce added value products in the form of energy, fuel and biofertilizers that can be used as a substitute of their conventional alternatives.

Moreover, the reduction of the waste sent to landfill is associated with a reduction of the pollution of air and water, GHG emissions, and a reduction of nuisances from odours and flies (Fagerström, et al., 2018). Additionally, AD technology can be sourced from local equipment, machinery, and expertise (FAO, 2019), which promotes the development of the local economy.

1.5. Literature review

Multiple studies have been conducted that assess different aspects of the AD technology in Argentina (e.g., economic, environmental, design-oriented, etc) for a variety of substrates (e.g., wastewater, sewage sludge, food waste and their combination). Regarding the economical aspect of the AD technology studies were recently conducted, for example by the FAO (2020) and the Argentinian Chamber of Renewable Energy (hereafter CADER), where the investment and operational costs of hypothetical biogas plants are estimated. Regarding the selection of the substrate, the former does not define the one that is used, while the latter selects pig slurry and corn fodder as the substrates. In both cases, the studies do not provide to the reader with all the assumptions used, sources and a detailed description of the methodology that is followed, thus making it impossible for validation and replication. Moreover, none of the mentioned studies performs an analysis on the financial indicators of the case studies, thus, the obtained results are also not an indication of whether the case studies are economically feasible.

Regarding the environmental performance of AD, Moreno et al., (2017) carried out an LCA on biogas production from co-digestion of sludge and municipal solid waste. However, the calculations only account for the environmental impacts associated with the plant operation, thus the upstream impact associated with the construction of the plant are not considered. Regarding the avoided burden or positive externalities of a biogas plant, there are no studies that consider the different environmental savings from such a project. In this regard, Galván, et al., (2022) only considers the carbon benefits from the energy produced by the plant in replacement of conventional electricity. Therefore, there are not equivalent studies that look into the carbon footprint of a plant, including the impacts associated with its construction, and that combine the carbon savings resulting from landfilling, and the substitutions of conventional energy sources and fertilizers.

All thing considered, the knowledge gap is given by the absence of studies that: 1) take the OFMSW alone as a substrate, 2) are performed in CABA, 3) combine the costs of the projects with an analysis of the financial indicators to determine their economic feasibility 4) market the products that are produced in the plant to estimate the revenue that it could potentially make, and 5) simultaneously evaluates the carbon footprint of the project.

1.6. Relevance of the research

In Latin America, despite the high share of organic waste in household streams and the benefits associated with its recovery, landfilling is the predominant solution, given that only three cities valorise this waste stream via composting, while none adopts AD (Tarapués, et al., 2020). According to Thi et al. (2015), the preference for composting over AD in developing countries could be related to the higher capital and operation costs of AD, which might be preventing cities from adopting this technology. In this context, the scientific relevance of this research lies in the knowledge expansion of AD in urban areas in Latin America, in this case in CABA, by not only evaluating the economical aspect of it, but also the environmental one.

Additionally, this thesis is rooted in the principles of industrial ecology, which follows the idea of using residual flows from one industry as a feedstock for other industries, aiming at improving resource efficiency and reducing the need for virgin materials (Anderse, 2006). Moreover, this thesis contributes to the further application of mass flow analysis and carbon footprint analysis, and the circular economy to arrive to practical solutions in the field of urban waste management and energy transition.

1.7. Aim of the research

Given that there is no precedent of the adoption of AD technology to treat the OFMSW in CABA, there is a big uncertainty on the costs associated with the technology, as well as its carbon footprint. Therefore, the present research will assess this technology from both angles, with the aim of providing to the government of CABA with more information for future decision making in this field.

1.7.1. Main research question

The main research question to be answered in this thesis is:

What is the economic and the environment performance of treating the OFMSW with AD to produce bioelectricity and bio-CNG in CABA?

1.7.2. Research sub-questions

The main research question will be answered with the help of the following 4 sub-questions:

1. What are the infrastructural design considerations for producing bioelectricity and bio-CNG from AD, and what are the mass flows and energy requirements?
2. How do the capital and operational costs associated with the production of bioelectricity compare to the production of bio-CNG?
3. How does the carbon footprint associated with the production of bioelectricity compare to the one of bio-CNG?
4. How do changes in the process and financial variables affect the results of the carbon footprint and the economic performance of the production of bioelectricity and the production of bio-CNG?

1.8. Thesis outline

The development of the previous main research question and sub-questions unfolds in 4 chapters, as shown in Figure 2 . In chapter 2, the methodology used for the design of the conceptual process design, the mass and energy balances, the techno-economic analysis, the carbon footprint analysis, and the sensitivity analysis is explained. Chapter 3 presents the results and responds to the research questions, and chapter 4 reflects on the outcomes of the thesis and compares them with the available literature on the subject. Finally, chapter 5 provides the conclusions of the research.

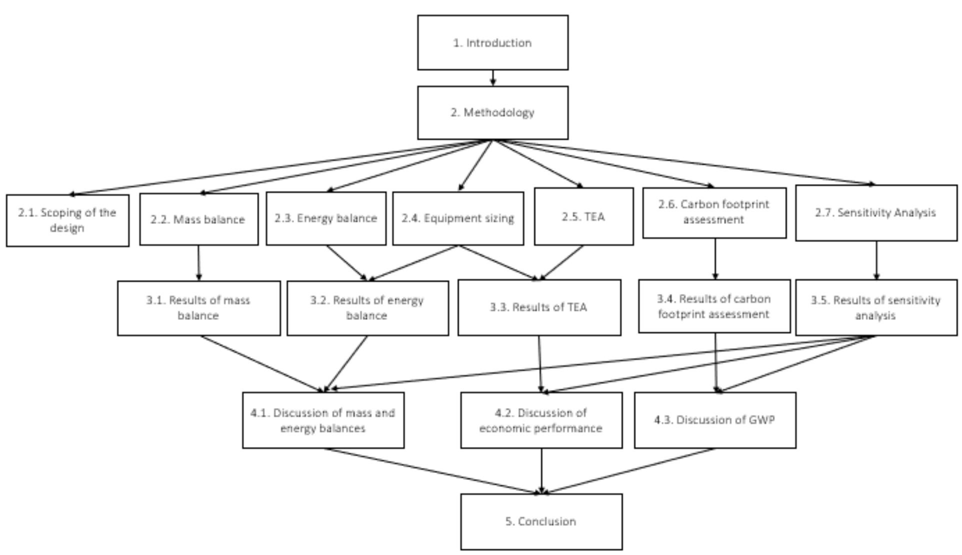

Figure 2 Structure of the thesis

2. Methodology

Answering the main research question requires the development of four consequential stages.1) Scoping out the design of the plants, one that can produce bioelectricity and the other one bio-CNG; and determine the mass and energy flows, 2) Calculating the capital and operational costs associated to the construction and operation of the plants 3) Calculating the carbon footprint of the plant for its construction and operations, and the avoided burden. 4) Assessing the sensitivity of the economic performance and carbon footprint of the case studies. The methodology that will be followed for each of these stages is explained hereafter.

2.1. Scoping of the design

In order to answer to the 1st sub-question and determine the infrastructural design to produce bioelectricity and bio-CNG, two separate AD plants need to be scoped, one that utilizes biogas to produce electricity and heat, and the other one that upgrades it into biomethane for vehicle use, which corresponds to the two case studies that are investigated throughout the present research, referred to as C-1 and C-2.

The design of the plants is carried out in two steps: 1) the preliminary design and 2) the validated design. A preliminary design is conducted by consulting literature on existing biogas plants that use proven technologies. The second step comprises the validation of the preliminary design with experts, with the aim of incorporating the feedback on the preliminary design to arrive to a more real-life and tailored design to the context of Argentina. Given that the company BGA Energía Sustentable are experts in the type of the technologies that are most suitable and commercially available in Argentina, their feedback on the draft design was adopted to arrive to the validated design.

2.1.1. Preliminary and validated design

A draft design involves deciding on the AD technology that is most suitable for each plant, according to the amount and composition of the substrate. In this regard, the treatment capacity of the plant used for the calculations is determined by the maximum size of the biodigesters installed by BGA Energía Sustentable, namely with a diameter of 30m, height of 8m, which can treat approximately 70tons of OFMSW a day. The reason that such a low amount of substrate is selected, compared to the total produced in the city, is that in real-life the OFMSW is still disposed together with other mixed waste materials. Therefore, a smaller plant size with only one biodigester might be more realistic for implementation in the near future than a biogas plant with the capacity of treating the total. Also, given that there is no precedent of a biogas plant that treats the OFMSW in CABA, it was decided that the mentioned amount and size are convenient for a first trial.

In addition, for this preliminary design shown in Figure 4, some key decisions had to be made regarding the type of AD technology (wet vs dry system), number of stages (single vs multistage), feeding method (batch vs continuous), and reactor type, which have an impact on the components that will be required and the overall dynamics of the system. In order to do this, desk research is carried out to identify the advantages and disadvantages of each of these alternatives before making the decisions.

After these technology-related decisions are made, the studies by Akbulut, (2012), Banks, et al., (2011), Piñas Velásquez, et al., (2018), Aguilar, et al., (2017), and Wellinger, et al., (2014) are consulted for deciding on the processes and components for C-1, and the studies by Ardolino, et al., (2021) and Jecha, et al., (2013) are consulted for C-2.

To validate the design, two online sessions with a representative from BGA Energía Sustentable took place where the preliminary design of the plants were shared, and feedback notes were taken to improve it.

2.1.2. AD technology selection

The following section discusses the main aspects of AD systems and the decisions that were made to define the system that is later use for analysis. Figure 3 shows the main features of AD systems, with the selected ones in bold. A brief analysis on the selected features follows hereafter.

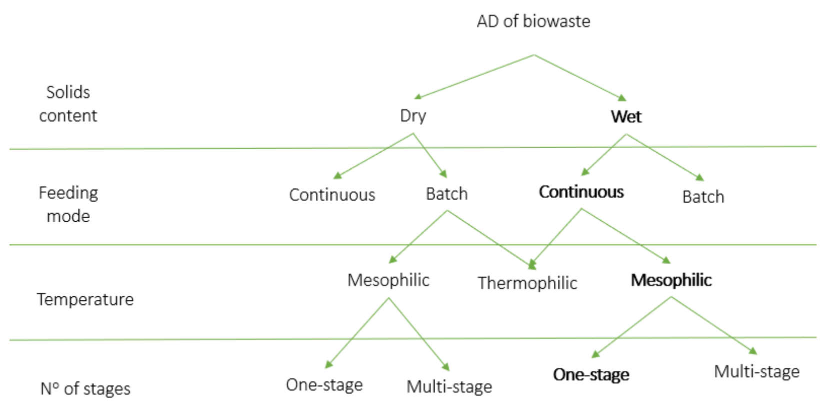

Figure 3 Overview of decisions made in the selection of the AD technology

2.1.2.1. Wet vs dry systems

Depending on the total solids (TS) content of the substrate fed into the digester, the system can be identified as wet or dry system. When the concentration of the TS is < 10%–15% it is a wet system, while the dry system ranges between 15%–20% (Fardin, et al., 2018). While dry systems allow for the treatment of higher amounts of waste per volume of digester and shorter retention times, they also presents some challenges, such as the lower methane and biogas yields compared to wet AD system, and the accumulation of inhibitors (Ge, et al., 2016) (Visvanathan, 2013). On the other hand, while wet systems have a higher water consumption and longer retention times, they produce more biogas, have lower capital costs, and overall have a better performance than dry AD systems (Angelonidi & Smith, 2015), thus wet AD is selected.

2.1.2.2. Single stage vs multi-stage digesters

In a single-stage system, all biochemical reactions of the AD process occur inside a single tank and compete among themselves. In a multiple-stage system, the biochemical reactions do not share the same optimal environmental conditions, and therefore they need to happen in separate tanks. According to Rapport et al. (2008), while single-stage systems are simple, easy to design, build and operate, and therefore less expensive than multi-stage systems, they are mainly used for small quantities, with a max capacity of around 50,000 tons/year. While multi-stage system have multiple advantages that involve the provision of optimal conditions for microbiota, the reduction of the inhibitory effect from by-products generated in different stages of the process, and the possibility of achieving higher biogas production, it is also typically associated with more complex control and operational requirement and higher capital costs (Li, et al., 2017). Considering that the amount of feedstock will not surpass the max levels and the mentioned advantages, a single-stage system is selected.

2.1.2.3. Batch vs continuous

In a batch digester, typically used in dry systems, the biomass feedstock supply is made at once, and is left for a period of time until the digestion process finishes, then opened again and replaced by new feedstock to restart the process. In a continuous digester, the feedstock supply is made at regular intervals while an equivalent volume of digestate leaves the digester, thereby enabling the constant production of biogas. While batch digesters are simple to build, and present low construction and operation costs, experience shows that these reactors present some limitations such as high fluctuations in gas production and quality, the risk of biogas losses and explosion, among others (Vögeli, et al., 2014) (United States Environmental Protection Agency, n.d.). For these reasons, and because a wet AD system was previously selected, a continuous operation mode is chosen.

2.1.2.4. Mesophilic vs thermophilic

Temperature is an important operational parameter and can also be used to classify AD systems into two categories. The mesophilic systems range between 30-40°C, and the thermophilic between 45-60°C. While the thermophilic system requires more energy than the mesophilic one, higher temperatures accelerate the reaction rates and in consequence, the gas production. Also, higher temperatures facilitate the hygienisation of the digestate (Vögeli, et al., 2014). However, up until now most commercial-scale anaerobic digesters are operated at mesophilic temperatures, as it appears to be a more reliable and cost-effective alternative (Labatut, et al., 2014). Particularly in tropical climate conditions, digesters are typically operated under the mesophilic temperature range, and are not or barely heated to maintain the temperature.

2.1.2.5. Reactor type

Based on the selection of the previous parameters, the reactor that operates wet systems, single step AD process and under mesophilic conditions is typically the continuously stirred tank reactor (or CSTR), which is also identified as the most common for urban environments (Angeli, et al., 2018). This type of digester works at a temperature between 20°C and 37°C, a HRT of 15-40 days, and an organic loading rate (OLR) between 1-5 kg COD/m3 a day (Tchobanoglous, et al., 2003) (Liu, et al., 2021).

The digester is typically composed of a tank in which the biomass feedstock (TS between 2%-15%) received is mixed and heated (Wellinger, et al., 2013). Continuous or intermittent mixing is applied to prevent the settling of solids. While this type of digester has an extended retention duration, they may use more energy than other type of reactors, and require high costs for construction and operation, due to the maintenance costs of the moving parts (Benerjee, et al., 2022).

2.1.3. Proposed design

After the AD technology has been selected, literature has been consulted to identify the main processes and components for each case study, and the design has been validated, Figure 4 is proposed. The system boundaries are set around the black rectangle, starting with the transportation of the OFMSW from the city to the treatment site, and ending with the pasteurisation of the digestate for its utilisation as fertiliser on one side, and the production of electricity and heat, or bio-CNG, on the other side.

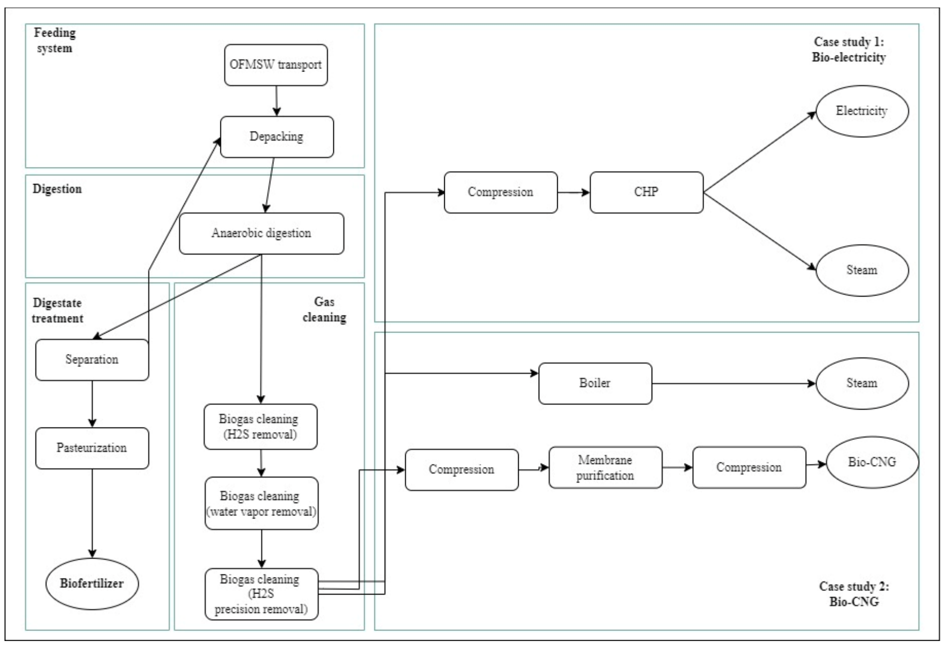

Figure 4 Process flow diagram on the two case studies proposed

As shown in Figure 4, both case studies evaluated have in common the feeding system, the anaerobic digestion process, the treatment of the digestate, and the cleaning of the gas, while the gas utilisation differs in each case study. While C-1 utilises the gas to produce electricity and heat, C-2 generates bio-CNG. A description of the case studies is presented below, together with the process flow diagrams (PFD) that correspond to C-1 (Figure 6) and C-2 (Figure 7), where all the components that correspond to the processes shown in Figure 5 are included. A summary of the tags used in the text are presented in Table 1.

2.1.4. Description of the systems in C-1 and C-2

Feeding system

The OFMSW received in the plant and temporary stored (T-101) is fed into the depacker with a screw conveyor (C-101). Inside the depacker (D-101), the rotating axle with paddles smashes the material, which forces the organic fraction to pass through the interchangeable screen, obtaining a clean organic output. The cleaned output is pumped (P-101) into the biodigester, while the packaging material leaves the machine (Mavitec Green Energy, n.d.). During the process, the liquid effluent is pumped (P-102) to the depacker (D-101) to be mixed with the solid waste and reduce the dry matter content to the one required in a wet anaerobic system.

In order to avoid any big temperature fluctuations and efficiency losses in the digester, the temperature of the substrate entering is preheated to reach 40°C. A heat exchanger (HX-101) heats the substrate with steam produced in the CHP unit in C-1, or in the boiler in C-2.

Digestion

In the digester (D-102), the biological decomposition of organic material in an oxygen-free environment takes place. The biological process is multiphase and is composed of several biochemical steps that are lined to each other, where some bacteria that uses the substrate as a food source, produce some by products that become the food source for another bacteria. AD consists mainly of three phases, namely enzymatic hydrolysis, acid formation, and gas production, as depicted in Figure 5.

The gas production corresponds to the methanogenesis step, where the methanogenic bacteria generates 70% of methane from acetate, and the remaining from the transformation of H2 and CO2. Given that methanogenic bacteria are the most sensitive to the operating conditions, especially temperature fluctuations, in a 1-step AD process, the process parameters are adjusted according to this last step, given that the other bacteria can more easily adapt to different environmental conditions.

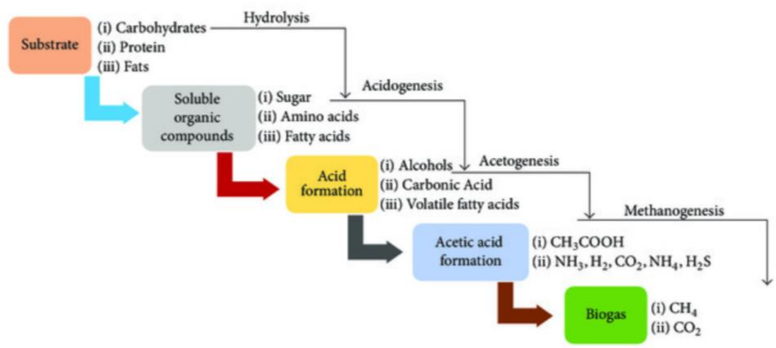

Figure 5 Main stages for the generation of biogas from food waste by anaerobic digestion from Paritosh, et al., (2017)

In the digester, the agitation of the feedstock is important for the distribution of the substrates, micro-organism and heat, to prevent the formation of floating or settling layers. Therefore, three propeller mechanical agitators (A-101) are installed to the wall of the biodigester. The digester produces two main streams: 1) biogas, 2) digestate.

Digestate treatment

As a result of the anaerobic digestion process, a wet effluent is obtained which goes through a screw press separator (C-102) that enables the separation of the solid from the liquid fraction of the effluent. The liquid fraction is pumped (P-103) to a storage tank (T-102) before it is sent to the depacker station (D-101) and mixed with the dry substrate, while the solid fraction is sent with a pump (P-104) to the pasteurisation tank (T-103). Before the solid fraction enters the pasteurisation tank, it is heated with a heat exchanger (HX-103) to a temperature of 70°. The substrate stays in the tank for one hour before it is sent to the storage tank (T-104), where the biofertilizer is stored upon its collection for utilization.

Gas cleaning

To purify the biogas for its further utilisation, a small amount of O2 is dosed with an air pump (B-101) into the digester's storage chamber to remove H2S from the gas. Given that H2S can cause corrosion in compressors, gas storage tanks and engines, due to the formation of sulphuric acid, it is important to reduced H2S from an early stage (Wellinger, et al., 2013). It is assumed that the air dosing technique reduces by 95% the amount of H2S present in the gas (Welligner & Lindberg, 2000).

Once the gas is desulphurized, it goes into a dehumidifier unit (D-103), where through refrigeration, excess water vapour is removed from the gas, as water in raw biogas can cause corrosion in pipelines and lower the energy content of the gas (Wellinger, et al., 2013). To remove water vapour, the gas is cooled with a water-cooled heat exchanger working with an air-cooled water chiller. The condensed water generated is removed with a cyclonic water separator (C-101).

For the adsorption of the remaining traces of HS2, a 2-tanks activated carbon filter (T-105) is used (Prodeval, 2022). Given that the temperature of its inlet gas needs to be between 10°C-70°C, and its moisture content needs to be below 15% to enter the activated carbon filter (Donau Carbon, n.d.), the gas is reheated with a heat exchanger (HX-102) after it passes the dehumidifier unit.

Case study 1: Bioelectricity

After the gas has been desulphurized and dehumidified, it is compressed (C-102) together with dry air to a pressure up to 6 bar before it enters the CHP unit (C-104). The electricity produced in the CHP is used to power the equipment in the plant, while the remaining is injected into the grid. The thermal energy produced is partially used by the heat exchangers and to heat the digester, while the remaining steam is lost in the environment.

