UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
INSTITUTO DE PESQUISA EM BIOENERGIA

PROGRAMA INTEGRADO (UNESP, USP E UNICAMP) DE PÓS-GRADUAÇÃO EM BIOENERGIA

SUSTAINABILITY OF THE UTILIZATION OF BIOGAS FROM SUGARCANE VINASSE IN ELECTRICITY GENERATION, TRANSPORT FUEL AND NATURAL GAS SUBSTITUTION

CARLA MAIA BRANDÃO

RIO CLARO - SP
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Tese apresentada ao Instituto de Pesquisa em Bioenergia de Rio Claro, Universidade Estadual Paulista, como parte dos requisitos para obtenção do título de Doutor em Bioenergia.

Orientador(a): Prof. Dr. Nelson Ramos Stradiotto

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Dedico este trabalho às gerações futuras esperando que possam ser mais sábias que nós em suas escolhas.

I dedicate this work to future generations hoping that they can be wiser than us in their choices.

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A Deus que em seu infinito amor, bondade e misericórdia me deu a vida e a saúde necessária ao desempenho de minhas capacidades físicas e intelectuais além de me cercar de pessoas incríveis que me auxiliaram no desenvolvimento desse trabalho.

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“Um pouco de ciência afasta a pessoa de Deus, mas muita ciência aproxima a pessoa Dele... Quanto mais estudo a natureza, mais fico maravilhado com a obra do Criador.”

“A bit of science distances one from God, but much science nears one to Him… The more I study nature, the more I stand amazed at the work of the Creator.”

(Louis Pasteur).

RESUMO

O Brasil é o segundo maior produtor mundial de etanol combustível, tendo produzido 35,6 milhões de m^3 na safra 2019/2020. O principal subproduto desse processo produtivo é a vinhaça, uma solução aquosa que é gerada na proporção de aproximadamente 13,4m^3 para cada 1m^3 de etanol, resultando em cerca de 477 milhões de m^3 de vinhaça na safra 2019/2020. Atualmente, a prática mais comum adotada pelas unidades produtoras é a utilização da vinhaça em fertirrigação dos canaviais para aproveitamento de seu teor de potássio e consequente redução de custos com fertilizantes. No entanto, o alto custo para transporte da vinhaça restringe sua aplicação apenas às áreas mais próximas às unidades produtoras, causando impactos ambientais negativos. É nesse contexto que a biodigestão anaeróbica da vinhaça surge como uma alternativa interessante visto que possibilita a produção de biogás e/ou biometano (biogás purificado) através da conversão da carga orgânica da vinhaça, mantendo o teor de potássio no efluente do reator, mas reduzindo seu potencial poluidor. Assim, o objetivo desse trabalho foi avaliar as possibilidades de usos do biogás ou biometano produzidos num estudo de caso específico, desenhado de forma a representar a maior parte das unidades produtoras de etanol existentes hoje no Brasil. Considerando dados médios históricos de 171 usinas de cana-de-açúcar do Estado de São Paulo (região com maior concentração de unidades produtoras no Brasil), considerou-se uma unidade produtora com capacidade de moagem de 2 milhões de toneladas de cana e cerca de 448 m^3 de etanol por dia, gerando cerca de 6.000m^3 de vinhaça por dia direcionada ao reator anaeróbico para biodigestão. A produção de cerca de 55.650m^3 de biogás por dia foi estudada em três diferentes usos: de forma direta, 1) para geração de eletricidade através de motores de combustão interna; e após purificação (36.173m^3 de biometano), 2) como substituto ao óleo diesel em veículos pesados e 3) como substituto ao gás natural. A partir dos resultados obtidos, chegou-se à conclusão de que: a) analisando as questões ambientais de forma isolada, quantificadas através do ganho econômico gerado pela venda de créditos de carbono, o uso do biometano como substituto ao óleo diesel em veículos pesados foi a opção mais vantajosa; b) analisando as questões sociais de forma isolada, quantificada pelo aumento do poder aquisitivo decorrente da geração de empregos, o uso do biogás para geração de energia elétrica foi a opção mais vantajosa e c) analisando economicamente, através do cálculo do valor presente líquido (VPL), e de forma conjunta as questões técnicas (receita gerada pela venda dos produtos finais), ambientais (receita gerada pela venda de créditos de carbono), sociais (aumento do poder aquisitivo decorrente da geração de empregos) e políticas/estratégicas (efeito dos créditos fiscais na receita gerada), obteve-se VPL<0 para geração de eletricidade, VPL~0 como substituto ao óleo diesel em veículos pesados e VPL>0 como substituto ao gás natural, indicando que a injeção de biometano na rede de gás natural foi o uso mais sustentável entre os três usos estudados.

Palavras-chave: Cana-de-açúcar, Etanol, Vinhaça, Biodigestão, Biogás, Sustentabilidade.

ABSTRACT

Brazil is the second largest producer of fuel ethanol in the world, having produced 35.6 million m3 in the 2019/2020 harvest. The main by-product of this production process is vinasse, an aqueous solution that is generated at a rate of approximately 13.4m3 for every 1m3 of ethanol, resulting in around 477 million m3 of vinasse in the 2019/2020 harvest. Currently, the most common practice adopted by production units is the use of vinasse in fertigation of sugarcane fields to take advantage of its potassium content and consequent reduction in fertilizer costs. However, the high cost of transporting vinasse restricts its application only to the areas closest to the production units, causing negative environmental impacts. It is in this context that the anaerobic digestion of vinasse emerges as an interesting alternative since it enables the production of biogas and/or biomethane (purified biogas) through the conversion of the organic load of vinasse, maintaining the potassium content in the reactor effluent, but reducing its polluting potential. Thus, the objective of this work was to evaluate the possibilities of using the biogas or biomethane produced in a specific case study, designed to represent most of the existing ethanol production units in Brazil today. Considering historical average data from 171 sugarcane mills in the State of São Paulo (region with the highest concentration of production units in Brazil), a production unit with a crushing capacity of 2 million tons of sugarcane and about 448 m3 of ethanol per day, generating around 6,000 m3 of vinasse per day directed to the anaerobic reactor for biodigestion. The production of around 55,650m3 of biogas per day was studied in three different uses: directly, 1) for electricity generation through internal combustion engines; and after purification (36,173m3 of biomethane), 2) as a substitute for diesel oil in heavy vehicles and 3) as a substitute for natural gas. From the results obtained, it was concluded that: a) analyzing environmental issues in isolation, quantified through the economic gain generated by the sale of carbon credits, the use of biomethane as a substitute for diesel oil in heavy vehicles was the most advantageous option; b) analyzing social issues in isolation, quantified by the increase in purchasing power resulting from the generation of jobs, the use of biogas to generate electricity was the most advantageous option and c) analyzing economically, through the calculation of the net present value (NPV), and jointly the technical issues (revenue generated by the sale of final products), environmental (revenue generated by the sale of carbon credits), social (increase in purchasing power resulting from the generation of jobs) and political/strategic (effect of tax credits on generated revenue), NPV<0 for electricity generation, NPV~0 as a substitute for diesel oil in heavy vehicles and NPV>0 as a substitute for natural gas, indicating that the injection of biomethane into the natural gas network was the most sustainable use among the three uses studied.

Keywords: Sugarcane, Ethanol, Vinasse, Biodigestion, Biogas, Sustainability.

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LIST OF ABBREVIATIONS AND SYMBOLS

ηCH_4	Methane yield coefficient
η_{ICE}	Internal combustion engine efficiency
ABNT	Associação Brasileira de Normas Técnicas (Brazillian Association of Technical Standards)
AC	Activated carbon
AFBR	Anaerobic fixed bed reactor
AfBR	Anaerobic fluidized bed reactor
ANP	Agência Nacional do Petróleo (Oil National Agency)
APBR	Anaerobic packed bed reactor
ASTBR	Anaerobic structured-bed reactor
ASTBR	Anaerobic structured-bed reactor
BB/RR	Brick ballast / Raschig rings
BEN	Balanço Energético Nacional (National Energetic Balance)
CAPEX	Capital Expenditure
cbe	Specific heat of beer
CBIO	Crédito de Descarbonização (Biofuel Decarbonization Credit)
CF	Cash Flow
CH_4(lo)	Methane losses
CH_4bg	Methane content of biogas
CH_4r	Methane release rate in open channels
CNG	Compressed Natural Gas
CNPE	Conselho Nacional de Política Energética (National Energy Policy Council)
CO_2eq	CO_2 equivalent emissions
COD	Chemical Oxygen Demand
$COD_{influent}$	Influent chemical oxygen demand
$COD_{removed}$	Load of COD removed from the reactor and converted into methane
CODvi	Available COD of vinasse
cphc	Specific heat of phlegmace
CSTR	Continuous stirred-tank reactor
cvi	Specific heat of vinasse
Dbe	Density of beer
Det	Density of ethanol
Dph	Density of phlegma
Dphc	Density of phlegmace
Dvi	Density of vinasse
EA_{CO2eq} (di)	Avoided emission of CO_{2eq} (diesel oil replacement)
EA_{CO2eq} (el)	Avoided emission of CO_{2eq} (electricity generation)
EA_{CO2eq} (na)	Avoided emission of CO_{2eq} (natural gas replacement)
EA_{CO2eq} (vi)	Avoided emission of CO_{2eq} (biogas plant)
Ebe	Energy in beer
Ec	Energy consumption of biomethane
EF	Average emission factor
EF(di)	Average emission factor of diesel oil
EF(na)	Average emission factor of natural gas
Eg	Electricity generated
E_{HE}	Energy in hydrous ethanol
EinA	Incoming energy of column A
EinB	Incoming energy of column B
EloA	Energy losses in column A
EloB	Energy losses in column B
EoutA	Outgoing energy of column A
EoutB	Outgoing energy of column B

Eph	Total phlegma energy
$Eph_{A \rightarrow B}$	Phlegma energy from column A to column B
$Eph_{D \rightarrow B}$	Phlegma energy from column D to column B
Ephc	Phlegmace energy
E_R	Reflux energy
EstA	Energy in steam of column A
EstB	Energy in steam of column B
Etbe	Ethanol weight in beer
Etph	Ethanol weight in phlegma
Evi	Vinasse Energy
FEL	Front End Loading
GDP	Gross Domestic Product
GHG	Greenhouse gas
HAIB	Horizontal-flow immobilized biomass
HD	Human Development
HDI	Human Development Index
HDR	Human Development Report
HDT / HRT	Hydraulic Detention Time / Hydraulic Retention Time
HE	Hydrous ethanol weight
Het	Ethanol latent heat
Hph	Enthalpy of liquid phlegma
HstA	Enthalpy of steam consumed by column A
HstB	Enthalpy of steam consumed by column B
IAA	Instituto do Açúcar e do Álcool (Sugar and Ethanol Institute)
K(t)	COD corresponding to one mole of CH_4
LCV_{CH4}	Methane Low Calorific Value
M%etbe	% molar ethanol in beer
M%etph	% molar ethanol in phlegma
$M\%_{HE}$	% molar ethanol in hydrous ethanol
Met	Ethanol molar weight
MMA	Ministério do Meio Ambiente (Ministry of Environment)
MME	Ministério das Minas e Energia (Ministry of Mines and Energy)
M_{WA}	Water molar weight
NA	Not Available
NDC	Nationally Determined Contribution
NPV	Net Present Value
NZ	Natural zeolite
OECD	Organization for Economic Co-operation and Development
ºGLbe	Ethanol content of beer
OLR	Organic Loading Rate
$OLR_{máx}$	Maximum Organic Loading Rate
ONU	Organização das Nações Unidas (United Nations Organization)
OPEX	Operational Expenditure
P	Atmosphere pressure
PE	Polyethylene
Pg	Power generated
PS	Polystyrene
Q	Flow rate
Q_{CH4}	Methane flow rate
Qet	Ethanol production
Qvi	Daily quantity of vinasse
R	Gas constant
rCOD	COD removal efficiency
Reais	Official currency of Brazil
R_R	Reflux rate of column B

R_{Rmin}	Minimum reflux rate
SCFFAR	Semi continuous fixed film anaerobic reactor
SRB	Sulfate-Reducing Bacteria
StA	Steam consumed by column A
StB	Steam consumed by column B
T	Operational temperature of the reactor
TbA	Temperature of the bottom of column A
TbB	Temperature of the bottom of column B
Tbe	Temperature of beer
THet	Total heat of hydrous ethanol
THstA	Total heat of steam of column A
THstB	Total heat of steam of column B
Tphc	Temperature of phlegmace
Tvi	Temperature of vinasse
UAF	Upflow anaerobic filter
UAR	Upflow anaerobic reactor
UASB	Upflow anaerobic sludge blanket
UF	Unidade da Federação (Federative Unit)
UFD	Upflow floc digester
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
USM	Usina São Martinho (São Martinho Mill)
V	Useful volume of the reactor
Vbe	Volume of beer
Vbg	Volume of biogas
V_{CH4}	Volume of methane produced
Vet	Volume of ethanol
VFA	Volatile Fatty Acids
Vph	Volume of phlegma
Vphc	Volume of phlegmace
Vphct	Volume of phlegmace total
Vst	Volume of steam
Vvi	Volume of vinasse
Vviy	Volume of vinasse per year
WA	Water weight

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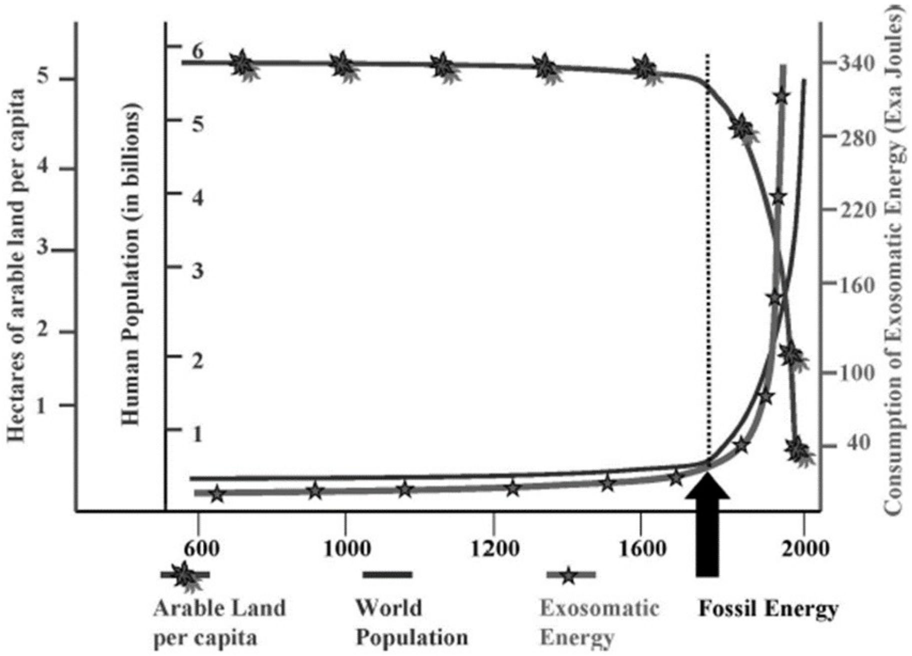
1 INTRODUCTION

Dennis et al. (2006) states that people have long tried to use energy to meet their individual needs, which grew with the development of civilization. As illustrated by Figure 1, the world's population has grown at a rate never seen before, arable land has declined, and energy consumption has skyrocketed. According to forecasts for the next 100 years, energy consumption will increase by approximately 250-300% (Badjor et al., 2011).

Figure 1: The role of fossil energy in the history of human civilization.



Source: Giampietro et al.,2005.

Since the industrial revolution of the eighteenth century, industries have become the driving force behind the development of the capitalist model. It was from the first industrial revolution that a fossil fuel became the most important energy resource. First was the mineral coal and then the oil, the most important fuel. Today, in the twenty-first century, world economies are still heavily dependent on traditional fossil fuels (Giampietro et al., 2012).

The crucial role of fossil energy in boosting human civilization – the key feature that justified the use of the term "industrial revolution" - came at a cost. The resulting continuous growth of human activity on the planet reached a point that is raising concerns for its potential negative consequences in terms of environmental degradation (Giampietro et al., 2005). The scenario is clear: human beings need energy to survive, this energy is today strongly based on fossil fuels whose sources are not renewable and, worst, cause great negative impacts to the environment, putting in risk the human sustainability.

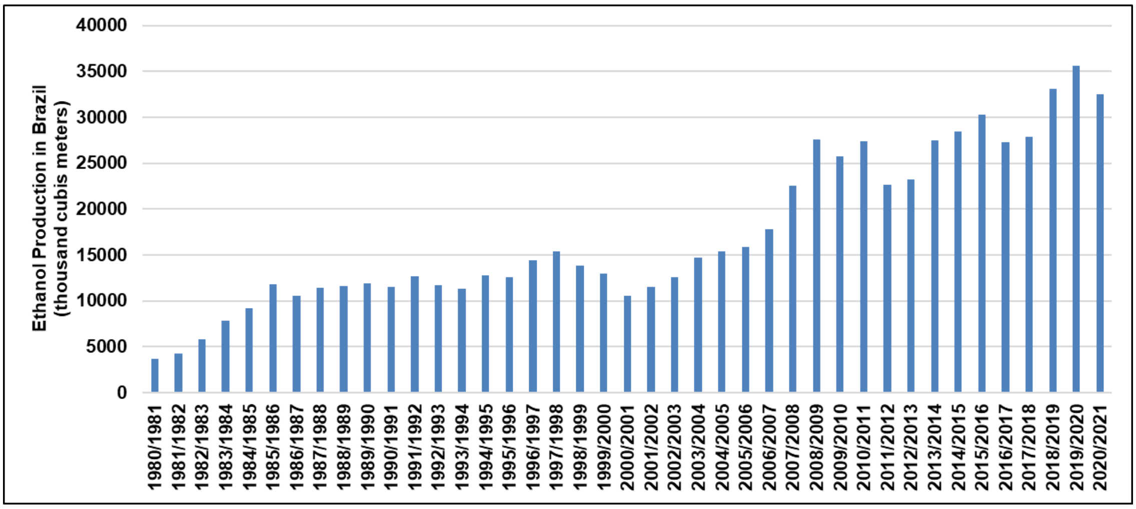
One of the initiatives to sustainability of human beings is the consumption of clean and renewable energy sources to reduce the use of fossil fuels. This action not only preserves the mining resources reserves, but it aims to reduce air pollution, therefore, improving the quality of life of humans. Although several strategies have been implemented to control available reserves and to invest in efficiency and renewable sources, these efforts have not generated the desired feeling that the problem is under control. There is still a large dose of uncertainty about the future availability of fossil reserves. Actual physical quantity and quality of the reserves, international market and strategies, demographic variables, geo-political conflicts, effects of climate change, financial crisis, relatively cheap fossil fuel, among others, are examples of sources of uncertainty which play a key role in the prediction of the best strategy for the development of renewable energies sources (Giampietro et al., 2012).

Among several possible renewable energy sources, such as nuclear (fusion and fission), hydraulic, wind, solar photovoltaic and bioenergy, the biogas gas production from anaerobic digestion of biomass deserves attention. It is well accepted that not a single source of alternative energy will be capable of covering humanity’s increasing energy demand. Instead, the energy system of the future will be a mix of various renewable energy sources and, at least for the next decades, still complemented by fossil energy. Although wind and solar energy sources provide cheap energy, these systems are characterized by highly fluctuating and poorly predictable production profiles. Biomass energy conversion techniques can produce constant base load and balance out supply-demand-gaps in the energy sector. This is the reason why it is expected that biomass-based energy sources will have a significant percentage of participation in the electrical system in the future. An important share amongst biomass energy sources is covered by the utilization of biogas from anaerobic digestion (Miltner et al., 2017).

Biogas can be produced from different feedstocks and the present work proposed to analyze one of them: sugarcane vinasse, a by-product of ethanol production.

The cultivation of sugarcane in Brazil goes back to the period of its colonization and since then sugar and, more recently, ethanol are products of essential importance for the Brazilian economy. Figure 2 shows the evolution of ethanol production in Brazil since 1980, evidencing the growing demand and production of ethanol in Brazil, placing such fuel as essential from the point of view of Brazilian sustainable development, since it is a renewable fuel that replaces fuels from fossil sources such as gasoline.

Figure 2: Ethanol production in Brazil, in thousand m^3



Source: Adapted from UNICA, 2023.

Such production is linked to the generation of waste and/or by-products which, if not carefully managed, can have negative impacts from the point of view of sustainability. The main by-product of ethanol production is vinasse, an aqueous solution from the alcoholic distillation process. Through mass and energy balances, it is possible to estimate the amount of vinasse generated per liter of ethanol. This quantity is dependent on several factors, such as: alcoholic degree of the beer to be distilled, whether there is thermal insulation of the distillation columns and type of column heating (direct or indirect), among others. Brazilian distilleries produce from 7 to 15m^3 of vinasse per and 1m^3 of ethanol depending on the size of the installation and the technology used, with the smallest and oldest distilleries generating the highest amount of this waste (ANA, 2009 *apud* Poveda, 2019).

The destination of the vinasse over time has been treated in different ways. At first, like most of the generated industrial waste, prevention was sought because it was believed that avoiding the production of a waste is better than performing its treatment after the process. In a second moment, it was possible to regulate the use of vinasse in fertigation of sugarcane cultivation since its potassium content could prevent or reduce the use of artificial fertilizers. This has been the practice of most of the sugar and ethanol plants in Brazil. However, due to the high amount of water in the vinasse, between 94 and 98%, its application in all extension of the sugar cane plantation area becomes very expensive (mainly because of the transport cost) and it is common that all the vinasse generated to be applied only in the closest areas around industrial plants, therefore resulting in negative environmental impacts. Recently, some vinasse concentration initiatives have been implemented with the purpose of reducing transport costs over long distances and allowing their application in a more distributed way. In parallel, since the 1980s, studies have been developed to make vinasse more than an opportunity to reduce costs with fertilizers, but also as a source of energy due to the possibility of converting its organic load.

The organic load of the vinasse is variable according to the composition of the compound used in the alcoholic fermentation. In Brazil, there are three different possible feedstocks to the ethanol production from sugarcane: sugarcane juice, sugarcane molasses and a mixture of the first two. Depending on the proportion of sugarcane juice and molasses, the COD of vinasse can vary from 15 to 85 g/L (Moraes et al., 2015).

The gas produced by microbial degradation of biomass under anaerobic conditions is known as biogas and its main component that determines the energy content of the gas is flammable methane (CH_4). Depending on the substrate digested in the biogas plant, the methane content of the biogas varies between 50% and 85%. The second main component of biogas is carbon dioxide (CO_2) with a share between 25% and 50%. Other components of biogas are water (H_2O), oxygen (O_2) and hydrogen sulfide (H_2S) (Gomez, 2013).

Over the last century, methane, the main component of biogas, has become one of the most used fuels for power generation, heating, and transportation purposes. While most of the methane used in society today comes in the form of natural gas, there is rapidly growing interest in capturing the methane formed from decaying biomass. It means setting up dedicated biogas facilities where biogas process can be fully contained, controlled, and optimized and a commercially viable industry can be established, harnessing nature's potential to produce renewable, environmentally sustainable, gaseous biofuel.

Vinasse biodigestion has been the object of investment by some companies since the 1980s. The Central Jacques Richer Distillery, in Campos/RJ, with a 330m^3 biodigester operated until 1982. São João Distillery maintained an anaerobic vinasse digestion plant in operation until 1977. One unit of São Martinho located in Pradópolis/SP, currently (2019) has an anaerobic vinasse digestion system in operation (Poveda, 2019).

In more recent times, new projects have been carried out, such as the lagoon system at Usina Ester in Cordeirópolis/SP. The company OMNIS Biotechnology S.A. developed this pilot-scale project with funding from Companhia Paulista de Força e Luz (CPFL), a distribution and energy company in the interior of São Paulo (Poveda, 2019). Other pilot projects emerged, such as Cetrel, which, in partnership with the JB group, inaugurated in Vitória de Santo Antão/PE, in 2012, a thermoelectric plant using 0.85MWe of vinasse biogas with motor generators (Falcão, 2012 *apud* Poveda, 2019). Also, in 2012, the enterprise GEO-Energética installed 4 MWe of electricity in Tamboara/PR using biogas from the co-digestion of vinasse with other solid organic waste received from the Copcana plant (GEO-Energética, 2019 *apud* Poveda , 2019), and now has a biomethane production plant.

In October 2020, the company Raízen inaugurated its first biogas plant using by-products from the industrial process (vinasse and filter cake) to generate biogas, in Guariba/SP. At Raízen's facility, biogas can be converted into both electricity and biomethane gas (Raízen, 2023).

Grupo Cocal started operating, in June 2021, a plant dedicated to the production of biomethane from by-products of the sugar-energy sector, located in the municipality of Narandiba/SP. With an investment of R$ 139 million, the plant has the capacity to produce, annually, 33.5 million Nm^3 of biogas from vinasse and filter cake, with the potential to expand this production with straw biodigestion. As raw material, 1.5 million m^3 of vinasse, 135 thousand tons of filter cake and 10 thousand tons of straw will be used. With this production, the export of energy will be up to 33.3 thousand MWh and the purification of biogas will generate 8.9 million Nm^3 of biomethane. Part of this biogas will be purified to produce biomethane, a fuel with the same quality and efficiency as natural gas. Compressed and injected into the GasBrasiliano gas pipeline, the fuel will supply the cities of Narandiba, Pirapozinho and Presidente Prudente. According to Copersucar (2023), 47% of the biogas produced will be used as fuel for motor generators. The other 53% will be converted to 8.9 million m^3 of biomethane per year to replace diesel in Cocal's fleet and supply the region using trucks and the gas pipeline built in partnership with GasBrasiliano (Copersucar, 2023).

The Cocal Group project foresees the use of biogas to generate electricity, but also the use of biomethane as a substitute for diesel oil in heavy vehicles and as a substitute for natural gas in the GasBrasiliano network. But what is the most sustainable use? Is there a difference if we consider only environmental aspects, or only social aspects, or only economic aspects? And from the broader point of view of sustainability, in which, in addition to environmental, social, and economic aspects, political and strategic factors are also considered? These are the questions that this work seeks to answer.

The differential and originality of the present work reside in the fact that: i) it brings the analysis of a case that, although specific, was based on historical average data, seeking to approach the reality of the majority of ethanol production units existing in Brazil (more specifically in the State of São Paulo); ii) it presents an analysis of aspects of sustainability in a simple and broad way, encompassing, in addition to environmental, social and economic issues, the political and strategic dimensions; and iii) it was structured in order to provide subsidies for better decision-making, stimulating the growth of initiatives for the use of biogas in the area of bioenergy, more specifically, promoting sustainable development solutions for the Brazilian economy and population.

For this purpose, this work is structured in eight more chapters, numbered from 2 to 9, which will cover the following topics: 2) Objectives, 3) Biogas

Production, 4) Biogas Uses, 5) Biogas Sustainability, 6) Methodology, 7) Results and Discussion, 8) Conclusions and 9) Future Studies.

Chapter 2 brings the general objective as well as the specific objectives of the present work to clarify its originality and justify its development. Chapter 3 addresses the aspects involved in the production of biogas, bringing a bibliographic review of topics such as sugarcane vinasse, biotechnological conversion of sugarcane vinasse, anaerobic reactors, and biogas purification systems, thus providing subsidies for the establishment of the premises of the case study. Chapter 4 addresses and contextualizes the concepts of the three uses of biogas analyzed here - electricity generation, replacement of diesel oil in heavy vehicles and replacement of natural gas – also providing subsidies for the establishment of the premises of the case study. Chapter 5 seeks to clarify the studies already developed in terms of biogas sustainability analysis, serving as a starting point and comparison for the results obtained. Chapter 6 clarifies the methodology used to achieve the objectives outlined. Chapter 7 presents the results obtained as well as their analysis and discussion, drawing a parallel with the previous chapters and bringing the differential and original contribution of the present work. Chapter 8 brings the conclusions arising from the results obtained, explaining their originality, but also addressing the difficulties of the study. Chapter 9 proposes possible future studies that may complement and/or deepen issues not explored or explored superficially in this work.

2 OBJECTIVES

The general objective of this work was to evaluate the sustainability of the uses of biogas from sugarcane vinasse focusing on electricity production, transport fuel and natural gas substitution based on the results obtained from a specific case.

Based on this general objective, the present study intended to be aligned with and to contribute to the climate goals assumed by Brazil at COP26. During the Conference of the Parties, COP26, held in Glasgow in November 2021, Brazil renewed and assumed new climate commitments, including (i) mitigating 50% of its emissions by 2030 and (ii) helping to reduce 30% of global methane emissions (Rolim *et al*., 2023).

Federal Decree No. 11,003/2022 established the Federal Strategy to Incentive the Sustainable Use of Biogas and Biomethane, aiming to a) encourage programs and actions to reduce methane emissions; b) promote the use of biogas and biomethane as renewable sources of energy and fuel; and c) contribute to fulfilling the climate commitments assumed by Brazil. The instruments for implementing the strategy are: the National Program for Green Growth, the National Fund on Climate Change, the National Biofuels Policy (RenovaBio), and scientific research, in which this work could contribute (Rolim *et al*., 2023).

Additionally, this work aimed to contribute to the Ministry of the Environment (MMA) that edited the Ordinance No. 71/2022, which instituted the National Program for the Reduction of Methane Emissions (Zero Methane). The Program was created with the aim of contributing to the Global Methane Agreement signed by Brazil and has its guidelines: encouraging the carbon market (Methane Credit); promote the implementation of biodigesters and biogas purification systems; encourage the implementation of technologies that allow the use of biogas and biomethane; encourage the creation of points and green corridors for the supply of light and heavy vehicles and vessels powered by biomethane or hybrids with biomethane; promote and develop scientific-technological research and innovations, and the dissemination of technologies, processes and practices to mitigate methane emissions.

Based on the new incentive strategy, Ordinance No. 627/GM/MME/2022 was also published, which included projects for the production of non-associated natural gas and biomethane production as eligible for the benefit of the Special Regime of Infrastructure Development Incentives (REIDI). Projects included in this regime have suspended the collection of PIS and COFINS for the acquisition of machinery, construction materials, equipment, among other components. These are tax credits whose impact this study intended to explore and to understand the extent to which such incentives can represent a real benefit in stimulating the implementation of projects in the area.

So, in a comprehensive manner, the present work aimed to propose solutions that, in line with the new regulatory framework, can boost the national production of biogas and biomethane, considering that they are indispensable renewable sources to achieve the energy transition, stimulate the diversification of the Brazilian energy matrix in a safe way, as well as achieve the assumed emission reduction targets for Brazil.

The specific objectives of this work were:

I. To analyze the study case designed based on historical average data, seeking to approach the reality of the majority of ethanol production units existing in Brazil (more specifically in the State of São Paulo).
II. To compare different technological routes for the production and use of biogas from vinasse. The final uses of biogas considered in this work are three: generation of electricity via internal combustion engines, vehicle use in place of diesel oil and injection of biomethane into the natural gas network.
III. To analyze the aspects of sustainability in a simple and broad way, seeking to answer the following questions:
    a. What is the most sustainable biogas/biomethane use? Is there a difference if we consider only environmental aspects, or only social aspects, or only economic aspects comparing to the three combined results?

b. From the broader point of view of sustainability, what is the impact of political and strategic factors?

IV. To provide subsidies for better decision-making, stimulating the growth of initiatives for the use of biogas, more specifically, promoting sustainable development solutions for the Brazilian economy and population.

To evidence the originality of the study proposed here, a very brief bibliographical review is presented below, explaining the differences in relation to previous studies and the relevance and contribution of the present work.

It is not new that sugarcane vinasse biodigestion systems have been studied. The first studies date back to the 1980s. Since then, several authors have dedicated their research to understanding both the characterization of vinasse and the viability of its conversion into biogas and the different possible uses of it.

Most of the studies developed for the Brazilian context have evaluated the use of biogas in electricity generation. This is the case of Salomon and Lora (2009), Moraes *et al.* (2014), Fuess and Garcia (2015), Santos *et al.* (2016), Bernal *et al*. (2017), Fuess *et al*. (2017), Santos *et. al*. (2018) and Poveda (2019). The assessment of the use of biogas in electricity generation was carried out in different ways in these cited studies, but in general they included energetic, economic and/or environmental analyses. Moraes *et al.* (2014) and Poveda (2019) also evaluated economically and environmentally the use of biogas in cogeneration and as transport fuel. Nadaletti *et al*. (2015) have performed energetic, environmental, and social analysis of the biogas use as transport fuel. Poveda (2019) also evaluated economically and environmentally the use of biogas as substitute of natural gas. All these authors concluded that the anaerobic digestion of vinasse has environmental and energetic advantages.

Based on the results obtained so far, this work aimed to deepen and expand this research and to address issues not previously covered, given the complexity and extension of the subject. Despite their unquestionable relevance, the analyzes conducted so far were restricted to some dimensions of sustainability, favoring economic and environmental analyzes to the detriment of social analyses. In addition, such studies frequently cite political and strategic spheres as promoters and motivators of projects and research related to biogas production, but none presents or quantifies the impact that such dimensions have on the viability of projects, gap that this work intended to fill.

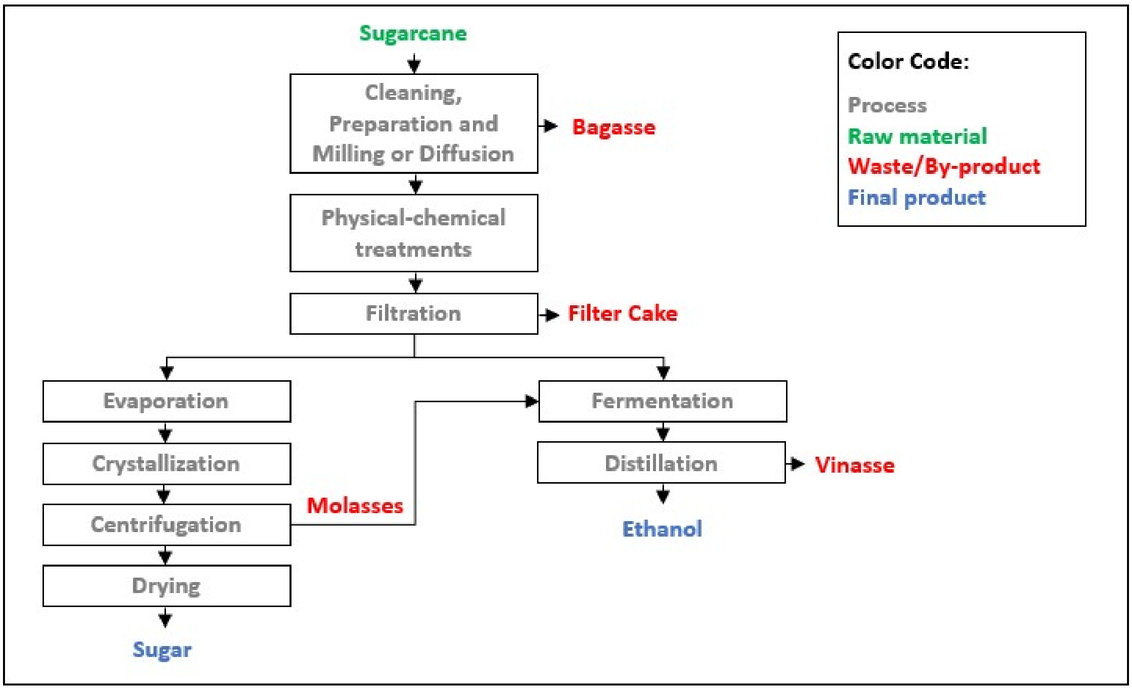
In view of the recent investment initiatives in biogas production plants from sugarcane vinasse, this work intended to provide support to decision makers to make viable and perpetuate the projects in operation and under evaluation. In this sense, it was performed a study case designed to be close to most of the ethanol producing units in the State of São Paulo, expanding the potential applicability of the results obtained here.

3 BIOGAS PRODUCTION

3.1 Sugarcane vinasse

Brazilian ethanol production began to gain space around the year 1933 with the creation of the IAA (Sugar and Ethanol Institute) created by Getulio Vargas' government to face the threat of overproduction of sugar in Brazil. The process of modernization of the mills and the creation of Proálcool (program to encourage the production and use of ethanol as fuel instead of gasoline) in 1975 were of fundamental importance for Brazil to face the oil crises from the 1970s and, in less than five years, production of just over 300 thousand m^3 exceeded 11 million m^3 (Machado, 2018). Figure 3 illustrate the process flowchart of sugar and ethanol production from sugarcane.

Figure 3: Sugar and ethanol production process flowchart



Source: Adapted from Poveda, 2019.

In Brazil, sugar and ethanol are produced from sugarcane, with ethanol production normally attached to sugar production. All information about the process of sugar and ethanol production process described below is based in this author's thirteen years of professional experience, working in production units of this sector.

To obtain sugar in its commercial form, it is necessary to extract sucrose, separating it from the other components of the plant. Sugarcane consists basically of water (65 - 75%), solids (11 - 18%), fibers (8 - 14%) and small amounts of organic and inorganic acids, proteins, starch, waxes, greases, and dyes. Solids include: sucrose, glucose, fructose, and salts.

Sugarcane harvesting can be done manually or mechanically. In the first case, the cane is obtained whole and in the second case, 20 to 25 cm pieces are obtained. The cane unloaded on the feeder tables may or may not be cleaned depending on the mill. This cleaning is intended to remove part of foreign matter, such as soil and sand, to obtain a better quality juice and avoid excessive abrasion of the equipment. The mechanically harvested cane is not cleaned because, due to its form of stalks, the drag of sucrose by the water would be too great.

Right after cleaning, the cane is taken through conveyor belts to a set of leveling knives, followed by the chopper, the shredder, and the electromagnet. This step is known as cane preparation. The leveler provides uniform feeding. The chopper and the shredder aim to increase the density, increasing the milling capacity, and breaking up the cells as much as possible to force a greater efficiency of sugar extraction. The electromagnet aims to remove possible ferrous materials that may come with the sugarcane to prevent breakage of the milling rollers.

The extraction of solids from the cane is done by crushing it in the milling rollers that exert strong pressure. The mills separate water and solids from the fiber that will form the bagasse. Sucrose is dissolved in the juice, so the objective of milling is to extract as much solids as possible from the cane. In practice, 94 - 96% of the sugarcane juice is extracted, which is used to produce sugar or ethanol.

A second objective of milling, but of extreme importance, is the production of a final bagasse with low humidity to be burned in boilers aiming at the production of energy in the form of steam at high pressure. This steam is used to drive steam turbines, transforming thermal energy into mechanical energy. These turbines move the choppers, shredders, mills, etc., as well as generators of electrical energy, necessary in various sectors of industry. The steam released in the turbines, called exhaust steam, is low pressure steam and is used as a basic source of energy throughout the sugar and ethanol manufacturing process.

The juice resulting from the extraction by the mills goes through some treatment steps before being sent to the production of sugar and/or ethanol. This juice is sieved to remove the coarsest impurities. However, minor impurities (soluble, insoluble, or colloidal) are not removed just by using sieves. In the case of this type of impurities, a sequence of procedures is adopted to coagulate them, so that decantation can separate them. After the physical-chemical treatment sequence, described below, the juice is sent to the production of sugar and/or ethanol.

- Liming: liming is done by adding milk of lime ($Ca(OH)_2$) which also coagulates colloidal material, helps in the precipitation and removal of soluble and insoluble impurities, and raises the pH to neutral values.
- Heating: the juice is then heated to approximately 105ºC to accelerate and facilitate the coagulation and flocculation reactions of colloids and protein non-sugars and to emulsify greases and waxes. Heating at this stage of the process essentially aims to increase the efficiency of the decanting process and promote the subsequent removal of air.
- Flashing: in the flash flask, a sudden decrease in pressure causes the juice to boil spontaneously, thus eliminating the air dissolved in it, which, when present, makes it difficult to decant the lighter impurities.
- Decantation: also called clarification, is the purification step of the juice by removing the impurities flocculated in previous treatments. The juice, free of impurities, is called decanted juice and goes on to produce sugar or ethanol. The impurities constitute what is called sludge. The sludge is sent to the filtering stage.
- Filtration: To recover the sugar contained in the sludge, this is filtered. In this way, the filtered juice is separated from what is

retained in the filter - the cake, basically formed by the residues removed in the decantation. The juice returns to the process and the cake is used as fertilizer in the field.

After filtration, sugarcane juice goes to sugar or ethanol manufacturing. The steps of sugar manufacturing are:

- Evaporation: it constitutes the first stage of concentration of the juice from the treatment stage. The decanted juice contains about 85% water. Evaporation aims to reduce this percentage to approximately 40%. Concentrated juice is called syrup. This evaporation is carried out in concurrent multiple effect evaporators, that is, the steam generated by the evaporation of water from the juice (vegetable steam) present in one evaporator is used as a heating source for the next evaporator.
- Cooking: leaving the evaporation stage, the syrup is sent to cooking, which is a new concentration stage, but now with the formation of sucrose crystals. Cookers are equipment like evaporators and their final product, sugar crystals wrapped in molasses (sugar solution), is called cooked mass. In this stage, a concentration between 90 and 95 ºbrix (percentage by weight of solids) is reached at a temperature between 58 and 65ºC.
- Crystallization: the cooked mass is then sent to crystallizers which cool it slowly. In this way, it is possible to recover part of the sucrose that was still contained in the molasses by its deposition in the existing crystals, generating their consequent increase.
- Centrifugation: From the crystallizers, the cooked mass goes to the centrifuges. Centrifugal force promotes the separation of sugar. The sugar discharged from the centrifuges has a high moisture content (0.5 to 2%) and high temperature (65 to 95ºC).
- Drying: by means of a bucket elevator, the sugar crystals go to drying in rotating drums, slightly inclined in relation to the horizontal, and using hot air in countercurrent with the sugar to be dried. This sugar can be sold in this way as crystal sugar or can

be used to manufacture other products such as invert sugar, refined sugar, or liquid sugar.

- Storage: two types of storage and handling of sugar are generally accepted: storage in bags and in bulk. The storage system in bags is giving way to the bulk system. Bulk storage brings a series of economic advantages, the main one being the fact that it ensures a slower deterioration than bagged sugar, with the possibility of the phenomenon or humidification occurring but being restricted to the surface of the storage pile without major consequences on its interior.

The molasses separated from the sugar crystals in the centrifuges with part of the juice from treatment steps go to the ethanol production, whose first step is fermentation. Contrary to what happens in the manufacture of sugar, the juice that will serve as raw material in the production of ethanol must be cooled. It is common to make the hot juice exchange heat with the cold juice, the latter being heated and the other cooled. If this is not enough, the juice that goes to the fermentation must pass through a heat exchanger in which it will exchange heat with cold water until it reaches a temperature of approximately 30ºC, the ideal temperature for fermentation system. Before fermentation, wort and yeast must be prepared.

The wort is a sugar solution whose concentration has been adjusted in order to make the fermentation more efficient. The wort is prepared from molasses, juice, and water so that the mixture has a final concentration of around 16 to 23ºbrix. Normally, the Melle-Boinot fermentation process is used in distilleries. This process has as its main characteristic the recovery of yeasts through the centrifugation of the beer. To provide optimal fermentation conditions and avoid bacterial infection, the recovered yeast is treated before returning to the process. This treatment consists of adding water, reducing the ethanol content, and sulfuric acid to pH = 2.5, generating a mixture known as foot-in-the-cub.

Fermentation takes place in tanks called fermentation vats. Sugars (sucrose, glucose, and fructose) are transformed into ethanol according to the Gay-Lussac reaction:

$$\underset{sucrose}{C_{12}H_{22}O_{11}} + \underset{water}{H_2O} \rightarrow \underset{glucose}{C_6H_{12}O_6} + \underset{fructose}{C_6H_{12}O_6}$$

$$\underset{glucose/fructose}{C_6H_{12}O_6} \rightarrow 2\ \underset{ethanol}{CH_3CH_2OH} + 2\ \underset{carbon\ dioxide}{CO_2} + \underset{heat}{23{,}5\ kcal}$$

After a time of 4 to 12 hours, fermentation ends, generating a final product with an ethanol content between 7 and 10%, called fermented beer. From the fermentation vats, the beer is centrifuged to separate the yeast. This recovered yeast is called yeast milk and is returned to the fermentation vats. The fermented beer is sent to the wheel vat and then to the distillation columns.

The beer that comes from fermentation is basically composed of components in the liquid phase, mainly ethanol (7 to 10 ºGL) and water (89 to 93%). The different boiling points of the components of the mixture are responsible for the separation (distillation process). Vinasse is the aqueous byproduct from the first distillation step.

The amount of vinasse from the Brazilian sugarcane industry is substantial, as is the environmental impact caused by its disposal “in natura.” In 2005, it was edited by Environment Company of the State of São Paulo (CETESB), the Technical Standard P4.231. Currently in the third edition, second version, the standard brings criteria and detailed procedures for applying the vinasse in the agricultural soil, such as the prohibition or limitation of application in certain areas (preservation and protection areas, water wells, supply, area dominated by railroads and highways, population centers, etc.). The norm brings technical requirements related to the construction of storage tanks, waterproofing of channels, to the maximum concentration of elements in inspected samples and application instructions of the effluent (São Paulo, 2015). Currently, this is the norm that provides industrial agents with the guidelines for disposal of vinasse, at the same time in which it gives legal shelter to the bodies supervisory.

Alternative possible uses for vinasse, in addition to using it “in natura” in fertigation, can bring sustainability to the sector. Anaerobic digestion is the most suitable approach for managing vinasse based on potential biogas applications (Fuess and Zaiat, 2018). Chemical oxygen demand (COD) is a parameter that indicates the total chemically oxidizable material and the energy content of a feedstock (Drosg, 2013). Due to this organic load, the vinasse presents an important energetic potential. Table 1 presents the main parameters for vinasse characterization from different feedstocks (sugarcane juice and molasses).

Table 1: Main parameters for vinasse characterization from different feedstocks.

Parameter	Unit	Sugarcane juice	Sugarcane molasses
Biological Oxygen Demand (BOD)	$g.L^{-1}$	6 - 17	25
Chemical Oxygen Demand (COD)	$g.L^{-1}$	15 - 33	65
Calcium (Ca)	$g.L^{-1}$	0.1 – 1.1	0.3 – 3.6
Magnesium (Mg)	$g.L^{-1}$	0.1 – 0.3	0.3 – 0.9
Nitrogen (N)	$g.L^{-1}$	0.2 – 0.7	0.5 – 1.6
Phosphorus (P)	$g.L^{-1}$	0.004 – 0.1	0.04 – 0.13
Potassium (K)	$g.L^{-1}$	1.0 – 1.7	3.1 – 6.5
Sulfur (SO_4^{2-} - S)	$g.L^{-1}$	0.2 – 0.3	2.2

Source: Adapted from Costa, 1986 *et al*. apud Moraes et al., 2015.

3.2 Biotechnological conversion

Wet biomass (like vinasse) is less suitable for thermal conversion (such as combustion, gasification, and pyrolysis) because transport and drying require considerable amount of energy, which leads to a limited or even negative overall CO_2 reduction. Biotechnological conversion processes are particularly useful for this application because they are catalyzed by microorganisms in an aqueous environment at low temperature and pressure (Reith, 2003). In biological treatment, the microorganisms use the organic matter from the waste as carbon source and they transform it into simple chemicals substances, such as minerals, carbon dioxide and others. These processes can be aerobic or anaerobic depending on the presence or absence of oxygen, respectively. Table 2 presents the main advantages and disadvantages of anaerobic processes.

For industrial wastewater treatment, it is possible to highlight at least two characteristics of anaerobic digestion that make it more advantageous than aerobic digestion. Firstly, the relation sludge/bacteria produced from aerobic and anaerobic conversion of glucose is 450kg and 45kg of dry microbial biomass per ton of chemical oxygen demand (COD) converted, respectively (Murphy, 2013). Secondly, anaerobic digestion produces methane, an important renewable energy source, as it is possible to note from the reactions presented in the Table 3.

Table 2: Advantages and disadvantages of anaerobic processes

Advantages	Disadvantages
• Low production of solids, about 3 to 5 times lower than that in aerobic processes • Low energy consumption, usually associated with an influent pumping station, leading to very low operational costs • Low land requirements • Low construction costs • Production of methane, a highly calorific fuel gas • Possibility of preservation of the biomass, with no reactor feeding, for several months • Tolerance to high organic loads • Application in small and large scale • Low nutrient consumption	• Anaerobic microorganisms are susceptible to inhibition by a large number of compounds • Process start-up can be slow in the absence of adapted sludge • Some form of post-treatment is usually necessary • The biochemistry and microbiology of anaerobic digestion are complex, and still require further studies • Possible generation of bad odors, although they are controllable • Unsatisfactory removal of nitrogen, phosphorus, and pathogens

Source: Adapted from Chernicharo, 2007.