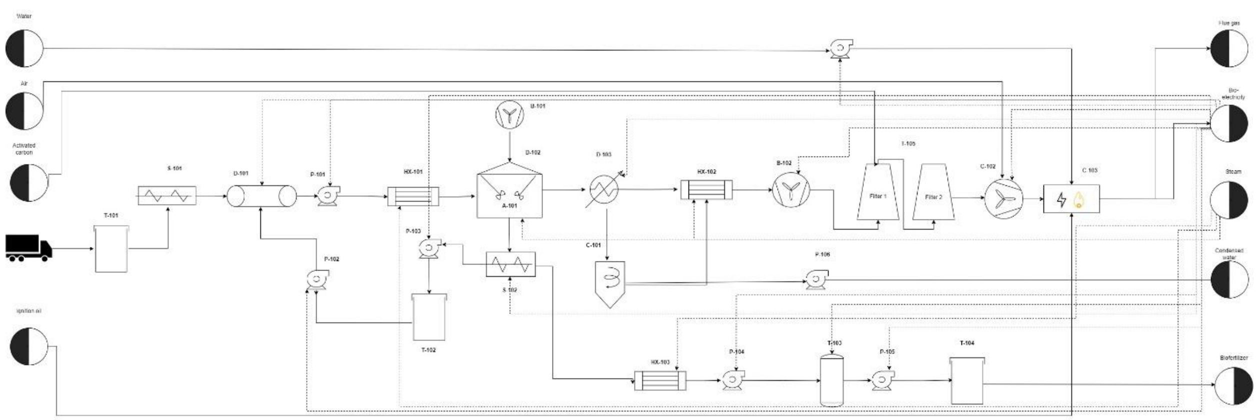

Figure 6 PFD for C-1

Case study 2: Bio-CNG

In C-2, after the gas has been dried and desulphurized, it takes two directions. A part of it is sent to the boiler (B-103), where heat in the form of steam is produced to supply the heat demand from the digester and heat exchangers. The other part of the biogas is compressed (C-102) to a working pressure of between 10 and 16 bar before being fed into the 3-stages membrane filtration unit (M-101) to remove the CO2 in the biogas (Prodeval, 2022). The CO2 decreases the energy content of the gas and therefore it is considered as an impurity that must be removed (Wellinger, et al., 2013).

A 3-stage membrane unit allows about 99.5% removal of C02 with a very low methane slip of less than 0.5% (Prodeval, 2022). After CO2 is removed from biogas, the resulting biomethane is compressed to around 300 bars for high-pressure storage (C-103).

Besides biomethane, the membrane unit produces a secondary output called off-gas. The high-quality pre-treatment and the efficiency of the membranes gives the off gas a certain level of cleanliness with an expected content of CH4 of 0.87%, which is released to the atmosphere without any further treatment. (Prodeval, 2022).

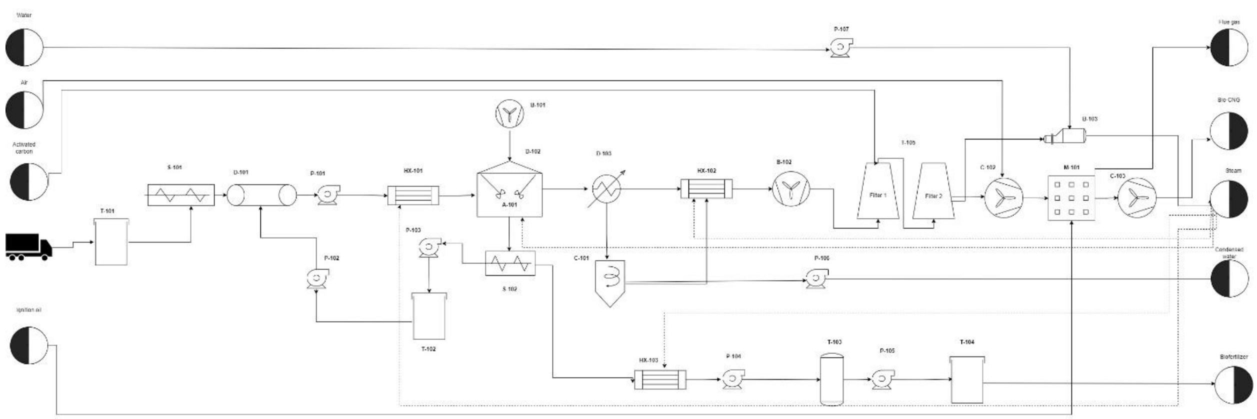

Figure 7 PFD for C-2

Table 1 Reference table for Figure 6 and Figure 7

Case studies	TAG	Equipment	Description
1&2	A-101	Agitators	Agitators in digester
1&2	B-101	Blower	Air into gas holder for H2S removal
1&2	B-102	Blower	Heated biogas to activated carbon filter
2	B-103	Boiler	Steam generation
1&2	C-101	Cyclonic water separator	Removes condensed water from gas
1&2	C-102	Compressor	Compressor before CHP unit (in C-1)/membrane (in C-2)
2	C-103	Compressor	High pressure compressor
1	C-104	CHP unit	Co-generation unit producing heat and electricity
1&2	D-101	Depacker	Separates plastic bags from the OFMSW
1&2	D-102	Digester	Reactor where biochemical reactions occur
1&2	D-103	Dehumidifier unit	Removes excess water vapour through refrigeration
1&2	HX-101	Heat exchanger	Substrate heated with steam before entering digester
1&2	HX-102	Heat exchanger	Gas heated with steam before entering activated carbon filter
1&2	HX-103	Heat exchanger	Solid fraction heated before entering pasteurisation tank
2	M-101	Membrane unit	Membrane for CO2 removal for biomethane production
1&2	P-101	Pump	Substrate to digester
1&2	P-102	Pump	Liquid fraction from storage tank back to depacker
1&2	P-103	Pump	Liquid fractionfrom separator to storage tank
1&2	P-104	Pump	Solid fraction from separator to pasteurizer
1&2	P-105	Pump	Solid fraction from pasteurizer to storage tank
1&2	P-106	Pump	Condensed water from cyclone exiting the system
2	P-107	Pump	Water for boiler for steam production
1&2	S-101	Screw conveyor	Screw conveyor that transports OFMSW to depacker
1&2	S-102	Screw press	Screw press to separate the liquid and solid fraction of effluent
1&2	T-101	Tank	OFMSW storage tank
1&2	T-102	Tank	Liquid storage tank
1&2	T-103	Tank	Pasteurisation tank
1&2	T-104	Tank	Solid storage tank
1&2	T-105	Tank	2-Tank activated carbon filter

2.2. Mass balance calculation

To answer to the second part of the 1st sub-research question, a mass balance for each plant in C-1 and C-2 is carried out. In order to do so, a mass balance for each process in the plant is calculated, assuming a constant amount and a stable composition of the substrate. Because the operational properties of the equipment are not known, data gathered from literature is adapted and correlations are used to calculate the individual process flows.

Table 2 presents a summary of the substrate's characteristics used in the following calculations, corresponding to average numbers obtained from literature. The DM content in food waste is obtained from Ho & Chu, (2019) and Chiew, et al., (2015), the VS from Chiew, et al., (2015), and the conversion index from Antognoni, et al., (2013).

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Characteristics of substrate	Value	Unit
Dry matter in OFMSW	28	%
VS (% of DM of substrate)	89	%
Density of substrate	997	kg/m³
Conversion index	460	Nm3/tVS

Table 2 Substrate's characteristics

A detailed explanation follows on how the mass balance for each process is estimated. As shown in Figure 4, most of the processes are common to both case studies, thus the method and the results are common to both case studies.

2.2.1. Common components to both case studies

2.2.1.1. Depacker

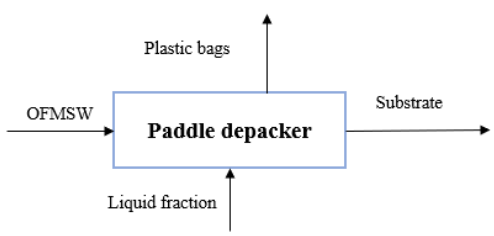

Figure 8 System boundary for the depacker mass balance

The amount of OFMSW entering the depacker is estimated based on the size of the digester, and the DM content that the substrate needs to contain in order to be fed into the digester. According to the correlations given by Akbulut (2012), it was estimated that 1.5 tons of water are required for every ton of OFMSW to reach a DM content of 15%.

As for the outflow, the plastic bags are calculated based on their average size and weight, namely 0,25m3 and 8gr (UrbaCor, n.d.). The amount of substrate leaving the process corresponds to the difference between the inflows and the weight of the plastic bags exiting the process.

2.2.1.2. Digester

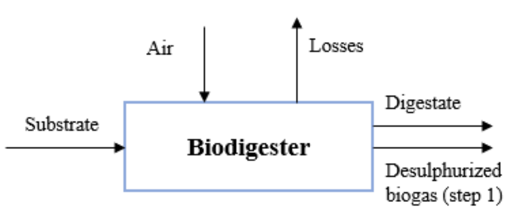

Figure 9 System boundary for the biodigester mass balance

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To obtain the amount of air dosed into the digester's chamber, an average of 4% from the total amount of biogas is added to remove part of the H2S in biogas (Welligner & Lindberg, 2000).

The amount of biogas produced is calculated with equation (1), following the methodology of Akbulut (2012), where S substrate, DM substrate, VS substrate and BY substrate, respectively, define the substrate quantity, the dry matter content, the VS content, and the conversion index of the substrate. Regarding the amount of digestate produced, it is assumed to be the difference in mass between the inflows, the losses, and the amount of biogas produced.

$$Vbiogas = Ssubstrate\ x\ DM\ substrate\ x\ VSsubstrate\ x\ BYsubstrate \quad (1)$$

The losses occurring in the digester are assumed to account for 0.017% of the total methane content of the biogas, or 0.032% of the total amount of biogas, assuming a methane content of 53% (IEA Bioenergy, 2017).

2.2.1.3. Separator

Figure 10 System boundary for the screw press mass balance

It is assumed that 16% of the effluent corresponds to the solid fraction and 84% to the liquid fraction. The mentioned values are averages obtained from Yunjun, et al., (2018) and Akbulut, (2012).

2.2.1.4. Storage tank

Figure 11 System boundary for the storage tank mass balance

The quantity of liquid digestate corresponds to the amount of liquid needed in the depacker to mix with the OFMSW, obtained from the depacker's mass balance. The remaining liquid exits the process.

2.2.1.5. Pasteurization tank

Figure 12 System boundary for the pasteurization tank mass balance

The mass balance in the pasteurization tank is estimated assuming that no losses occur during the pasteurisation process, thus the totality of the solid digestate leaves the process as pasteurized digestate in the same amount that it enters.

2.2.1.6. Dehumidifier

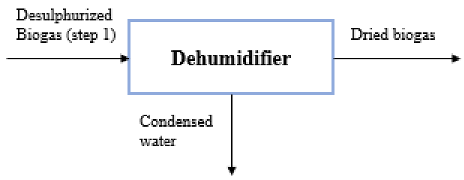


Figure 13 System boundary for the dehumidifier mass balance

To calculate the amount of condensed water that is purged, a water vapour content of 65g per m3 biogas, and a dryer efficiency of 95% are assumed. The dried biogas corresponds to the difference in mass between the desulphurized biogas and the condensed water.

2.2.1.7. Activated carbon filter

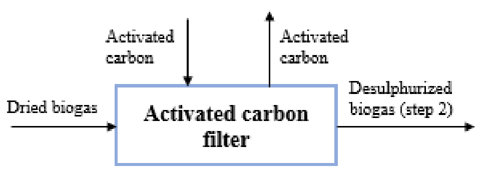
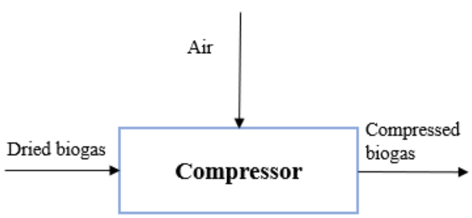


Figure 14 System boundary for the activated carbon filter mass balance

The amount of activated carbon used is obtained from the correlations found in Fang, et al., (2020). It is assumed that the activated carbon used is not recuperated, thus the amount entering also leaves the process. The desulphurized gas (step 2) exiting the process equals the amount of dried biogas.

2.2.2. C-1 components:

2.2.2.1. Compressor



Fi
mass balance

The stoichiometric air-fuel ratio for natural gas is used as a reference to estimate the amount of air needed. This ratio is obtained from literature and corresponds to 4.17 kg, which means that this amount of air is needed for every 1kg of biogas (Noor, et al., 2014). Typically, more than the stoichiometric amount of air is required to ensure the complete combustion of the fuel, thus an additional 15% of excess air is introduced (UTM, n.d.). The compressed gas leaving the process corresponds to the sum of the inflows.

2.2.2.2. CHP unit

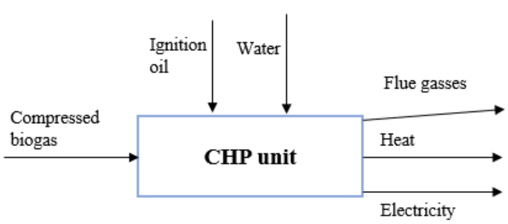


Figure 16 System boundary for the CHP unit mass balance

The amount of ignition oil needed is obtained from the correlations found in Deublein & Steinhauser, (2008), namely 0.09kg of oil per kg of biogas. Regarding the amount of water, it is assumed that it corresponds to 75% of the incoming gas (Department for Business, Energy and Industrial Strategy, 2021).

To calculate the outputs, a CHP efficiency of 45% thermal and 40% electric efficiency is used (Koseva & Webb, 2020) (BGA Energía Sustentable, n.d.). The remaining 15% corresponds to flue gasses.

2.2.3. C-2 components

2.2.3.1. Boiler

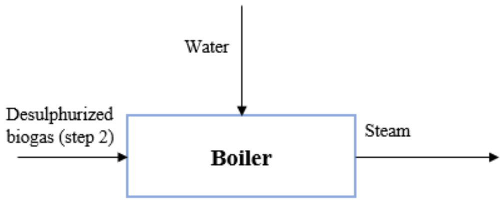


Figure 17 System boundary for the boiler mass balance

The amount of desulphurized gas that enters the boiler is calculated in relation to the amount of steam that needs to be produced to cover the heat consumed in the plant, obtained from section 2.3. The amount of water needed is calculated in the same way as for the CHP unit.

2.2.3.2. Membrane unit

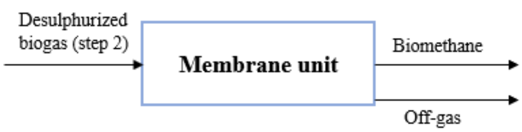


Figure 18 System boundary for the membrane unit mass balance

The amount of biogas entering the membrane unit process corresponds to the difference between the desulphurized biogas exiting the activated carbon filter process and the amount of biogas used as an input in the boiler. An average efficiency of the membrane unit is obtained from Ardolino et al., (2021) and Prodeval (2022) to estimate the amount of biomethane and off-gas produced, corresponding to 43% of the biogas that is converted to biomethane, while 53% exits the process as off-gas.

2.2.3.3. High pressure compressor

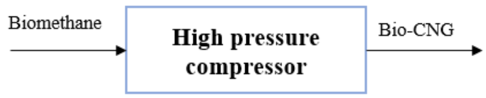


Figure 19 System boundary for the compressor mass balance

The amount of biomethane entering the process corresponds to the same amount of bio-CNG produced, as no losses are accounted for in this process.

2.3. Energy balance

To answer to the second part of the 1st sub-question, an energy balance is carried out for C-1 and C-2, for which a heat balance and electricity balance are separately calculated.

2.3.1. Heat balance

The heat production in the CHP and the boiler, and the heat consumption in the digester and by the heat exchangers is estimated following the methodology proposed by Deublein et al., (2008).

2.3.1.1. Heat production

In C-1 and C-2, steam is produced in the CHP and in the boiler, respectively. To calculate the amount of steam produced, equation **(2)** is used, together with the thermal efficiency of either the CHP unit (45%) or the boiler (95%). In the case of C-2, Vbr corresponds to the amount of biogas needed to produce the required heat for the plant. Thus, in this case, the heat consumed is first calculated, to then estimate the amount of steam that should be produced. A summary of the parameters and values used in the equations are shown in Table 3.

$$Etot = Egas\ x\ Vbr + Eoil\ x\ Moil \qquad (2)$$

The amount of ignition oil needed can be obtained using equation **(3)** where Vbr corresponds to the amount of biogas produced, obtained from equation **(1)**, and Mo corresponds to the amount of ignition oil for every kg of biogas produced, both obtained from Deublein et al., (2008).

$$Moil = Vbr\ x\ (\frac{Mo}{100}) \qquad (3)$$

Table 3 Summary of parameters used in Eq. 2 & 3

	Parameters	Value	Unit
Eoil	Ignition oil energy content	10	kWh/kg
Vbr	Yield of biogas	Equation 1	m3/d
Egas	Biogas energy content	6	kWh/m3
Mo	Ignition oil per kg of biogas	9	kg

2.3.1.2. Heat consumption

The steam needed to heat the material flows is calculated using equation **(4)**, where s is the mass flow of the substrate, Csu is the heat capacity of the substrate, dT is the difference between the incoming and outcoming temperature of the material. The values used to calculate the steam needed for every heat exchanger are shown in Table 4.

Regarding the differences in temperatures, for HX-101, the temperature of the incoming fluid is assumed to be 20°C, corresponding to the average annual temperature in CABA, and the outgoing temperature of the fluid shall be 40°C, as this is the temperature under which the mesophilic digester works and hence the temperature that the substrate should have when entering the digester. For HX-102, the increase in the temperature corresponds to the temperature of the substrate after it leaves the digester, assumed to be 40°, and the temperature that it needs to reach to enter the pasteurisation tank, namely 70°. Lastly, HX-103 is used to increase the temperature of biogas after it has been dehumidified, which reduces the temperature of the gas to 5° and needs to be reheated to reach approximately 20° to enter the activated carbon filter.

$$Q_{= s * Csu * dT} \tag{4}$$

Table 4 Summary of parameters used in Eq. 4

Tag		Parameters	Value	Unit
HX-101	s	Input load - solid fraction digestate	Mass balance	kg/h
HX-101	T1	Temperature of fluid in	20	C°
HX-101	T2	Temperature of fluid out	40	C°
HX-102	s	Input load - substrate	1909	kg/h
HX-102	T1	Temperature of fluid in	40	C°
HX-102	T2	Temperature of fluid out	70	C°
HX-103	s	Input load - deshumidified gas	433	kg/h
HX-103	T1	Temperature of fluid in	5	C°
HX-103	T2	Temperature of fluid out	20	C°
HX-101	Csu	Substrate heat capacity	4.2	kJ/kg
HX-103	Csu	Biogas heat capacity	1.7	kJ/kg

2.3.1.3. Heat losses

The heat loss through the digester surface (kWh/a) is calculated following equation (5) , where A is the heat transfer surface area (m2), U is the overall heat transfer coefficient (W/m2.°C), Ti is the inside temperature (°C), and Ta is the outside temperature (°C).

$$Qlost = A * U * (Ti - Ta) \tag{5}$$

The heat surface area (A) is estimated using equation (6), which calculates the surface area of an open-top cylinder since the heat losses through the ceiling are negligibly low, because it is in contact with gas, as the gas storage chamber is placed on top of the digester. In this equation, r corresponds to the radius and h to the height of the digester. To calculate the radius of the tank, equation (7) is used, where VD and h correspond to the digester's volume and the height. While h is known, VD is calculated in equation (8), following the methodology of Akbulut (2012), where D, and H, respectively, are defined as the diameter of the digester (30m), and the height of the digester (8m), obtained from the BGA Energía Sustentable. Table 5 shows the parameters used to calculate the mentioned equations.

$$A = \pi r(2r + h) \qquad (6)$$

$$r = \sqrt{\frac{VD}{\pi h}} \qquad (7)$$

$$D = \frac{4\ x\ VD}{H\ x\ \pi} \qquad (8)$$

Table 5 Summary of parameters used in Eq. 5, 6 & 7

	Parameters	Values	Unit
D	Diameter of digester	30	m
h	High of digester	8	m
r	Radius cylinder	15	m2
Ti	Inside temperature	40	°C
Ta	Outside temperature	20	°C

The overall heat transfer coefficient (U) of the digester and the heat exchangers is calculated following equation (9), where d1 and d2 correspond to the thickness of the material, k1 and k2 the thermal conductivity of the material, and ha and hi the convection heat transfer coefficient inside and outside the respective component. The values used to calculate U for the digester are obtained from Deublein et al., (2008). In the case of the heat exchangers, the transfer coefficient for biogas is obtained from Engineering ToolBox (n.d.), the thickness of aluminium is from Morris (2011), the thermal conductivity of aluminium from the Engineering ToolBox, (n.d.), and the heat transfer coefficient of steam corresponds to the average obtained from TLV (n.d.). Table 6 and Table 7 show the values used to calcutate equation **(9)**. Once equations 6 to 9 are calculated, equation **(5)** can be solved.

$$U = \frac{1}{\frac{1}{hi} + \frac{d1}{k1} * \frac{d2}{k2} + \frac{1}{ha}} \quad (9)$$

Table 6 Summary of parameters used in Eq. 8 for digester

	Parameters	Values	Unit
hi	Convection heat transfer coef-ficient of substrate	850	W/m2.°C
d1 & d2	Thickness of insulation (polystyrene)	0.01	m2
k1 & k2	Thermal conductivity of insulation	0.05	W/m2.°C
ha	Convection heat transfer coefficient outside the digester	400	W/m2.°C

Table 7 Summary of parameters used in Eq. 8 for heat exchangers

	Parameters	Values	Unit
hi	Convection heat transfer coefficient of substrate (HX-101 and HX-102)	850	W/m2.°C
hi	Convection heat transfer coefficient of biogas (HX-103)	500	W/m2.°C
d1 & d2	Thickness of aluminium	0.1	m2
k1 & k2	Thermal conductivity of aluminium	239	W/m2.°C
ha	Convection heat transfer coefficient outside HXs	10,500	W/m2.°C

2.3.1.4. Residual heat

The residual heat is calculated following equation **(10)**, where Eth, Qsu and Qlost correspond to the thermal energy generated by the CHP unit, the heat consumed, and the heat lost. The result of this equation aims to show the amount of thermal energy produced that is left after internal consumption.

$$\dot{Q}rh = \dot{E}th - (\dot{Q}su + \dot{Q}lost) \quad (10)$$

2.3.2. Electricity balance

2.3.2.1. Electricity consumption

The total electricity consumed in C-1 and C-2 is determine by the sum of electricity demand of the individual components. The electricity needed by all the components for both case studies is calculated in the section 2.4. The results are multiplied by 8000 operating hours a year, in order to obtain the yearly electricity consumption of the plant.

2.3.2.2. Electricity production

The electricity produced in C-1 is obtained from the result of equation **(2)**, by multiplying it by the electrical efficiency of the CHP unit. The difference between the electricity produced and consumed by the plant indicates the electricity that can be delivered to homes and businesses through the electric grid.

2.4. Equipment sizing

To calculate the total equipment costs, as part of the CAPEX, and the energy requirements of the plant, as part of the OPEX, the size or capacity of the components needs to be calculated. The main components of the case studies are shown in Figure 6 and Figure 7, respectively. The size of the components is either estimated from equations, following Deublein & Steinhauser's (2008) methodology, or from the processing capacity of each component, obtained from the mass balance. Only the pipes, valves, and system control are not sized, given that their price is estimated as a fraction of the total equipment costs, namely 3%, 1% and 7%, respectively (Akbulut, 2012).