Table 3: Reaction of aerobic and anaerobic processes

Digestion	**Reactions**	**ΔG (kJ/reaction)**
Aerobic	Glucose + 6 O_2 → 6 CO_2 + 6 H_2O	- 2826
Anaerobic	Glucose → 3 CO_2 + 3 CH_4	- 403

Source: Adapted from Murphy, 2013.

The gas produced by bacterial degradation of biomass under anaerobic conditions is known as biogas and its main component that determines the energy content of the gas is flammable methane (CH_4). Depending on the substrate digested in the biogas plant, the methane content of the biogas varies between 50% and 75%. The second main component of biogas is carbon dioxide (CO_2) with a share between 25% and 50%. Other components of biogas are water (H_2O), oxygen (O_2) and traces of sulfur (S_2) and hydrogen sulfide (H_2S) (Gomez, 2013).

The biomass resources amenable to biogas production can be grouped into categories according to the sector generating them, they can be agricultural (animal manures and slurries, vegetable by-products and residues, energy crops), industrial (organic wastes, by-products and residues from agro-industries, food industries, fodder and brewery industries, organic-loaded wastewaters an sludges from industrial processes, organic by-products from biofuel production and biorefineries, etc), municipal (source-separated household waste, sewage sludge, municipal solid waste and food residues). Across these sectors, wastes, residues, and by-products of different biomass value chains are the most sustainable materials used as AD (anaerobic digestion) feedstocks (Seadi *et al*, 2013).

The potential of aquatic biomass as a feedstock for biogas has received increasing attention and has become the focus of research efforts around the world in attempts to develop cost sustainable and technically feasible full-scale applications for the culture, harvesting and utilization of biogas feedstocks (Wellinger, 2009 *apud* Seadi *et al*, 2013). Although its utilization as a biogas feedstock is still in the research phase, aquatic biomass is one of the biomass types with the highest potential for renewable energy production as well as various industrial applications and a possible future alternative to energy crops (Seadi *et al*, 2013).

Vinasse is included in the group of organic by-products from biofuel production and biorefineries. It can be biodigested alone or co-digested through the incorporation of filter cake and sugarcane straw, which is energetically favorable.

In a very simplified way, four steps allow the biogas production: 1) Hydrolysis and Acidogenesis, 2) Acetogenesis, 3) Methanogenesis and 4) Sulfate reduction. The first phase of the anaerobic digestion processes consists in the hydrolysis of complex particulate material (polymers) into simpler dissolved materials such as volatile fatty acids, ethanols, lactic acid, carbon dioxide, hydrogen, ammonia, and hydrogen sulphide by hydrolytic fermentative bacteria. Acidogenesis is conducted by a large and diverse group of fermentative bacteria participating in the degradation of sugars and amino acids. In the second phase acetogenic bacteria are responsible for the oxidation of the products generated in the acidogenic phase into acetic acid, hydrogen, and carbon dioxide. Then, methanogenic archaea degrade organic compounds into methane and carbon dioxide. The sulfate reduction occurs in reactors producing hydrogen sulfide through the action of sulfate-reducing bacteria (SRB) (Chernicharo, 2007).

Knowing the chemical composition of the wastewater enables an estimation of the amount of methane to be produced and, consequently, of the amount of degraded organic matter (Chernicharo, 2007). A method of evaluating the production of methane is from the estimation of the COD degradation in the reactor, according to the reaction:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$
$$(16g) + (64g) \rightarrow (44g) + (36g)$$

It can be concluded that one mole of methane requires two moles of oxygen for its complete oxidation to carbon dioxide and water. Therefore, every 16 grams of CH_4 produced and lost to the atmosphere corresponds to the removal of 64 grams of COD from the waste. Under normal temperature and pressure (NTP) conditions, this corresponds to 350mL of CH_4 for each gram of degraded COD (Chernicharo, 2007).

3.3 Anaerobic reactors

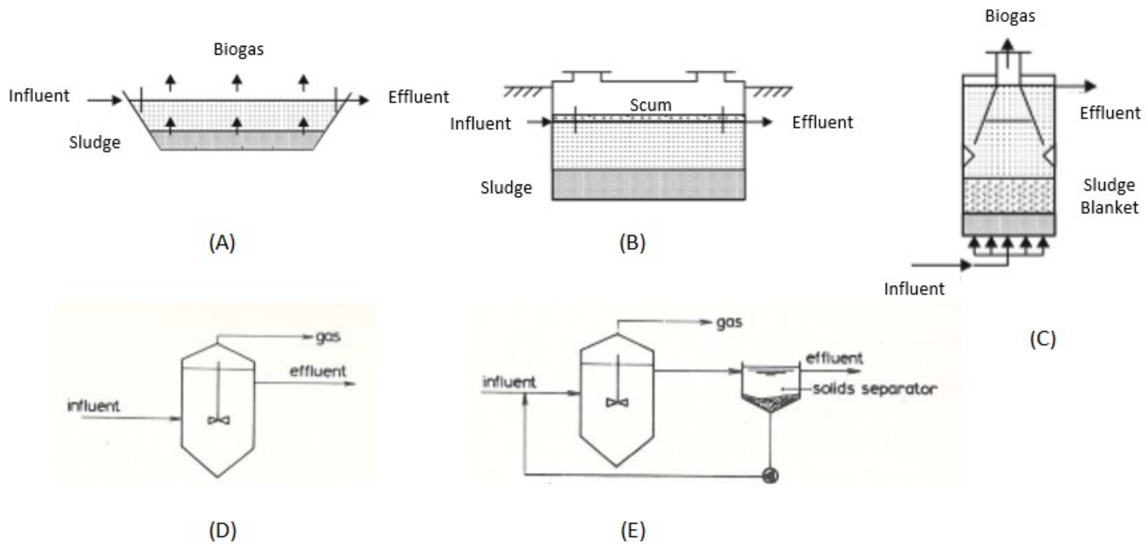
Certain basic conditions must be met to enable the bacteria to degrade the substrate efficiently, such as: i) absence of air (anaerobic atmosphere); ii) uniform temperature; iii) optimum nutrient supply and iv) optimum and uniform pH (Gomez, 2013). The equipment of a biogas plant should be able to meet these basic requirements. Therefore, a biogas plant designer should know from the beginning what kind of substrate the plant will feed on so that the right equipment for efficient biogas production can be selected.

There are some types of reactors already studied for anaerobic digestion and they can be classified in different ways: a) by temperature of operation or b) by the existence or absence of support material for biomass immobilization.

Considering the temperature of operation, anaerobic reactors may be operated under mesophilic or thermophilic temperature conditions. Increasing the process temperature from the mesophilic (32-42ºC) to the thermophilic (45-57ºC) level speeds up degradation and improves the health status of the substrate (Gomez, 2013). Depending on the substrate, the rate of methane generation in thermophilic systems may be 25 – 50% higher than in mesophilic systems, allowing shorter detention times (Banks, 2013). Specifically, for the case of sugarcane vinasse, thermophilic systems may be favorable since the vinasse is generated at 110ºC at the bottom of the distillation column and even if it is used in thermal regenerations its temperature would be reduced to values in the order of 55ºC or more.

Another classification of anaerobic reactors can be made based on the existence or not of support material for biomass immobilization. This biomass immobilization occurs in the form of biofilms, which are complex communities of microorganisms associated with surfaces and interfaces giving high resistance to biocides and antibiotics. Figure 4 shows five configurations of reactors without support material.

Figure 4: Schematic diagram of anaerobic reactors without support material



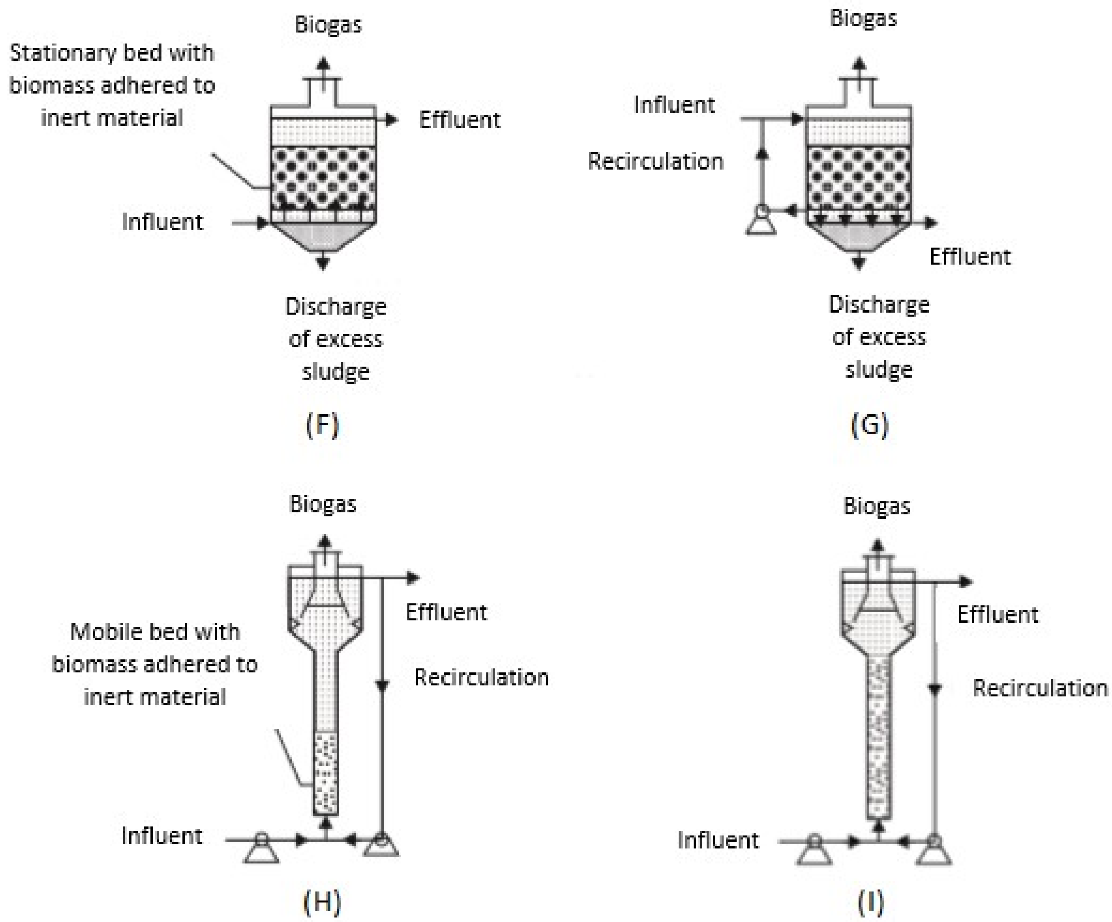
Note: (A) Anaerobic lagoon; (B) Septic tank; (C) UASB – Upflow Anaerobic Sludge Blanket; (D) CSTR (Continuous Stirred-Tank Reactor); (E) Anaerobic contact process.

Source: Adapted from Campos, 1999 and Lettinga, 1979.

In the case of anaerobic reactors with support material, the biomass is immobilized in the support material. The support material can be stationary or mobile and its selection should consider physical characteristics as size, shape, density, strength and roughness and chemical characteristics because it should be inert. It also should: be porous having high specific surface area, have good mechanical resistance, allow adsorption, and have low cost. Figure 5 illustrates four anaerobic reactors with support material, being two of them packed bed (also called anaerobic filter), one expanded bed and one fluidized bed.

In the case of reactor A and B from Figure 4, it is possible to say that it was a solution widely applied due to its installation and operation low cost, but they were not designed for biogas production, so their efficiency is low. They are commonly applied for sewage treatment.

Figure 5: Schematic diagram of anaerobic reactors with support material.



Note: (G) Anaerobic filter with upward flow; (H) Anaerobic filter with downward flow; (H) Expanded bed; (I) Fluidized bed.

Source: Adapted from Campos, 1999.

Comparing the other options (reactors from C to I), the main criteria to be considered when choosing an anaerobic reactor is the retention of an enough quantity of active sludge in the reactor. Based on this assumption, the reactor D, the CSTR of the flow through type, shown in the Figure 4, is inadequate because it does not retain enough quantity of active sludge in the reactor. The reactor E (Figure 4), the anaerobic contact process, seems to be better, regarding the activated sludge retention, because the wash out of activated sludge is controlled by a sludge separation with a recirculation system. However, the major problem in the practical application of the anaerobic contact process is the separation and concentration of the sludge from the digester effluent solution. The reactors from the Figure 5 (reactors from F to I) are promising approaches, but it is reported that although laboratory and pilot-plant experiences with these anaerobic reactors presented promising results, they are still in the experimental phase. The reactor C (Figure 4), the upflow anaerobic sludge blanket, known by the initials UASB, has been extensively investigated and seems to represent the much-needed breakthrough in the application of anaerobic digestion for the direct treatment of wastes (Lettinga, 1979).

In the UASB reactor concept, contrary to the ideas underlying the anerobic contact process, mechanical mixing and/or sludge recirculation are kept at a minimum of the sake of the settleability of the sludge. The basic idea of the UASB concept is that anaerobic sludge inherently has a superior settling characteristic, provided that the physical and chemical conditions for sludge granulation are favorable. Once this condition is met, retention of sludge mainly depends on an effective gas separation (Lettinga, 1979).

The ability of the UASB reactor to accumulate large amounts of biomass is due to the adhesion of bacterial cells to each another forming granules of biomass which can be several millimeters in diameter (MacLeod et al., 1990). These dense granules remain in the reactor providing stability, high levels of sedimentation and retention of biomass and favorable conditions for microorganisms and their syntrophic interactions.

Two of the main design criteria for reactors treating organic wastes are: Hydraulic Detention Time (HDT) and Organic Loading Rate (OLR) (Chernicharo, 2007). The hydraulic detention time parameter is of fundamental importance, since it is directly related to the velocity of the anaerobic digestion process, and that, in turn, depends on the size of the reactor. It is given by the relation between the total volume of the reactor (V, m^3) and the flow rate (Q, m^3/d), according to Eq.3-1.

$$HDT = V / Q \qquad \text{(Eq.3-1)}$$

The design of reactors with lower hydraulic detention times can be detrimental to the operation of the system because: i) excessive loss of biomass, that is washed out with the effluent, due to the resulting high upflow velocities in the digestion and settling compartments; ii) reduced solids detention time (sludge age), and a consequently decreased degree of stabilization of the solids and iii) possibility of failure in the system, once the biomass residence time in the system becomes shorter than its growth rate.

The volumetric organic load is defined as the amount (mass) of organic matter applied daily to the reactor, per volume unit and it is given by the following equation:

$$OLR = Q \times COD_{influent} / V \qquad (Eq.3\text{-}2)$$

where: ORL = Organic loading rate (gCOD/L·d), Q = flow rate (L/d), $COD_{influent}$ = influent substrate concentration (g COD/L) and V = useful volume of the reactor (L).

Hence, knowing the flow rate and the concentration of the influent wastewater, and assuming a certain design organic loading rate (OLR), the volume of the reactor can be calculated rearranging the previous equation:

$$V = Q \times COD_{influent} / OLR \qquad (Eq.3\text{-}3)$$

Several reactor configurations were found in literature (Table 4), including reactor with and without support material for biomass immobilization. Examples of reactors without support material found in the literature were: CSTR (Continuous Stirred-Tank Reactor), UASB (Upflow Anaerobic Sludge Blanket), UFD (Upflow Floc Digester) and UAR (Upflow Anaerobic Reactor). Examples of reactors with support material found in the literature were: AFBR (Anaerobic Fixed Bed Reactor), AfBR (Anaerobic fluidized Bed Reactor), APBR (Anaerobic Packed Bed Reactor), ASTBR (Anaerobic Structured-Bed Reactor), HAIB (Horizontal-flow Immobilized Biomass), UAF (Upflow Anaerobic Filter) and SCFFAR (Semi Continuous Fixed Film Anaerobic Reactor). Among support materials, there were: LDPF (Low-Density Polyurethane Foam), PE (Polyethylene), AC (Activated Carbon), NZ (Natural Zeolite), PS (Polystyrene), BB (Brick Ballast) and RR (Raschig Rings).

Table 4: Reactors for anaerobic digestion of sugarcane vinasse

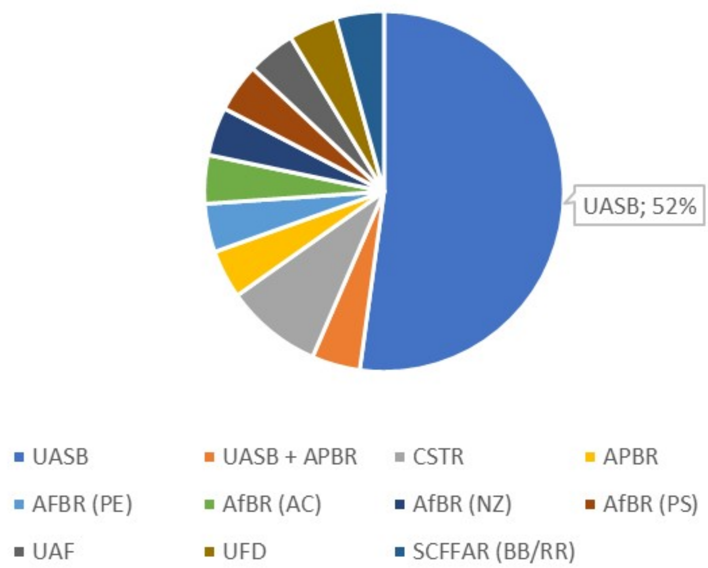
	T (ºC)	Reactor configuration	V (L)	Sugarcane vinasse origin	$COD_{influent}$ (g L^{-1})	HDT (d)	$OLR_{máx}$ (g L^{-1} d^{-1})	r_{COD} (%)	η_{CH4} (NLg^{-1})	References
MESOPHILIC SYSTEMS	22	UAR + CSTR	6.7 + 24.0	Juice	17.7	6.4	2.8	96.9	NA	Mota et al. (2013)
	40	UASB	100	Molasses	47.2	2.9	16.3	69.5	0.316	Riera et. al. (1985)
	NA	UASB	11,000	Molasses + Juice	45.0	0.83	18.3	76.0	0.368	Costa et. al. (1986)
	28 - 33	UASB	11,000	Juice	31.3	4.9	10.5	88.5	0.244	Craveiro et. al. (1986)
	38 - 40	UASB	5.8	NA	2.6	3.8	18.0	60.0	NA	Rintala (1991)
	35	UASB	2.3	Molasses	68.9	3.2	21.5	58.0	0.29	Espinosa et al. (1995)
	25 - 35	UASB	3	Molasses	121	7.5	17.05	69.0	0.381	España-Gamboa et al. (2012)
	20 - 30	UASB	40.5	NA	17.55	2.8	7.5	67.0	0.181	Barros et al. (2016)
	20 - 30	UASB	21.5	NA	16.24	2.8	7.5	77.0	0.185	Barros et al. (2016)
	40	UASB	1.3	Juice	22.9	2.5	9.6	NA	0.239	Janke et al. (2016)
	32 – 37	UASB	NA	Molasses + juice	37.5	19.92	NA	74.0	0.33	Bernal et al. (2017)
	32 - 37	UASB	NA	Juice	21.0	19.92	NA	74.0	0.33	Bernal et al. (2017)
	35	UASB	4.3	Molasses + Juice	27.8	2.0	12.5	71.2	0.289	Cabrera-Díaz et al. (2017)
	35	UASB + APBR (LDPF)	NA	Molasses + Juice	27.8	2.0	12.5 / 4.4	86.7	0.289/0.207	Cabrera-Díaz et al. (2017)
	35	CSTR	50	NA	62.3	NA	NA	NA	0.24	González et al. (2017)
	NA	CSTR	4,500	Molasses	132	26.2	5.1	63.2	NA	Yeoh (1997)
	35	APBR (LDPF)	3.5	Molasses + juice	27.8	1.4	8.3	62.5	0.166	Cabrera-Díaz et al. (2017)
	35	AFBR (PE)	23	NA	10 - 24	< 1	> 30	> 80.0	NA	Thanikal et al. (2007)
	NA	AfBR (AC)	0.75	Molasses	79.2	NA	10	75 -78	0.267	Fernández et al. (2001)
	NA	AfBR (NZ)	1.0	Molasses	56.2 – 83.0	NA	10	70 -90	0.200	Fernández et al. (2001)
	30	AfBR (PS)	4.2	Molasses	20.1	24	26.2	51.0	0.32	Siqueira et al. (2013)
	35	UAF	21	Juice	21.5	6.0	3.4	89.0	0.38	Russo et al. (1985)
	35	UFD	10	Juice	30.0	1.2	25.4	70.0	0.32	Cail and Barford (1985)
	35	SCFFAR (BB/RR)	NA	Molasses	50.0	20	NA	82.1	0.243	Shrihari and Tare (1989)
THERMOPHILIC SYSTEMS	55	UASB	5.8	NA	3.8	3.8	23.0	68.0	NA	Rintala (1991)
	55 – 57	UASB (USM)	70,000	Molasses + juice	31.5	0.45	26.5	71.7	0.310	Souza et al. (1992)
	55	UASB	140	Molasses	10.0	NA	28.0	67.0	0.29	Harada et al. (1996)
	55	UASB I	10	NA	25.8	NA	25	72.6	0.234	Ferraz Júnior et al. (2016)
	55	APBR-UASB II	3.4	NA	25.8	NA	25	96.1	0.306	Ferraz Júnior et al. (2016)
	55	APBR + UASB	2.3 + 3.5	NA	28.3	1	25	70.2	0.313	Fuess et al. (2017)
	55	APBR + ASTBR	2.3 + 2.5	NA	28.3	1.1	30	76.2	0.329	Fuess et al. (2017)
	55	CSTR	5.0	Molasses	130	9.0	14.5	65.2	0.084	Yeoh (1997)
	55	2-CSTR	3.6 + 5.0	Molasses	115	7.6	20.0	65.2	0.258	Yeoh (1997)
	55	NA	NA	Molasses + juice	33.6	NA	NA	72.0	0.29	Moraes et al. (2014)

Note: (NA – Not Available; USM – Usina São Martinho) Source: elaborated by the author

Some initial findings can be drawn from the analysis of this table. The first one refers to the greater number of studies performed in mesophilic conditions than those performed under thermophilic conditions. One possible reason for this finding could be related to the fact that most reactors are laboratory scale treating vinasse not directly from the industrial unit, but rather are often stored at low temperatures and then heated and biodigested. In the case of the 4,500-liter (Yoeh, 1997), pilot scale, the author explains that due to operational reasons, the uninsulated methanogenic bioreactors were operated at mesophilic temperatures. Already in the case of the reactor of 11,000 liters (Craveiro et al., 1986 and Costa et al., 1986), installed in the Penedo Agroindustrial S.A. Distillery (PAISA) in Penedo, Alagoas, northeast of Brazil, there is no cited reason for choosing the mesophilic operating system.

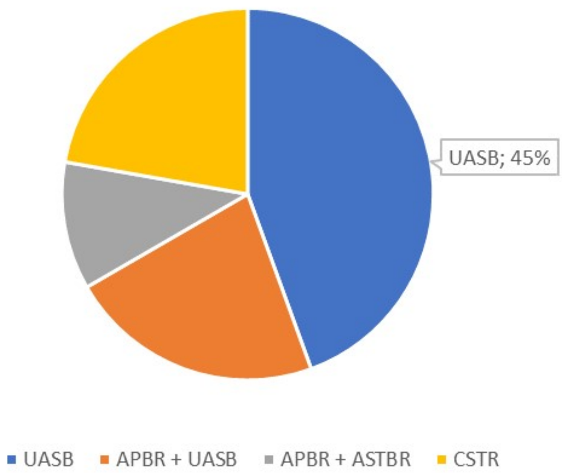
As predicted by Lettinga (1979), in both mesophilic and thermophilic conditions, there is a predominance of the use of the UASB reactor in the anaerobic biodigestion systems of sugarcane vinasse, 52% and 45%, respectively, as illustrated by Figures 6 and 7. In the case of thermophilic systems, there is also an expressive use of this type of reactor combined with other types.

Figure 6: Types of reactors studied under mesophilic conditions.



Source: elaborated by the author based on the data from Table 3-4.

Figure 7: Types of reactors studied under thermophilic conditions



Source: elaborated by the author based on the data from Table 3-4.

By making a temporal analysis, that is, an analysis of the use of each type of reactor over time, it is realized that the UASB reactor under mesophilic conditions has been increasingly adopted: 5 studies between 1985 and 2000 and 7 studies between 2001-2017. In the case of thermophilic systems, there is a tendency to use other types of reactors or even a combination of other reactors with UASB in more recent studies. Thus, as predicted by the authors mentioned in the introduction of the present work, the survey presented here confirms the highlight of the UASB reactor as the one of greater use and representativeness among the analyzed anaerobic reactors for biodigestion of the sugarcane vinasse.