Table 7 summarizes the method followed to size each component, which is explained hereafter in more detail. The prices of all the equipment are obtained from BGA Energía Sustentable.

Anaerobic digester: Obtained from equation **(8)**, in section 2.3.

Propeller-agitators (x3): Three propeller agitators are needed to mix the substrate inside the digester. To calculate the capacity per agitator drive, equation **(11)** is used. The revolutions and the diameter of the agitators are obtained from the equipment's technical specifications of the Paumilch Mammut RP3 agitator (Paulmilch, n.d.). Table 8 summarises the values used in equation **(11)**.

$$P = 1.3\ x\ NeBRR\ x\ \rho G\ x\ \ nBRR^3 x\ DBRR^5 \quad (11)$$

Table 8 Summary of variables used in Equation 11

	Parameters	Value	Unit
NeBRR	Newton number	0.5	
PG	Density of substrate	997	kg/m3
nBRR	Revolution of agitator in digester	81	rpm
DBRR	Diameter of agitator	1.6	m

Pumps: To calculate the energy used by the pumps, equation **(12)** is used. The amount of delivered feedstock are obtained from the material streams described for P-101 to P-107 in Table 1. The pressure head is obtained from the equipment's technical specifications (Vogelsang, n.d.), and the efficiency of the pump is assumed to be 50% (Deublein, 2008). Table 9 shows the values used to calculate equation **(12)**

$$Pvp = Vvp\ x\,\frac{Pvp}{\eta vp} \tag{12}$$

Table 9 Summary of variables used in Equation 12

	Parameters	Values	Unit
Vvp	Amount of delivered feedstock	Mass balance	m3/s
Pvp	Pressure head	10	bar
Nvp	Efficiency of pump	50	%

Storage tanks x 3: As described in Table 1, T-101, T-102 and T-104 are needed to store the OFMSW upon arrival to the plant, and to temporary store the liquid and solid effluents separately. Equation **(13)** is used to calculate the volume of each storage tank. Table 10 shows the parameters used to solve equation **(13)**.

$$Ve = \left(\frac{Df}{\rho} - Ve\right) x\ tE \tag{13}$$

Table 10 Summary of variables used in Equation 13

	Parameters	Values	Unit
Df	Daily feed	Mass balance	ton/d
p	Density of substrate	1	ton/m3
Ve	Feed leaving the process	Mass balance	m3/d
tE	Residence time of residue	30	d

CHP unit: The nominal capacity of the engine is calculated, assuming a reserve of 30%, thus, the electricity produced by the CHP, obtained from equation **(2)**, is multiplied by 0.30 to obtain the engine's capacity. (Deublein & Steinhauser, 2008)

Heat exchangers (x3): Three heat exchangers are needed in the biogas plant, HX-101, HX-102, and HX-103. To calculate the area of the heat exchanger, equation **(14)** is used. Q is obtained from equation **(4)** and U from equation **(9)**, and the differences in temperature can be found in Table 4.

$$A = \frac{Q}{U * \Delta T} \tag{14}$$

Pasteurisation tank: The volume of the tank is calculated in equation **(15)** by multiplying the daily feed by the residence time of the substrate in days. The substrate must be treated for a period of an hour; thus, the HRT corresponds to 0.4 days. The daily feed is obtained from the mass balance.

$$V = Qt\ x\ HRT \tag{15}$$

Screw conveyor: The power of the screw conveyor was estimated from the processing capacity required, obtained from the mass balance. The correlations from the Screw Conveyor Corporation, (n.d.) are followed to estimate the power from the input capacity.

Table 11 Overview of calculation method to size components & obtain price

Case study	Equipment	Sizing method
1&2	Anaerobic digester	Equation 8
1&2	Agitators	Equation 11
1&2	Pumps	Equation 12
1&2	Storage tanks	Equation 13
1&2	Heat exchangers	Equation 14
1&2	Pasteurization tank	Equation 15
1&2	Screw conveyor	Literature
1&2	Pipes	Literature
1&2	Valves	Literature
1&2	System control automation	Literature
1&2	Depacker	Mass balance
1&2	Screw press	Mass balance
1&2	Dehumidifier	Mass balance
1&2	Compressors	Mass balance
1&2	Activated carbon filter	Mass balance
1	CHP	Equation 2
1	Blower	Mass balance
2	Boiler	Mass balance
2	Membrane unit	Mass balance

2.5. Techno-economic assessment

To answer to the 2nd sub-question, a techno-economic assessment (TEA) is conducted to identify the main costs associated with the construction and the operation of the plant in C-1 and in C-2. Moreover, the economic performance of the plant is assessed by calculating the net present value (NPV), internal rate of return (IRR), and the payback period of each case study.

2.5.1. Total costs

In a TEA, the total costs are composed of two components, the capital costs (CAPEX) and the operational costs (OPEX). The CAPEX corresponds to the total capital investment costs, namely the expenditure for the plant construction, including equipment, installation, piping, and other costs linked to the electricity or the building (Lawson, et al., 2021). The OPEX includes variable and fixed costs of production and corresponds to the sum of all the costs related to labour, maintenance, utilities, chemicals, transportation costs and taxes (Fernández-Dacosta, 2015).

To estimate the equipment investment costs as part of the CAPEX, the size of all components is calculated in the previous section, and the price are obtained from BGA Energía Sustentable. Regarding the other categories, namely the civil engineering work, and the electric & mechanical installation costs, they are estimated as a fraction of the total CAPEX, corresponding to 30%, and 9%, respectively, following the correlations from CADER (2020). The value added tax (VAT) is also included as part of the CAPEX and corresponds to 21% of it. No investment costs are included related to the purchase of land as it is owned by the government.

For the OPEX, regarding the cost associated with labour, it is assumed that 3 employers are needed to run the plant for 8 hours a day. The average salary corresponds to €17,561, thus a total of €52 685 is estimated (FAO, 2020). The maintenance costs are assumed to be 3% of the total investment costs (Smith, 2005). Utilities are calculated according to the energy and mass balances, and it comprises the costs associated with the water, oil, wastewater discharge, and electricity consumed in the plant. The prices assumed are 0.4 €/m3 for water and wastewater (Aysa, n.d.), 13€/kg for diesel oil (NH Department of Energy, 2022), and 0.02€/kwh for the electricity purchased, according to the average so-called stationary monomic price from the period July 2021-July 2022 (CAMMESA, 2022).

Under chemicals, the amount of activated carbon is obtained from the mass balance, and the price is assumed to be 12,7€/kg according to Ou et al., (2020). The transportation costs are calculated assuming a max travelled distance from the households to the biogas plant of 25km, and a truck capacity of 21m3.The cost per km corresponds to 0.2 €/km, value shared by the government of CABA. Additionally, taxes correspond to a total of 29% of the income generated in the plant (Ministerio de Economía Argentina, 2021).

The total income is obtained from the monetary benefits of selling biofertilizers, and electricity or biomethane. The selling price of biofertilizers are assumed to be 7€/ton obtained (Allendes, 2015), for bioelectricity it is assumed to be 0.18€ per kwh, according to last price offered by the government to electricity producers (CAMESSA, 2022), and 1.28€ /m3 for biomethane. As it can be noted, the selling price of electricity is subsidized, which explains the difference between the price at which the electricity is purchased and sold. Additionally, a subsidy of €0.005/kwh is added to the income, as part of the promotion of electricity from renewables under the Law 27.191.

2.5.2. Financial indicators

As for all investment, the economic performance of a project is an important factor in the final go/no-go decision and is evaluated by calculating the NPV, IRR, and the payback period of the case studies.

The annual interest rate is expected to be 3.9%, as this is the annual reference interest rate offered by the DIB (Inter-American Development Bank). It is assumed that 80% of the total investment is funded, and the loan life is the same as the project´s lifespan, 20 years. Lastly, the discount rate is assumed to be 6% (Carlini, et al., 2017).

The NPV is the sum of the expected net cash flow measured in today's currency and is given in equation **(16)**, where CF is the expected cash flow at time t, i is the discount rate, and t is the time of the cash flow. To calculate the cash flow, equation **(17)** is used, and indicates the amount of income minus the outcomes, which corresponds to the variable and fixed costs.

$$NPV = \frac{CFt}{(1+i)^t} \tag{16}$$

$$CF = net\ income - capital\ cost \tag{17}$$

The IRR measures the profit derived from the total investment made, and its calculations relies on the same formula used for NPV, where i becomes the unknown IRR. Lastly, the payback time, namely the length of time the investor needs to reach a breakeven point, is calculated in equation 18.

$$Payback\ period = \frac{Initial\ investment}{Cash\ inflows} \tag{18}$$

There are two financial incentives that are included in the calculations, namely the refund of the VAT in during the first 5 years of the project, and a refund of 35% of the annual interest paid, according to the Law 27191 (InfoLEG, 2015).

2.6. Carbon footprint analysis

To answer to the 3rd sub-research question, a carbon footprint analysis is conducted. A carbon footprint is the measurement of GHG-emitting processes, their origins, their compositions, and amounts (Franchetti & Apul, 2013), and while a Life-Cycle Assessment focuses on 15 impact categories, a carbon footprint focuses only on the single issue of global warming (De Schryver & Zampori, 2022). The largest contributors to a carbon footprint are GHG emissions from the use of fossil fuel-based energy (Franchetti & Apul, 2013).

Therefore, it is relevant to evaluate the performance of the case studies in relation to the global warming category given that: 1) the construction of the plant comprises the use of energy-intensive materials, 2) the operation of the plant is associated with GHG emissions to air, and 3) the products produced can avoid the emissions from fossil fuel intensive industries.

2.6.1. Scope and goal definition

The carbon footprint analysis includes the impact of the processes within the boundaries defined in Figure 4. The carbon footprint will be calculated for a year of operation of the biogas plant and the functional unit (FU) corresponds to 1 ton of OFMSW treated. Most of the impact factors are obtained from ecoinvent 3.8 database (ecoinvent, 2021), and others from literature. The results for the GWP of the case studies are calculated using the environmental impact factors and the results from the mass or energy balances.

The avoided emissions correspond to the substitution of conventional energy sources and fertilizers by their alternatives produced in the plant. In this regard, bio-CNG substitutes the conventional production of CNG from natural gas, bioelectricity replaces conventional electricity from the grid, and bio-fertilizers replace the production of conventional fertilizers, the latter being credited to both case studies, as shown in Figure 20. These avoided emissions are subtracted from the environmental burdens of the plant, to obtain the net zero carbon footprint.

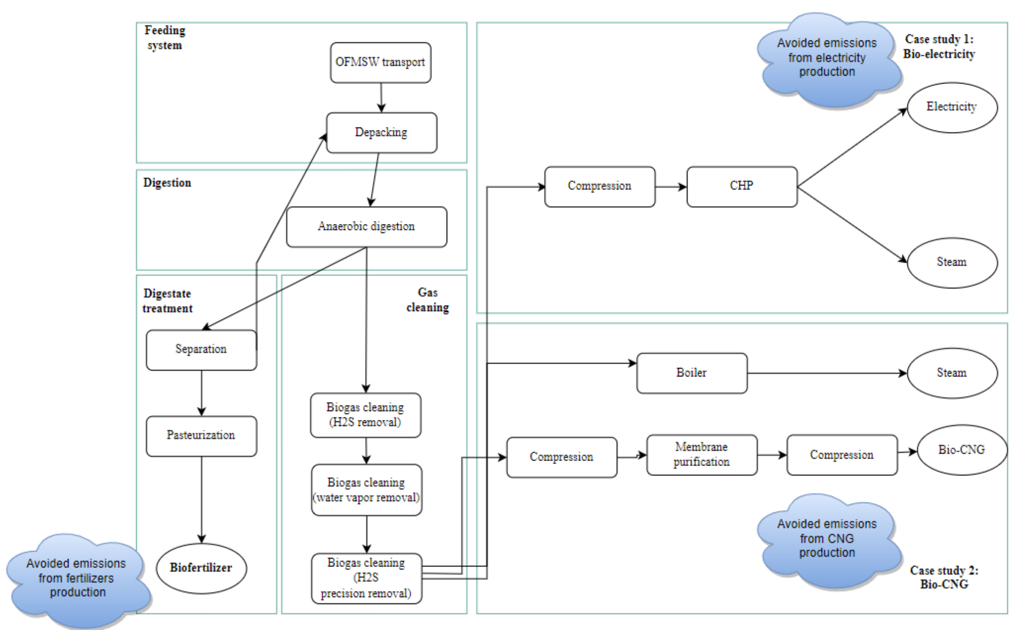


Figure 20 Process flow diagram of two case studies with avoided burden

2.6.2. Global warming potential

2.6.2.1. Plant construction

The impact of the construction of the plant corresponds to the sum of the impact of the production of the individual components. For most of them, an equivalent ecoinvent process is found and accordingly adjusted to the size of the equipment. However, when this is not possible, the impact of main materials that comprise the equipment are accounted for (i.e., depacker, the screw press and the activated carbon filter) or their impact factors are obtained from literature (i.e., CHP and membrane units) (Florio et al, 2019).

Table 12 shows the ecoinvent 3.8 processes used to estimate the impact of the production of each of the components.

Table 12 Overview of ecoinvent 3.8 processes used in plant construction

Component	Ecoinvent 3.8 process	Location
Depacker	steel production, electric, low-alloyed	Row
	gas motor production, 206kW	
Screw conveyor	conveyor belt production	Row
	steel production, electric, low-alloyed	
Anaerobic digester	anaerobic digestion plant construction, for biowaste	Row
Screw press	steel production, electric, low-alloyed	Row
Pasteurization tank	liquid storage tank production, chemicals, organics	Row
Biofertilizer storage tank	liquid storage tank production, chemicals, organics	Row
Liquid storage tank	liquid storage tank production, chemicals, organics	Row
Dehumidifier/dryer	absorption chiller production, 100kW	Row
Activated carbon filter	steel production, electric, low-alloyed	Row
	glass fibre reinforced plastic production, polyamide,	
	polyvinylchloride production, suspension polymerisation	
	polypropylene production, granulate	
Compressor before CHP	air compressor production, screw-type compressor,	Row
High pressure compressor	air compressor production, screw-type compressor,	Row
Heat exchangers	chromium steel pipe production	GLO
Pumps	pump production, 40W	Row
Boiler	gas boiler production	Row
Blower	blower and heat exchange unit production,	Row

2.6.2.2. Plant operation

The environmental impact during operations comprises the impact of transportation, the consumption of utilities (i.e., energy, diesel, water and activated carbon), and the losses of GHG emissions to the air during the operation of the different components. The calculations are conducted using the emissions factors, obtained from ecoinvent 3.8 processes in Table 13, and the results obtained from the mass and energy balances.

Table 13 Overview of ecoinvent 3.8 processes used in plant operation

Category	Ecoinvent 3.8 process	Location
Transportation	municipal waste collection service by 21 metric ton lorry	Row
Electricity	electricity, high voltage, production mix_AR	AR
Ignition oil	market for diesel	Row
Water	market for tap water	Row
Activated carbon	activated carbon production, granular from hard coal	Row

The GHG emissions to air typically correspond to the emissions from CO_2, CH_4 and N_2O. Nevertheless, due to the use of a close storage tank to store the digestate, where no oxygen is infiltrated, N_2O emissions are not included in this analysis since oxygen is a prerequisite for N_2O formation (Möller, 2015), and thus are only included for open storage tanks (Ruiz, et al., 2018). Moreover, in the case of CO_2 emissions associated with the biogas combustion, they are considered as biogenic, and thus, calculated neutral with regards to the impact on climate.

The climate metric utilised is the Global Warming Potential (GWP) at a time horizon of 100 years, according to the CML 2001 method (Guinée, et al., 2001). The GWP (100) values chosen are the ones detailed in the IPCC AR4 (2007) and they are equal to 25 for methane.

During operation, CH_4 losses are identified in the screw conveyor, the CHP, the membrane unit and the storage tanks. The impact factors selected correspond to average estimation taken from Wellinger, et al., 2014), Liebetrau, et al., (2017) and Ardolino et al (2020) and the IEA, (2017), respectively. To calculate the total amount of CH_4 emissions to air, a 64% methane content of the gas is assumed (Huiru, et al., 2018). Table 14 summarizes the CH_4 losses of the different components.

Table 14 Summary of losses from components

Components	CH_4 losses (%)	
Screw conveyor	0.01	of the total inflow
Digester	0.02	of the total inflow
CHP unit	1.89	of the total methane contained in the biogas
Membrane unit	0.69	of the produced gas (off-gas)
Storage tank (covered)	1.41	of total methane contained in digester

2.6.3. Avoided burden

To determine the “net” emission rates, GHG sinks, and removal rates should be included in a carbon footprint analysis (Franchetti & Apul, 2013). Therefore, the avoided emissions from substituting the production of equivalent conventional alternatives are included in it.

All emissions factors are obtained from ecoinvent 3.8 processes, except for landfilling, for which the City Inventory Reporting and Information System (CIRIS) excel-based tool is used to calculate it. Here, a landfill gas collection efficiency of 85%, and 0% of landfill gas collection are assumed, given that the information about gas collection is not public and therefore cannot be incorporated in this calculation. Moreover, the composition of the OFMSW is assumed to be 91% food waste and 9% garden waste (Ceamse, 2018).

To calculate the avoided production of conventional fertilizers, the amounts of nitrogen (N), phosphorus (P), and potassium (K) present in the solid digestate fraction are calculated. The average N, P, and K in organic household waste corresponds to 3%, 0.4%, and 1% of the DM content (Davidsson, et al., 2007), assumed to be 25% (Romero-Güiza, et al., 2016). The ecoinvent processes corresponding to urea, monoammonium phosphate, and potassium chloride productions are used, since they are the main nutrients in fertilizers (García & San Juan González, 2007). Consequently, the avoided burden calculation is performed from the results of the mass balance, the DM content, and the mentioned emission factors.

An overview of the ecoinvent processes and the impact factors that are used for all avoided burden calculations can be found in Table 15.

Table 15 Overview of ecoinvent 3.8 processes used in avoided burden calculations

Category	Type	Ecoinvet 3.8 process	Location	Impact factor	Unit
Avoided electricity	Electricity mix	electricity, high voltage, production mix	AR	0.37	kwh of electricity
Avoided CNG	High pressure natural gas	natural gas production, high pressure, vehicle grade	Row	0.58	kg of natural gas
Avoided production of N, P and K for conventional fertilisers	Nitrogen	urea ammonium nitrate production	Row	1.8	kg of N
	Phosphorus	monoammonium phosphate production	Row	0.9	kg of P
	Potassium	potassium chloride production	Row	0.44	kg of K
Avoided waste disposal in landfill	Landfill in CABA	N/A	N/A	0.2	ton per ton of MSW

2.7. Sensitivity analysis

The presence of uncertainties in the data that are used to estimate parameter values makes the accuracy of the results often complicated. Therefore, a sensitivity analysis is performed with the aim of evaluating how different values of an independent variable (inputs) affect dependent variables (outputs).

This sensitivity analysis studies the effect of two different variables: the ones affecting the 1) process and 2) financial variables. The process variables refer to those parameters affecting the conditions of any of the processes in Figure 4, while the financial ones refer to those affecting the TEA. The aim of the sensitivity analysis is to perform multiple simulation to understand under which conditions the project show positive financial indicators, and to evaluate how the carbon footprint is impacted by them.

3. Results

3.1. Mass balance

In both case studies shown in Figure 21 and Figure 22, the mass flow analysis shows that 23,333 tons of OFMSW enters the depacker, together with 35,000 tons of liquid digestate. From the total effluent that is obtained from the anaerobic digestion process, 69% of it is recirculated and mixed with the solid substrate. Minimal losses are accounted for corresponding to the plastic bags in which the OFMSW is transported to the plant, corresponding to only 2 tons a year.

In the anaerobic digestion process, only a small fraction of the substrate is converted into gas, namely 3,291 tons, while the other 55,168 tons leaves the process as digestate. The gas losses from the digester are minimal, corresponding to 1 ton a year.

The effluent is rather liquid, corresponding to a total of 46,342 tons, from which 35,000 is recycled. The remaining 11,342 tons of excess liquid is sent for wastewater treatment (out of boundaries). On the other hand, the solid fraction, corresponds to 8,826 tons, and is pasteurised for its utilisation as biofertilizer for land application. Although the storage tank has a storage capacity equivalent to 30 days of biofertilizers production, this process assumes that the totality of the biofertilizer produced is sold to the farmers or other individuals within a shorter period. The amount of N, P and K present in the biofertilizers corresponds to 58, 10 and 23 tons a year, respectively, which is not shown in the STAN diagram but in the Appendix A: Mass balance.

Regarding the production of biogas, the cleaning consists of 3 stages, namely a first desulphurization, drying and a final precise desulphurization process carried out with 2 activated carbon filters. As shown in the STAN diagrams, during the drying of the gas, some condensed water is purged, equivalent to 244 tons, while the remaining 3,047 tons of dehumidified biogas goes into the activated carbon filters. Here, 4 tons of activated carbon for the carbon filters is used. This amount consumed is not recuperated and therefore exits the system in the same amount.

In C-1 (Figure 21), in the CHP unit, 3,060 tons of desulphurized biogas, 275 tons of ignition oil and 2,295 tons of water enter the system, and 282 tons, 2,534 tons and 2,815 tons of flue gases, steam, and electricity exit the process.

In C-2 (Figure 22), the part of the cleaned gas, namely 366 tons goes into a boiler to produce steam, while the remaining goes into the membrane unit, producing biomethane and off-gas as outputs. The off gas corresponds to 1,536 tons, and the biomethane to 1,159 tons. No losses are assumed in the high-pressure compressor and therefore, the amount of bio-CNG is the same as the amount of biomethane.

The inflows and outflow of each process shown in Figure 21 and Figure 22 can be found in Appendix A: Mass balance.

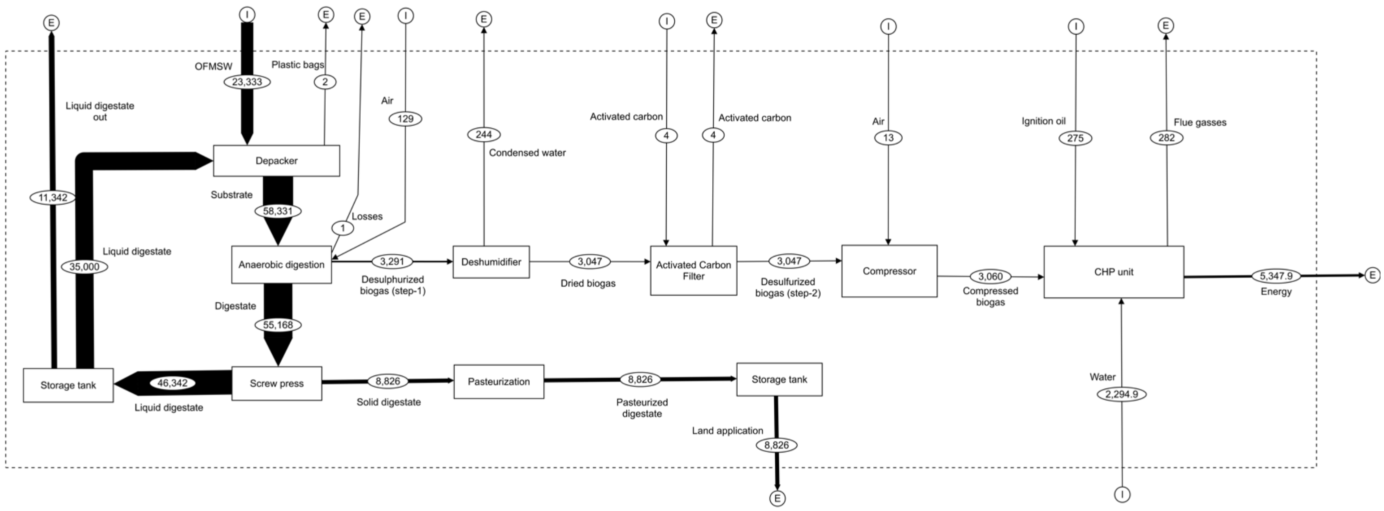


Figure 21 C-1 Mass balance in STAN

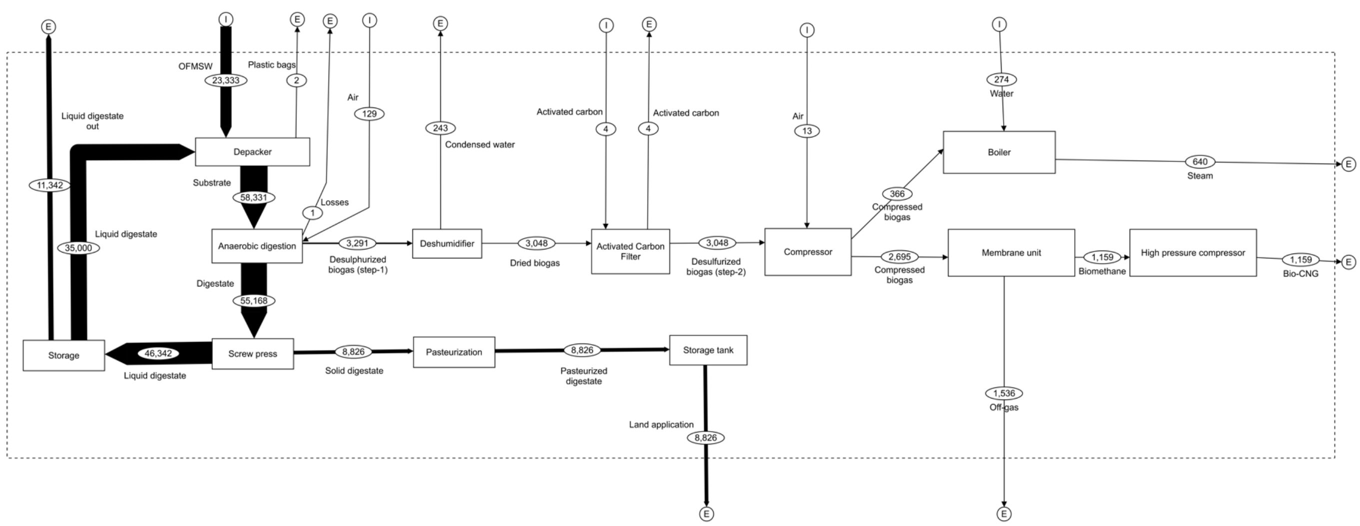


Figure 22 C-2 Mass balance in STAN

3.2. Energy requirements

According to the results obtained from the energy balance, Figure 23 shows that, in the case of C-1, 19% of the electricity produced in the CHP unit is consumed in the plant. In C-2, the electricity consumed is 74% higher than in C-1 and is supplied from the electric grid in its totality, considering that C-2 does not produce any. Regarding heat, both case studies consume the same amount of heat. In C-1, the heat consumed corresponds to 9% of the heat produced, and for C-2, all the heat produced is consumed.

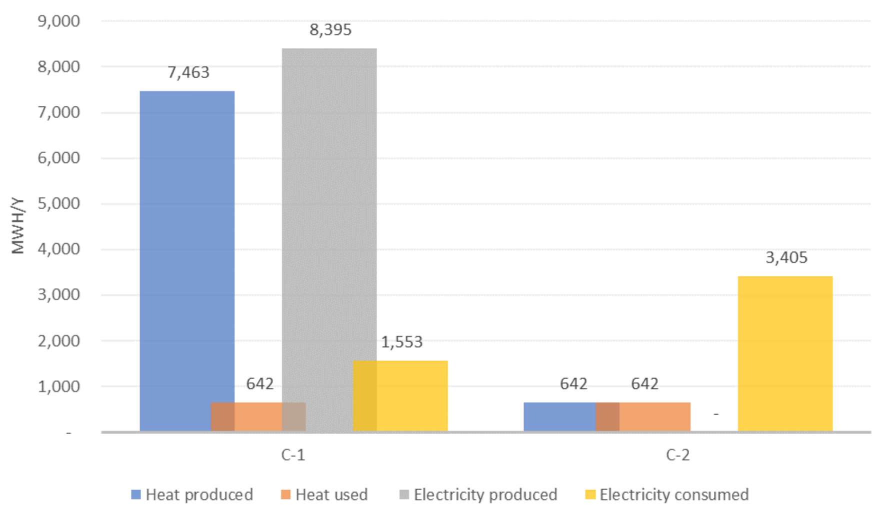


Figure 23 Heat and electricity production and consumption in C-1 & C-2

As shown in Figure 24, around 90% of the total electricity demand in C-1 is consumed by the agitators, the depacker, the dehumidifier and the pumps, while in C-2, it is distributed among the high pressure compressor, the agitators, the depacker and the dehumidifier, as shown in Figure 25.

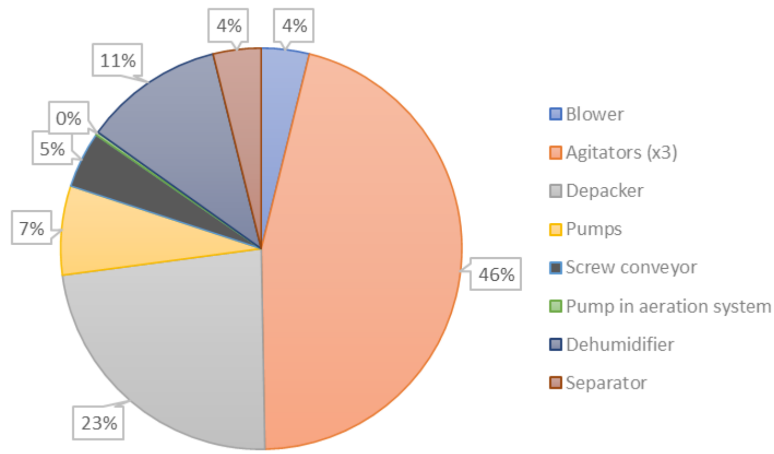


Figure 24 Distribution of electricity consumption among the components in C-1

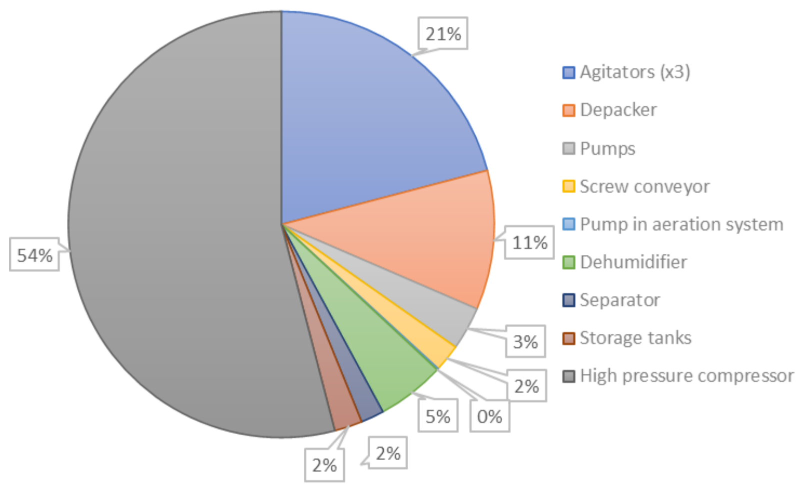


Figure 25 Distribution of electricity consumption among the components in C-2

3.3. Techno-economic assessment

3.3.1. Total costs

The costs associated with the OPEX and CAPEX in C-1 and C-2 are shown in Table 16. In C-1, the OPEX and the CAPEX represent 66% and 34% of the total annual cost respectively, whereas in C-2, it corresponds to 78% and 32%. The investment costs in C-1 are higher than C-2 by only 5%.

Table 16 Total costs for C-1 and C-2

	C-1	C-2
Annual CAPEX	€ 183,964	€ 174,751
Annual OPEX	€ 359,699	€ 428,682
Income	€ 1,299,490	€ 1,408,289

As it is shown in Figure 26 , the operational costs for C-1 are mainly driven by the maintenance costs (31%), the cost of insurance (18%), PM (17%), chemicals (16%) and labour (15%), and transportation costs and utilities (2% each). In C-2, the contributors to the operational costs are maintenance (24%), utilities (18%), chemicals (13%), PM (14%), insurance (15%), labour (13%), and lastly, transportation (1%). As it can be seen, the distribution of the operational costs is very similar in both case studies given that they are calculated as a fraction of the capital costs, which happen to be similar for both. The main difference between the two are the utilities costs, mainly related to the cost of electricity consumption, not needed in C-1.

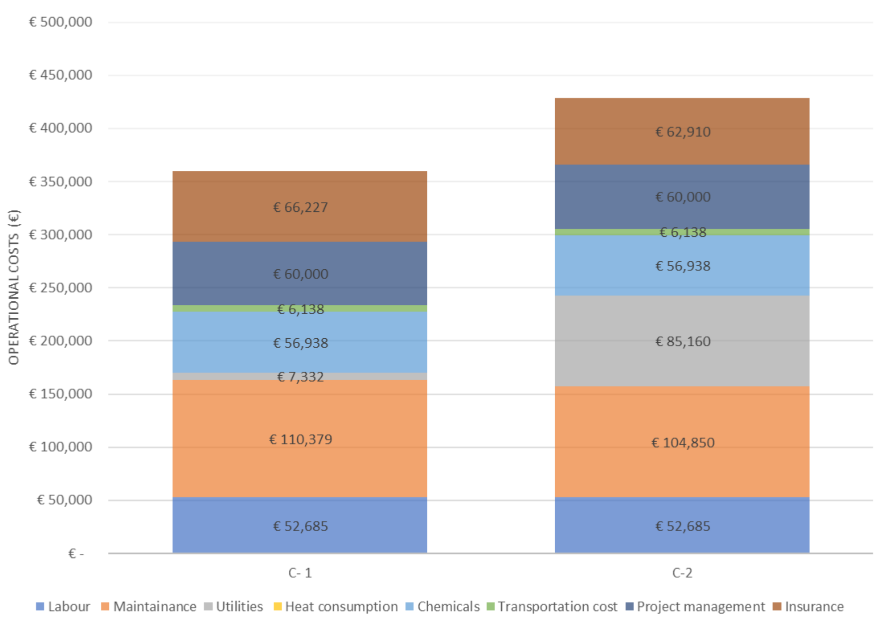


Figure 26 Distribution of the operational costs in C-1 and C-2

The CAPEX in C-1 and C-2 corresponds to €3,679,288 and €3,495,017, respectively. Figure 27 shows how it is distributed for both case studies, which is primarily driven by the cost of the equipment (60% & 58%), followed by the civil engineering work (31% & 33%), taxes (21%), and the electric and mechanical installations (9% & 10%). As it can be seen, the only difference between the case studies can be found in the equipment costs, which for C-1 are slightly higher, due to higher costs associated with the CHP unit, compared to the cost of the upgrading membrane unit of C-2.

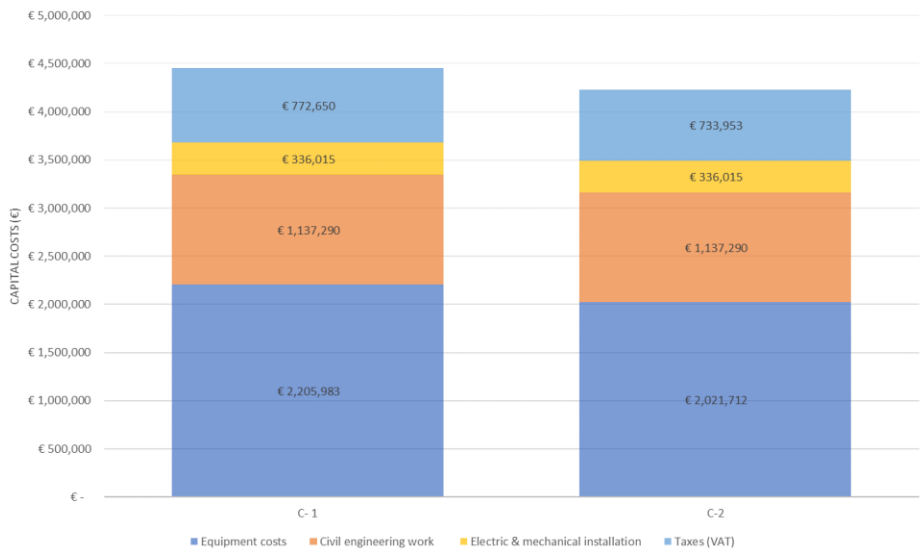


Figure 27 Distribution of the capital costs in C-1 and C-2

Regarding the equipment investment costs, Table 17 and Table 18 show the power capacity or volume of and the price of each of the components in C-1 and C-2, respectively. While the majority of the components are the same in both case studies, the ones in green are different.

Table 17 List of components in C-1, their capacity and price

Component	Size	Unit	Price
Blower	7.50	kw	€ 5,889
Compressor	97.17	kw	€ 211,839
CHP unit	1,494.47	kw	€ 1,026,783
Digester	5,775.00	m3	€ 392,604
Agitators (x3)	89.01	kw	€ 73,613
Depacker	45.00	kw	€ 37,217
Pumps	13.93	kw	€ 11,518
Screw conveyor	8.80	kw	€ 7,278
Temporary storage tank before depacker	1,316.32	m3	€ 25,840
Heat exchanger to digester	12.34	m2	€ 10,208
Heat exchanger to pasteurization unit	2.95	m2	€ 2,439
Heat exchanger to activated carbon filter	0.42	m2	€ 345
Pump in aeration system	0.50	kw	€ 982
Dehumidifier	21.90	kw	€ 42,990
Activated carbon filter (x2 tanks)	2.00	m3	€ 20,000
Lagoon for biofertilizers after pasteurization	1,378.90	m3	€ 27,068
Separator	7.50	kw	€ 19,630
Pasteurization tank	0.09	m3	€ 80,681
Torch	/		€ 29,445
Pipes	/		€ 59,242
Valves	/		€ 16,334
System control automation	/		€ 104,038
Total			**€ 2,205,983**

Table 18 List of components in C-2, their capacity and price

Component	Size	Unit	Price
Boiler	581.0	kw	€ 17,667
Compressor	97.17	kw	€ 211,839
Membrane upgrading unit	9.0	kw	€ 368,620
High pressure compressor	230.0	kw	€ 400,000
Digester	5775.0	m3	€ 392,604
Agitators	89.0	kw	€ 73,613
Depacker	45.0	kw	€ 37,217
Pumps	13.9	kw	€ 11,518
Screw conveyor	8.8	kw	€ 7,278
Liquid storage tank	1316.3	m3	€ 25,840
Heat exchanger to digester	12.3	m2	€ 10,208
Heat exchanger to pasteurization unit	2.9	m2	€ 2,439
Heat exchanger to activated carbon filter	0.4	m2	€ 345
Pump in aeration system	0.5	kw	€ 982
Dehumidifier	21.9	kw	€ 42,990
Activated carbon filter	2.0	m3	€ 20,000
Biofertilizer storage tank	1378.9	m3	€ 27,068
Separator	7.5	kw	€ 19,630
Pasteurization tank	0.1	m3	€ 80,681
Torch	/		€ 29,445
Pipes	/		€ 67,097
Valves	/		€ 22,831
System control automation	/		€ 151,799
Total			**€ 2,021,712**

Figure 28 and Figure 29 show the distribution of the equipment costs among the two case studies. In C-1, the top 5 main contributors to the total equipment costs are: CHP unit, digester, system control, pasteurization tank, and agitators. The high costs associated with the CHP unit is explained by the power capacity of the unit, which corresponds to 1494 KW. In C-2, the top 5 main contributors are: high-pressure compressor, digester, membrane unit, system control and agitators. The high cost associated with the high-pressure compressor is also explained by its power capacity of 230 KW, able to process up to 500 m3/h of biogas. Regarding the digester, its high cost is explained by its volume (5774 m3), caused by the high HRT value needed for the fermentation of the substrate.

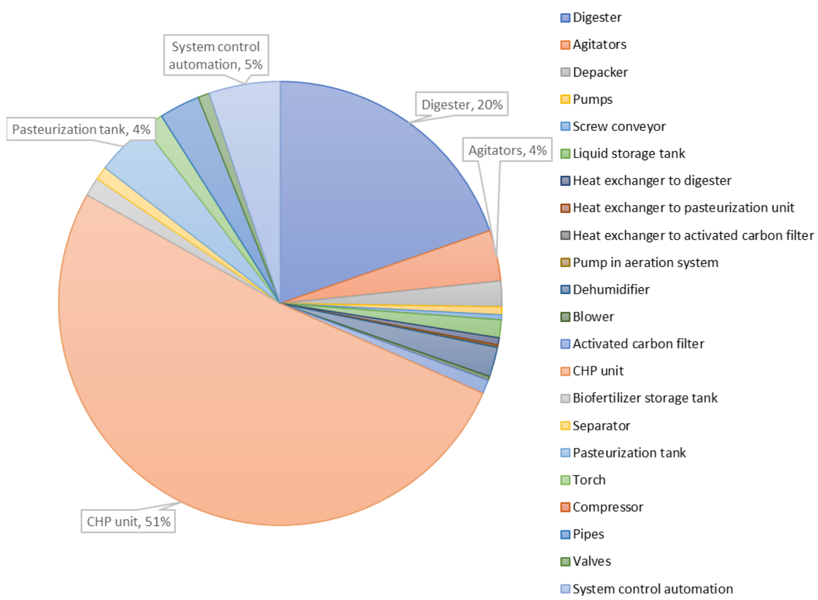


Figure 28 Distribution of the equipment costs in C-1

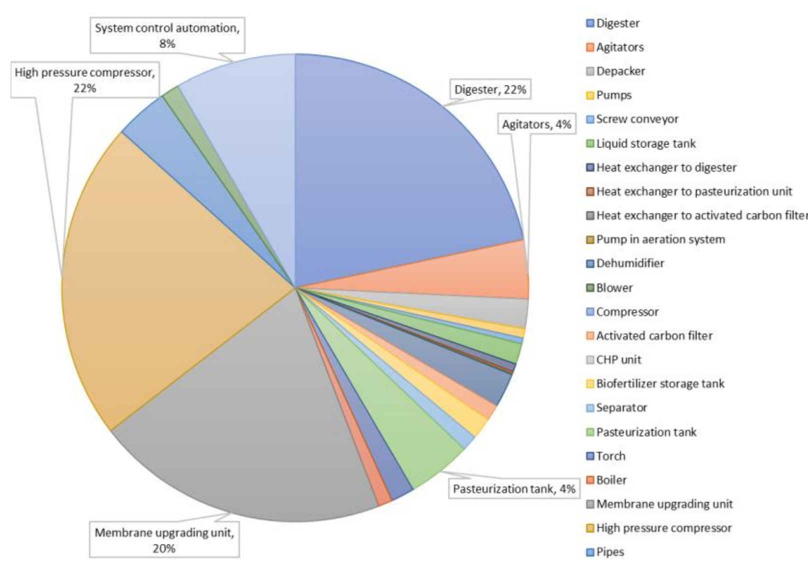


Figure 29 Distribution of the equipment costs in C-2

Regarding the total annual income, C-1 and C-2 have a total income of €1,299,490 and €1,408,289, respectively. Figure 30 shows the distribution among the products sold in C-1 and C-2. In both case studies, the income from electricity and bio-CNG correspond to most of the revenue made, namely 95% and 96% of the total income, while the income from biofertilizers only represent 5% and 4% of it. C-2 makes 8% more revenue than C-1.

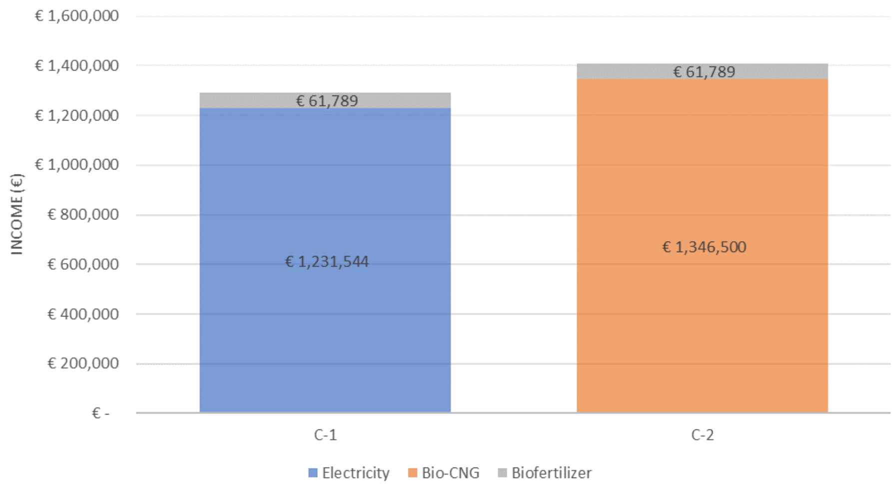


Figure 30 Distribution of the impact in C-1 and C-2

Lastly, the unitary production cost associated with the treatment of the OFMSW in both case studies, the production of electricity in C-1, and the production of bio-CNG in C-2 is shown in Table 19. The difference in the unitary cost of the ton of OFMSW treated can be explained by more elevated annual costs in C-2, compared to C-1.

Table 19 Unitary costs in C-1 and C-2

Unitary cost	C-1	C-2
Unitary costs (EUR/ton of OFMSW treated)	€ 23	€ 26
Unitary costs (EUR/mwh of electricity produced)	€ 65	
Unitary costs (EUR/MMBTU of biomethane produced)		€ 16

3.3.2. Financial indicators

Under the assumptions that were defined in the methodology, which includes subsidized selling prices for energy, the financial indicators show positive results for both case studies, as shown in Table 20. However, C-2 shows a better performance than C-1 with a 24% higher NPV, a 12% higher IRR, and a shorter payback period. The cash-flows corresponding to each of the case studies can be found in Appendix C: Financial indicators.