Analyzing specifically the UASB reactors, it was possible to verify that: i) as in the case of reactors in general, a greater number of studies in mesophilic conditions than under thermophilic conditions was observed for the UASB reactor, 12 and 4, respectively; ii) the average COD of influent was significantly higher in studies under mesophilic conditions than under thermophilic conditions, 38.2 g COD/L and 17.8g COD/L, respectively.

It was expected, based on the statements of Banks (2013), that the rate of methane generation in thermophilic systems would be 25 – 50% higher than in mesophilic systems. However, contrary to expectations, the average results in terms of efficiency of COD removal and conversion of COD to methane were better for mesophilic systems than for thermophilic systems. The difference between the average COD removal efficiency was low, around 2%, however the highest value, 71.7%, was found in mesophilic systems, which was not expected. Analogously, the average methane yield coefficient was higher in mesophilic conditions, 0.287 NL CH_4 / g $COD_{removed}$, than in thermophilic conditions, 0.278 NL CH_4 / g $COD_{removed}$.

Considering operational parameters such as hydraulic detention time and organic loading rate, parameters of great importance in terms of plant design, better results were obtained for thermophilic systems than for mesophilic systems. The average hydraulic detention time was 6 days in mesophilic conditions against 2 days in thermophilic operations. The average maximum organic loading rate was 13.9 and 25.6 g/L/d in mesophilic and thermophilic systems, respectively.

In order to compare the theoretical (B) and practical (A) methane yield coefficients, Table 5 was developed based on the application of equations from 6-36 to 6-39, obtaining the relation (A/B) in %. From the data presented in Table 3-5, it can be reported that on average the COD conversion efficiency into methane based on its theoretical potential is of the order of 70% regardless of the type of reactor or the operating temperature. However, there is a large variation between the data obtained, with the standard deviation around 17%. Special highlight for reactors UASB (Upflow Anaerobic Sludge Blanket) from España-Gamboa et al. (2012) and UAF (Upflow Anaerobic Filter) from Russo et al. (1985) which reach values greater than 90%.

Table 5: Theoretical COD conversion efficiency and practical values.

	REACTOR CONFIGURATION	$COD_{removed}$ (g L^{-1})	K (gCOD L^{-1})	V_{CH4} (L)	Theoretical η_{CH4} (NLg^{-1})	Relation (A/B)	REF.
MESOPHILIC SYSTEMS	UAR + CSTR	17.2	2.64	6.5	0.378	-	Mota et al. (2013)
	UASB	32.8	2.49	13.2	0.401	79%	Riera et. al. (1985)
	UASB	-	-	-	-	-	Costa et. al. (1986)
	UASB	27.7	2.57	10.8	0.389	63%	Craveiro et. al. (1986)
	UASB	1.6	2.50	0.6	0.400	-	Rintala (1991)
	UASB	40.0	2.53	15.8	0.395	73%	Espinosa et al. (1995)
	UASB	83.5	2.57	32.4	0.389	98%	España-Gamboa et al. (2012)
	UASB	11.8	2.62	4.5	0.382	47%	Barros et al. (2016)
	UASB	12.5	2.62	4.8	0.382	48%	Barros et al. (2016)
	UASB	-	-	-	-	-	Janke et al. (2016)
	UASB	27.8	2.54	10.9	0.394	84%	Bernal et al. (2017)
	UASB	15.5	2.54	6.1	0.394	84%	Bernal et al. (2017)
	UASB	19.8	2.53	7.8	0.395	73%	Cabrera-Díaz et al. (2017)
	UASB + APBR (LDPF)	24.1	2.53	9.5	0.395	73%	Cabrera-Díaz et al. (2017)
	CSTR	-	-	-	-	-	González et al. (2017)
	CSTR	-	-	-	-	-	Yeoh (1997)
	APBR (LDPF)	17.4	2.53	6.9	0.395	42%	Cabrera-Díaz et al. (2017)
	AFBR (PE)	13.6	2.53	5.4	0.395	-	Thanikal et al. (2007)
	AfBR (AC)	-	-	-	-	-	Fernández et al. (2001)
	AfBR (NZ)	-	-	-	-	-	Fernández et al. (2001)
	AfBR (PS)	10.3	2.57	4.0	0.389	82%	Siqueira et al. (2013)
	UAF	19.1	2.53	7.6	0.395	96%	Russo et al. (1985)
	UFD	21.0	2.53	8.3	0.395	81%	Cail and Barford (1985)
	SCFFAR (BB/RR)	41.1	2.53	16.2	0.395	62%	Shrihari and Tare (1989)
THERMOPHILIC SYSTEMS	UASB	2.6	2.38	1.1	0.421	-	Rintala (1991)
	UASB (USM)	22.6	2.37	9.5	0.422	73%	Souza et al. (1992)
	UASB	6.7	2.38	2.8	0.421	69%	Harada et al. (1996)
	UASB I	18.7	2.38	7.9	0.421	56%	Ferraz Júnior et al. (2016)
	APBR-UASB II	24.8	2.38	10.4	0.421	73%	Ferraz Júnior et al. (2016)
	APBR + UASB	19.9	2.38	8.4	0.421	74%	Fuess et al. (2017)
	APBR + ASTBR	21.6	2.38	9.1	0.421	78%	Fuess et al. (2017)
	CSTR	84.8	2.38	35.6	0.421	20%	Yeoh (1997)
	2-CSTR	75.0	2.38	31.5	0.421	61%	Yeoh (1997)
		24.2	2.38	10.2	0.421	69%	Moraes et al. (2014)

Source: elaborated by the author

3.4 Biogas purification (biogas cleaning and methane upgrading)

Biogas purification is related to the removal of contaminants from the raw biogas to obtain biomethane of a certain desired quality (Miltner *et al.*, 2017).

Usually, the first treatment or stage of the biogas upgrading is called "biogas cleaning" and includes the removal of harmful and/or toxic compounds such as hydrogen sulfide, H_2S (Angelidaki *et al*., 2018). Besides being a toxic and harmful gas, threatening human physical health, H_2S can also cause corrosion in the metal pipes and equipment in hot and humid conditions, and it has an unpleasant odor. Besides, when burning, H_2S is oxidized to SO_2, one of the major atmospheric pollutants (Cong Xiao *et al*., 2017). There are several commercial cleaning technologies, summarized in the Table 6.

The second treatment or stage is called "methane upgrading" and aims to increase the low calorific value (LCV) of the biogas through CO_2 removal, since the higher CO_2 content is, the lower the LCV in biogas (Angelidaki *et al*., 2018). Like cleaning technologies, there are several commercial methane upgrading technologies, showed in Tables 7 and 8.

Table 6: Commercial biogas cleaning technologies.

Technology	**Mechanism**	**Description**
Wet desulfurization	Chemical absorption	An alkali reversible reaction between a chemical solvent and the gas removes H_2S; Usually, chemical absorption includes amine method, carbonate method and ammonia method; The amine method, the most commonly used, is the use of alkyl amines as solvent, such as anhydrous monoethanolamine (MEA), diglycolamine (DGA), diethanolamine (DEA), di-2-propanolamine (DIPA), methyldiethanolamine (MDEA) and dimethylethanolamine (DMEA).
	Physical absorption	Naphthoquinone absorption method and ammonia method use solvents to remove H_2S taking advantage from different solubilities and precipitating H_2S through the pressure drop.
	Wet oxidation	Absorption and oxidation of H_2S of the gas by a neutral or basic solution (usually an alkaline solution) containing oxidant (usually ferric oxide), so it can be reduced to elemental sulfur.
Dry desulfurization	Membrane separation	Membrane based gas separation is combined with traditional physical absorption, chemical absorption, cryogenic rectification, and cryogenic treatment.
	Molecular sieve	Strong adsorption between polar or polarized compounds such as hydrogen and hydrogen groups in the sulfur and zeolitic molecular sieves removes H_2S from the biogas.
	Fixed bed adsorption	Adsorption on metal oxides or hydroxides, usually iron oxide is used but zinc and cooper also have been reported. In all cases, Sulphur is bound as metal sulphide and water is released to the biogas. Adsorptive H_2S removal can also be performed on activated carbon impregnated with potassium iodide or sulphuric acid, dosing oxygen in order to oxidize H_2S to elemental sulphur.
	Claus oxidation	The first step of Claus process consists in the partially oxidation of H_2S to SO_2 with air. The mixture of H_2S and SO_2 reacts over a bauxite catalyst to yield elemental sulfur and water.
Biological desulfurization	Photoautotroph or Chemoautotroph	Firstly, the H_2S gas is dissolved, then the dissolved H_2S enters the desulfurization bacteria through the cell membrane and the intracellular H_2S is converted and utilized to remove H_2S from biogas.

Source: Adapted from Cong Xiao *et al.* (2017) and Miltner *et al.* (2017).

Table 7: Commercial methane upgrading physical and chemical technologies.

Technologies	Principle of separation	Cost	CH_4 losses (%)	CH_4 recovery (%)
Physical absorption method using water scrubbing system	This process relies on the separation of CO_2 from biogas due to its increased solubility in water compared to CH_4 (according to Henry's law, the solubility of CO_2 in water at 25ºC is approximately 26 times higher compared to CH_4).	Medium	< 2	96 - 98
Physical absorption method using organic solvents	This method relies on the same principle as water scrubbing system; however, the absorption of CO2 is accomplished using organic solvents (commonly, mixtures of methanol and dimethyl ethers of polyethylene glycol) instead of water.	Medium	2 - 4	96 - 98
Chemical absorption method using amine solutions	Chemical scrubbers use aqueous amine solutions to bind the CO_2 molecules contained in the biogas through an exothermic reaction strongly selective and thus the methane loss can be very low.	High	< 0.1	96 – 99
Pressure swing adsorption (PSA)	The main principle of this technology relies on the proprieties of pressurized gasses to be attracted to solid surfaces based on their molecular characteristics and the affinity of the adsorbent material such as carbon molecular sieve, activated carbon, zeolites, and other adsorbent material with high surface area.	Medium	< 4	96 – 98
Membrane separation	The main principle of this technology relies on the selective permeability properties of polymeric membranes such as cellulose acetate and polyimide.	High	< 0.6	96 – 98
Cryogenic separation process	Conduction of a gradual decrease of biogas temperature separating the liquified CH_4 from CO_2. Usually, this technology is considered to obtain a product in accordance with the quality standards for Liquefied Natural Gas (LNG).	High	2	97 – 98
Chemical Hydrogenation process	Reduction of CO_2 with H_2 that can be conducted biologically or chemically, based on the Sabatier reaction. Regarding to chemical hydrogenation process, the most used catalysts are Nickel and Ruthenium.	Medium	Not found	97 – 99

Source: Adapted from Angelidaki *et al.* (2018).

Table 8: Commercial methane upgrading biological technologies.

Technologies	**Principle of separation**
Chemautotrophic methods	The principle of this technology is based on the action of hydrogenotrophic methanogens that can utilize H_2 to convert CO_2 to CH_4. It can be classified as in-situ, ex-situ, and hybrid designs.
Phototrophic methods	Methanation process catalyzed by phototrophic organisms like algae in enclosed or open photobioreactors.
Fermentation processes	Valuable liquids production (e.g., acetate, butyrate, butanol, etc) that can also be precursors of liquid biofuels production.
Microbial electrochemical methods	In the microbial electrolysis cell (MEC), electrons released by bacteria from oxidation of organics on anode can combine with protons to generate hydrogen in the cathode chamber and this H_2 can be used in the methanation process of CO_2.

Source: Adapted from Angelidaki *et al.* (2018).

4 BIOGAS USES

Cleaned biogas (raw biogas) can be used for heat generation, electricity generation and for cogeneration (simultaneous electricity and heat generation). Cleaned and upgraded biogas (biomethane) is required for use as a transport fuel or for injection into the natural gas grid. The choice of the most viable and relevant use will depend on factors related to local needs and/or limitations. As an example of local needs, in European countries, it is possible that the choice would include the generation of heat while in tropical countries such as Brazil, the choice would be the production of electricity. If there is a prediction of a growing demand of natural gas without certainty about the quality and quantity of the natural gas reserves, maybe the production of biomethane replacing it could be an interesting choice, since the natural gas grid can reach the consumer area.

From the technology point of view, the production of biogas via anaerobic digestion is a developed technology. The produced biogas usually is a mixture of methane and carbon dioxide as more representative components, but biogas may also contain other compounds in small amounts that can have a negative effect in some biogas uses. The typical composition of raw biogas from an anaerobic digester is 50-75% methane (CH_4), 25-50% carbon dioxide (CO_2) and 2-8% other gases such as nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), ammonia (NH_3) and hydrogen (H_2) (Gomez, 2013).

There are different aspects on quality demands for biogas use. In general, raw biogas can be used for heat and power production while cleaned and upgraded biogas is required for transport fuel or for injection into the natural gas grid. But there are some exceptions as in the case of fuel cells for power production from biogas, for example. Different types of fuel cells have different sensitivities to impurities in the biogas. High-temperature fuel cells are more fuel flexible and are also more tolerant to impurities in the fuel, but for low-temperature fuel cells biomethane must be catalytically reformed to hydrogen which can be used as a fuel. For biogas to be used as transport fuel, it is advantageous that its energy content would be high, so cleaning and enriching processes would be recommended. If biogas is going to be injected to the natural gas grid, it must fulfil the natural gas quality requirement for the grid, independent of the final use of the gas (Petersson, 2013).

Still related to technology aspects, the uses of biogas present different levels of maturity. The main and most developed technologies found in the literature are: internal combustion engine (ICE), microturbine and fuel cell for power generation, boiler for heat generation, combined heat, and power for cogeneration, upgrading and converted engine for transport and upgrading technologies for injection in the natural gas grid (Tables 7 and 8).

4.1 Electricity production

According to Cortez et al. (2008), the interest related to the production of electricity from biomass can be attributed to a set of factors, among which the following should be highlighted:

i. If the production of biomass is sustainable, greenhouse gas emissions are very low or even zero, giving a clear advantage in relation to the use of fossil fuels.
ii. As for the other environmental aspects, considering the conversion stage, the generation of electricity from biomass can bring advantages in relation to the use of fossil fuels in terms of sulfur oxide emissions and, in general, also in terms of nitrogen oxide emissions.
iii. In the United States and Europe, large sums are allocated annually to agricultural subsidies and even non-production subsidies. The production of electricity from biomass would allow the maintenance of agricultural activity, the appropriate use of land and the minimization of expenses with subsidies or their repositioning.
iv. For many countries, it is necessary to diversify the electricity generation matrix, reducing the risk of shortages and drastically increasing generation costs. The production of electricity from biomass can help in this regard.

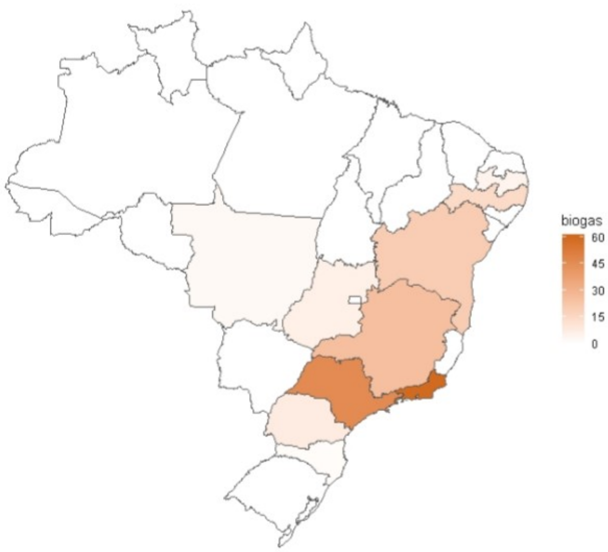
However, despite the mentioned advantages, the main limitations to the use of biomass in electricity production are:

i. The costs of producing biomass and, in some cases, transport costs, are decisive for the economic viability of electricity generation projects, and few regions in the world have adequate conditions to produce biomass with high productivity and low cost.
ii. Considering the technologies now commercial, the reduced efficiency of energy conversion from biomass to electricity and the low unit capacity of the systems impair economic viability.
iii. The production of electricity from biomass needs to be sustainable from an environmental, social, and economic point of view. It is necessary that the environmental benefits are ensured throughout the biomass-electricity production chain since the environmental issue is one of its main justifications.

In view of the relevance of the positive aspects and the prospects of minimizing the barriers that exist in the medium term, several countries have ambitious plans to make viable projects to produce electricity from biomass.

The Figure 8 shows the installed capacity of electricity generation from biogas in the states of Brazil.

Figure 8: Installed Biogas generation capacity per UF, in MW.



Source: Adapted from BEN, 2020.

Another aspect of fundamental relevance is highlighted by Cogen (2005) and refers to the fact that the main bioelectricity offer in the State of São Paulo is regionalized close to the main consumer center, which contributes to lower losses and investments in electricity systems. electricity distribution.

4.2 Transport fuel

Raw biogas can be converted to bio-compressed natural gas (bio-CNG) at 20-25 MPa (2900 - 3600 psi) after cleaning and upgrading technologies to meet the standards established in ANP nº8 of 01/30/2015 to be able to be mixed with natural gas or replace it in its end uses (Table 9)

Table 9: ANP specifications for biomethane - Southeast Region of Brazil.

Specification of biomethane for the Southeast Region of Brazil (ANP No. 8 of 01/30/2015)		
CH_4	96.5	% vol
CO_2	3.0	% vol
O_2	0.5	% vol
H_2S maximum	10	mg/Nm^3
Total sulfur maximum	70	mg/Nm^3

Note: CH_4 - Methane; CO_2 - Carbon dioxide; O_2 – Oxygen; H_2S – Hydrogen sulfide.

Source: Adapted from Poveda (2019).

The compressed biomethane (bio-CNG) has the same properties as CNG in terms of engine performance, gas consumption and efficiency, when used as vehicular fuel (Khan et al., 2017). For heavy vehicles, the use of bio-CNG is very advantageous because it has higher calorific value and it is more environmentally friendly compared to any other fuel, as it is showed by Table 10. Bio-CNG has a great potential for becoming one of the most sustainable vehicular fuels soon.

Table 10: Gaseous emissions from heavy vehicles using different types of fuel.

Fuel	CO (g/km)	HC (g/km)	NO_x (g/km)	CO_2 (g/km)	Particulates (g/km)	Calorific value (kJ/kg)
Diesel	0.20	0.40	9.73	1053	0.100	44,800
Natural Gas	0.40	0.60	1.10	524	0.22	50,000
Biogas	0.08	0.35	5.44	223	0.5	35,000
Bio-CNG	0.02	0.12	0.48	100	0.1	52,000

Note: CO: Carbon monoxide; HC: Hydrocarbons; NO_X: Nitrogen oxides; CO_2: Carbon dioxide.

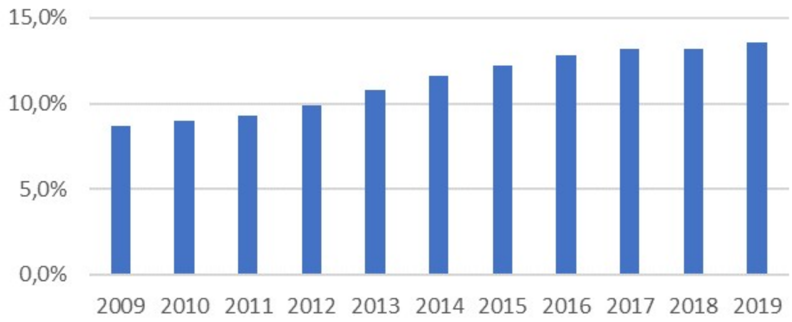
Source: Adapted from Vijay and Chandra (2006).

To biomethane replace fuels such as diesel, heavy-duty vehicles system must be adapted. In October 2022, Scania, a heavy vehicle manufacturer, announced that it is continuing to expand and improve its biogas solutions for heavy trucks with the introduction of two new engines. The new 13-litre engines deliver 420 horsepower and 460 hp, meeting most of the energy-intensive market in Europe, including long-haul trucks. Interest in locally produced biomethane for trucks is, according to the company, growing rapidly due to initiatives to decarbonize road transport and move away from fossil fuel. The new engines run on complete combustion of both fuel and oxygen, without the need for diesel or AdBlue (Arla 32). Spark plugs start, as in gasoline engines. Gas pre-mixing takes place in the intake manifold on the way to the cylinders. The company points out that an important objective for the cars was to guarantee the best possible drivability, with Scania Super diesel engines as a benchmark for performance and other characteristics. When compared to a diesel engine of the same power level, the most noticeable difference to a layperson would probably be that the gas engine is much quieter (Tecnologística, 2022). Biomethane can be transported to a refueling station either by a dedicated biomethane pipeline or natural gas pipeline.

4.3 Natural gas substitutive

The natural gas share in Brazilian energy matrix is increasing during the past years, as presented in Figure 9.

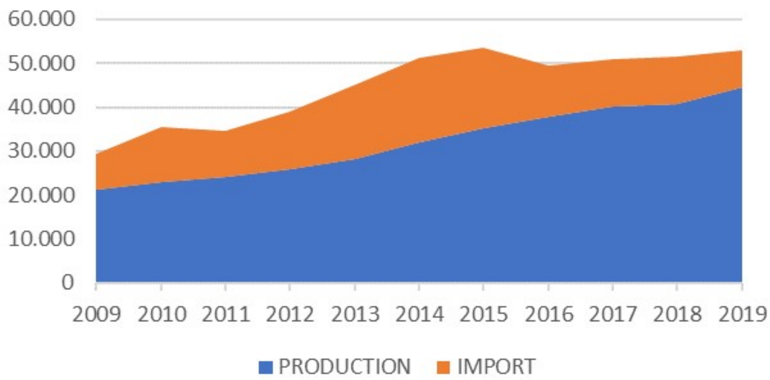
Figure 9: Natural gas share in Brazilian energy matrix



Source: Adapted from BEN, 2020.

Although the percentage of natural gas importation is decreasing in the past years, from 38% in years 2013 and 2014 to 16% in 2019, Brazil is still dependent of natural gas importation as presented in Figure 10.

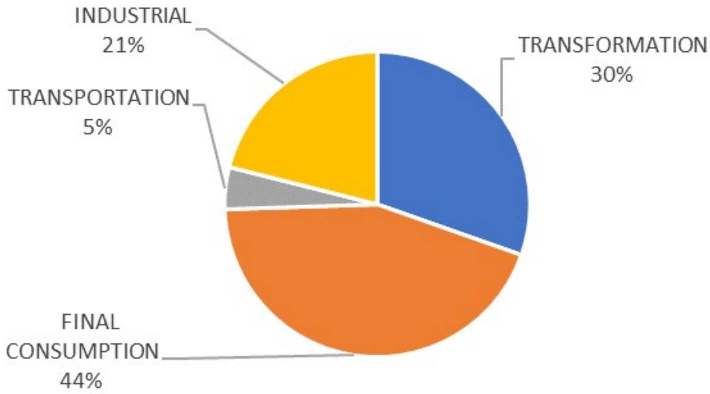
Figure 10: Brazilian natural gas flows, in 10^6 m^3



Source: Adapted from BEN, 2020.

From the consumption perspective, natural gas is distributed among the consuming sectors as illustrated in Figure 11.

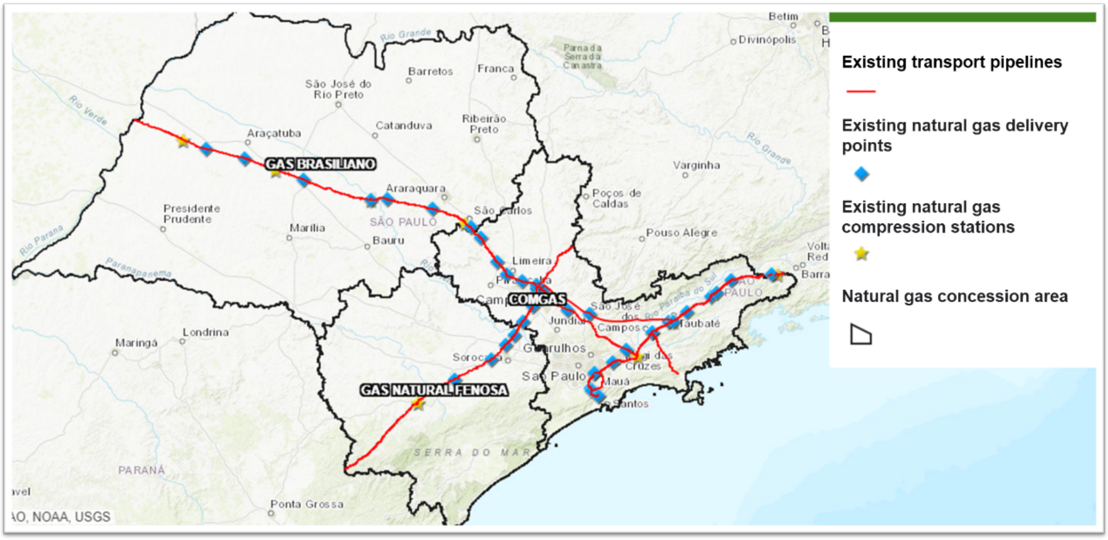
Figure 11: Brazilian natural gas consumption



Source: Adapted from BEN, 2019.

Due to the depletion and low quality of natural gas reserves, special attention has been given to the possibility of using upgraded biogas as a substitute for natural gas to be injected into the existing network lines. In Brazil, natural gas networks are reduced, as can be seen in Figure 12, which shows the natural gas network in the State of São Paulo, the most developed Brazilian State with the largest infrastructure. Biogas is distributed throughout the country and can promote the creation of demand and attract regional investments. There is no doubt that the logistics for the distribution of gas, whether renewable or not, is essential for the country's economy, which should benefit from its great opportunities for the national production of gaseous fuels. In São Paulo, GasBrasiliano will be the first concessionaire in the country to distribute 100% biomethane in a dedicated network that it is building in the western region of São Paulo (GasNet, 2022).

Figure 12: Natural gas network in the State of São Paulo



Source: Adapted from Arcgis, 2023.

For this, biogas must have the same quality as natural gas or better through adequate and efficient upgrading processes. Biogas requirements regarding CH_4, CO_2 and H_2S contents for injection into natural gas grid set by Sweden, France, Switzerland, Germany, Netherlands, and Austria are shown in the Table 11.

Table 11: Selected biogas requirements for injection into natural gas grid.

Component	Sweden	France	Switzerland	Germany	Netherlands	Austria
CH_4 (%vol)	≥ 97	≥ 86	≥ 96	≥ 96	≥ 85	≥ 96
CO_2 (%vol)	≤ 3	≤ 2.5	≤ 6	≤ 6	≤ 6	≤ 3
H_2S (mg/Nm^3)	≤ 10	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5

Source: Adapted from Khan *et al.* (2017).

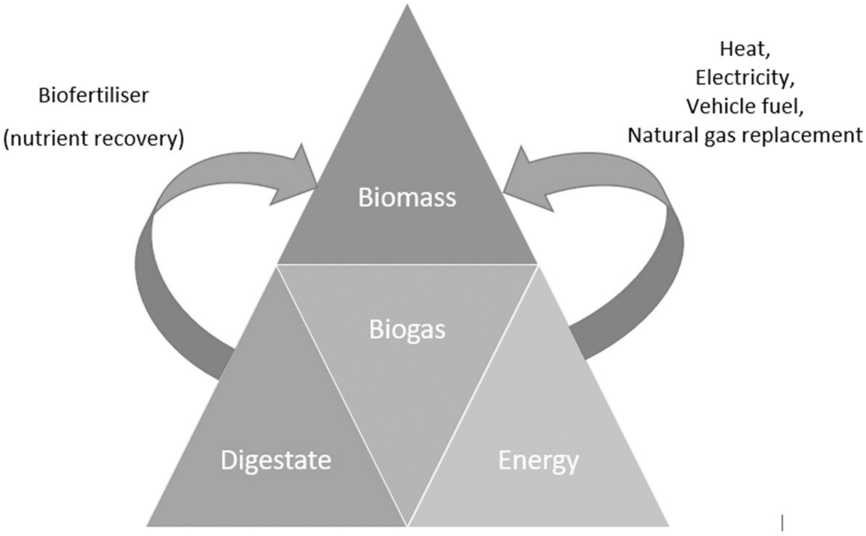
One important advantage of using natural gas grid for biomethane distribution is that the grid connects the production sites of biomethane, which is usually in rural areas in a decentralized way, with more densely populated areas where the gas consumers are (Dada and Mbohwa, 2017).

5 BIOGAS SUSTAINABILITY

The extreme limits of global development may be determined by the availability of energy resources and the ability of the biosphere to absorb the by-products of energy use. These energy limits can be reached much faster than the limits imposed by other material resources. First, there are supply problems: the depletion of oil reserves, the high cost and environmental impact of coal mining, and the risks of nuclear technology. Second, there are emission problems, especially acid pollution, and carbon dioxide buildup, which cause the Earth to warm. It is possible to solve some of these problems by using more renewable energy resources and by placing greater emphasis on energy conservation and efficient use (Brundtland, 1991).

Usually, biomass used in the biogas production represents a waste from a production unit (agricultural wastes, forests wastes, industrial wastes, municipal wastes, manure, etc.…). So, it is possible to produce energy and to reduce waste generation in a single technology route. Biogas solutions can contribute to better sustainability performance because enable the conversion of biomass into energy and digestate through anaerobic digestion. Energy carriers can be used for heat and electricity, for vehicle, or for substituting natural gas in a gas grid. Digestate can be used as biofertilizer, allowing for nutrient recovery (Hangman et al., 2018), as illustrated in Figure 13. The use as a biofertilizer depends on compliance with the 2016 CONAMA regulation that deals with the subject in Brazilian territory.

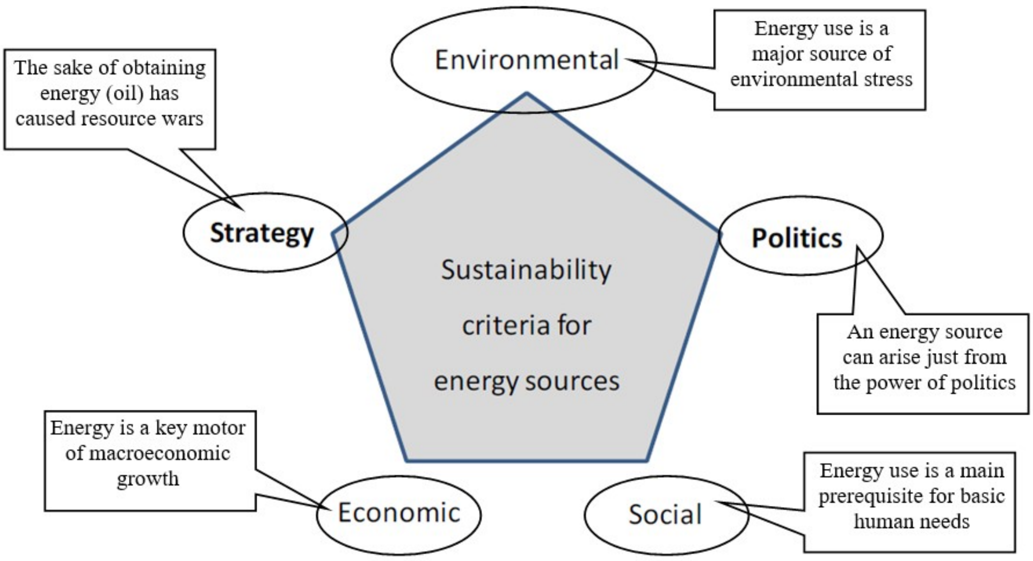
Figure 13: The role of biogas solution in sustainable development



Source: Elaborated by the author.

Besides the Triple Bottom Line - respect to the environment, economic viability and social welfare, energy has two extra aspects that are vital: strategy and politics (Romanelli, 2009), as illustrated in the Figure 14. To better understand the sustainability criteria for energy sources, it is essential to consider all five dimensions: economic, environmental, social, strategic, and politic.

Figure 14: The sustainability basis for energy.



Source: Adapted from Romanelli, 2009.

In line with this broader vision of sustainable development, the Brundtland Report (Brundtland, 1991) argues that the pursuit of sustainable development requires:

- a political system that ensures the effective participation of citizens in the decision-making process.
- an economic system capable of generating surpluses and technical knowledge on a reliable and constant basis.
- a social system that can resolve tensions caused by unbalanced development.
- a production system that respects the obligation to preserve the ecological basis of development.
- a technological system that constantly seeks new solutions.
- an international system that encourages sustainable patterns of trade and finance.
- a flexible and self-healing administrative system

Also bringing a broader vision of sustainability, the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go together with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests (United Nations, 2023). The 17 SDGs are shown in the Figure 15:

Figure 15: The 17 Sustainable Development Goals

Source: Adapted United Nations, 2023.

As shown in Tables 12 and 13, it was possible to find several studies about the sustainability of the five most common utilizations of biogas: electricity generation, heat generation, cogeneration (simultaneous electricity and heat generation), transport fuel and injection in the natural gas grid.

Table 12: Types of analysis made in each biogas application (part 1 of 2)

	REFERENCE	COUNTRY	TECHNICAL ANALYSIS	ENERGETIC ANALYSIS	ECONOMIC ANALYSIS	ENVIRONMENTAL ANALYSIS	SOCIAL ANALYSIS
ELECTRICITY GENERATION	Bernal et al., 2017	Brazil	-	-	X	-	-
	Moraes et al., 2014	Brazil	-	-	X	X	-
	Fuess et al., 2017	Brazil	-	X	X	-	-
	Fues and Garcia, 2015	Brazil	-	X	X	-	-
	Salomon and Lora, 2009	Brazil	-	X	-	-	-
	Santos et al., 2016	Brazil	-	X	X	X	-
	Santos et al., 2018	Brazil	-	X	X	X	-
	Hakawati et al., 2017	United Kingdom	-	X	-	-	-
	Wu et al., 2016	China	-	X	X	X	-
	Ravina and Genon, 2015	Italy	-	-	-	X	-
	Kan et al., 2018	Singapore	X	X	-	X	-
	Chandra et al. 2011	India	X	-	-	-	-
HEAT GENERATION	Patterson et al., 2011	United Kingdom	-	-	-	X	-
	Hakawati et al., 2017	United Kingdom	-	X	-	-	-
	Horschig et al., 2016	Germany	-	-	-	X	-
	Horschig et al., 2016	United Kingdom	-	-	-	X	-
	Börjesson and Berglund, 2006 (Part I and II)	Sweden	-	-	-	X	-
ELECTRICITY AND HEAT GENERATION	Hakawati et al., 2017	United Kingdom	-	X	-	-	-
	Djatkov et al., 2014	-	X	-	-	-	-
	Moraes et al., 2014	Brazil	-	-	X	X	-
	Patrizio et al., 2015	Italy	-	X	X	X	-
	Pöschl et al., 2010	Germany	-	X	-	-	-
	Rehl et al., 2012	Germany	-	-	-	X	-
	Lauer et al., 2018	United States	-	-	X	X	-
	Poeschl et al., 2012 (Part I and II)	Germany	-	-	-	X	-
	Fubara et al., 2018	United Kingdom	X	-	X	X	-
	Akbulut, 2012	Turkey	-	-	X	X	-
	MosayebNezhad et al., 2018	Italy	-	X	X	-	-
	Evangelisti et al., 2014	United Kingdom	-	-	-	X	-
	Whiting and Azapagic, 2014	United Kingdom	-	-	-	X	-
	Horschig et al., 2016	Germany	-	-	-	X	-
	Horschig et al., 2016	United Kingdom	-	-	-	X	-
	Wu et al., 2016	China	-	X	X	X	-
	Münster et al., 2015	European Union	-	-	X	X	-
	Ravina and Genon, 2015	Italy	-	-	-	X	-
	Morero et al., 2015	Argentina	-	-	X	X	X
	Börjesson and Berglund, 2006 (Part I and	Sweden	-	-	-	X	-
	II)	Ireland	X	-	X	-	-
	Goulding and Power, 2013	Spain	-	-	X	X	-
	Ruiz et al., 2018	Italy	X	-	X	-	-
	Tricase and Lombardi, 2009	United Kingdom	-	-	-	X	-
	Patterson et al., 2011	Italy	-	-	-	X	-
	Ardolino et al., 2018	Iran	-	-	X	X	-
	Hamzehkolaei and Amjady, 2018	Italy	-	-	X	-	-
	Giarola et al., 2018	France	-	-	-	X	-
	Beylot et al., 2013	Ireland	X	-	X	X	-
	Murphy and McKeogh, 2004	Italy	-	-	X	X	-
	Venanzi et al., 2018						

Source: elaborated by the author

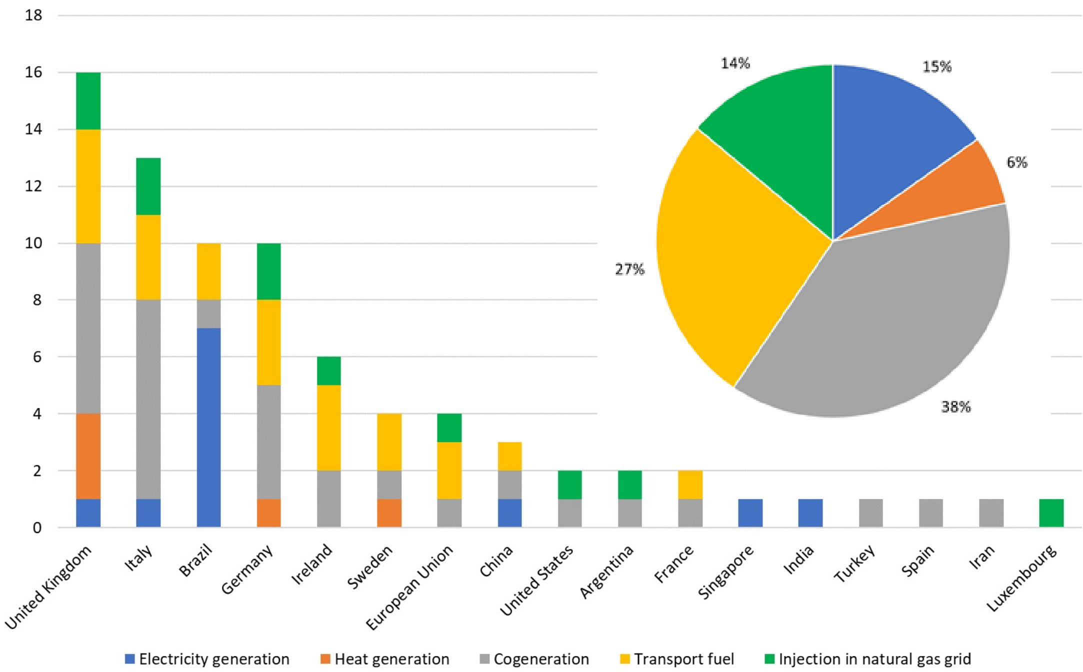
Table 13: Types of analysis made in each biogas application (part 2 of 2)

	REFERENCE	COUNTRY	TECHNICAL ANALYSIS	ENERGETIC ANALYISIS	ECONOMIC ANALYSIS	ENVIRONMENTAL ANALYSIS	SOCIAL ANALYSIS
TRANSPORT FUEL	Hakawati et al., 2017	United Kingdom	-	X	-	-	-
	Moraes et al., 2014 [9]	Brazil	-	-	X	X	-
	Nadaletti et al., 2015	Brazil	-	X	-	X	X
	Patrizio et al., 2015	Italy	-	X	X	X	-
	Pöschl et al., 2010	Germany	-	X	-	-	-
	Poeschl et al., 2012 (Part I and II)	Germany	-	-	-	X	-
	Wall et al., 2017	European Union	X	-	-	-	-
	Horschig et al., 2016	Germany	-	-	-	X	-
	Horschig et al., 2016	United Kingdom	-	-	-	X	-
	Wu et al., 2016	China	-	X	X	X	-
	Münster et al., 2015	European Union	-	-	X	X	-
	Ravina and Genon, 2015	Italy	-	-	-	X	-
	Börjesson and Berglund, 2006 (Part I)	Sweden	-	-	-	X	-
	Goulding and Power, 2013	Ireland	X	-	X	-	-
	Murphy and Power, 2009	Ireland	X	-	X	-	-
	Börjesson and Berglund, 2006 (Part II)	Sweden	-	-	-	X	-
	Patterson et al., 2011	United Kingdom	-	-	-	X	-
	Ardolino et al., 2018	Italy	-	-	-	X	-
	Patterson et al., 2013	United Kingdom	-	-	-	X	-
	Beylot et al., 2013	France	-	-	-	X	-
	Murphy and McKeogh, 2004	Ireland	X	-	X	X	-
INJECTION IN THE NATURAL GAS GRID	Patrizio et al., 2015	Italy	-	X	X	X	-
	Pöschl et al., 2010	Germany	-	X	-	-	-
	Lauer et al., 2018	United States	-	-	X	X	-
	Poeschl et al., 2012 (Part I and II)	Germany	-	-	-	X	-
	Fubara et al., 2018	United Kingdom	-	-	X	X	-
	Wall et al., 2017	European Union	X	-	-	-	-
	Ravina and Genon, 2015	Italy	-	-	-	X	-
	Morero et al., 2015	Argentina	-	-	X	X	X
	O'Shea et al., 2017	Ireland	-	-	X	X	-
	Jury et al., 2010	Luxembourg	-	-	-	X	-
	Patterson et al., 2011	United Kingdom	-	-	-	X	-

Source: elaborated by the author

Analyzing the distribution of biogas uses, the pie chart in Figure 16 shows that among all sampled studies 38% used biogas to cogeneration, 27% to transport fuel, 15% to electricity generation, 14% to injection in the natural gas grid and 6% to heat generation. From the country's perspective, the column-shape chart in Figure 16 illustrate how biogas uses are distributed among countries. United Kingdom was the country with a greater number of studies of biogas uses totalizing 16 studies, followed by Italy with 13 studies and Brazil and Germany with 10 studies both. Almost all countries except for Singapore, India, and Luxembourg, studied cogeneration as a biogas use. The countries with a greater number of studies of biogas as transport fuels were United Kingdom, Italy, Germany, and Ireland (all European countries). Brazil was highlighted by its high number of studies considering biogas to electricity generation. United Kingdom, Italy and Germany also represent the greater number of studies of biogas injection in the natural gas grid. Heat generation were studied only by European countries (Germany, Sweden and United Kingdom) justified by climate aspects.

Figure 16: Distribution of biogas uses



Notes: Pie chart shows the percentage distributions considering biogas uses; Column-shaped chart illustrated the number of studies by countries and biogas uses.

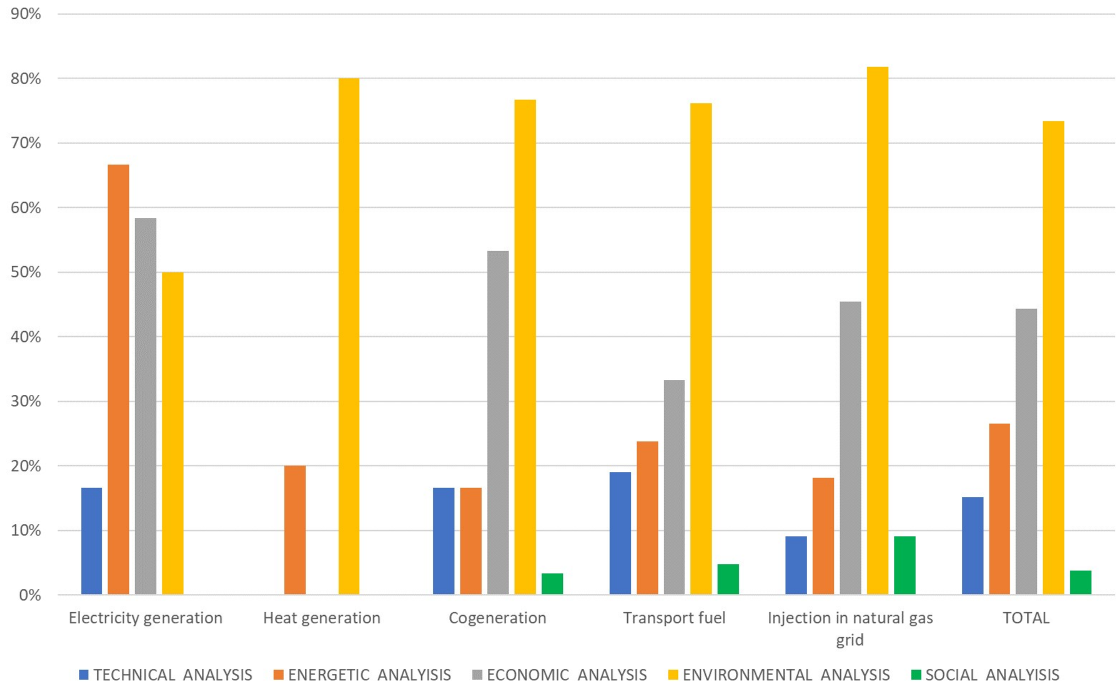
Source: elaborated by the author based on data from Table 12 and 13.

In addition to the biogas use considered in each study, it was verified which sustainability dimension had been analyzed in each study. As expected, sustainability analysis including the Triple Bottom Line (economic, environmental, and social), could be identified among the sampled studies. As expected also, the politic dimension was not quantified but it was cited in most studies. No analyzes were found that considered strategic aspects in terms of sustainability for the uses of biogas, at least not explicitly, which does not imply the inexistence of strategic thoughts associated to the policies of incentive to biogas in its different applications. However, two more dimensions were found: technical and energetic.

Concerning sustainability analysis, Figure 17 shows the percentage distributions among types of sustainability analysis for each biogas utilization.

The sum of each type of analysis will not necessarily be 100% because some studies considered more than one sustainability aspect to be evaluated.

Figure 17: Percentage distributions of sustainability analysis.



Source: elaborated by the author based on data from Table 12 and 13.

In the studies which analyzed the electricity generation as the biogas use, the most common analysis made was the energetic one (67%), followed by the economic (58%), environmental (50%) and technical (17%) ones. None of them considered social analysis as a parameter to measure sustainability of the electricity generation from biogas. Considering the studies on heat generation from biogas only two types of analysis were developed: energetic and environmental, being this last one present in 80% of the sampled studies. Environmental and economic analysis were most frequently found in studies about cogeneration as biogas use, few studies performed technical, energetic social analyzes. Also, the five types of sustainability analysis were found in the studies considering the biogas as a transport fuel, with highlight to environmental analysis which was present in 76% of the studies, followed by economic (33%), energetic (24%), technical (19%) and social (5%) ones. Analogy to the transport fuel use, biogas injection in the natural gas grid was evaluated technically (9%), energetically (18%), economically (45%), environmentally (82%) and socially (9%).

From the total (general) perspective, the last group of columns in Figure 17, it is easy to verify the predominance of environmental analysis (73%) in contrast to the little representativeness of social analysis (4%). The environmental argument is present in all studies even in the ones whose focus were not the environmental analysis. Economic analysis was present in 44% studies, energetic analysis in 27% studies and technical analysis in 15% studies.

Another way of illustrating the predominance of the economic and environmental view at the expense of the social, political, and strategic view in the sustainability analyzes of the sampled studies is presented in Figure 18.

Only the study of Morero et al. (2015) and Nadaletti et al. (2015) cited social aspects in their sustainability analysis but only in a qualitative, not quantitative, way. Morero et al. (2015) evaluated biogas upgrading processes listing impacts on human toxicity, job generation and socioeconomic development. Nadaletti et al. (2015) cited the decreasing of the spread of many diseases related to the human respiratory system as a result of the use of the potential energy of sanitary landfills and injuries to the human health caused by the substances released by the combustion of fossil fuels. More specifically, Nadaletti et al. (2015) listed carbon monoxide, particulate material, and air pollution effects on the human body. Vision problems, reduced cognitive ability, reduced manual skills, difficulty in perform complex tasks, breathing problems and even death would be related to the carbon monoxide effects. Respiratory symptoms, mortality in patients with cardiovascular and pulmonary diseases, neoplasm, worsening of asthma attacks and decrease the lung function in children would be related to the particulate material exposure. Air pollution could cause tear film instability, ocular discomfort and maybe even harmful effects on fertility and fetal health.

From the world distribution perspective, it was verified a greater number of studies performed in Europe (73%), followed by South America (15%), Asia (9%) and North America (3%) as illustrated by Table 14.