Table 20 Results of financial indicators in C-1 and C-2

Indicators	C-1	C-2
NPV	€ 1,180,576	€ 1,541,884
IRR	10%	11%
Payment period	9.0	8.2

3.4. Carbon footprint analysis

3.4.1. Emitted GHG emissions

The result calculations shows that C-1 produces 7.92E-02 tonCO2eq and C-2 1.03E-01 tonCO2eq. As shown in Figure 31, in the case of C-1 and C-2, the majority of the carbon footprint corresponds to the emissions during operation, equivalent to 94% and 96% of the total emissions, while the remaining 6% and 4% correspond to the emissions from the construction of the plant. The reasons that the impact of the plant construction is larger in C-1 than in C-2 is because the CHP unit has a bigger impact compared to the impact of the membrane unit. Nevertheless, C-2 has a larger carbon footprint during the operation of the plant, due to the impact associated with the electricity consumption.

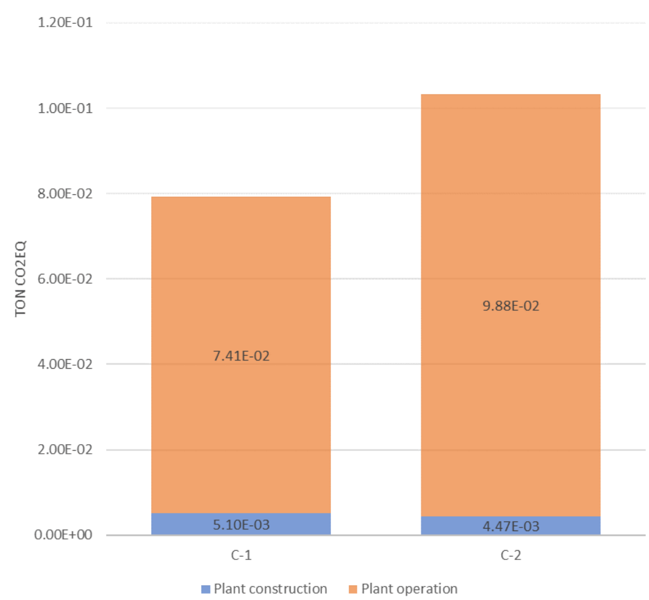


Figure 31 Distribution of carbon footprint between plant construction and operation

The main contributors to the carbon footprint of the plant construction in C-1 and C-2, as shown in Figure 31, are the construction of the CHP or the membrane unit, the digester, and the solid and liquid storage tanks. These four main components represent 97% and 96% of the total carbon footprint corresponding to the plant construction, in C-1 and C-2. While the remaining 3% and 4% are distributed among all other ones.

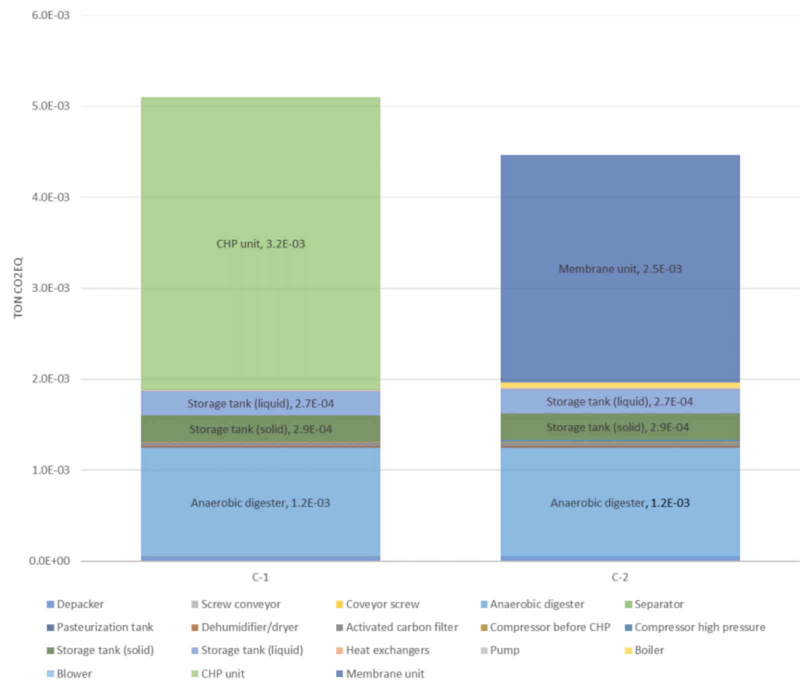


Figure 32 Distribution of carbon footprint in plant construction C-1 and C-2

The main contributors to the carbon footprint during plant operation in C-1 and C-2 are shown in Figure 33. It is noted that the top 4 contributors represent 99% of the carbon footprint, the remaining 1% corresponds to the impact of water consumption, and the losses to air in the digester and the screw conveyor. The carbon footprint contribution of each of the categories in C-1 and C-2 can be found in Appendix B: Carbon footprint analysis.

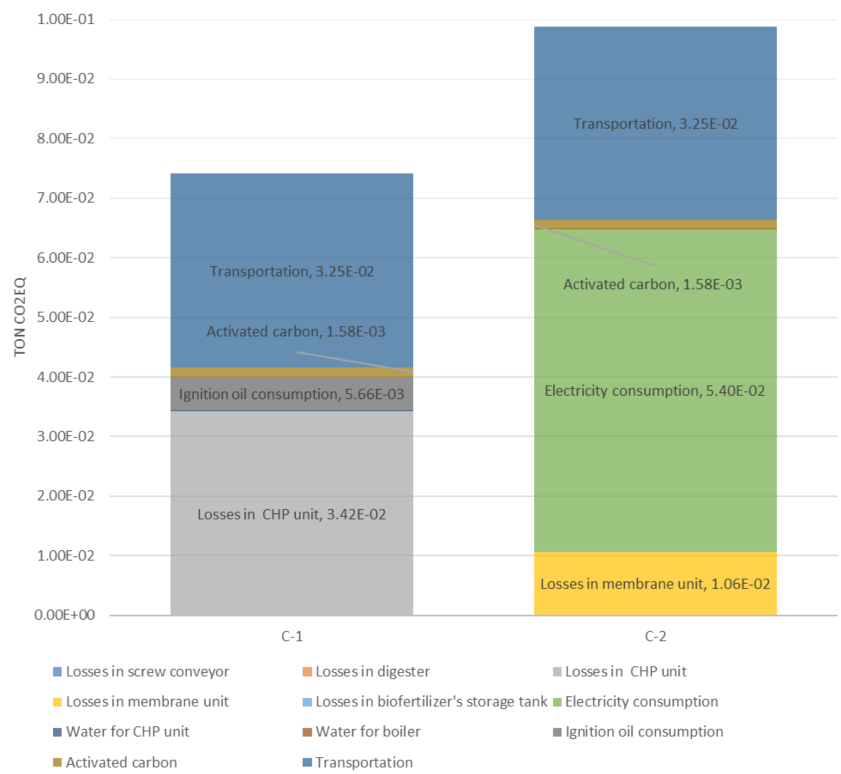


Figure 33 Distribution of carbon footprint during plant operations in C-1 and C-2

3.4.2. Avoided GHG emissions

As it is shown in Figure 34, C-1 has a higher avoided burden than C-2 by 26%. The main savings in C-1 and C-2 corresponds to the ones from landfill (60% and 78%), energy (33% and 13%), transportation (5%), and avoided production of nutrients (2.4% and 3%).

Given that the results for every category besides energy are the same for both case studies, the reason of this difference (25%) derives from the savings from electricity accounted for in C-1, which are larger than the ones from CNC in C-2.

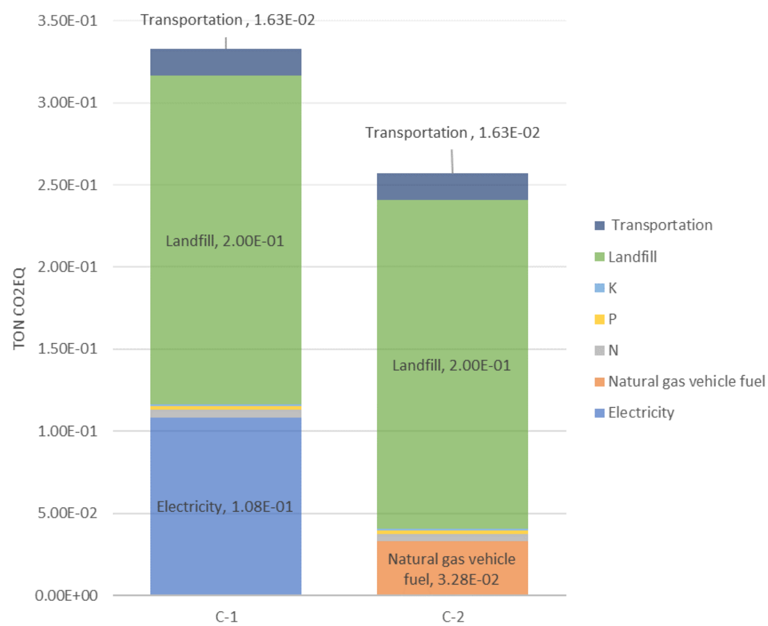


Figure 34 Distribution avoided burden among different categories in C-1 and C-2

As shown in Figure 35, the avoided emissions are 4.2 times higher than the carbon footprint in C-1, and 2.5 in C-2. In both cases, the environmental benefits surpass the impact, which means that C-1 and C-2 can save or sequester -2.53E-01 tonCO2eq and 5.42E-02tonCO2eq per ton of OFMSW treated. While both case studies can lead to substantial carbon savings, the benefits of C-1 are larger than C-2 and therefore this case study is preferable from a GWP point of view.

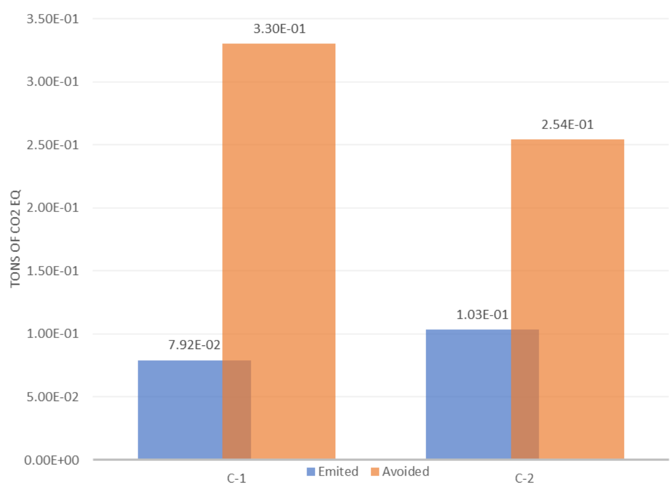


Figure 35 Emitted and avoided carbon footprint C-1 and C-2

3.4.3. Unitary environmental impact

As shown in Figure 36, only considering the emitted emissions (blue columns), the unitary impact of producing bioelectricity is slightly lower compared to the electricity mix, while the production of bio-CNG it is 3 times higher compared to the production of CNG. Nevertheless, considering the avoided carbon footprint (orange columns), the net unitary impact per unit of bioelectricity produced corresponds to -0.7kgCO2eq and -2.75kgCO2eq for bio-CNG. The impact factors used are presented in Table 15.

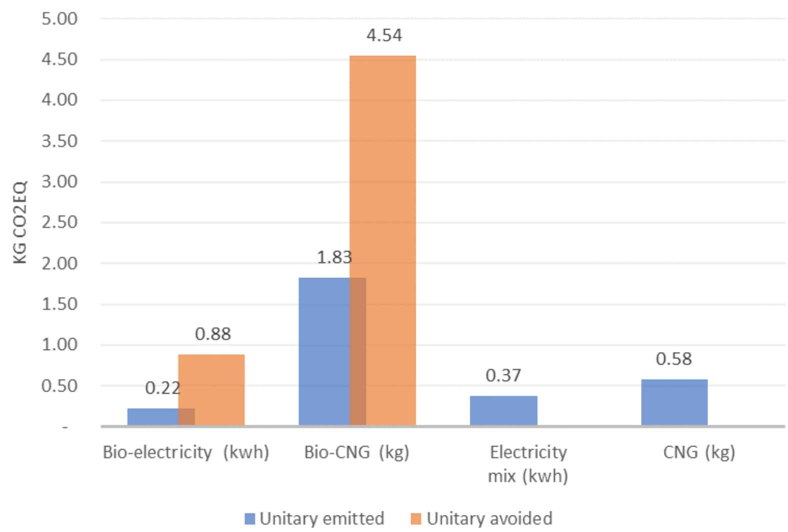


Figure 36 Comparison between unitary GWP

3.5. Sensitivity analysis

To answer to the 4th sub-question to evaluate how changes in the assumptions affect the economic performance and the carbon footprint of the case studies, a sensitivity analysis is conducted. The variables that were found to be more relevant to be evaluated are presented below. The EC or CF after each variable indicates whether the economic (EC) or the carbon footprint (CF) performance is assessed. An overview of the selected variables and their variations are shown in Table 21.

3.5.1. Process variables

S-1) Biogas potential of substrate- EC and CF

The biogas potential of the substrate was previously assumed to be 460 (mL/gVS). The impact of the range corresponding to 445-475 (Kigozi, et al., 2014) is evaluated.

S-2) CHP and membrane units' efficiency - EC and CF

The efficiency of the CHP was assumed to be 85% (45% electricity and 40% thermal efficiency). However, a typical efficiency can range between 75-90% (EEA, 2013). For the membrane, its efficiency ranges between 31-56%, Ardolino et al, (2021) and Prodeval (2022). The two efficiency ranges are evaluated in the economic and carbon footprint sensitivity analyses, given that the variation in the efficiency of the unit has implications in the emissions to air from the CHP and membrane units, and the avoided burden.

S-3) Selling price of energy - EC

The price at which the products can be sold are normally subject to external conditions, such as seasonal changes in the demand of energy, restrictions to imports, fluctuations in the price of commodities (e.g., oil), among others. Hence, the prices at which the energy is sold is most probably going to change throughout the 20 years period. The price initially assumed was 0.18 €/kwh, however a sensitivity analysis is conducted simulating a price in the range of 0.16 €/kwh - 0.20 €/kwh for electricity in C-1, and a price of 25 €/MMBTU - 40 €/MMBTU for bio-CNG in C-2. Moreover, a price without subsidies is also simulated, which corresponds to 0.07 €/kwh for electricity (CAMMESA, 2022), and 22€/MMBTU for CNG (Camuzzi, n.d.).

S-4) Reduction in the amount of biofertilizers sold - EC and CF

The amount of biofertilizers sold are reduced to 50% and 0%, which consequently means that the solid effluent that is not sold is sent to landfill. This not only leads to a reduction of the income, but also to additional transportation and treatment costs. Regarding the impact on the carbon footprint, sending the solid effluent to landfill instead of selling it as biofertilizer has several implications, such as the increase of the emissions related to transportation and landfilling, and the reduction of the substituted conventional fertilizers.

S-5) Selling heat production - EC and CF

The changes in the income by selling the remaining heat are assessed, as it is argued that it will bring about additional economic and environmental benefits (Hengeveld, et al., 2016). Nevertheless, this will only have an impact on C-1, given that C-2 does not produce additional steam. The selling price of steam is assumed to be 0.7€/kwh (Spaltro, 2021).

S-6) Variations in the maintenance costs- EC

The lack of regular follow-up led to the increase in the maintenance cost. An increase of 50% and 100% are simulated.

S-7) Variations in the investment costs- EC

The equipment investment costs can vary, in particular for imported equipment. Thus, an investment costs of -30% and 30% are simulated.

3.5.2. Financial variables

S-8) Discount rate- EC

The discount rate was initially set to 6%. However, similar studies have indicated a discount rate of 10% or even 14% (Allendes, 2015) (Akbulut, 2012). Thus, the impact on the financial indicators of these discount rates is studied.

S-9) Financed debt - EC

The external debt funded into the project is assumed to be 80%. A sensitivity analysis is conducted simulating an external financed debt of 0%, 50% and 100% of the total investment costs.

S-10) Removal of financial incentives

As studies have argued that the AD cannot have positive financial results without financial incentives (Gebrezgabher, et al., 2010), their removal is simulated.

Table 21 summarises the variables ad the simulated parameters.

Table 21 Summary parameters used in sensitivity analysis

N° S	Parameters	Values		Unit
	Process variables			
	Changes to income			
	Substrate properties			
S-1	Biogas potential	445	475	mL/gVS
	Efficiency of components			
S-2	Efficiency of CHP unit	75	90.00	%
	Efficiency of membrane unit	31	55.86	%
	Selling price of energy			
S-3	Bio-electricity	0.07	0.20	€/kwh
	Bio-CNG	22	40	€/MMBTU
	Reduction in the amount of digestate sold			
S-4	Biofertilizers	0	50	% sold
	Adding sales of heat			
S-5	Selling of heat	0	50	% sold
	Changes to CAPEX and OPEX			
S-6	Maintenance costs	50	100	%
S-7	Investment costs	-30	30	%
	Financial variables			
S-8	Discount rate	10	14	%
S-9	Financed debt	60	100	% funded
S-10	Fnancial incentives	0		%

3.5.3. Sensitivity analysis on the financial performance

The results presented hereafter aim to show how sensitivity the financial performance of the case studies can be under changing conditions. The results only will show the impact on the selected financial indicators, namely the NPV, IRR and the payback period.

To assess economic feasibility, the NPV and IRR values need to be positive, and the payment period within the 20 years duration of the project. Regarding the tables that present the results, the green row corresponds to the results of the baseline case studies (C-1&C-2), in red the negative values are indicated. For payment period that are above 20 years, "NP" will be indicated, which stands for "not-payable". Similarly, "NR" will be used to indicate when there is "no-return", and the IRR cannot be calculated.

S-1) Variation in the composition of the substrate

The variations in the DM content of the substrate shows that a biogas potential content of 445 mL/gVS lead to lead a positive NPV in the case of C-1, but to a negative one in C-2, as shown in Table 22 and Table 23. Moreover, as it can be seen in Figure 37, for C-2, a biogas potential below 452 mL/gVS can already lead to a negative financial performance.

Table 22 Financial indicators S-1 in C-1

% variation	Biogas potential (mL/gVS)	Income	C-1. NPV	IRR	Payback time
-3%	445	1,162,432	107,256	6%	12
Baseline	460	1,299,490	1,180,576	10%	9
3%	475	1,442,436	3,318,880	16%	6

Table 23 Financial indicators S-1 in C-2

% variation	Biogas potential (mL/gVS)	Income	C-2. NPV	IRR	Payback time
-3%	445	1,148,211	-1,428,264	0%	NP
Baseline	460	1,404,387	1,510,056	11%	8
3%	475	1,452,085	2,057,147	13%	8

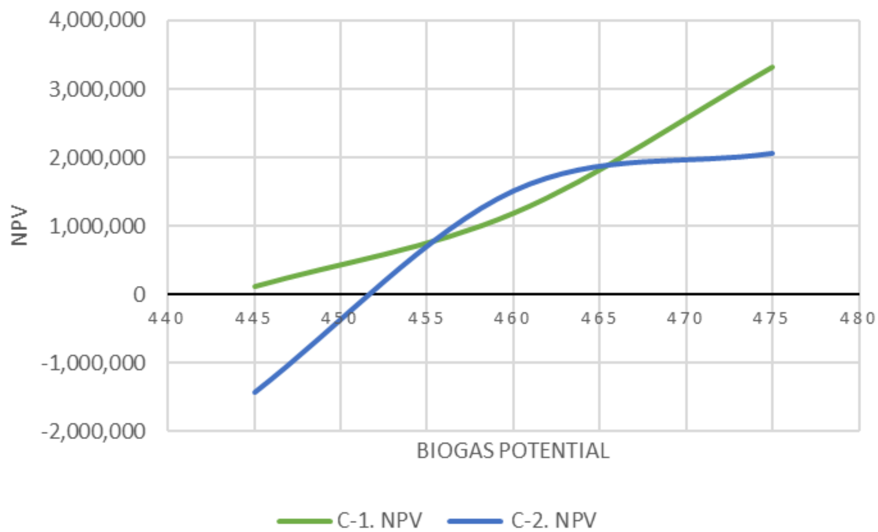


Figure 37 Impact of biogas potential variation on NPV in C-1 & C-2

S-2) Efficiency of CHP and membrane units

According to the results obtained in Table 24 and Table 25, with a reduction in the efficiency of 75% and 31% in the CHP and the membrane unit, respectively, the financial performance are negative, with an NPV of €-4M and €-13M, and an NR IRR, and an NP payback period. In the case of C-1, an efficiency below 83% in the CHP unit can already lead to negative results, while in the case of C-2, this corresponds to 41%. In both cases, the efficiency cannot lower more than 3% from the baseline to obtain positive results.

Table 24 Financial indicators S-2 in C-1

% variation	CHP efficiency (%)	Income	C-1. NPV	IRR	Payback time
-13%	75%	799,159	-4,524,088	NR	NP
Baseline	85%	1,299,490	1,180,576	10%	9
6%	90%	1,766,728	6,573,859	25%	4

Table 25 Financial indicators S-2 in C-2

% variation	Membrane efficiency (%)	Income	C-2. NPV	IRR	Payback time
-32%	31%	81,251	-13,295,151	NR	NP
Baseline	43%	1,408,289	1,541,884	11%	8
26%	56%	2,541,026	14,918,278	45%	2

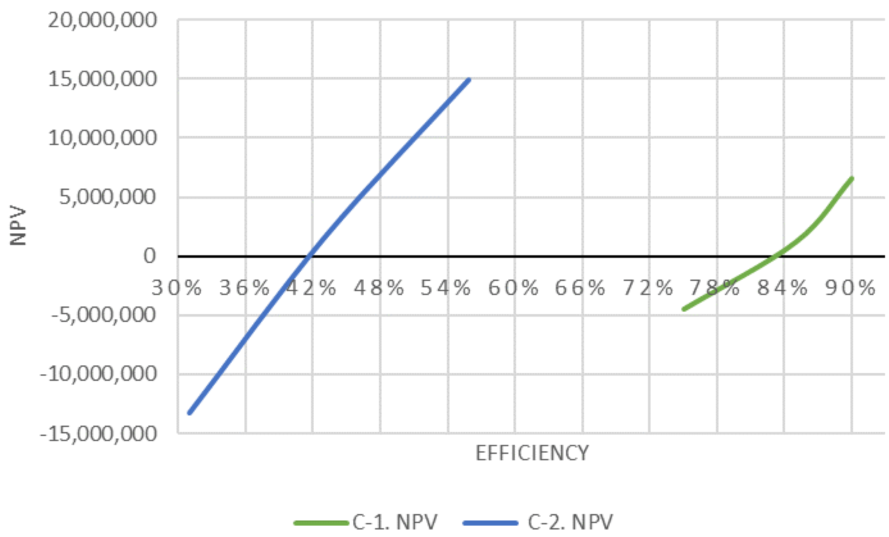


Figure 38 Impact of efficiency variation on NPV in C-1 & C-2

S-3) Variations in the selling price of energy

In both case studies, the unsubsidized selling price of electricity leads to drastic negative results that correspond to €-7.7M and €-7.4 for C-1 and C-2, respectively. Similarly, the reduction of the selling price to 0.15€/kwh for bioelectricity and 22€/MMBTU for bio-CNG also lead to a negative NPV. However, while the NPV is negative in C-1, the IRR and payback time are positive. In C-2, however, also the IRR and the payback time are negative. As it is shown in Figure 39 and Figure 40, in the case of C-1, with a selling price of 0.16€/kwh for bioelectricity and 33€/MMBTU for bio-CNG, the projects display results for their financial indicators.