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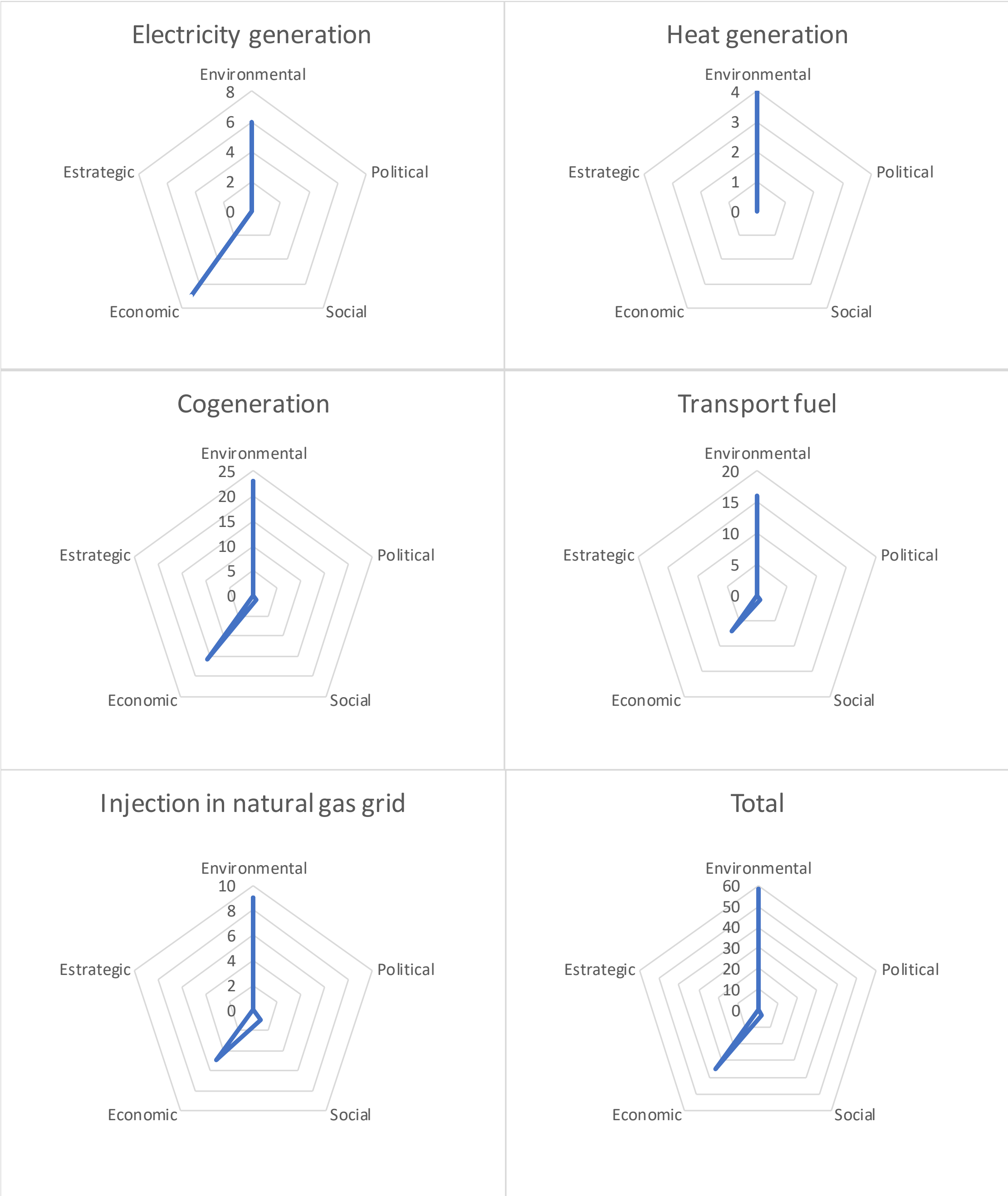
Figure 18: Sustainability analysis for each biogas use.



Source: elaborated by the author based on data from Table 12 and 13.

Table 14: Distribution of studies about sustainability of biogas from different matrices for different uses of biogas around the world.

Continent	Number of studies	%
Europe	58	73
South America	12	15
Asia	7	9
North America	2	3

Source: elaborated by the author.

Most European studies cited European Union (EU) guidelines, setting targets for increasing renewable energy consumption and reducing greenhouse gas emissions as promoters of the studies conducted. According to Goulding and Power (2013), the EU community introduced the Renewable Energy Source Directive 2009/28/EC which requires a 20% share of renewable energy sources in final energy consumption and a 10% share of renewable fuels in the transport sector in each member state by 2020. This directive allows individual member states to decide how to achieve the target.

Venanzi et al. (2018) cited that Italian legislators have periodically updated public subsidies for biogas plants according to the Renewable Energy Directive 2009/28/EC. Murphy and McKeogh (2004) pointed that European regulations related to the Landfill Directive was a concerning and a reference for Ireland which has a waste infrastructure based on landfill. Tricase and Lombardi (2009) highlighted that the regulations of the Energy and Environment Policy of the European Union Energy Policy, together with the Common Agricultural Policy have been aiming to increase the integration of renewable resources, and of biogas, into EU energy system thanks to the adoption of new tools for their promotion. Börjesson and Berglund (2006) cited that several initiatives have been taken in Sweden to facilitate the implementation of biogas systems, such as state subsidies for investment in projects that aim to reduce greenhouse gas emissions and targets set within the EU to reduce the amount of biodegradable waste going into landfill and to increase the use of biofuels in the transportation sector. Ravina and Genon (2015) considered the Directive 2009/28/EC an energy policy through which EU pushed member states toward the development of biofuels technologies. Münster et al. (2015) pointed that EU target of achieving 20% renewable energy by 2020 influenced the Denmark political goal of 50% share of wind power by 2020. Whiting and Azapagic (2014) highlighted that, despite being an established technology, the growth in anaerobic digestion installations in Europe has started only with the introduction of financial incentives present in 29 European countries that promote electricity generation from biogas. MosayebNezhad et al. (2018) cited that the European policies on energy and sustainability are contributing to the diversification of the primary energy sources and to the introduction of distributed power technologies with high efficiency and low carbon emissions. Wall et al. (2017)

also cited the EU legislation as responsible to become biofuels a renewable energy source truly sustainable in future energy systems. Pöschl et al. (2010) considered biogas production by anaerobic digestion of organic waste in Germany the key to meeting the targets imposed by European Energy Policy.

Therefore, as predicted by Romanelli (2009), political aspects are, at least in the case of European countries, truly related to the development of biogas as a renewable and sustainable energy source.

5.1 Economic analysis

If economic development increases vulnerability to crises, it is unsustainable. But vulnerability can be reduced by using technologies that reduce production risks, giving preference to institutional options that reduce market fluctuations. It is in this direction that the production of biogas and biomethane can contribute, combining less vulnerability in times of crisis and growth for the energy sector (Brundtland, 1991).

Economic analysis usually intends to secure a profitable product by efficient low-cost management and/or by creating value and to identify and manage risks to control financial losses due to unfortunate events. The most common economic indicators are related to investment indicators as Net Present Value (NPV), Minimum Selling Price (MSP) and Pay-back (Schoubroeck et al., 2018).

The initial cost of most projects occurs on the initial date of the analysis period and is compared with the present cash flow of the project considering a certain opportunity cost. Likewise, management makes decisions among the possible alternatives evaluated at the start date. In these cases, the net present value NPV is the indicated valuation procedure, as it measures the economic profit, or the value created by the project on the date of the investment decision. Therefore, if the NPV is greater than zero, the project must be accepted, as it will create value for the company. Otherwise, if the NPV is less than zero, the project should not be accepted, because if it is conducted it will destroy the company's value.

5.1.1 Front End Loading (FEL)

For the economic sensitivity analysis, the concept of the second phase of the FEL methodology (Front End Loading) was used. The FEL methodology was created by DuPont widely used for large capital projects, where 3 planning phases are established in which the project should only advance to the next phase if approved at the gate between the phases (Duarte, 2018).

The FEL Methodology is based on the premise that improvement in project definition activities reduces the number of claims that can occur during execution, when the costs for changes are high. In this process, a complex project is analyzed from three basic stages of approval, called FEL1, FEL2, FEL3. At each gate, critical questions are presented that may have an impact in relation to the objective of that phase. The FEL1 phase relates to the identification of the opportunity while the FEL2 phase to conceptual engineering and the FEL3 phase to basic engineering.

The objective of the FEL2 phase is to study the options identified and direct the project to an option; refine assumptions, update economic data, and begin defining the project. It is the option selection phase, in which the scope of the project is conceptually decided. The main focus of this stage is to develop the conceptual engineering of all options listed in FEL1, in order to compare the options and define, through the result of the economic and financial evaluation of each option, which will be forwarded to the next phase (FEL3 - details chosen option).

In this stage of the FEL Methodology, analyzes of the technological and constructive solutions associated with the enterprise are conducted, ending with the selection of one of these solutions and with the basic definitions (project briefing) of the facilities, including the buildings, with a variation in costs between –15 % and + 25%. In FEL2, the financial return is a decisive parameter for the project to proceed to the third stage: if no return is presented above the minimum attractiveness rate, that is, it presents NPV less than zero, the project is canceled.

5.2 Environmental analysis

Nature conservation should not be seen only as one of the objectives of development. It is part of our moral obligation to other living beings and future generations. Obviously, economic growth and development produce changes in the physical ecosystem. Regarding non-renewable resources, such as minerals and fossil fuels, their use reduces the amount available to future generations. This is not to say that these resources should not be used. But the levels of use must consider the availability of the resource, technologies that minimize its depletion, and the probability of obtaining substitutes for it. Therefore, such resources must not be deteriorated beyond a reasonable limit of recovery. Industry can adjust to scarcity if there is greater efficiency in using, recycling, and substituting (Brundtland, 1991).

So-called free goods, such as air and water, are also resources. Raw materials and energy used in production processes are only partly converted into useful products. The rest turns into waste. Air and water quality is threatened by the use of fertilizers and pesticides, urban dumping, burning of fossil fuels, use of some chemicals and various other industrial activities. Cleaning up what has already been polluted is an expensive solution. Thus, all countries need to anticipate and avoid pollution problems, seeking emission standards that take into account long-term effects, encouraging technologies that leave little waste and predicting the impact of new products, technologies, and waste (Brundtland, 1991).

Environmental analysis in most cases consider 1) the mitigation of climate change by reducing greenhouse gas, liquid and solid emissions, 2) the control and reduction of energy requirements and the use of renewable and cleaner energy technologies, 3) the management of land use, raw materials, process materials and water resources in an efficient, eco-friendly and economic way, and 4) the prevention of degradation of natural ecosystem and ecosystem services due to air pollution, eutrophication, ecotoxicity and waste disposal (Schoubroeck et al., 2018).

Environmentally speaking, there are several benefits linked to the digestion of vinasse, starting with the most appropriate management of vinasse itself. Among the alternatives for the use of vinasse developed around the world, fertigation is the most commonly application, as requires a low initial investment (tubes, pumps, trucks, and decantation thanks or lagoons), low maintenance cost, fast application, does not require complex technologies and increase crop yield (Camargo et al., 2009; Santana and Machado, 2008). This practice has totally or partially replaced the use of chemical fertilizers, mainly those containing phosphorous. According to Santana and Machado (2008), fertigation may be a palliative practice that provides a false impression of solving efficiently the problem of vinasse disposal, avoiding the discharge in rivers.

However, according to Parsaee et al. (2019), the reality is that vinasse causes emissions of greenhouse gases such as CH_4, N_2O and CO_2, of which 99.8% belong to methane. The same author states that, regarding the storage of vinasse, the methane release rate in open channels is equal to 1.36 kg CO_{2eq}/m^3. Since methane is a 21-times more potent greenhouse gas than CO_2 (Börjesson and Berghund, 2006), any losses of methane to the environment should be avoided. Uncontrolled losses of methane may also occur in parts of biogas production plant and in energy conversion in the biogas systems. Methane losses are typically assumed to amount of 2-3% (Börjesson and Berghund, 2006). According to Poveda (2019), methane loss is mainly due to dissolution in water and can range from 3 to 5%, although equipment suppliers claim it is possible to control such amounts below 2%.

Replacing fossil fuels with biogas normally reduces the emission not only of greenhouse gases, but also of nitrogen oxides, hydrocarbons, and particles. Most organic matter is converted in useful energy, decreasing the groundwater pollution but maintaining the benefits of fertigation through the application of the digestate.

5.3 Social analysis

Sustainable development must deal with the problem of the large number of people living in absolute poverty, that is, who cannot satisfy even the most basic needs. Poverty reduces people's ability to use resources sustainably, causing them to put greater pressure on the environment. A necessary but not sufficient condition for the elimination of absolute poverty is the relatively rapid increase in per capita incomes in developing countries. Growth needs to resume in these countries because they are where economic growth, poverty alleviation and environmental conditions are most directly intertwined. If these countries focus their efforts on eliminating poverty and meeting basic human needs, there will be an increase in domestic demand for agricultural and manufactured products and also for some services (Brundtland, 1991).

Income distribution is one aspect of the quality of growth, and fast growth combined with poor income distribution can be worse than slower growth combined with pro-poor redistribution. Economic development and social development can and must be mutually supportive. Money spent on education and health can increase the productivity of individuals. Economic development can accelerate social development by providing opportunities to disadvantaged groups or by spreading education more rapidly (Brundtland, 1991).

The main development challenge is to meet the needs and aspirations of an ever-increasing population. Of these, the main one is sustenance, that is, employment. It is necessary that the pace and pattern of economic development create sustainable job opportunities and at a level of productivity that allows poor families to live within the minimum standards of consumption (food, energy, housing, water supply, sanitation, and medical services) (Brundtland, 1991).

The major consumption of energy around the globe is related to human activities. Thus, it may be essential to quantify how renewable energy consumption influence process of human development. This area of research still needs to be explored (Wang et al., 2018).

Energy plays a key role in creating jobs, agriculture, transport, commerce, and economic development. Energy is also a major device for eliminating poverty and sustaining human development and all forms of energy contribute to economic growth. However, beyond the effect of energy on economic growth, it also affects human well-being. There is a direct relationship between the existence of energy services and availability of modern health facilities, education, and communication (Wang et al., 2018).

Specifically related to renewable energy, usually it improves the local economies, and it is a driver for human development, especially in rural areas. Results of Pîrlogea (2012) study revealed that fossil fuel negatively affects human development and renewable energy has a significant positive impact on human development.

Social analysis involves health, safety, and social cares. The intention is to secure public health by avoiding toxic compounds, to secure a safe working environment by identifying risks related to the production process and to promote a sustainable society for all stakeholders by contributing through employment, food security and quality of life. Although there are some social indicators, the social dimension analysis is limited. Some of them are in a few cases included in the sustainability evaluation as additional impacts being difficult to quantify. The fact is that few research has dealt with this dimension of sustainability (Schoubroeck et al., 2018). Moraes et al. (2016) concluded that the large-scale production of ethanol in Brazil has a positive impact in the south-central region, as evidenced by increases in the municipal GDP per capita. Their analysis revealed that the sugarcane industry has made a positive contribution to the development of host municipalities and the neighboring municipalities, due to spatial and temporal effects.

As discussed by Wu et al. (2016), problems can arise when only one or two indices (environmental, economic, or energetic) are assessed when evaluating biogas exploitation routes. Furthermore, ignoring political and societal conditions in any research leads to unrealistic conclusions (Nilsson et al., 2011).

According to Campoli et al. (2019), social efficiency corresponds to governmental competence to convert economic growth and public spending into human development and quality of life, which leads to the next topic: the effect of politics in the sustainability performance.

5.4 Politic and strategic dimensions

Development presupposes a progressive transformation of the economy and society. If a development path is physically sustainable, it can theoretically be attempted even in a rigid social and political context. But one can only be sure of physical sustainability if development policies consider the possibility of changes in access to resources and in the distribution of costs and benefits. Communities or governments can act preventively through laws, education, taxes, subsidies, and other methods. Compliance with the law and strict liability legislation can control harmful side effects. More importantly, if local communities participate in decision-making processes, they will be able to articulate and enforce their common interest (Brundtland, 1991).

The world must soon create strategies that allow nations to replace their current growth processes, often destructive, with sustainable development. Therefore, it is necessary that all countries modify their policies, both in relation to their own development and in relation to the impacts they may have on the development possibilities of other nations.

According to Brundtland (1991), in addition to the resumption of growth, the change in the quality of this growth and meeting the essential needs of employment, food, energy, water and sanitation, mentioned in the social sustainability session, four more objectives of sustainable development policies, stand out:

1. Maintenance of the population level: it is easier to pursue sustainable development when population size stabilizes at a level consistent with the productive capacity of the ecosystem. Population policies must be integrated with other economic and social development programs.
2. Conservation and improvement of the resource base: agricultural policies that protect farmers' incomes against short-term price declines can lessen their need to overexploit natural resources.
3. Technology reorientation and risk management: the capacity for technological innovation needs to be expanded through incentives for research, planning, development, and specialization. In addition, it is up to public policies to ensure, through incentives and disincentives, that commercial organizations strive to more fully consider the environmental factors present in the technologies they develop. Institutional mechanisms at national and international levels are needed to assess the potential impacts of new technologies, before they become widely disseminated, in order to ensure that their production, use and waste do not excessively deplete the environment's resources.

4. Inclusion of the environment and economy in the decision-making process: economic and ecological interdependence are rarely reflected in the way policies are crafted. For there to be sustainable development, such fragmentation must be overcome. This requires changes in legal and institutional structures that reinforce the common interest. The law alone cannot enforce the common interest. This mainly requires community awareness and support, which implies greater public participation in decision-making. The best way to achieve this is to decentralize resource management, empowering local communities, popular organizations and strengthening local democracy. It is also necessary to have changes in the attitudes and procedures of public and private companies, embedding sustainability objectives in taxation, in the prior approval of investments and in the choice of technologies, among others.

The politic dimension usually includes renewable energy targets, regulatory policies, fiscal incentives, and public financing. A summary of renewable energy promotion policies by country is presented in Table 15. It is possible to note from Table 15 that all countries listed has a certain level of public policies to promote renewable energy. The question is whether these policies have been translated into the implementation of viable and relevant investment projects.

At the 21st Conference of the Parties (COP21) of the UNFCCC, in Paris, a new agreement was adopted with the central objective of strengthening the global response to the threat of climate change and strengthening the countries' capacity to deal with the impacts arising from these changes.

The Paris Agreement was approved by the 195 UNFCCC Party countries to reduce greenhouse gas (GHG) emissions in the context of sustainable development. The commitment is to keep the global average temperature rise well below 2°C above pre-industrial levels and to endeavor to limit the temperature rise to 1.5°C above pre-industrial levels.

Table 15: Renewable energy promotion policies by country.

COUNTRY	RENEWABLE ENERGY TARGETS	REGULATORY POLICIES							FISCAL INCENTIVES AND PUBLIC FINANCING				
		Feed-in tariff / premium payment	Electric utility quota obligation / RPS	Net metering	Biofuels obligation / mandate	Heat obligation / mandate	Tradable REC	Tendering	Capital subsidy, grant or rebate	Investment or production tax credits	Reductions in sales, energy, CO_2, VAT, or other taxes	Energy production payment	Public investment, loans, or grants
Australia	○	●	○		●	●	○	★*	○				○
Austria	○	○			○		○		○	○			○
Belgium	○		●	●	○		○	○	●	○	○		
Canada	●	R*	●	●	○			○	○	○	○		○
France	R	R			○	○	○	○	○	○	○		○
Germany	○	R			○	○			○	○	○		○
Greece	○	R		○	○	○			○	○	○		○
Ireland	○	○			○	●	○	○					
Italy	○	R		○	★	○	○	○	○	R	○		○
Japan	R	R	○	○			○	○	○				○
Netherlands	○	○		○	○		○		○	○	○	○	○
New Zealand	○								○				○
Norway	○		○		○		○	○	○		○		○
Poland	○	R	○		○		○	R			○		○
South Korea	○		○	○	○	○	○		○	○	○		○
Spain	○			○	R	○	○		○	○		○	
Sweden	○	○	○		○		○		○	○	○		○
United Kingdom	○	○	○		○		○		○		○	○	○
United States [1]	R*	R*	R*	R*	○	●	●		○	R	○		○
Uruguay	○	○		○	○	○		○	○		○	○	○
Argentina	○	○		○	R			★	○	○	○	○	○
Brazil	○			○	R	●		★		○	○		○
China	R	R	○		○	○		○	○	○	○	○	○
Costa Rica	○	R		★	○			○			○		
Mexico	○			○				○		○			○
Peru	○	○	○		○			○			○		○
Romania	○		○		○		○						R
South Africa	R		○		○	○		★	R		R		○
Turkey	R	○			○				○				○
India	○	○	○	●	○	●	○	★	○	○	★	○	○
Philippines	○	○	○	○	○			○	○	○	○	○	○

Notes: ○ - Existing national (could also include state/provincial), ● - Existing state/provincial (but not national), ★ - new (* indicates state/provincial), R – revised (* indicates state/provincial); 1 State-level targets in the United States include RPS policies.

Source: Adapted from KPMG International, 2015.

For it to take effect, it needs to be ratified by at least fifty-five countries responsible for 55% of GHG emissions. The UN Secretary-General, in a ceremony in New York, on April 22, 2016, opened the period for the official signing of the agreement, by the signatory countries. This period ended on April 21, 2017.

To achieve the final objective of the Agreement, governments became involved in building their own commitments, based on the so-called Nationally Determined Contributions (iNDC). Through the iNDCs, each nation presented its contribution to reducing greenhouse gas emissions, following what each government considers feasible from the local social and economic scenario.

After approval by the National Congress, Brazil concluded, on September 12, 2016, the process of ratification of the Paris Agreement. On September 21, the instrument was handed over to the United Nations. As a result, the Brazilian goals were no longer intended and became official commitments. Now, therefore, the acronym has lost the letter "i" (from English, intended) and has come to be called only NDC.

NDC of Brazil pledged to reduce greenhouse gas emissions by 37% below 2005 levels, in 2025, with a subsequent indicative contribution to reduce greenhouse gas emissions by 43% below 2005 levels, in 2030. To this end, the country pledged to increase the share of sustainable bioenergy in its energy matrix to approximately 18% by 2030, restore and reforest twelve million hectares of forests, as well as achieving an estimated 45% share of energy in the composition of the energy matrix in 2030.

NDC of Brazil corresponds to an estimated reduction of 66% in terms of greenhouse gas emissions per unit of GDP (intensity of emissions) in 2025 and 75% in terms of intensity of emissions in 2030, both in relation to 2005. Therefore, Brazil will reduce greenhouse gas emissions in the context of a continuous increase in population and GDP, as well as per capita income, which gives ambition to these goals.

Regarding climate finance, the Paris Agreement states that developed countries must invest US$ 100 billion a year in measures to combat climate change and adaptation in developing countries. A novelty in the scope of financial support is the possibility of financing between developing countries, called “South-South cooperation,” which expands the base of project financiers.

It is noted in the text the concern with formalizing the process of developing national contributions, in addition to offering mandatory requirements to assess and review their progress. This mechanism requires countries to continually update their commitments, allowing them to broaden their ambitions and increase emission reduction targets, avoiding any setbacks. To this end, as from the beginning of the agreement, there will be cycles of review of these objectives for the reduction of greenhouse gases every five years.

5.4.1 RenovaBio

Providing an important contribution to the fulfillment of the commitments determined by Brazil under the Paris Agreement, RenovaBio is the new National Biofuel Policy, instituted by Law No. 13,576 / 2017, whose objective is to expand the production of biofuels in Brazil, based on predictability, environmental, economic, and social sustainability, and compatible with market growth. As a result of this expansion, the aim is to make an important contribution by biofuels in reducing greenhouse gas emissions in the country. In addition to a channel for closer dialogue with the private sector, RenovaBio will seek its performance based on four strategic axes: discussing the role of biofuels in the energy matrix; development based on environmental, economic, and financial sustainability; marketing rules and attentive to new biofuels.

The RenovaBio initiative seeks to expand the share of renewable fuels in a manner compatible with market growth. What is intended is the implementation of a public policy that brings predictability to the biofuels market, in harmonious coexistence with fossil fuels, through a stimulus to constant innovation, which seeks energy and environmental efficiency on an ongoing basis. In addition, RenovaBio's core is to transform a public good, which are the positive externalities of biofuels, into incentives for sustainable production, through market mechanisms, without subsidies or artificial measures. It is a structuring program that consolidates a strategic vision of the State for biofuels.

The entire construction of RenovaBio was done by listening to society, economic agents, and government representatives. Together they proposed guidelines for the construction of actions that expand the share of renewable fuels in an environment that encourages technological innovation and meeting the growth of the market. With values based on competitiveness with equity, credibility, dialogue, efficiency, predictability, and sustainability.

RenovaBio is designed to introduce market mechanisms to recognize the capacity of each biofuel to reduce emissions, individually, per production unit. Basically, there are two main instruments: 1) Establishment of national emission reduction targets for the fuel matrix, defined for a period of 10 years. The goals are important to bring predictability, in terms of the volumetric need for fuels (fossil and renewable) in this time horizon, and thus allow private agents to make their investment planning and analysis in an environment with less uncertainty. National targets will be broken down into individual targets, annually, mandatory for all fuel distributors, according to their participation in the fossil fuel market; 2) Certification of the production of biofuels, by private inspection firms, assigning different grades for each production unit (the higher the grade for the producer that produces the greatest amount of net energy, with the lowest CO_2eq emissions, in the life cycle). The note will accurately reflect the individual contribution of each producing agent to the mitigation of a specific amount of greenhouse gases, in relation to its fossil substitute (in terms of tons of CO_2eq). The certification process to produce biofuels within the scope of RenovaBio will be under the responsibility of ANP. The connection of these two instruments will take place with the creation of the Biofuel Decarbonization Credit (CBIO). It will be a financial asset, traded on a stock exchange, issued by the biofuel producer, from the sale of its production (after the issuance of the invoice). Fuel distributors will meet the target by demonstrating the required amount of CBIOs on their property. Other agents (individuals and companies) will be able to buy and sell CBIOs on the stock exchange, to bring greater liquidity to this market.

The purpose of this mechanism is to gradually decarbonize the Brazilian energy matrix in the short, medium, and long terms. The proposal encourages market mechanisms and includes the creation of instruments and incentives based on market mechanisms, taking advantage of positive aspects of successful experiences in other countries, without the adoption of artificial and unsustainable policies in the medium and long term, without subsidies. Thus, unlike traditional measures, RenovaBio does not propose the creation of a carbon tax, subsidies, presumed credit or volumetric mandates for adding biofuels to fuels, nor does it choose a biofuel at the expense of the advancement of another biofuel. RenovaBio also does not change the existing mandates (anhydrous ethanol in gasoline and biodiesel in diesel).

RenovaBio has the potential to employ 1.4 million workers by 2030 in the construction area and in the operation of the sector's new productive capacity. The first estimates show a large investment in the sector with RenovaBio. The ethanol sector alone will have investments of approximately R$ 90 billion by 2030, generating more than four hundred thousand jobs. If Brazil decides to produce oil products to supply the domestic market demand, instead of expanding the production of biofuels, only 180 thousand jobs will be generated by 2030.

RenovaBio is in line with what was contacted by Fuess and Zaiat (2018): the importance of external agents, mainly the government, in encouraging the implementation of biodigestion plants, making the use of biogas even more attractive from an economic point of view. Subsides to reduce investment costs and increase revenue also can be used as mechanisms to stimulate more efficient systems (Fuess et al, 2018).

5.4.2 Programa Metano Zero

The Metano Zero Program is an initiative of the Brazilian Federal Government implemented with the involvement of Brazilian society (private sector, civil society, and scientific and research sector). It promotes the reduction of methane emissions in line with sustainable development, based on cooperation for financing, incentives, exemption, training, development, transfer and dissemination of technologies and processes. Among others, measures to encourage the use of biomethane and biogas stand out. Specific lines of credit and financing from public and private financial agents for the development of actions and activities, including, but not limited to:

- implementation of biodigesters.
- implementation of a biogas purification system, production, and compression of biomethane.

- creation of points and "green corridors" for fueling heavy vehicles powered by biomethane, such as buses, trucks, and agricultural implements, contributing to the reduction of greenhouse gases and to the improvement of air quality.
- implementation of technologies that allow the use of sustainable fuels and low intensity of greenhouse gas emissions in Otto cycle or diesel internal combustion engines, in compliance with the standards established by the competent bodies.
- leveraging the use or development of vehicle technology.
- tax relief for infrastructure related to biogas and biomethane projects.

The Program also aims to promote and consolidate carbon credit markets by recognizing and valuing the environmental activities conducted and encouraged to mitigate methane emissions, including the generation of specific credits for this greenhouse gas, resulting in monetary retribution, linked to initiatives aimed at this objective (MMA, 2022).

5.4.3 Projeto de Lei PL 3865/2021

Bill PL 3865/2021 institutes the Incentive Program for Production and Use of Biogas, Biomethane and Associated Coproducts - PIBB. The objectives of this law are (Câmara Legislativa, 2022):

i. To encourage and expand the participation of renewable energies in national energy matrix through the generation of fuel gases from biomass.
ii. To reduce negative impacts on the environment from agroindustry activities and sanitation waste disposal.
iii. To promote the use of biomass and biodigestion through its use on an industrial and commercial scale, as a way of generating employment and social development.
iv. To stimulate the technological development of biogas, biomethane, from biomass and derived products.

v. To diversify the Brazilian energy matrix by expanding the participation of renewable sources from biogas, biomethane and biomass.
vi. To assist in the achievement of the emission reduction targets of greenhouse gases.
vii. To encourage research and development related to production and use of biogas, biomethane and co-products associates.
viii. To encourage the use of biomethane in public transport.
ix. To encourage the use of digestate, after adequate treatment, soil fertilization, including in public areas.
x. To encourage the integration of production and use of biomethane and natural gas through existing and future gas pipelines.
xi. To stimulate the creation of companies that hold technologies appropriate national facilities for the development and production of equipment necessary for the production and use of biogas, biomethane and associated co-products.
xii. To stimulate the capacity of production and transformation of the biomass into energy, green chemistry, and renewable materials.
xiii. To foster the necessary logistical infrastructure to mobilize the biomass and promote the interiorization and expansion of the use of biogas and biomethane.

Initiatives such as RenovaBio, the Metano Zero Program and the bill "Incentive Program for the Production and Use of Biogas, Biomethane and Associated Coproducts (PIBB)" may become landmarks for biogas in Brazil.

6 METHODOLOGY

To reach the objective of studying the sustainability of utilization of biogas from sugarcane vinasse, the methodology included aspects related to biogas production, to biogas utilization and to the sustainability of these uses. Biogas production focused in anaerobic biodigestion reactors, quantification of vinasse and vinasse conversion into biogas. Biogas utilization considered electricity generation, transport fuel and natural gas replacement. Sustainability of biogas uses established parameters to economic, environmental, and social analysis.

6.1 Biogas production

6.1.1 Vinasse generation per ethanol unit

The Figure 19 illustrates the traditional distillation process to produce hydrous ethanol. The production of anhydrous ethanol does not influence the quantity of vinasse produced and, therefore, was not included in the process illustrated. Vinasse is the product from the bottom of the so-called "column A" and often it incorporates the phlegmace, product from the bottom of the so-called "column B". Since the amount of vinasse generated is about five times greater than the amount of phlegmace generated, it is common the blending of these two products to be called vinasse as well.

The mass and energy balance illustrated in Figure 19 considered: ethanolic degree of the beer equal to 8.5 (v/v), thermal insulation of the distillation columns and direct column heating (incorporation of heating steam in vinasse and phlegmace).

Through mass and energy balances of distillation process of hydrous ethanol production, the relation between the volume of vinasse produced by volume of ethanol was determined. Input data used in this mass and energy balances is presented in Table 16.

The mass balance of column A (Figure 19) is given by the following equations:

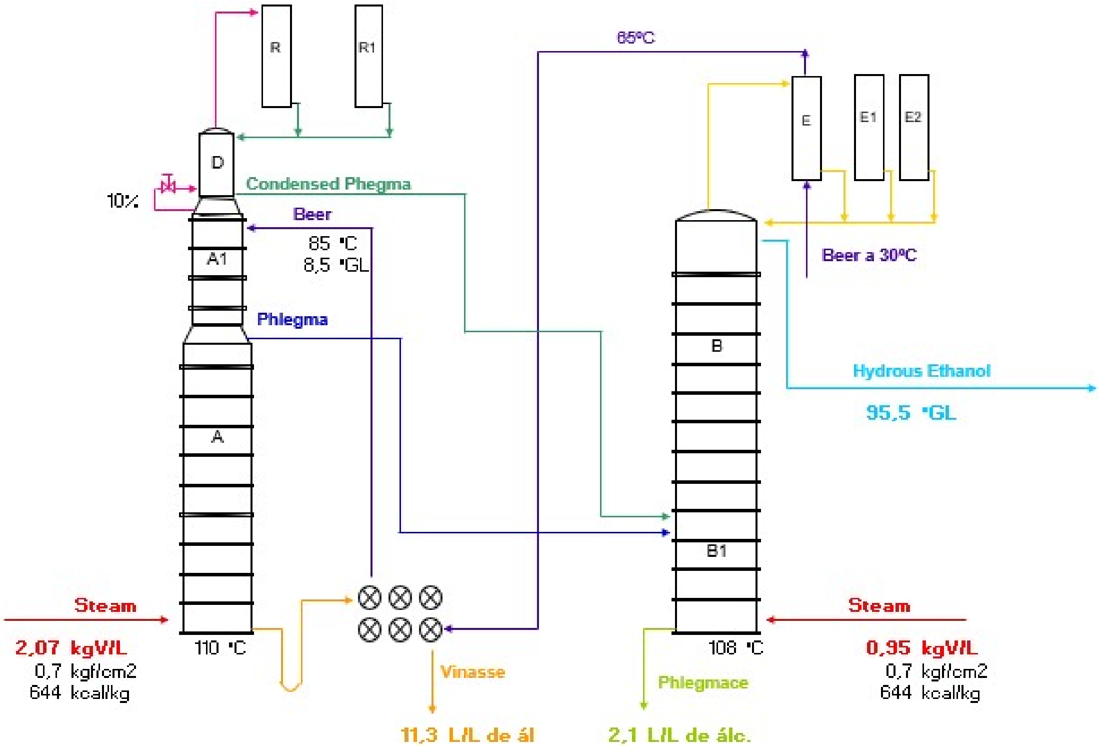
$$Vbe + Vst = Vph + Vvi \quad \text{(Eq.6-1)}$$

$$Vvi = Vbe + Vst - Vph \quad \text{(Eq.6-2)}$$

$$Vvi / Vet = (Vbe - Vph) / Vet + Vst / Vet \quad \text{(Eq.6-3)}$$

where Vbe is the volume of the beer, Vst is the volume of the steam, Vph is the volume of the phlegma, Vvi is the volume of vinasse e Vet is the volume of ethanol.

Figure 19: Distillation process to produce hydrous ethanol



Source: Created by the author based on her thirteen years of professional experience working in ethanol production units and on mass and energy balance of the ethanol production process.

Table 16: Input data used in mass and energy balances of distillation process

Parameter	Value	Source
Beer – Volume (calculation basis)	100 liters	Adopted by the author
Beer - Ethanol content (v/v)	8.5ºGL	Adopted by the author
Beer - Ethanol content (m/m)	6.84ºINPM	Sorel (1894)
Beer - Temperature at the entrance of column A	85ºC	Adopted by the author
Hydrous ethanol – Ethanol content (v/v)	95.5ºGL	Adopted by the author
Hydrous ethanol – Ethanol content (m/m)	93.2ºINPM	Sorel (1894)
Hydrous ethanol - Total heat[1]	288.66 kcal/kg	Mariller (1948)
Hydrous ethanol – Latent heat of steam	230.25 kcal/kg	Mariller (1948)
Hydrous ethanol – Enthalpy of liquid	58.41 kcal/kg	Mariller (1948)
Hydrous ethanol – Density	0.81 kg/L	Mariller (1948)
Phlegma ethanol – Ethanol content (v/v)	48.4ºGL	Sorel (1894)
Phlegma ethanol – Ethanol content (m/m)	40.99ºINPM	Sorel (1894)
Phlegma – Density	0.9399 kg/L	Sorel (1894)
Phlegma – Total Heat	499 kcal/kg	Sorel (1894)
Phlegma - Enthalpy of liquid	92.18kcal/kg	Sorel (1894)
Thermal insulation of the distillation columns	Yes	Adopted by the author
Energy loss - Distillation columns	3%	Adopted by the author
Energy loss – Lines	4%	Adopted by the author
Type of column heating	Direct	Adopted by the author
Heating steam - Temperature	110ºC	Adopted by the author
Heating steam - Absolute pressure	1.646 kgf/cm^2	Adopted by the author
Heating steam - Total heat[1]	644 kcal/kg	Mariller (1948)
Vinasse - Temperature (bottom of column A)	110ºC	Adopted by the author
Vinasse – Density	0.81 kg/L	Adopted by the author
Vinasse – Specific heat	1 kcal/kgºC	Adopted by the author
Plegmace - Temperature (bottom of column B)	108ºC	Adopted by the author
Phlegmace – Density	1 kg/L	Adopted by the author
Phlegmace – Specific heat	1 kcal/kgºC	Adopted by the author
Reflux rate / minimum reflux rate (column B)	1.5	Adopted by the author
Condensed phlegma from column D to column B	10%	Adopted by the author

1) Total heat = Enthalpy of saturated steam

Source: created by the author

Based on data from Marilier (1948), linear regressions were made, and the following relations based on the ethanol content of beer (ºGLbe) were stablished:

$$Vph = f(°GLbe) = 1.1 * (°GLbe) + 9.65 \quad (Eq.6\text{-}4)$$
$$= 1.1 * 8.5 + 9.65 = 19.0L$$

$$Vet = f(°GLbe) = 1.0366 * (°GLbe) \quad (Eq.6\text{-}5)$$
$$= 1.0366 * 8.5 = 8.81L$$

To calculate the steam consumed in the column, it is necessary to calculate the energy balance of the column.

$$EinA = EoutA \quad (Eq.6\text{-}6)$$

where EinA is the incoming energy of column A and EoutA is the outgoing energy of column A. The incoming energy of column A can also be calculated by Eq.6-7.

$$EinA = Ebe + EstA \quad (Eq.6\text{-}7)$$

where Ebe is the energy in beer (kcal) and EstA is the energy in the steam of column A (kcal).

The energy in beer is given by the Eq.6-8.

$$Ebe = Vbe * Dbe * cbe * Tbe \quad (Eq.6\text{-}8)$$

where Dbe is the density of the beer (kg/L), cbe is the specific heat of beer (kcal/kgºC) and Tbe is the temperature of the beer (ºC).

Also based on data from Marilier (1948), linear regressions were made based on the ethanol content of beer (ºGLbe), and the following relations were stablished:

$$Dbe = f(°GLbe) = -0.0012 * (°GLbe) + 0.9987 \quad (Eq.6\text{-}9)$$
$$= -0.0012 * 8.5 + 0.9987 = 0.9885 \text{ kg/L}$$

cbe = f (ºGLbe) = - 0.00035 * (ºGLbe)^2 + 0.0109 * (ºGLbe) + 0.992 (Eq.6-10)
= - 0.00035 * 8.5^2 + 0.0109 * 8.5 + 0.9929 = 1.060 kcal / kgºC

Therefore, considering 100 liters of beer:

Ebe = 100L * 0.9885 kg / L * 1.060 kcal / kgºC * 85ºC = 8.906 kcal (Eq.6-11)

The energy in the steam of column A is given by the Eq.6-12.

EstA = StA * HstA (Eq.6-12)

where StA is the steam consumed (kg) and HstA is the enthalpy of the steam consumed (kcal/kg) by column A.

The steam consumed by column A is calculated through Eq.6-13.

StA (kg) = (Eph + Evi - Ebe) / (THstA - TbA - EloA) (Eq.6-13)

where Eph is the total phlegma energy, Evi is the vinasse energy, THstA is the total heat of steam of column A, TbA is the temperature of the bottom of column A and EloA is the energy losses in column A.

The total phlegma energy and the vinasse energy are calculated by Eqs. 6-14 and 6-15.

Eph = Vph * Dph * THph (Eq.6-14)
= 19 * 0,9399 * 499 = 8,911 kcal

Evi = Vvi * Dvi * cvi * Tvi (Eq.6-15)

where Dph is the density of the phlegma (kg/L), Dvi is the density of the vinasse (kg/L), cvi is the specific heat of vinasse (kcal/kgºC) and Tvi is the temperature of vinasse.

Therefore, from Eqs. 6-15, 6-13, 6-7 and 6-3, respectively:
Evi = (100 – 19) * 1 * 1 * 110 = 8,910 kcal
StA = (8,911 + 8,910 - 8,906) / (644 - 110 - 644 * (3% + 4%)) = 18.2kg
EinA = 8,906 + 18.2 * 644 = 20,627 kcal
Vvi / Vet = (100 - 19) / 8.81 + 18.2 / 8.81 = 11.3 L of vinasse / L of ethanol

For the case where there is no separation of vinasse and phlegmace (common practice), it is necessary to calculate the amount of phlegmace generated. In the process illustrated by Figure 6-1, phlegmace production was calculated based on the energy balance of column B as it follows:

$$EinB = EoutB \qquad \text{(Eq.6-16)}$$

where EinB is the incoming energy of column B and EoutB is the outgoing energy of column B. The incoming energy of column A can also be calculated by Eq.6-17.

$$EinB = Eph_{A \rightarrow B} + Eph_{D \rightarrow B} + EstB \qquad \text{(Eq.6-17)}$$

where $Eph_{A \rightarrow B}$ is the phlegma energy from column A to column B and is given by Eq. 6-18, $Eph_{D \rightarrow B}$ is the phlegma energy from column D to column B and is given by the Eq.6-19 and EstB is the energy in steam of column B.

$$Eph_{A \rightarrow B} = 90\% * Eph \qquad \text{(Eq.6-18)}$$
$$= 8,020\text{kcal}$$

$$Eph_{D \rightarrow B} = 10\% * Vph * Dph * Hph \qquad \text{(Eq.6-19)}$$
$$= 164.62 \text{ kcal}$$

where Hph is the enthalpy of liquid phlegma (kcal/kg).

The energy in the steam of column B is given by the Eq.6-20.

$$EstB = StB * HstB \qquad \text{(Eq.6-20)}$$

where StB is the steam consumed (kg) and HstB is the enthalpy of the steam consumed (kcal/kg) by column B.

The steam consumed by column B is calculated through Eq.6-21.

$$StB = (Ephc + E_R + E_{HE} – Eph_{A \rightarrow B} – Eph_{D \rightarrow B}) / (THstB - TbB - EloB) \quad (Eq. 6\text{-}21)$$

where Ephc is the total phlegmace energy, E_R is the reflux energy, E_{HE} is the energy in hydrous ethanol, THstB is the total heat of steam of column B, TbB is the temperature of the bottom of column B and EloB is the energy losses in column B.

The total phlegmace energy and the volume of phlegmace (Vphc) are calculated by Eqs. 6-22 and 6-23.

$$Ephc = Vphc * Dphc * cphc * Tphc \quad (Eq.6\text{-}22)$$

$$Vphc = Vph - Vet \quad (Eq.6\text{-}23)$$

$$= 19 – 8.81 = 10.19 \text{ L}$$

Therefore: Ephc = 10,19 * 1 * 1 * 108 = 1.101 kcal

The reflux energy is calculated by the Eq. 6-24.

$$E_R = R_R * Vet * Det * Het + (R_R +1) * 0.2 * 30 * Vet * Det \quad (Eq.6\text{-}24)$$

where R_R is the reflux rate of column B, Det is the density of ethanol, Het is the ethanol latent heat. The reflux rate is given by the Eq.6-25:

$$R_R = 1.5 * R_{Rmin} \quad (Eq.6\text{-}25)$$

where R_{Rmin} is the minimum reflux rate and is calculated by Eq.6-26.

R_{Rmin} = (M%$_{HE}$ - M%etph) / (M%etph - M%etbe) (Eq.6-26)

where M%$_{HE}$ is the molar percentage of ethanol in hydrous ethanol, M%etph is the molar percentage of ethanol in phlegma and M%etbe is the molar percentage of ethanol in beer.

The molar percentage of ethanol in the hydrous ethanol is calculated by the Eq. 6-27.

M%$_{HE}$ = (Et_{HE} / Met) / ((Et_{HE} / Met) + (WA / M_{WA})) * 100 (Eq.6-27)

where Et_{HE} is the ethanol weight in the hydrous ethanol, Met is the hydrous ethanol molar weight, WA is the water weight and M_{WA} is the water molar weight.

The ethanol molar weight and the water molar weight are given by the Eqs. 6-28 and 6-29, as it follows:

Met (CH_3CH_2OH) = 46g (Eq. 6-28)

M_{WA} (H_2O) = 18g (Eq. 6-29)

Therefore, considering ethanol content in hydrous ethanol is 93.2% in mass (Table 11), M%$_{HE}$ = 84.2%.

The molar percentage of ethanol in phlegma and in beer are given by Eqs. 6-30 and 6-31, respectively:

M%etph = (Etph / Met) / ((Etph / Met) + (WA / M_{WA})) * 100 (Eq.6-30)

M%etbe = (Etbe / Met) / ((Etbe / Met) + (WA / M_{WA})) * 100 (Eq.6-31)

Therefore, considering the data from Table 6-1 (ethanol content in phlegma is 40.99% in mass and in beer is 6.84% in mass): M%etph = 20.6% and M%etbe = 2.79%. Applying these results in Eqs. 6-26, 6-25 and 6-24: R_{Rmin} = 3.6, R_R = 5.4 and E_R = 9.124 kcal.

The energy in hydrous ethanol (E_{HE}) is given by Eq. 6-32:

$$E_{HE} = Vet * Det * THet \qquad (Eq.6\text{-}32)$$

where THet is the total heat of hydrous ethanol.

Calculating Eqs. 6-32 and 6-21: E_{HE} = 2,060 kcal and StB = 8.4kg. Therefore, for direct heating, Eq.6-33 gives the relation between the volume of phlegmace total per volume of ethanol:

$$Vphct / Vet = Vphc / Vet + StB / Vet \qquad (Eq.6\text{-}33)$$
$$= 2.1 \text{ L of phlegmace / L of ethanol}$$

The result of the calculations was: 11.3 m^3 of vinasse per 1 m^3 of ethanol and 2.1m^3 of phlegm per 1 m^3 of ethanol. So, the calculation of the mass and energy balance of the ethanol distillation process resulted in 13.4 liters of vinasse per liter of ethanol (sum of the results of Eqs.6-3 and 6-33).

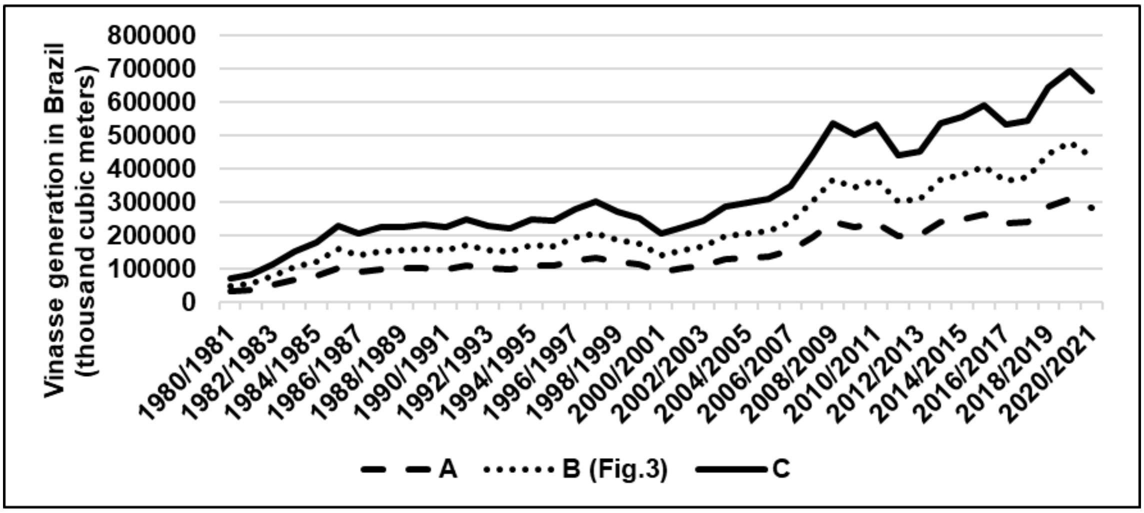
The amount of "vinasse" (vinasse plus phlegmace) generated can vary greatly depending on the operating and installation conditions. To understand better the extent of this variation, Table 17 presents two other group of assumptions (scenarios A and C), different from the one considered in the calculations of Figure 19 (scenario B) and the calculated quantity of vinasse and phlegmace. However, whatever the scenario, the amount of vinasse generated is relevant and represents an important opportunity in the search for more sustainable energy sources. Figure 20 illustrates the vinasse generation in the three scenarios of the Table 17.

Table 17: Estimation of the quantity of vinasse and phlegmace

Scenario	A	B (Fig.3)	C
Ethanolic degree of the beer (v/v)	10	8.5	6
Thermal insulation of the distillation columns	Yes	Yes	No
Type of column heating	Indirect	Direct	Direct
Vinasse production per liter of ethanol (m^3/m^3)	7.7	11.3	16.5
Phlegmace production per liter of ethanol (m^3/m^3)	1.0	2.1	3.0
Total – Vinasse + Phlegmace (m^3/m^3)	8.7	13.4	19.5

Source: Prepared by the author based on her thirteen years of professional experience working in ethanol production units and on mass and energy balance of the ethanol production process.