Table 26 Financial indicators S-3 in C-1

% variation	Price of bioelectricity (kwh)	Income	C-1. NPV	IRR	Payback time
-91%	0.07	522,821	-7,707,359	NR	NP
-18%	0.15	1,088,075	-530,163	4%	17
Baseline	0.18	1,299,490	1,180,576	10%	9
11%	0.20	1,430,171	2,260,189	13%	8

Table 27 Financial indicators S-3 in C-2

% variation	Price of bio-CNG (MMBTU)	Income	C-2. NPV	IRR	Payback time
-46%	22	603,432	-7,438,304	NR	NP
-15%	30	944,155	-3,515,069	NR	NP
Baseline	35	1,408,289	1,541,884	11%	8
13%	40	1,473,574	2,557,330	14%	7

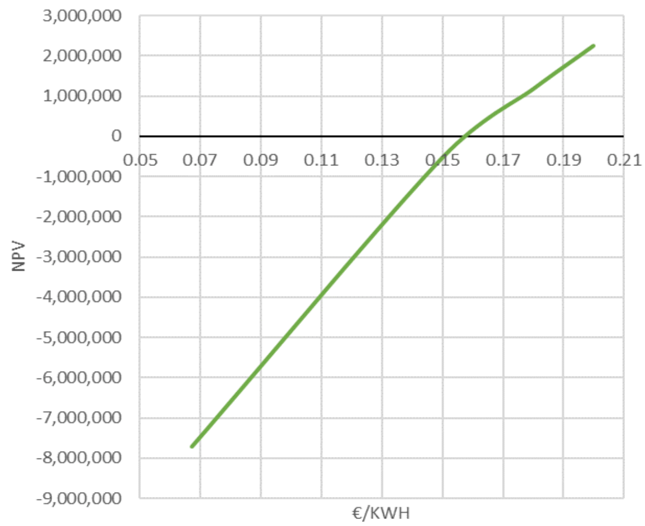


Figure 39 Impact of price variation on NPV in C-1

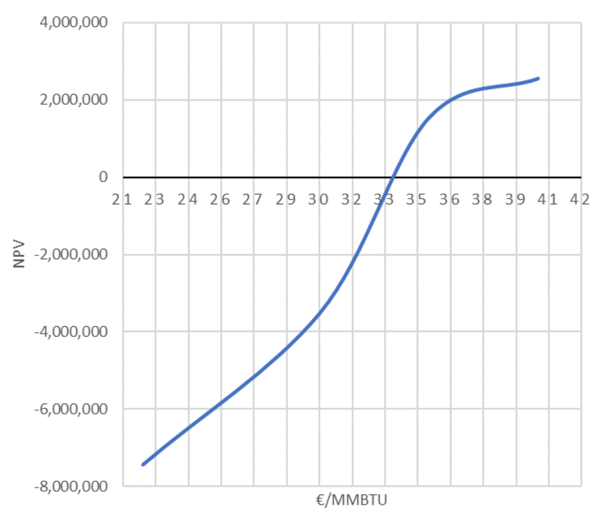


Figure 40 Impact of price variation on NPV in C-2

S-4) Variations in the amount of dry digestate sold

In the case of C-1 and C-2, reducing the amount of biofertilizers sold to 50% does not lead to a negative economic performance, however, reducing it to 0% does lead to a negative NPV, while it still shows a positive IRR and a payback time of 16 and 14 years in C-1 and C-2. Nevertheless, as show in Figure 41, if less than 2.5 and 1.8 thousand tons of biofertilizers are sold in C-1 and C-2, or the equivalent to 28% and 20% of the total, the case studies will show negative NPV results.

Table 28 Financial indicators S-4 in C-1

% variation	Amount of biofertilizers (tons)	Income	C-1. NPV	IRR	Payback time
0%	0	1,231,544	-514,750	4%	16
50%	4413	1,262,438	382,314	7%	12
Baseline	8827	1,299,490	1,180,576	10%	9

Table 29 Financial indicators S-4 in C-2

Percentage dif	Amount of biofertilizers (tons)	Income	C-2. NPV	IRR	Payback time
0%	0	1,346,500	-122,356	6%	14
50%	4413	1,377,395	312,755	7%	12
Baseline	8827	1,408,289	1,541,884	11%	8

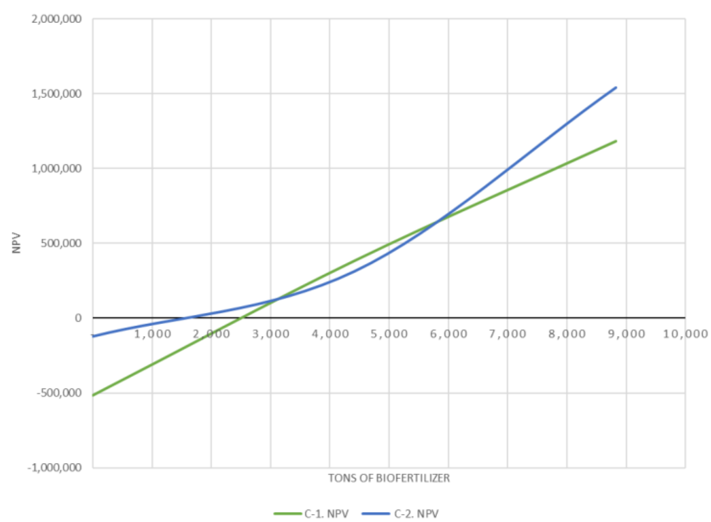


Figure 41 Impact of biofertilizer sold variation on NPV in C-1 & C-2

S-5) Heat sold

As expected, selling heat in C-1 substantially increases the income, and the results obtained in the financial indicators, which can become 5 times higher compared to the baseline, as shown in Table 30..

Table 30 Financial indicators S-5 in C-1

% variation	Heat sold (kwh)	Income	C-1. NPV	IRR	Payback time
Baseline	-	1,299,490	1,180,576	10%	9
50%	3,410,248.38	1,536,844	3,833,014	18%	6
100%	6,820,496.75	1,774,197	6,535,678	24%	4

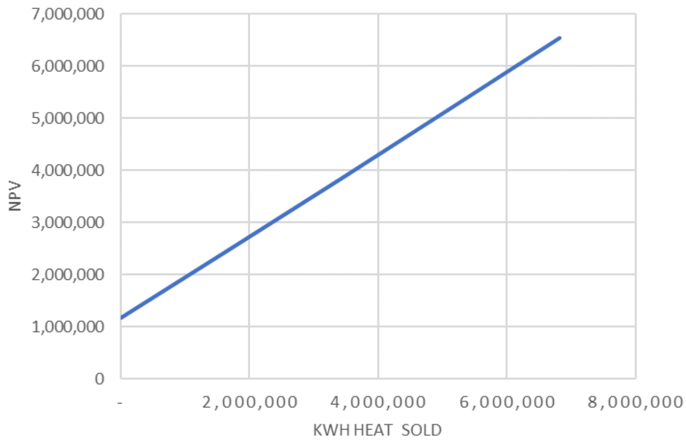


Figure 42 Impact of heat sold variation on the NPV in C-1

S-6) Variations in the maintenance costs

The increase in the maintenance costs by 50%, does not lead to negative financial indicators, while doubling the maintenance cost does, as seen in Table 31 and Table 32. In both case studies, increasing the maintenance cost by 100% leads to a negative NPV, however, while the IRR and payback period remain positive in C-1, this is not the case in C-2. As shown in Figure 43, maintenance costs above €220,000 and €240,000, in C-1 and C-2, can lead to a negative economic performance.

Table 31 Financial indicators S-6 in C-1

% variation	Cost of maintenance (€)	Operational cost	C-1. NPV	IRR	Payback time
Baseline	110,379	359,699	1,180,576	10%	9
50%	165,568	414,888	547,559	8%	10
100%	220,757	470,077	-85,458	6%	12

Table 32 Financial indicators S-6 in C-2

% variation	Cost of maintenance (€)	Operational cost	C-2. NPV	IRR	Payback time
Baseline	110,379	428,682	1,541,884	11%	8
50%	165,568	489,399	813,631.37	9%	9.63
100%	331,136	654,967	-1,085,420	1%	NP

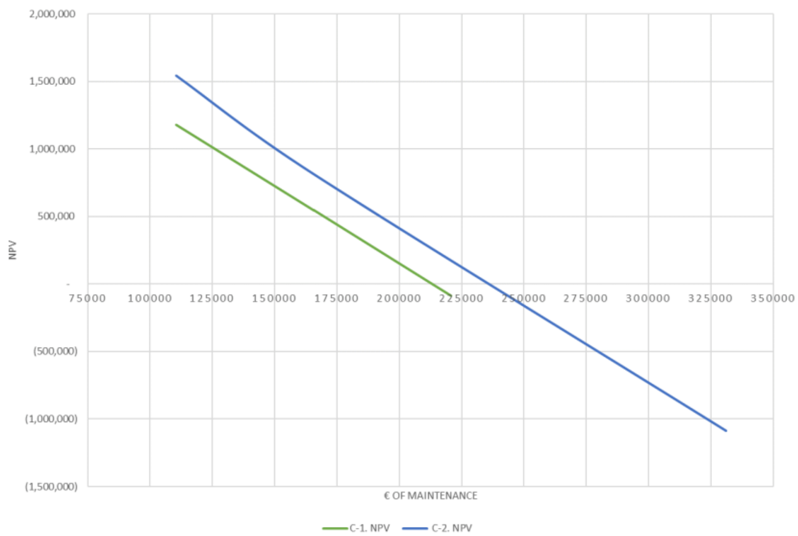


Figure 43 Impact of maintenance costs variation on the NPV in C-1 & C-2

S-7) Variations in the investment costs- EC

The simulations performed on the equipment investment costs shows that, while their reduction certainly leads to a more favourable economic performance, the 30% increase leads to a negative NPV in C-2, but a positive IRR and payback time, as shown in Table 33 and Table 34. However, in C-1, all indicators show positive results. As it is observed in Figure 44, the equipment costs cannot exceed €2,5M and €2,9M, in C-1 and C-2, to remain NVP positive.

Table 33 Financial indicators S-7 in C-1

% variation	Equipment cost (€)	CAPEX	C-1. NPV	IRR	Payback time
-30%	1,544,188	3,017,493	2,236,516	15%	7
Baseline	2,205,983	3,679,288	1,180,576	10%	9
30%	2,867,778	4,341,083	124,636	6%	12

Table 34 Financial indicators S-7 in C-2

% variation	Equipment cost (€)	CAPEX	C-2. NPV	IRR	Payback time
-30%	1,415,198	2,888,503	2,477,790	16%	6
Baseline	2,021,712	3,495,017	1,541,884	11%	8
30%	2,628,226	4,101,530	-285,834	5%	12

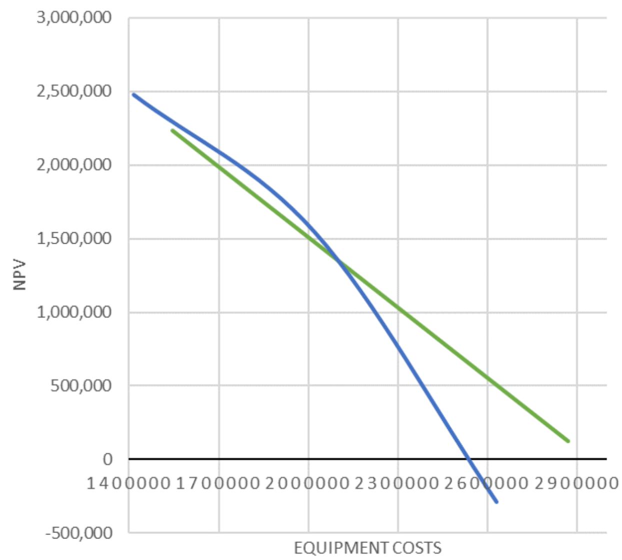


Figure 44 Impact of investment costs variations on the NPV in C-1 & C-2

S-8) Discount rate

In C-1, a discount rate of 10% shows a negative NPV, but positive IRR and payback time results, while in C-2, a 10% discount rate shows positive results, as shown in Table 35 and Table 36. As it can be observed in Figure 45, with a discount rate higher than 10% and 11%, the case studies can lead to a negative NPV in C-1 and C-2.

Table 35 Financial indicators S-8 in C-1

% variation	Discount rate	C-1. NPV	IRR	Payback time
Baseline	6.00	1,180,576	10%	9
50%	10	-9,987	10%	10
80%	14	-787,491	10%	10

Table 36 Financial indicators S-8 in C-2

% variation	Discount rate	C-2. NPV	IRR	Payback time
Baseline	6.00	1,541,884	11%	8
50%	10	304,034	11%	9
80%	14	-502,916	11%	9

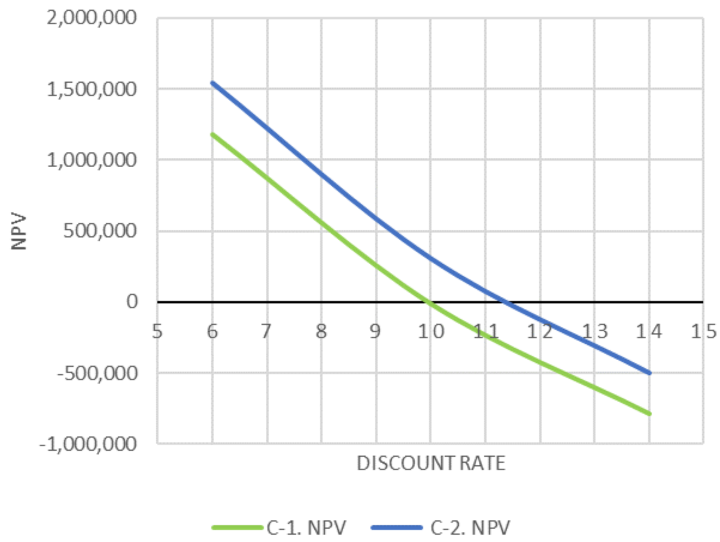


Figure 45 Impact of the discount rate variations on the NPV in C-1 & C-2

S-9) Financed debt

The results in Table 37 and Table 38 show that even if the project will be completely financed by external debt, the project will still display positive financial results. A reduction in the amount of the debt financed can certainly lead to a more favourable performance, with a higher NPV, IRR and a reduced payback time. Figure 46 shows a linear trend where the more the debt is financed by the bank, the lower the NPV becomes, since more money needs to be allocated to pay the interest rate of the debt.

Table 37 Financial indicators S-9 in C-1

% variation	Debt financed	C-1. NPV	IRR	Payback time
-120%	20%	2,773,804	15%	7
Baseline	80%	1,180,576	10%	9
22%	100%	582,532	8%	12

Table 38 Financial indicators S-9 in C-2

% variation	Debt financed	C-2. NPV	IRR	Payback time
-120%	20%	3,071,200	16%	7
Baseline	80%	1,541,884	11%	8
22%	100%	989,674	10%	10

Figure 46 Impact of financed debt variations on the NPV in C-1 & C-2

S-10) Removal financial incentives

Removing the financial incentives certainly affects the economic performance of the case studies, given that the NPV drops 73% and 53% in C-1 and C-2. Nevertheless, their removal does not lead to negative results of the financial indicators.

Table 39 Financial indicators S-10 in C-1

% variation	Financial incentives (VAT)	C-1. NPV	IRR	Payback time
-200%	0	315,343	7%	11
Baseline	772,650	1,180,576	10%	9

Table 40 Financial indicators S-10 in C-2

% variation	Financial incentives (VAT)	C-2. NPV	IRR	Payback time
-200%	0.00	717,723	8%	10
Baseline	733,953	1,541,884	11%	8

The results obtained in the sensitivity analysis showed how the conducted simulations can impact the economic performance and lead to negative results of the financial indicators for both case studies. In this regard, except for S-4, S-9 and S-10, all the simulations performed, lead to negative results for at least one of the case studies, as shown in red in Table 41.

Both case studies are almost equally sensitive to the changes simulated, since in C-1 and C-2, 6 and 7 simulations out of the 21 leads to negative results. The case studies are mainly sensitive to changes to the income, given that the income margin is very low, as it can be seen in Table 42 which explains why S-2 and S-3 lead to the lowest NPV results. However, in the case of the CAPEX and the OPEX, there is a higher margin before the project becomes NPV-negative, being the OPEX the one with the highest margin, and therefore the one that is less sensitive from the three.

Table 41 TEA sensitivity analysis results' overview

Simulation	Description	C-1	C-2
S-1.1	Biogas potential 445	107,256	-1,428,264
S-1.2	Biogas potential 475	3,318,880	2,057,147
S-2.1	Low efficiency	-4,524,088	-13,295,151
S-2.2	High efficiency	6,573,859	14,918,278
S-3.1	Price energy non-subsidized	-7,707,359	-7,438,304
S-3.2	Price energy low	-530,163	-3,515,069
S-3.3	Price energy high	2,260,189	2,557,330
S-4.1	50% Biof sold	382,314	312,755
S-4.2	100% Biof sold	1,180,576	1,541,884
S-5.1	0% heat sold	1,180,576	
S-5.2	50% heat sold	3,833,014	
S-6.1	Maintenance cost low	1,180,576	1,541,884
S-6.2	Maintenance cost high	-85,458	-1,085,420
S-7.1	Investment cost low	2,236,516	2,477,790
S-7.2	Investment cost high	124,636	-285,834
S-8.2	10% DR	-9,987	304,034
S-8.3	14% DR	-787,491	-502,916
S-9.1	20% debt financed	2,773,804	3,071,200
S-9.3	100% debt financed	582,532	989,674
S-10.1	0% financial incentive	315,343	717,723
S-10.2	Baseline financial incentive	1,180,576	1,541,884

Table 42 Reduction margin of income, CAPEX and OPEX

Income	
C-1	C-2
1,186,148.36	1,261,584.15
1,299,490.26	1,404,387.13
-9%	-11%
CAPEX	
C-1	C-2
4,419,196.62	4,020,911.92
3,679,287.69	3,495,016.57
18%	14%
OPEX	
C-1	C-2
462,626.76	560,335.14
359,698.75	428,681.60
25%	27%

3.5.4. Sensitivity analysis on the GWP

The impact on the carbon footprint of S-1, S-2, S-4, and S-5 are evaluated. As it is shown in Figure 47 and Figure 48, the case studies can lead to carbon savings despite the changes performed in the simulations, given that in the baselines the avoided emissions were already so much higher than the emitted ones.

As it can be seen in the last column in Table 43, the ratio of avoided and emitted emissions becomes the smallest in S-4. The reason is that additional transportation and landfill emissions are included, which increases the emissions by 62% and 49% compared to the baselines. On the other hand, the biggest ratio corresponds to the improvements in the efficiency of the CHP and the membrane units. A higher efficiency leads to more energy production, and hence a higher avoided burden of +11% and +13% in C-1 and C-2, respectively, while at the same time also reduces the negative impacts by 5% and 7%, since more efficient equipment leads to a reduction in the losses to the air.

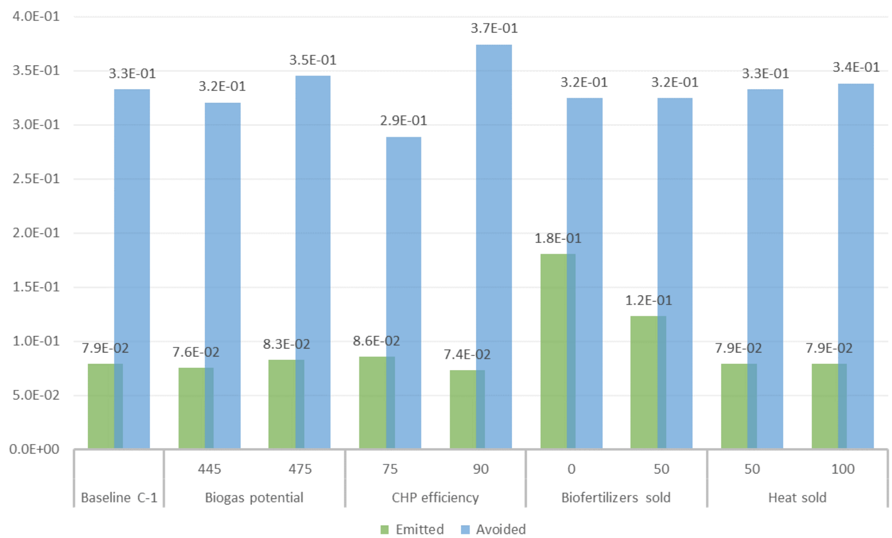


Figure 47 Result of simulation on the carbon footprint in C-1

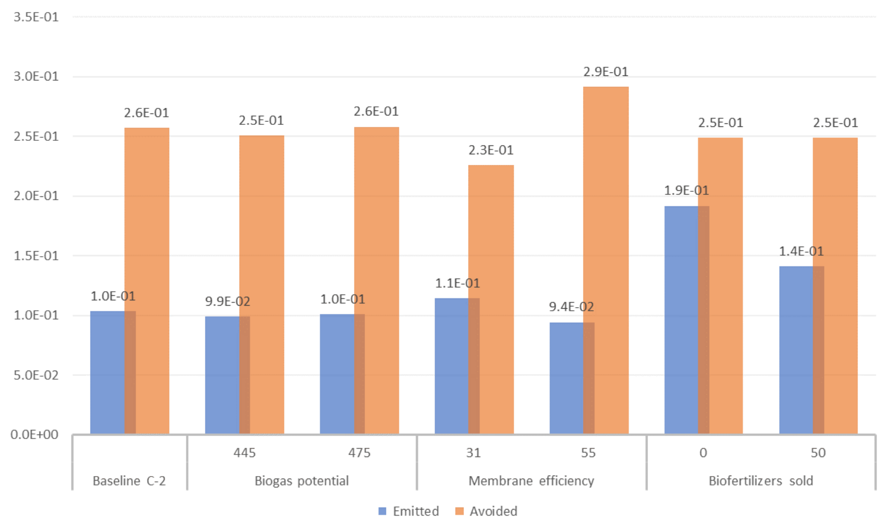


Figure 48 Result of simulation on the carbon footprint in C-2

Table 43 Overview of emitted and avoided emissions in C-1 and C-2

N° S	Parameters	Values	Unit	Emitted	Difference to baseline	Avoided	Difference to baseline	Ratio avoided/emitted
	Baseline C-1			**7.9E-02**		**3.3E-01**		**4.2**
		445	mL/gVS	7.6E-02	-5%	3.2E-01	-4%	4.2
S-1	Biogas potential	475	mL/gVS	8.3E-02	5%	3.5E-01	4%	4.2
		75	%	8.6E-02	8%	2.9E-01	-14%	3.4
S-2	CHP efficiency	90	%	7.4E-02	-7%	3.7E-01	12%	5.1
		0	%	1.8E-01	78%	3.2E-01	-2%	1.8
S-4	Biofertilizers sold	50	%	1.2E-01	44%	3.2E-01	-2%	2.6
		50	%	7.9E-02	0%	3.3E-01	0%	4.2
S-5	Heat sold	100	%	7.9E-02	0%	3.4E-01	2%	4.3
	Baseline C-2			**1.0E-01**		**2.6E-01**		**2.5**
		445	mL/gVS	9.9E-02	-4%	2.5E-01	-3%	2.5
S-1	Biogas potential	475	mL/gVS	1.0E-01	-2%	2.6E-01	0%	2.6
	Membrane	31	%	1.1E-01	10%	2.3E-01	-13%	2.0
S-2	efficiency	55	%	9.4E-02	-9%	2.9E-01	13%	3.1
		0	%	1.9E-01	60%	2.5E-01	-3%	1.3
S-4	Biofertilizers sold	50	%	1.4E-01	31%	2.5E-01	-3%	1.8

4. Discussion

4.1. Mass and energy balance

4.1.1. Co-substrate alternatives: sewage sludge and aquatic biomass

The present analysis uses the recycled liquid fraction as the co-substrate that is mixed with the OFMSW. Nevertheless, there are other co-substrates that could have been considered, such as biomass originating from forestry and agriculture, along with industrial and municipal residues and waste. In an urban context, sewage sludge was found to be the feedstock that is mostly mixed with the OFMSW (Ratanatamskula, et al., 2015) (Kim, et al., 2003). According to literature, their combination could improve the biogas yield and the process stability (Kuglarz & Mroviec, 2009).

Three wastewater treatment plants (WWTP) are located within 10km from the area where the biogas plant is located (AySa, n.d.), which could be a great opportunity for also treating this waste flow with AD, considering that sewage sludge in CABA is stabilized, treated as biosolids, and disposed of in sanitary landfills (Luisina, et al., 2018). The results of the study from Luisina, et al., (2018) showed that while sewage sludge from CABA has a biogas potential between 250-300 mL gSV-1 and a methane content between 71-73%, the main limiting factor is the high content of pollutants. Thus, the sanitation of the sludge would have to take place prior to its utilization.

Furthermore, there is a growing interest in the utilization of aquatic biomass, not only for its utilization in food and feed production, but also as a raw material for biofuel production, including biogas (Burton, 2009; Wellinger, 2009; Angelidakiet al., 2011). Recent studies showed that the co-digestion of algae and food waste could lead to a higher biogas yield than that of algae and food waste alone (Zhao & Ruan, 2013).

Two groups of algae are particularly interesting for the biogas sector, macroalgae and microalgae (Wellinger, et al., 2013). In the context of a biogas plant, they can be harvested in a pond with the liquid effluent from the digester, but also during wastewater treatment in WWTP (Cai, et al., 2018). While the cultivation of algae in installations used controlled conditions are not cost-effective, the application of wastewaters as a culture medium contributes to a cost reduction related to the supply of water and nutrients necessary for the effective growth of algae biomass, including high C02 concentration, which intensifies algae growth (Dębowski, et al., 2013). Therefore, considering the proximity of WWTP to the biogas plant, potential synergies between them could be explored.

4.1.2. Heat and energy requirements

Regarding the electricity and heat consumption, it can be noticed that C-2 consumes almost 2 times more electricity than C-1, given that the high-pressure compressor requires a large amount of electricity, namely 53% of the total electricity consumption of the plant. However, in both case studies, the consumption of steam is estimated to be the same as the heat requirements correspond to processes that are common to both case studies.

As for the relationship between energy consumption and production. In C-1, the total heat consumption compared to the total heat produced by the CHP system is equivalent to 9%. Compared to other similar studies, the heat consumed ranges between 12% to 23% of the heat produced in the plant (Piñas Velásquez, et al., 2018). The obtained 9% value, even if lower than what other studies have estimated, can be considered as an acceptable result, given that the thermal efficiency assumed in the study by Piñas Velásquez, et al., (2018) is lower than the one in the present study.

The remaining 91% of the steam produced in the CHP unit that is not consumed, is assumed to be wasted as there is not an existing way to send the steam for its utilisation in households. Supplying heat to a district heating system will be efficient and economically viable depending on the temperature of the steam, and a sufficient heat demand in the proximities of the biogas plant (Hijazi, et al., 2016) (Esteves Mano, et al., 2019). Moreover, the excess heat could be also utilized with the purpose of closing the food-energy cycle, for example, by using it in agricultural greenhouses (Gholizadeh & Roshandel, 2021) (Burg, et al., 2020) and for algae cultivation (Andersson, et al., 2012).

Regarding electricity in C-1, the total electricity consumption compared to the total electricity produced in the CHP system is equivalent to 18%. Comparable systems consume between 5.7% and 26% of the electricity (Hijazi, et al., 2016) (Piñas Velásquez, et al., 2018), showing that the obtained value is situated within the mentioned range. The remaining 82% of the electricity produced is injected to the grid. It is estimated that the total electricity produced in the plant could supply 3109 households (Hipotecario Seguros, 2021).

4.1.3. Market for AD products

4.1.3.1. Market for renewable electricity

According to the Law 27191, the national government set renewable energy targets to reach a share of the electricity mix of 16% in the year 2021, and 20% in the year 2025 (Honorable Congreso de la Nación Argentina, 2021). However, in the year 2021, the share of renewables corresponded to 13% of the total demand, namely 3% behind the targets (CAMMESA, n.d.). Thus, the local government is expected to take action to accelerate the incorporation of renewable energy into the energy matrix and reach the future targets.

Additionally, the government expressed their interest in smaller-scale and distributed energy generation projects that can directly supply to the local grid. While centralized energy production can be more sensitive to the risk of interruption of energy distribution in case of significant weather events, distributed electricity production could balance energy production, when grids are more vulnerable, and also act as energy storage and balance other renewable intermittent energy sources such as wind and solar (Persson, et al., 2014).

In this regard, with a net electricity production of 7 Gwh/y, C-1 could supply 0.08% of CABA's households with electricity. If the totality of the current OFMSW was treated with AD (1,617 tons/d), 189 Gwh/y could be produced, equivalent to 2.3% of the residential electricity consumed in the city.

4.1.3.2. Market for bio-CNG

The CNG market represented 5% of the total demand for natural gas in 2021, a consumption of 183M m3 of CNG during the last year (Buenos Aires Ciudad, 2022). With the increase of the prices of liquified vehicle fuel, the demand for CNG has been growing (Fagerström, et al., 2018), and is expected to increase by a total of 135% by the year 2025 (FAO, 2020).

In this regard, with a production of around 1M m3/y of bio-CNG, C-2 could cover 1% of CABA's total yearly CNG demand. If the totality of the current OFMSW was treated with AD, the production of bio-CNG could reach 14% of the total demand.

4.1.3.3. Market for biofertilizers

Organic fertilizers are becoming increasingly valuable given the growing market for organically grown foods. In Argentina, during the year 2020, the organic harvested area increased by 22% compared to the previous year, maintaining the positive trend of the past 10 years. The province of Buenos Aires was the one that increased the most its organic harvested area compared to the year 2019 (69%), with 29 thousand new hectares, or a total of 153,894 organic harvested hectares in the province in the year 2020 (SENASA, 2021). While only 1,16% of the province's surface corresponds to organic harvested crops, it can be noted that there is an increasing demand for organic grown food and hence, the use of organic fertilisers.

Agricultural use of biofertilizers

Although the City of Buenos Aires is an urbanised area with almost no agricultural activity, within a distance of 100km from the location of the potential biogas plant, a significant agricultural activity can be found in its neighbouring departments, namely Campana, Pilar, General Rodriguez, Marcos Paz, Cañuelas, San Vicente, Bransen and La Plata, as shown in grey in Figure 49. Only considering the main crops (wheat, corn, soy, and sunflower), there is a yearly demand of N, K, and P of 1,071, 818 and 89 tons, respectively (see Appendix D: Nutrients' consumption) (Gobierno de la Provincia de Buenos Aires, n.d.) (IPNI, 2011).

Figure 49 CABA and surrounding area from (Observatorio Metropolitano, n.d.)

Urban use of biofertilizers

Additionally, biofertilizers could be used in lower quantities in urban farms, and communal or private gardens where food is grown. In this regard, CABA's government enacted Law 6377 in 2020, with the aim of promoting and disseminating urban agriculture practices with sustainable methods. Additionally, the Climate Action Plan 2050 for CABA aims to have organic gardens in every low-income neighbourhood of the city by the year 2025 (Gobierno de la Ciudad de Buenos Aires, 2020).

The biofertilizer produced from digestate could be then employed by the agricultural sector or by individuals, and public and private initiatives (e.g., as InterHuertas CABA, Red de Huertas Comunitarias, and Sitopa) that promote the urban production of organic food. Only considering the agricultural consumption of nutrients, C-1 and C-2 could cover 5%, 1% and 26% of the demand of N, P and K. If the totality of the OFMSW would be treated, then the values would be of 113%, 25% and 540%, indicating that additional markets would need to be found for N and K as it exceeds the consumed nutrients by the mentioned crops within a certain distance. Nevertheless, the allocation of the additional nutrients should not pose any issues considering the vast agricultural activity that can be found in the Province of Buenos Aires. However, the additional costs of transportation over longer distances would need to be considered.

4.2. Economic performance

4.2.1. Total costs

According to the results obtained from the TEA, the CAPEX is slightly higher in C-1 compared to C-2, mainly given by the cost of the CHP unit in C-1, which is 46% higher than the cost of the biogas upgrading unit in C-2. Regarding the OPEX, C-1 has 15% lower operational costs than C-2, due to the higher cost of the utilities. A higher CAPEX for the production of bioelectricity, and a higher OPEX for the production of biomethane are supported by the findings of Budzianowski & Budzianowski, (2015).

However, they don not always match with the results found in literature, given that the opposite is true in Morero, et al., (2017) for example, where the equipment investment costs are higher for bio-CNG compared to bioelectricity. However, the paper does not explain which upgrading unit is selected in the analysis, which certainly can impact the economic output, as shown by Florio, et al., (2019). Similarly, the study by Goulding & Power, (2013) concluded that bio-CNG is a more expensive alternative than bioelectricity, mainly due to the elevated investment costs. This can be explained by the boundaries defined in their analysis, which also take the capital costs for distributing the product to the consumers, which leads to the distribution costs being higher for bio-CNG than for bioelectricity.

Regarding the income, the results of the present analysis showed that C-2 can make higher revenues compared to C-1. Literature shows that this is typically the case, as found in the studies from Goulding &

Power, (2013), Morero, et al., (2017), and Budzianowski & Budzianowski, (2015), despite that the selling prices and subsidies assigned are different depending on the country where the study has been conducted.

4.2.2. Unitary costs

4.2.2.1. Bioelectricity

The obtained cost of producing 1 Mwh of electricity corresponds to 65€/Mwh. While this price is not competitive with conventional electricity prices, nor with solar and wind sources in Argentina, whose production cost is around 50 Euro/ton, it is substantially lower than the market price at which electricity from biogas has been purchased during the last tendering round, ranging from €0.15-€0.18/kwh (Ministerio de Energía y Minería de la Presidencia de la Nación, n.d.).

The result obtained is similar to the one from a study in Chile, corresponding to 67€/Mwh (Allendes, 2015). Nevertheless, in Europe, the average production cost of electricity from biogas is about €38/Mwh (European Comission, 2016), which can be explained by the fact that AD has been more adopted in Europe compared to Latin America, consequently leading to the reduction of its costs.

4.2.2.2. Bio-CNG

Regarding bio-CNG, the unitary production cost obtained is 16€/MMBTU, in the range of what similar studies in Argentina have concluded, namely between 15 and 19.6 Euro/MMBTU (CADER, 2020) (FAO, 2020). The result obtain is also in line with the worldwide average of 16 €/MMBTU for small industrial biodigesters (IEA, n.d.), and is comparable to the cost estimated in Europe, ranging from 17 to 19 Euro/MMBTU (European Comission, 2016).

The study from CADER, which estimates a unitary production cost of 19.6 Euro/MMBTU can be attributed to the higher operational cost as a result of the rental of the land where the plant is built, and additional cost related to chemical analyses, which were not considered in the present research. Additionally, that study also accounts for the costs of transporting the bio-CNC from the plant to the distribution point, which is also out of the scope in the present research. In the case of the study that obtained a unitary cost of 15 €/MMBTU, it is important to note that it corresponds to a project with a larger production scale, namely 500 m3/h of biogas, whereas the one studied in this thesis produces 360m3/h. Following the economies of scale principle, the higher the production, the lower the unitary costs.

Similar to the production of bioelectricity, the price of bio-CNG cannot compete with the price of CNG from natural gas, given that the unitary production cost of CNG from natural gas corresponds to 21 Euro/MMBTU (Camuzzi, n.d.).

4.2.2.3. Cost of waste treatment

In C-1, the unitary costs of treating 1 ton of the OFMSW corresponds to 23 €/ton and 26 €/ton in C-2, about 52% and 68% more expensive than what the municipality currently pays to transport and dispose municipal solid waste in sanitary landfill, which corresponds to 15 €/ton. Considering that the government expressed that they would consider paying up to 100€ per ton of waste treated in AD, the results obtained are very optimistic.

4.2.3. Financial results

In C-1 and C-2, a positive NPV, and IRR, and a payment period below the 20 years of the plant operation were obtained. These results indicate that in both cases the projects show positive financial results, which means that they not only can cover its investment costs but also can generate additional revenue. Nevertheless, it is important to note that this is only possible due to highly subsidized selling prices.

The results obtained for the financial indicators in the present study are comparable with the results obtained in similar studies, which show IRR values that range from 8% to 21%, and a payback period ranging from 4 to 9 years (Asian Development Bank, 2022) (Allendes, 2015) (Klimek, et al., 2021) (Yunjun, et al., 2018). It is observed that, while the obtained results of this study are within the ranges presented, it is important to note that every study uses different assumptions. For example, in the study by Allendes, (2015), which is the one that perform the best among the cited studies, his analysis of the total costs did not include the cost associated with the transportation of the substrate to the plant, the depacker station and the pasteurization of the substrate, leading to lower investment costs and hence more favourable financial results.

4.2.3.1. Sensitivity analysis on the economic performance

Regarding the sensitivity analysis of the CAPEX, OPEX and the income, the results of the present study concluded that while changes to the capital and operational expenditures are one of the main factors that can led to a negative NPV (Allendes, 2015) (Fuess & Zaiat, 2018), the economic performance of the case studies is more sensitive to changes in the income. Similarly, the analyses by the Asian Development Bank, (2022), Klimek, et al., (2021), Yunjun, et al., (2018), concluded that changes made to the benefits had a bigger impact on the performance, than changes made to the costs. As showed in those studies, a decrease of the benefits in the range of 10%- 20% lead to a negative NPV.

The amount of biogas produced, and the selling prices are key factors for the income that can be obtained, and in consequence the economic performance of the projects, as it pointed out by Fuess & Zaiat, (2018), Lawson, et al., (2021) and Li, et al., (2017) and Fuess & Zaiat, (2018). In addition, regarding the selling price of biomethane, Goulding & Power, (2013) concluded that a price of 32€/MMBTU will make such a project financially unfeasible. Similarly, the results obtained in the present research showed that, for C-2, a negative NPV is obtained with a selling price lower than 33€/MMBTU.

In the same line, the performance of the case studies was largely affected by the removal of the subsidies in the selling price of bioelectricity and bio-CNG. This was also stated by Gebrezgabher, et al., (2010), and Klimek, et al., (2021), among others, who showed that removing the subsidies embedded in the selling price always led to negative results. Thus, unless subsidies are provided, the market selling price of conventional electricity and natural gas will not be sufficient for the project to reach the amount of income needed for the projects to be economically feasible. Nevertheless, the study from Morero, et al., (2017) argues the opposite. Nevertheless, it is observed that this is possible due to the high selling price of biofertilizers, assumed to be 80€/ton, which is around 10 times higher than the price assumed in this study. If the price of biofertilizers in Morero, et al., (2017) would be the one assumed here (€0.7/ton), the project will certainly not be NPV positive, thus subsidies will be needed to make it so.

Lastly, the variations in the discount rate are also an important factor in the performance of a project. However, while a 50% change can lead to a negative NPV, this parameter is not as sensitive as the other ones that were mentioned. Nevertheless, the sensitivity of the discount rate depends on the value of the other variables. In this regard, in the study from Li, et al., (2017), a change in the discount rate of 10% made the difference between a positive and negative NPV. However, this is because the project evaluated in that study had higher capital expenditure, which made it more vulnerable to changes in the discount rate.

4.4.2. Potential AD promotion strategies

As it was mentioned, without price subsidies, none of the case studies would have shown positive results of the financial indicators. However, even then, the sensitivity analysis showed that a positive economic performance is not guaranteed, and that there are high chances that the project becomes NPV negative.

Thus, the support of the government is important for this technology to take-off and over time, see a reduction of its costs, as it has happened with other renewable energy sources. In this regard, there are different supporting schemes and instruments that are currently explored in other countries and could be considered in the context of Argentina (Thrän, et al., 2014). In this regard, the FAO (2020) and CADER (2020) have reflected on the possible promotion strategies and concluded that there are three that are the most relevant ones: feed-in tariffs, pricing of externalities, and tenders. A brief review of the current state of these three promotion mechanisms in CABA are presented hereafter.

4.4.2.1. Feed-in tariffs

To promote renewable energy investments and reach the energy targets by the year 2025, the Law 27191 established the provision of subsidy with a feed-in tariff for facilities producing electricity up to 30MW of US$0.11/kWh for solar projects and US$0.005/kWh for wind, geothermal, biomass, biogas and hydro projects. However, there is no such feed-in tariff program for vehicle fuels (Norton Rose Fulbright, 2016). Similar to the feed-in tariff for electricity, a feed-in tariff for biomethane, while it would increase the price of fuel, it would also compensate and cover for the costs associated with the production of biomethane (FAO, 2020). A higher support for renewable electricity compared to fuel is also identified in European countries, where the allocation of supporting schemes also goes primarily to the electricity sector (European Comission, 2016).

4.4.2.2. Taxing externalities

Externalities correspond to the unintended and often unaccounted side effect of any economic activity. Environmental externalities are a particular class of external market effect which are directed to society, and can be positive when they generate benefits, and negative externalities, when they generate costs that are not compensated for by other parties (Ding & Chao Deng, 2014) (Larkin, 2013) As it was observed in the carbon footprint, the emitted CO_2eq emissions corresponds to environmental cost, and the avoided burden, to environmental benefits.

As mentioned before, the selling prices of bioelectricity and bio-CNG are not competitive with conventional FF-based energy sources. In this regard, changes were made in 2018 to the Law 27430 on income taxes, whose modifications included the addition of a CO_2 tax with the aim of internalising the environmental impacts to the price of fuels. The tax is being gradually applied, starting in 2019 with 1 USD/ton of CO_2 until reaching the regimen level in 2028 of 10 USD/ton of CO_2. Nevertheless, the Law exempted natural gas of fossil origin from the list of the products taxed. Since the majority of the electricity mix corresponds to natural gas, and natural gas is also used in vehicle fuel (CNG), this Law does not help with the promotion of bioelectricity and bio-CNG.

While taxing CO2 emission is one way of promoting renewable energy investment, another way is to compensate for positive externalities. Studies suggest that if the environmental and societal benefits such as job creation or urban development were compensated to the cost of biomethane, between €40-60/Mwh could be deducted (Simon, 2019).

4.4.2.3. Tendering program

In early 2016, the Government of Argentina launched the RenovAr initiative. It is an auction-based renewable energy program designed to scale-up private renewable generation capacity. There were already 3 rounds of the program in the past years, and a potential 4th one which was expected to come into force at the end of the year 2019, but so far it did not take place. Some of the financial benefits include a max of €2.5 M in tax savings, and an exemption of taxes from the year 9, which created more favourable and less risky conditions for investors (Argentina.gob.ar, n.d.). According to the experts, the 2025 energy targets can be met only with this program, given how successful the previous programs were in accelerating the implementation of renewables (El Economista, 2019).

4.3. Global warming potential

4.3.1. Carbon footprint distribution

The results of the carbon footprint showed that C-1 has a lower GWP compared to C-2. The latter has a larger environmental impact resulting mainly from the electricity that needs to be supplied from the grid, predominantly composed of fossil fuel sources; and a lower avoided burden. Consequently, the study has claimed that C-1 is a better option from a carbon footprint point of view. In this regard, Labutong et al. (2012) and Thyø, et al., (2007) support this statement by claiming their studies that biogas should be used for CHP rather than upgrading it into biomethane, to maximize GHG mitigation. Nevertheless, the study from the European Commission (2016) states the opposite, which can be explained by the fact that emission factors for electricity in Europe are rapidly declining with the growth of the incorporation of renewables to the grid.

Regarding the results obtained from the distribution of the carbon footprint for each case study, it was concluded that the big majority of the impact corresponded to the plant operation, supported widely in literature by Mezzullo et al., (2013), Hartmann, (2006), Berglund, (2006), Poeschl, et al., (2012), Bacenetti, et al., (2016), who state that the impacts associated with the plant construction are negligible.

Regarding the distribution of the carbon footprint in the construction phase, the present study showed that the main impact corresponds to the CHP and membrane units, followed by the digester, and the storage tanks. Similarly, the study from Mezullo et al., (2013) concluded that the main contributors are the manufacturing of the digester and the storage tank. Given that this study set its system boundaries around the production of biogas, their results are comparable to the ones obtained here.

In the same line, Hartmann et al., (2006) concluded that the main contributors are the digester, the CHP unit, and the storage tanks. Nevertheless, the reason that the digester has the largest footprint is because it is made of steel, which has a bigger impact than a digester made of concrete (Kua & Maghimai, 2016), like the one chosen in this study. Regarding the distribution of the carbon footprint during plant operations, similar to the results by Hartmann et al., (2006) the emissions in the CHP unit and the transportation were identified as the main contributors.

The results of the carbon footprint showed that both case studies have a negative GWP, which is widely supported in literature (Evangelisti, et al., 2014) (Labutong, et al., 2012) (EBA, 2020) (Mezzullo, et al., 2013) (Hartmann, 2006). Nevertheless, according to Hijazi, et al., (2016), if cultivated crops are used as a substrate for biogas production, the results might not be as favourable.

Additionally, this research showed that more than one avoided burden category (e.g., energy, biofertilizers, landfilling) had to be included to reach a negative GWP in C-2, also supported by Styles, et al., (2022), and Tian, et al., (2021). Nevertheless, for Ardolino, et al., (2018), the savings from fuel alone were sufficient to surpass the amount emitted.

The results of the present research showed that the savings from landfilling correspond to the largest reduction category, however the vast majority of the mentioned studies do not include landfill as one of their categories, given that most of them do not take the OFMSW as their feedstock, but plant biomass and animal slurry (Hijazi, et al., 2016). Nevertheless, for those who do, the avoided waste management represents the larger reduction category (Styles, et al., 2022). After the saving from landfilling, most of the credits generated are obtained from the substitution of conventional energy and chemical fertilizers (Mezullo et al., 2013) (Tian, et al., 2021) (Morero, et al., 2017).

4.3.2. Sensitivity analysis of the GWP

The results from the carbon footprint showed that the case studies can lead to carbon savings despite the simulations performed in the sensitivity analysis due to the significant difference between the avoided and the emitted emissions. Nevertheless, the changes in the amount of biofertilizers sold had the largest impact on the carbon footprint balance, as the benefits were reduced, and the impact of additional transportation and landfilling were added. In this regard, it was found in literature that projects are particularly sensitive to changes in the transportation distance (Tian, et al., 2021). While changes to the transportation alone were not simulated here, the additional transportation in S-4 had a significant impact in the total amount of CO2eq emitted in S-4.

Moreover, the reduction of the equipment's efficiency had the second largest impact, since it substantially reduced the amount of energy produced and hence, the avoided burden associated to it. In this regard, Morero, et al., (2017) stated that changes in the efficiency of +/-10% can lead to a reduction in the emissions of +/-16%, like the results obtained in the present carbon footprint.

4.3.3. GHG reduction strategies

While the sensitivity analysis showed that under certain circumstances the emitted emissions are reduced, the sensitivity analysis did not evaluate any technology-related reduction strategies, which can individually address the carbon hotpots of project's operation. Therefore, common reduction measures found in literature are briefly presented hereafter.

Case study 1

The carbon hotspots identified in C-1 are associated with the losses to the air in CHP unit, followed by the transportation, consumption of ignition oil and activated carbon. Besides improving the efficiency of the CHP unit, other techniques could be incorporated to reduce its impact, such as avoidance techniques or the treatment of the exhausted gas (Hijazi, et al., 2016). The exhausted gas comprises methane emissions that have passed through the combustion process unburned and into the exhaust gas flow, also called "methane slip". Because methane burns more completely at hotter temperatures, some gas can pass unburned if it is close to any of the cooler areas found in the combustion chamber. Thus, by optimising the chamber to minimise these cool areas and eliminate any crevices where methane can escape combustion, the methane slip can be reduced (Wärtsilä Corporation, 2020). Another strategy to reduce the methane slip is to minimize the overlap time of the inlet and the outlet vales, which while it helps with cooling, it also increases the methane slip. Additionally, besides prevention strategies, catalysts are being developed to treat the exhausted gas before it is released to the air (MWM , 2016) (Wärtsilä Corporation, 2020).

Regarding the emissions from transportation, minimising transportation distances could reduce the environmental impact, together with choosing alternative greener fuels. However, in this case study, reducing the distance is not possible, thus the latter might be a more suitable option. Additionally, to reduce the impact of the consumed ignition oil and AC, plant oil fuel can be used instead (Thuneke, 2013), and the recuperation of AC with thermal regeneration with CO2 could be an environmentally sound option compared to its immediate disposal after utilization (Copola & Papurello, 2018).

Case study 2

The carbon hotspots identified in C-2 are associated with the emissions from electricity consumption, losses to the air in the membrane and the consumption of activated carbon. In this regard, to reduce the impact during plant operation in C-2, the electricity consumed on site could be supplied from low-emission sources given that in the present analysis, the electricity is consumed from the electricity mix, where fossil fuel energy sources are predominant. However, alternative local renewable electricity could be purchased from local producers or could be produced on site, where the AD plant is located, either by installing solar panels or a wind turbine. Moreover, to minimise the impact of the losses from the membrane unit, instead of releasing the off gas to the environment, it could be treated with oxidation, which consequently prevents almost any methane from being released (Prodeval, 2022).

5. Conclusion

Two case studies were assessed in the present study of two alternatives for the end use of biogas: bioelectricity (C-1) and bio-CNG (C-2), with the aim of evaluating and comparing their performance from an economic and environmental perspective.

The assessed case studies involved the scoping of an AD biogas facility to be implemented in the outskirts of the City of Buenos Aires. The project involved the treatment of 58 thousand of tons of substrate a year of OFMSW and a recycled liquid fraction. The AD technology corresponds to a one stage wet mesophilic system, that is continuously fed with substrate which remains there for 33 days, the duration of the digestion process. Biogas and digestate are produced as a result of this process. The latter is sent for pasteurization for its future utilization as biofertilizer, while the former goes through a cleaning process, where H2S and H2O are removed from the biogas before bioelectricity can be produced from it. To produce biomethane as vehicle fuel, biogas needs to go through an additional cleaning step to remove CO2 before it can be compressed.

The results of the mass and the energy balance showed that 8,827 tons of biofertilizer can be produced a year in both case studies. In C-1, a total of 8,394 Mwh/y of electricity and 7,462Mwh/y of heat are produced in the CHP unit, from which a total of 1,553 Mwh/y (19% of total) is used internally to power the equipment in the plant, and 691 Mwh/y of heat (9% of total) is used to heat the digester and heat exchangers. While the remaining electricity is injected to the grid and supplies over 3 thousand households in CABA, the remaining heat is not used externally and hence is lost. In C-2, 3,405 Mwh/y of electricity and 619 Mwh/y of heat are consumed in the plant. The demand of steam is covered by its production in the boiler, while electricity is sourced from the grid given that none is produced in the plant.

The amount of electricity, bio-CNG, and biofertilizers produced in the plant could supply 0.08% of the total household electricity demand in C-1, 12% of the total CNG demand in C-2, and 5%, 1% and 26% of the demand of N, P and K in both case studies. Nevertheless, if the total of the OFMSW produced in CABA was treated with AD, 2.3% of the residential electricity, 14% of CNG, and 113%, 25% and 540%, of the demand of N, P and K could be supplied. While the amount of nutrients that could be produced surpasses the neighbouring department's demand of nutrient for harvesting some crops, allocating the additional amount of nutrients should not pose any issues considering the vast agricultural activity that can be found in the Province of Buenos Aires. In addition, regarding heat, while its utilization is not foreseeing in any of the case studies, it could be considered to use it in a nearby district heating system or in agricultural greenhouses or algae cultivations, in line with closing the food-energy cycle.

Regarding the total costs, the investment costs in C-1 corresponded to €3,679,288, and €3,495,017 in C-2, the operational costs to €359,699 and €428,682, and the income to 1,2M and 1,4M in C-1 and C-2, respectively. The results of the TEA showed that C-1 had 5% higher investment costs compared to C-2, while the latter had larger operational costs by 17%, and an 8% greater income. In the case of C-1, the higher CAPEX is explained by higher equipment costs of the CHP unit compared to the membrane unit. Regarding the OPEX, the utilities were higher in C-1 compared to C-2, given the additional costs that are associated with supplying the plant with electricity from the grid. Lastly, C-2 has a greater income compared to C-1 given that the revenue made from selling bio-CNG is higher than the revenue made from selling bioelectricity. Additionally, the unitary costs obtained for the products corresponds to 65€/Mwh for bioelectricity, 16€/MMBTU for bio-CNG and €23 and €26 per ton of waste treated, which are values that are comparable to ranges found in literature.

The results of the financial indicators showed that, with an NPV, IRR and a payback period of €1,5M, 11% and 8,2 years, C-2 has a better economic performance than C-1, which has an NPV, IRR and payback period of 1,1M, 9% and 9 years. Thus, from an economical perspective, C-2 is considered to be the best alternative of the two.

Nevertheless, the results of the sensitivity analysis showed that both case studies are sensitive to the changes simulated. From all simulations, changes to the selling price (S-3), to the quantities of biofertilizers sold (S-4), and to the amount of energy produced (S-2), had a substantial impact on the of revenue made, and consequently, the economic performance. In this regard, it was noted that the income is the most sensitive to variations, compared to the CAPEX and the OPEX, given that a variation of -9% and -11%, 18% and 14%, and 25% and 27% in C-1, and C-2, respectively, can lead to a negative NPV. Therefore, the simulations showed that even with subsidized selling prices, there are high chances that the case studies become NPV negative, thus further promotion strategies should be considered by the government to encourage the implementation of this technology, such as feed-in tariffs, taxing externalities, and the implementation of tendering programs.

The results of the carbon footprint showed that C-2 had higher annual emissions than C1, corresponding to 1.03E-01 tonCO2eq/ton OFSMW vs 7.92E-02 tonCO2eq/ton OFSMW. The reasons for this difference lays in the fact that C-2 is not electricity self-sufficient like C-1, and thus needed to supply electricity from the grid. Regarding the avoided burden, the reductions were primarily caused by the avoided landfilling, and the replacement of conventional energy sources and fertilizers, which lead to a reduction of 3.33E-01 tonCO2eq/ton OFSMW in C-1, and 2.57E-01 tonCO2eq/ton OFSMW in C-2.

The sensitivity analysis of the carbon footprint showed that, despite the simulations performed, the case studies can have large carbon savings. However, both case studies were most sensitive to the changes in the amount of biofertilizers sold (S-4) since the impact of the additional transportation to the landfill and the impact of the landfill are substantial. Secondly, the variations in the efficiency had the second largest impact on the carbon footprint, given that a reduced efficiency leads to a lower energy production and an increase of the losses to air.

To improve the net carbon footprint of the case studies, further reduction strategies could be considered to address the hotspots, corresponding to the losses to the air in CHP unit, followed by the transportation, consumption of ignition oil and activated carbon, in C-1, and to impact of electricity consumption, losses to the air in the membrane and the consumption of activated carbon, in C-2. Some reduction strategies that can be considered in C-1 are related to 1) reducing the methane slip in the CHP by minimising cool areas and eliminating any crevices where methane can escape combustion, 2) using alternative transportation fuels, 3) replacing diesel oil by a plant oil fuel, and 4) recovering activated carbon. In C-2, reduction strategies are in line with 1) procuring renewable electricity to power the plant, 2) treating the off-gas that exits the membrane, and like C-1, 3) recuperating activated carbon so it is not disposed after utilization.

Additionally, while the case studies analysed in the present research use the OFMSW as a substrate, the co-substrate used could be expanded to other waste flows, such as sewage sludge, considering the proximity of WWTP to the biogas plant, but also algae biomass. Research shows that while their cultivation in controlled environments has been proven cost-inefficient, synergies related to their cultivated in WWTP could be explored in the context of CABA.

To conclude, while C-2 is preferable from an economic point of view, C-1 has a better GWP than C-2. However, the simulations showed that both case studies are sensitive to changing conditions, which can easily lead to negative results of the financial indicators. Therefore, the role of the government is crucial to create more favourable conditions for the investment in this technology, considering the benefits associated to it, that were identified throughout this research, and can be summarized as follows: 1) distributed energy generation, and nutrient recycling, 2) avoidance of the impacts related to landfilling organic waste, 3) avoidance of the impact related to the production of conventional electricity, vehicle fuel and fertilizers, 4) potential of reaching organic waste reduction targets, 5) increase of the amount of renewables in the energy mix, 6) development of the local economy, and 7) job creation.

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Appendices

Appendix A: Mass balance

The incoming and outcoming flows from each process shown in Figure 4 are presented in the following table.

Component: Depacker

	Stream	Flow (t/y)
IN	OFMSW	23,333
IN	Liquid fraction	35,000
OUT	Plastic bags	2
OUT	Substrate	58,331

Component: Anaerobic digester

	Stream	Flow (t/y)
IN	Substrate	58,331
IN	Air	129
OUT	Digestate	55,169
OUT	Desulphurized biogas (step-1)	3,291
OUT	Losses to air	1

Component: Screw press

	Stream	Flow (t/y)
IN	Digestate	55,169
OUT	Liquid digestate	46,342
OUT	Solid digestate	8,827

Component: Liquid storage tank

	Stream	Flow (t/y)
IN	Liquid digestate	46,342
OUT	Liquid fraction to depacker	35,000
OUT	Liquid fraction purged	11,342

Component: Pasteurization tank

	Stream	Flow (t/y)
IN	Solid digestate	8,827
OUT	Pasteurized digestate	8,827

Component: Solid storage tank

	Stream	Flow (t/y)
IN	Pasteurized digestate	8,827
OUT	Biofertilizer	8,827

Biofertilizer	Flow (t/y)
N	58
P	10
K	23

Component: Activated carbon filter

	Stream	Flow (t/y)
IN	Dried biogas	3,047
IN	Activated carbon filter	4
OUT	Dried biogas	3,047
OUT	Activated carbon filter	4

Component: Compressor before CHP

	Stream	Flow (t/y)
IN	Dried biogas	3,047
IN	Air	13
OUT	Cleaned biogas	3,060

Component: CHP unit

	Stream	Flow (t/y)
IN	Cleaned biogas	3,060
IN	Ignition oil	275
IN	Water	2,295
OUT	Flue gases	282
OUT	Heat (hot water)	2,534
OUT	Electricity	2,815

Component: Boiler

	Stream	Flow (t/y)
IN	Cleaned biogas	366
IN	Water	274
OUT	Heat	640

Component: Membrane unit

	Stream	Flow (t/y)
IN	Cleaned biogas	2,694
OUT	Biomethane	1,159
OUT	Off-gas	1,536

Component: High pressure compressor

	Stream	Flow (t/y)
IN	Biomethane	1,159
OUT	Bio-CNG	1,159

Appendix B: Carbon footprint analysis

Source	Reference process in ecoinvent	Process	C-1 (tCO2 eq)	C-2 (tCO2 eq)
Ecoinvent 3.8	steel production, electric, low-alloyed	Depacker	4.3E-05	4.3E-05
Ecoinvent 3.8	gas motor production, 206kW	Motor of depacker	1.9E-06	1.9E-06
Ecoinvent 3.8	conveyor belt production (RoW)	Screw conveyor	5.6E-06	5.6E-06
Ecoinvent 3.8	steel production, electric, low-alloyed		1.7E-07	0.0E+00
Ecoinvent 3.8	anaerobic digestion plant construction, for biowaste (RoW)	Anaerobic digester	1.2E-03	1.2E-03
Ecoinvent 3.8	steel production, electric, low-alloyed	Screw press	4.7E-06	4.7E-06
Ecoinvent 3.8	liquid storage tank production, chemicals, organics (roW)	Pasteurization tank	1.8E-08	1.8E-08
Ecoinvent 3.8	absorption chiller production, 100kW	Dehumidifier unit	1.2E-05	1.2E-05
Ecoinvent 3.8	steel production, electric, low-alloyed	Activated carbon filter	3.0E-06	3.0E-06
Ecoinvent 3.8	, glass fibre reinforced plastic production, polyamide, injection moulded		2.1E-05	2.1E-05
Ecoinvent 3.8	polyvinylchloride production, suspension polymerisation		1.2E-05	1.2E-05
Ecoinvent 3.8	polypropylene production, granulate		5.3E-06	5.3E-06
Ecoinvent 3.8	air compressor production, screw-type compressor, 300kW	Compressor before CHP	1.0E-05	4.3E-10
Ecoinvent 3.8	air compressor production, screw-type compressor, 300kW	Compressor high pressure		2.4E-05
Ecoinvent 3.8	liquid storage tank production, chemicals, organics (roW)	Storage tank (solid)	2.9E-04	2.9E-04
Ecoinvent 3.8	liquid storage tank production, chemicals, organics (roW)	Storage tank (liquid)	2.7E-04	2.7E-04
Ecoinvent 3.8	chromium steel pipe production	Heat exchangers	4.9E-06	4.9E-06
Ecoinvent 3.8	pump production, 40W	Pump	6.6E-06	6.6E-06
Ecoinvent 3.8	gas boiler production (RoW)	Boiler		6.1E-05
Ecoinvent 3.8	blower and heat exchange unit, decentralized, 180-250 m3/h | blower and heat exchange unit production, decentralized, 180-250 m3/h | RoW | unit	Blower	3.8E-08	
Literature		CHP unit	3.2E-03	0.0E+00
Literature		Membrane unit		2.5E-03
Literature		Losses in screw conveyor	1.3E-06	1.3E-06
Literature		Losses in digester	1.1E-05	1.1E-05
Literature		Losses in CHP unit	3.4E-02	-
Literature		Losses in membrane unit		1.1E-02
Literature		Losses in biofertilizer's storage tank	8.3E-05	8.3E-05
Ecoinvent 3.8	electricity, high voltage, production mix	Electricity consumption	-	5.4E-02
Ecoinvent 3.8	market for tap water (RoW)	Water for CHP unit	1.0E-04	
Ecoinvent 3.8	market for tap water (RoW)	Water for boiler		1.2E-05
Ecoinvent 3.8	market for diesel (RoW)	Ignition oil consumption	5.7E-03	0.0E+00
Ecoinvent 3.8	activated carbon production, granular from hard coal	Activated carbon	1.6E-03	1.6E-03
Ecoinvent 3.8	transport, freight, lorry 16-32 metric ton, EURO5 | market for transport, freight, lorry 16-32 metric ton, EURO5 | RoW | ton kilometer	Transportation	3.3E-02	3.3E-02
			7.9E-02	1.03E-01

Appendix C: Financial indicators

To calculate the cash flow and consequently the financial indicators (NPV, IRR and payback period) for C-1, the following parameters were used, obtained from the TEA.

Table 44 Parameters used for cash flow calculation in C-1

Parameters	Value		Unit
Operational life	20		Years
Total funding requirement	€	3,679,288	EUR
Annual project income	€	1,299,490	EUR
Operating expenditure	€	359,699	EUR
Taxes	€	376,852	EUR
VAT	€	772,650	EUR
Gearing	80		%
Repayment profile	Annuity		-
Interest rate	3.9		%
Loan life (years)	20		Years
Annual depreciation	6		%

Debt	€	2,943,430
Equity	€	(735,858)

Discount rate	€	1.06
	6.0%	

Annual payment of debt	€	(214,669)
Debt Service	€	(4,293,385)
Cashflow Available	€	11,258,787

Table 45 Cash flow C-1

Year	CAPEX	Loan payments	OPEX	Tax	Annual income	Return of VAT	Return 35% of annual interest rate	Net income	Depreciation rate	Annual depreciated income	depreciation rate
0	€ 3,679,288	€ -	€ -	€ -				€ (3,679,288)		€ (3,679,288)	€ (3,679,288)
1		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 1	€ 350,844	€ (3,328,444)
2		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 1	€ 330,985	€ (2,997,459)
3		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 1	€ 312,250	€ (2,685,210)
4		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490	€ 376,852	€ 23,624	€ 748,746	€ 1	€ 593,077	€ (2,092,132)
5		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490	€ 395,798	€ 23,624	€ 767,693	€ 1	€ 573,665	€ (1,518,468)
6		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 1	€ 262,171	€ (1,256,297)
7		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 247,331	€ (1,008,966)
8		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 233,331	€ (775,635)
9		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 220,124	€ (555,512)
10		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 207,664	€ (347,848)
11		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 195,909	€ (151,938)
12		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 184,820	€ 32,882
13		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 174,359	€ 207,240
14		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 164,489	€ 371,729
15		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 2	€ 155,178	€ 526,908
16		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 3	€ 146,395	€ 673,303
17		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 3	€ 138,108	€ 811,411
18		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 3	€ 130,291	€ 941,702
19		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 3	€ 122,916	€ 1,064,618
20		€ (214,669)	€ (359,699)	€ (376,852)	€ 1,299,490		€ 23,624	€ 371,894	€ 3	€ 115,958	€ 1,180,576

Table 46 Results of financial indicators C-1

NPV	€ 1,180,576
IRR	10%
Payment period	9

To calculate the cash flow and consequently the financial indicators (NPV, IRR and payback period) for C-2, the following parameters were used, obtained from the TEA.

Table 47 Parameters used for cash flow calculation in C-2

Parameters	Value	Unit
Operational life	20	Years
Total funding requirement	€ 3,495,017	EUR
Annual project income	€ 1,408,289	EUR
Operating expenditure	€ 428,682	EUR
Taxes	€ 408,404	EUR
VAT	€ 733,953	EUR
debt is funded into the project)	80	%
Repayment profile	Annuity	-
Interest rate	3.9	%
Loan life (years)	20	years
Annual depreciation	6	%

Debt	€ 2,796,013
Equity	€ (699,003)

Discount rate	1.06
	6.0%

Annual payment of debt	€ (203,918)
Debt Service	€ (3,058,769)
Cashflow Available	€ 11,424,075

Table 48 Cash flow C-2

Year	CAPEX	Loan payments	OPEX	Tax	Annual income	Return of VAT	Return 35% of annual interest rate	Net income	Depreciation rate	Annual depreciated income	depreciation rate
0	€ 3,495,017	€ -	€ -	€ -				€ (3,495,017)		€ (3,495,017)	€ (3,495,017)
1		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 1	€ 367,667	€ (3,127,350)
2		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 1	€ 346,856	€ (2,780,494)
3		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 1	€ 327,222	€ (2,453,272)
4		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289	€ 408,404	€ 22,441	€ 798,131	€ 1	€ 632,194	€ (1,821,078)
5		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289	€ 325,550	€ 22,441	€ 715,276	€ 1	€ 534,496	€ (1,286,581)
6		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 1	€ 274,742	€ (1,011,839)
7		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 259,191	€ (752,649)
8		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 244,519	€ (508,129)
9		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 230,679	€ (277,450)
10		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 217,621	€ (59,829)
11		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 205,303	€ 145,474
12		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 193,682	€ 339,157
13		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 182,719	€ 521,876
14		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 172,377	€ 694,252
15		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 2	€ 162,619	€ 856,872
16		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 3	€ 153,415	€ 1,010,286
17		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 3	€ 144,731	€ 1,155,017
18		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 3	€ 136,538	€ 1,291,555
19		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 3	€ 128,810	€ 1,420,365
20		€ (203,918)	€ (428,682)	€ (408,404)	€ 1,408,289		€ 22,441	€ 389,727	€ 3	€ 121,519	€ 1,541,884

Table 49 Results of financial indicators C-2

NPV	€ 1,541,884
IRR	11%
Payment period	8

Appendix D: Nutrients' consumption

To estimate the yearly amount of nutrients consumed in the departments of Campana, Pilar, General Rodriguez, Marcos Paz, Cañuelas, San Vicente, Bransen and La Plata for growing corn, soy, wheat and sunflower, the number of harvested hectares per crop type is obtained from the Gobierno de la Provincia de Buenos Aires, (n.d.). The results are displayed in Table 50. Moreover, the nutrients needed per hectare were obtained from IPNI, (2011), and are shown in Table 50. The results of the calculation are shown in Table 52.

Table 50 Number of hectares per crop and department

Department	Corn	Soy	Wheat	Sunflower
Campana	2,800.00	15,500.00	3,100.00	-
Pilar	470.00	1,430.00	300.00	-
Gr Rodriguez	1,000.00	5,650.00	450.00	-
Marcos Paz	2,390.00	7,100.00	1,100.00	200.00
Cañuelas	2,420.00	3,420.00	2,100.00	900.00
San Vicente	700.00	510.00	450.00	250.00
Brandsen	1,600.00	380.00	500.00	100.00
La Plata	400.00	450.00	250.00	-

Table 51 Nutrients needed per type of crop

Crop	N (kg)	P (kg)	K (kg)
Wheat	46	15	1
Corn	57	14	1
Soy		15	2
Sunflower	15	9	0.2

Table 52 Total demand of nutrient per crop type

Nutrient	Corn	Soy	Wheat	Sunflower	Total (tons)
N	671.46	-	379.50	21.75	1,072.71
P	164.92	516.60	123.75	13.05	818.32
K	11.78	68.88	8.25	0.29	89.20