Figure 20: Estimated vinasse generation in Brazil, in thousand m^3



Source: Prepared by the author based on her thirteen years of professional experience working in ethanol production units and on mass and energy balance of the ethanol production process.

6.1.2 Vinasse generation considered in the case study

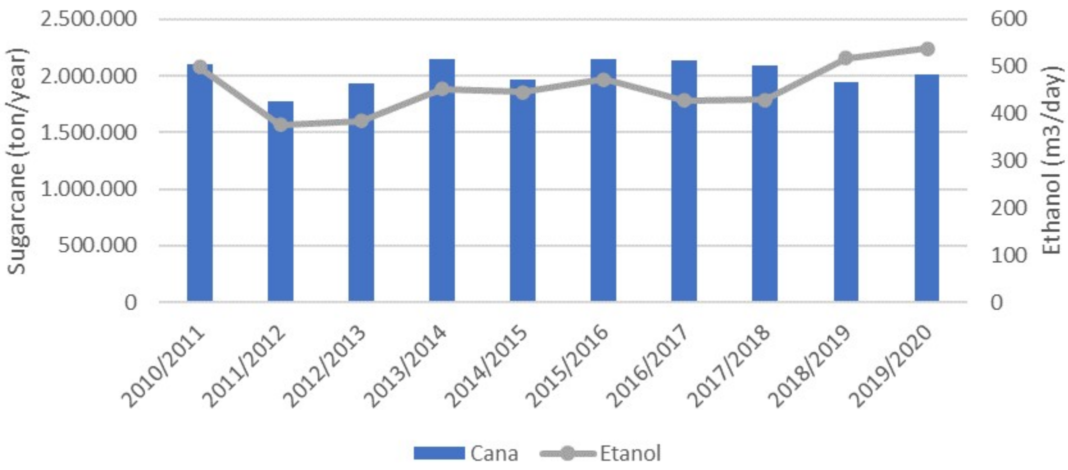
With the purpose of dimensioning the anaerobic reactor, we tried to design the case study in a way that represented a sugar and ethanol production unit close to most of the existing units. The intention was to allow a greater range of applicability of the analyzes developed here. Therefore, based on UNICA (2020), historical data from the last ten years indicates that in São Paulo State there are 171 sugarcane plants whose crushing capacity is around 2.0 million tons of cane. Based in these data and assumptions cited in method section, the ethanol production is around 448m^3 of ethanol per day. Figure 21 shows the historical data from the last ten years considering the medium sugarcane crushed and the daily ethanol production calculated.

The ethanol production was estimated by the Eq. 6-34:

$$Qet\ (m^3/day) = Qety / Np / d \qquad (Eq.\ 6\text{-}34)$$

where Qety is the average annual ethanol production (last 10 years), Np is the number of plants and d is the useful days.

Figure 21: Historical data of sugarcane plants in São Paulo State.



Source: Adapted from UNICA, 2020.

The daily quantity of vinasse is given by the Eq.6-35:

$$Qvi\ (m^3/day) = (Vvi / Vet) \times Qet\ (m^3/day) \qquad (Eq.6\text{-}35)$$

where Qvi is the daily quantity of vinasse, Vvi/Vet is the relation between the volume of vinasse produced by volume of ethanol and Qet is the daily ethanol production.

Thus, using the equations 6-35 and 6-34, about 6000 m^3 of vinasse per day was generated. The average annual ethanol production and the number of plants were based on data survey from the last ten years. Based on author thirteen years of experience working in a sugarcane company, it was assumed a harvest starting on May 2 and ending on November 30, 212 calendar days, with 85% of useful time, would be 180 working days of crushing.

To perform economic analysis, the companies Paques, Acesa and Aspro were asked for a technical-commercial proposal.

6.1.3 Reactors

The general expression that determines the theoretical production of methane is given by Eq. (6-36).

$$V_{CH4} = COD_{removed} / K(t) \qquad \text{(Eq.6-36)}$$

where: V_{CH4} = volume of methane produced (L), $COD_{removed}$ = load of COD removed from the reactor and converted into methane (gCOD) and K(t) = COD corresponding to one mole of CH_4.

$$COD_{removed} = COD_{influent} \times rCOD \qquad \text{(Eq.6-37)}$$

where: $COD_{influent}$ = Influent chemical oxygen demand and rCOD = COD removal efficiency.

$$K(t) = (P \times K) / [R \times (273 + T)] \qquad \text{(Eq.6-38)}$$

where: P = atmosphere pressure (1 atm), K = COD corresponding to one mole of CH_4 (64g COD/mole), R = gas constant (0.08206 atm.L/mole.ºK) and T = operational temperature of the reactor (ºC).

Considering that the production of methane can be easily determined in an anaerobic reactor, this is a fast, direct measurement of the conversion degree of the waste and of the efficiency of the treatment system. The theoretical methane yield coefficient (ηCH_4 in NL CH_4 / g $COD_{removed}$) is given by Eq. (6-39).

$$\text{Theoretical } \eta CH_4 = V_{CH4} / COD_{removed} \qquad \text{(Eq.6-39)}$$

where: V_{CH4} = volume of methane produced (L), $COD_{removed}$ = load of COD removed from the reactor.

6.1.3 Biogas

The present work did not consider vinasse co-digestion with filter cake or straw. Only vinasse biodigestion was considered. The amount of biogas generated by the biodigestion of vinasse is a function of the amount of organic matter available. An estimate can be made from the COD (Chemical Oxygen Demand) of the vinasse. According to Souza (1986, apud Salomon, 2007, p.32), there are three criteria to be considered when calculating the estimate of biogas production from waste, namely:

1) In a constant and normal state of temperature and pressure, the theoretical production of CH_4 is proportional to the amount of COD consumed in the reactor at the rate of 0.35 liters of CH_4 per 1g of COD consumed.

2) Part of the biogas produced is dissolved and lost in the effluent.

3) Part of the available COD is converted to biomass.

In this way, the estimate of the amount of biogas generated was done by the Eq. 6-40 and 6-41:

$$Vbg = COD_{influent} * rCOD * \eta CH_4 / CH_4bg \qquad (Eq.6\text{-}40)$$

$$COD_{influent} = CODvi * Vvi \qquad (Eq.6\text{-}41)$$

where Vbg is the volume of biogas (L), CH_4bg is the CH_4 content of biogas (%) and CODvi is the available COD of vinasse (g/L)

Table 18 shows a summary of the technical premises assumed in the present study. Based on these technical premises, Paques' team of specialists was able to dimension the commercial plant to produce biogas from sugarcane vinasse. It was also based on these technical premises that the biogas purification and biomethane compression systems were designed by Acesa and Aspro.

Table 18: Summary of the technical premises

Parameter	Value	Unit	Source
Vinasse flow	6000	m^3/day	Eq. 8 and 42
COD	26500	mg/L	Technical proposal from Paques (2019)
BOD	14500	mg/L	Technical proposal from Paques (2019)
Calcium	180	mg/L	Technical proposal from Paques (2019)
Potassium	1500	mg/L	Technical proposal from Paques (2019)
TSS	1000	mg/L	Technical proposal from Paques (2019)
Total Nitrogen - N Kjeldahl	430	mg/L	Technical proposal from Paques (2019)
Total Phosphorous	40	mg/L	Technical proposal from Paques (2019)
Sulfates	850	mg/L	Technical proposal from Paques (2019)
Temperature	35 - 38	ºC	Technical proposal from Paques (2019)
pH	3,5 – 3,7	-	Technical proposal from Paques (2019)
Oils	< 50	mg/L	Technical proposal from Paques (2019)
Conductivity	10,2	mS/cm	Technical proposal from Paques (2019)
Theoretical production of CH_4	0,35	L/g COD	Souza apud Salomon
COD removal efficiency	65	%	Technical proposal from Paques (2019)
H_2S removal efficiency	99	%	Technical proposal from Paques (2019)
Biogas - CH_4 content	65	%	Technical proposal from Paques (2019)
Biogas – CO_2 content	34	%	Technical proposal from Paques (2019)
Biogas – H_2S content	1	%	Technical proposal from Paques (2019)
Available COD	159000	kg/day	Technical proposal from Paques (2019)
CH_4 production	36173	Nm^3/day	Technical proposal from Paques (2019)
Biogas production	55650	Nm^3/day	Technical proposal from Paques (2019) confirmed by Eq. 43 and 44

Source: elaborated by the author.

6.2 Biogas utilization

6.2.1 Electricity generation

Using the methane flow, the power and the energy generated in the process are calculated by using the following equations:

$$Pg = Q_{CH4} \times \eta_{ICE} \times LCV_{CH4} / 86{,}400 \text{ seconds/day} \qquad \text{(Eq.6-42)}$$

$$Eg = Pg \times \text{days of operation} \times 24 \text{ hours} \qquad \text{(Eq.6-43)}$$

Table 19 shows a summary of the technical premises for the electricity generation assumed in the present study.

Table 19: Summary of the technical premises for electricity generation

Parameter	Value	Unit	Source
Internal Combustion Engine Efficiency	33%		Bernal et al. (2017)
Power generation	4,9	MW	Eq.45
Days of operation	180	days	Assumed by the author
Energy generation	21168	MWh/year	Eq.46
Relation Diesel/Biomethane	0,57	L/m^3	Nadaletti et al. (2015)

Source: elaborated by the author.

Based on these technical assumptions, the calculation of revenue from the sale of electricity and of carbon credits was performed, composing the estimate of the net present value of this alternative for the utilization of biogas.

6.2.2 Transport fuel

The utilization of biogas as transport fuel in heavy vehicles replaces partially the diesel oil consumption. According to Nadaletti *et al*. (2015), 1 cubic meter of biomethane can replace around 0.57 liters of diesel oil (based on LCV of each fuel). Based on this relation of replacing diesel with biogas, it was possible to calculate the monetary savings (based on the historical price of diesel oil) and the environmental benefit (in the form of carbon credits), both entering as revenues in the calculation of the net present value of this utilization of biogas.

6.2.3 Natural gas replacement

The composition of biomethane in terms of methane content is equivalent to the composition of natural gas, having pretty much the same calorific power, so the substitution is in the proportion of one to one. Based on this relation of replacing natural gas with biogas, it was possible to calculate the monetary savings (based on the historical price of natural gas) and the environmental benefit (in the form of carbon credits), both entering as revenues in the calculation of the net present value of this utilization of biogas.

6.3 Sustainability of utilization

6.3.1 Economic analysis

To invest is to commit money on a certain date and for a certain period which will generate a flow of returns that will compensate the investor for the time that the money was committed, for the inflation of that period and for the uncertainty of the flow of returns (Lapponi, 2007). In all cases, the company or the investor today exchanges an amount of money known at present, I, for an expected cash flow that adds value, considering the corresponding opportunity cost (required rate adjusted to the project's risk).

The measurement of the project's value creation is conducted by the net present value NPV of the project's cash flow in each year $CF(t)$ considering the opportunity cost i, the current year t and biogas plant lifespan n in years.

$$NPV = \sum_{t=1}^{n} \frac{CF(t)}{(1+i)^t} - I$$

(Eq. 6-44)

where: CF = Revenue (Sale of electricity and carbon credits) – OPEX

The flow cash for the calculation of NPV considered as entries the net receipts with sale of products (electricity or methane) and with the sale of carbon credits (the economic impact of environmental dimension). Also, the flow cash for the calculation of NPV considered as outputs the total operational cost (OPEX – Operational Expenditure) with consumables (as electricity and inputs) and with labor the economic impact of social dimension). The economic impact of the political dimension was also evaluated through the calculation of two different cases: with and without tax credits.

The sensibility analysis was performed considering two input data as variables: the percentual of the estimated capex (capital expenditure or investment) ranging from 85% to 125%, according to FEL2 concept, at intervals of 10% and the price of the products ranging from minus one standard deviation to plus one standard deviation in half standard deviation intervals for electricity and ranging from minus two standard deviations to plus two standard deviations at intervals of one standard deviation for natural gas and diesel oil. The average prices and the standard deviations were calculated based on historical monthly average prices from January 2013 to May 2020 corrected by the inflation (IPCA index).

A summary of the economic premises used in economic analysis is presented in Table 20.

Table 20: Summary of the economic premises

Parameter	Value	Unit
Equity	100,00%	
Opportunity cost	12,00%	
Interest rate	5,50%	
Income tax	34,00%	
Weighted average cost of capital	12,00%	
Sales tax	15,00%	
CAPEX	100%	
Tax credit (ICMS)	6,00%	
Credit installment (ICMS)	4	years
Tax credit (PIS/COFINS)	9,25%	
Credit installment (PIS/COFINS)	10	years
Projection period	15	years
Depreciation period	10	years
Amortization period	10	years
Exchange rate	5,00	R$/USD
Carbon Credit price (per tCO_2)	R$ 140,67	$28,13

Source: Adopted by the author

6.3.2 Environmental analysis

The environmental benefit of a biogas plant using vinasse as feedstock can be estimated by the following equation:

$$EA_{CO2eq}\ (vi)\ /\ year = Vviy \times CH4_r\ /\ 1000 \quad (Eq.6\text{-}45)$$

where: EA_{CO2eq} (vi) is the avoided emission of CO2eq (biogas plant), Vviy is the volume of vinasse per year and CH4r is the methane release rate in open channels.

Depending on the biogas application, additional benefits should be considered. If biogas is used to produce electricity through an internal combustion engine, the additional environmental benefit can be estimated as it follows:

$$EA_{CO2eq}\,(el)\ /\ year = EF(el) \times Eg \times (1 - \%\ CH_4\,(lo)) \qquad (Eq.6\text{-}46)$$

where EF(el) is the average emission factor related to the electricity generation and is equal to 0.075 tCO_2/MWh (Brazil, 2019).

In the case in which biomethane is used replacing natural gas (being injected into natural gas grid) or diesel (being used as a complementary fuel in vehicles), the avoided CO_2 emissions can be calculated according to the expressions below:

$$EA_{CO2eq}\,(na)\ /\ year = EF(na) \times Ec \times (1 - \%\ CH_4\,(lo)) \qquad (Eq.6\text{-}47)$$

$$EA_{CO2eq}\,(di)\ /\ year = EF(di) \times Ec \times (1 - \%\ CH_4\,(lo)) \qquad (Eq.6\text{-}48)$$

where EA_{CO2eq} (na) is the avoided emission of CO_2 related to the natural gas replacement, EF(na) is the average CO_2 emission factor of natural gas and is equal to 56.1 tCO_2/TJ, EA_{CO2eq} (di) is the avoided emission of CO_2 related to the diesel replacement ,EF(di) is the average CO_2 emission factor of diesel and is equal to 74.1 tCO_2/TJ and Ec is the energy consumption of biomethane (TJ/year) and is equal to 35.5 MJ/m^3 (Bernal et al., 2017) x $m^3/year\ /\ 10^6$.

A summary of the environmental premises used in economic analysis is presented in Table 21.

The calculation of the revenue was based only on the sale of carbon credits and on the environmental premises (Table 21). The three alternatives considered the gain related to the discontinuity in the use of open vinasse channels (avoided emission of the biogas plant) in addition to the individual gain referring to each alternative.

Table 21: Summary of the environmental premises

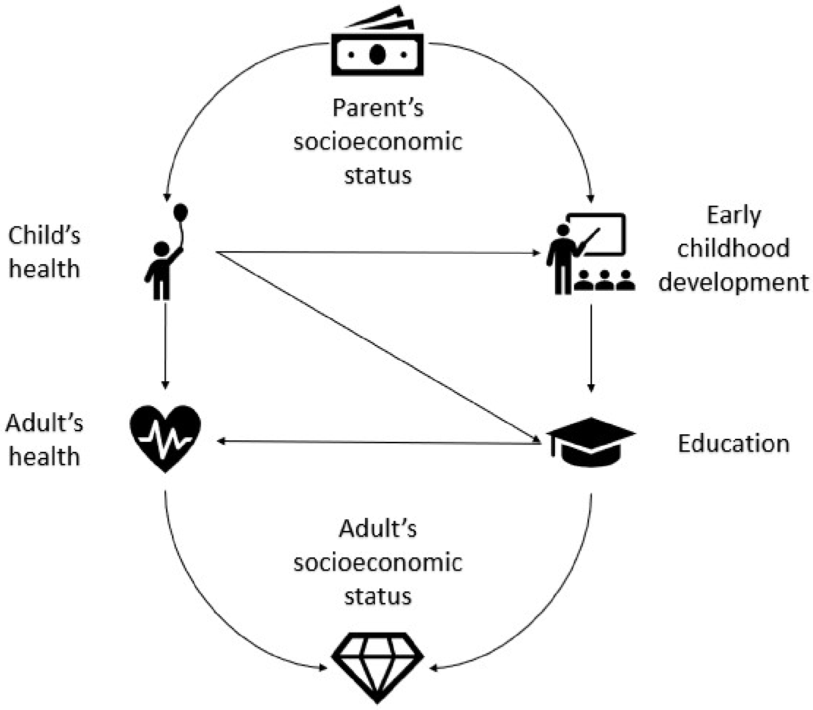
ENVIRONMENTAL PREMISES			
Parameter	**Value**	**Unit**	**Source**
Days of operation	180	days	Assumed by the author
Vinasse flow	6.000,00	m^3/day	Eq. 8 and 42
Volume of vinasse generated (m3/year)	1.080.000,00	m3/year	m3/day x days
Methane release rate in open channels	1,36	kgCO2eq/m3	Parsaee et al. (2019)
CO_2 avoided emission of the biogas plant	**1.468,80**	**tCO_2eq/year**	Eq.48
Electricity sale	21.168	MWh/year	Eq.46
Average CO_2 emission factor	0,075	tCO_2/MWh	MCTIC (2020)
CO_2 avoided emission of the electricity production	**1.587,60**	**tCO_2eq/year**	Eq.49
Biomethane production	36173	Nm^3/day	Paques proposal (2019)
Biomethane calorific power	35,5	MJ/m^3	Bernal et al., 2017
Energy consumption	231,1	TJ/year	Calculated by the author
Average CO_2 emission factor (natural gas)	56,1	tCO_2/TJ	Álvares Jr. and Linke (2019)
Methane losses	2%		Börjesson and Berghund (2006)
CO_2 avoided emission of the natural gas replacement	**12.707,92**	**t CO_{2eq}**	Eq.50
Average CO_2 emission factor (diesel)	74,1	tCO_2/TJ	Álvares Jr. and Linke (2019)
CO_2 avoided emission of the diesel replacement	**16.785,32**	**t CO_{2eq}**	Eq.51

Source: elaborated by the author.

6.3.3 Social analysis

Based on the Brundtland (1991), the main social needs and aspirations is sustenance, that is, employment. So, it is necessary that the pace and pattern of economic development create sustainable job opportunities and at a level of productivity that allows poor families to live within the minimum standards of consumption (food, energy, housing, water supply, sanitation, and medical services). It is expected a virtuous cycle , as shown in Figure 22.

Figure 22: Education and health along the lifecycle.



Source: Adapted from UNDP, 2019.

The generation of jobs in a biogas production plant from sugarcane vinasse could be greater if it were not normally linked to an ethanol producing unit. However, this would not be a reasonable situation since transport costs would most likely make the project unfeasible. More rational is the hypothesis that the biogas plant would be installed alongside the ethanol producing unit and would benefit from the existing structure, including human resources. Thus, the generation of jobs occurs only at the operational level and not managerial. Salaries and benefits compatible with such job and function profiles within the sugar and ethanol sector and with Brazilian legislation will be considered.

Social analysis was based on the job creation in each of biogas application showed in the Table 22. The number of jobs created as well as wages and charges were provided by the companies consulted for equipment budget.

Table 22: Job creation in each of biogas application

JOB GENERATION	Electricity	Transport Fuel	Natural Gas Substitutive
Operator (Biogas Plant)	4	4	4
Chemical Analyst (Biogas Plant)	1	1	1
Operator (Biogas Purification)	0	4	4
Operator (Powerhouse)	4	0	0
Operator (Compression System)	0	4	0
TOTAL	9	13	9

Source: estimated by the author based on her professional experience and on conversation with equipment suppliers.

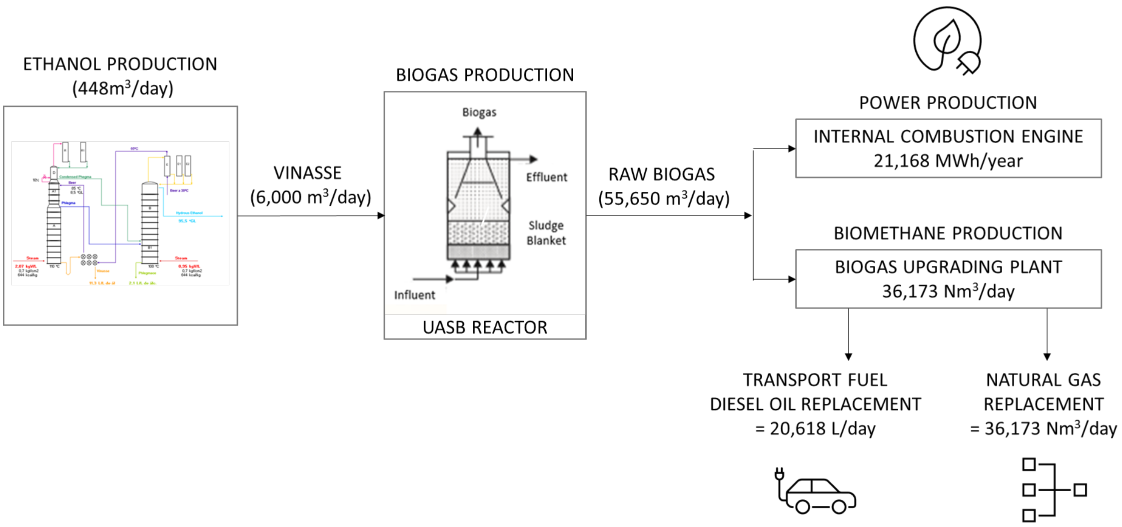
Although job creation has a positive social impact, as opposed to the environmental impact, it is not captured as a positive entry in the study of the project's economic viability. On the contrary, the generation of jobs enters as OPEX, burdening the project.

7 RESULTS AND DISCUSSION

7.1 Economic analysis

The economic analysis was performed based on the calculations explained in Methodology. A summary of the main technical data is showed in Figure 23.

Figure 23: Diagram - main technical data used for the economic analysis.



Source: elaborated by the author.

In the next sections, all the other technical assumptions are detailed, as well as the economic assumptions, including the sale of carbon credits and labor costs. Also presented and discussed are the results of the economic evaluation that indicates the viability of the projects within the assumptions made.

7.1.1. Electricity generation

To analyze the sustainability of biogas use in electricity generation, both environmental and social impacts were converted in economic values to compose the economic analysis. Based on FEL methodology and budgets from supplier companies, capital and operational expenditures were estimated and are presented in Tables 23 and 24.

Table 23: Capital expenditure for electricity generation

CAPEX	R$/USD 5,00		Source
Anaerobic Treatment - Biodigester BIOPAQ ICX (2 x 5,400m^3)	R$ 19.980.000,00	$ 3.996.000,00	Budget from PAQUES (2019)
Design and Execution of Civil Works	R$ 2.450.000,00	$ 490.000,00	Budget from PAQUES (2019)
H_2S Removal Plant - THIOPAQ	R$ 5.010.000,00	$ 1.002.000,00	Budget from PAQUES (2019)
Design and Execution of Civil Works	R$ 250.000,00	$ 50.000,00	Budget from PAQUES (2019)
Burner (Flare)	R$ 428.120,00	$ 85.624,00	Bernal et al. (2017)
Gasometer (43.7 USD/m^3)	R$ 527.000,00	$ 105.400,00	Bernal et al. (2017)
Compressor (242.8 USD/m^3)	R$ 2.930.000,00	$ 586.000,00	Bernal et al. (2017)
Pipeline (121.4 USD/m) – 380m	R$ 240.000,00	$ 48.000,00	Bernal et al. (2017)
ICE equipment and installation (USD 1800/kW)	R$ 44.100.000,00	$ 8.820.000,00	EPA (2017)
BIOGAS TO ELECTRICITY GENERATION	**R$ 75.915.120,00**	**$ 15.183.024,00**	

Note: Including taxes and considering required area = 2,000m² (50m x 40m) available (no investment required).

Source: elaborated by the author.

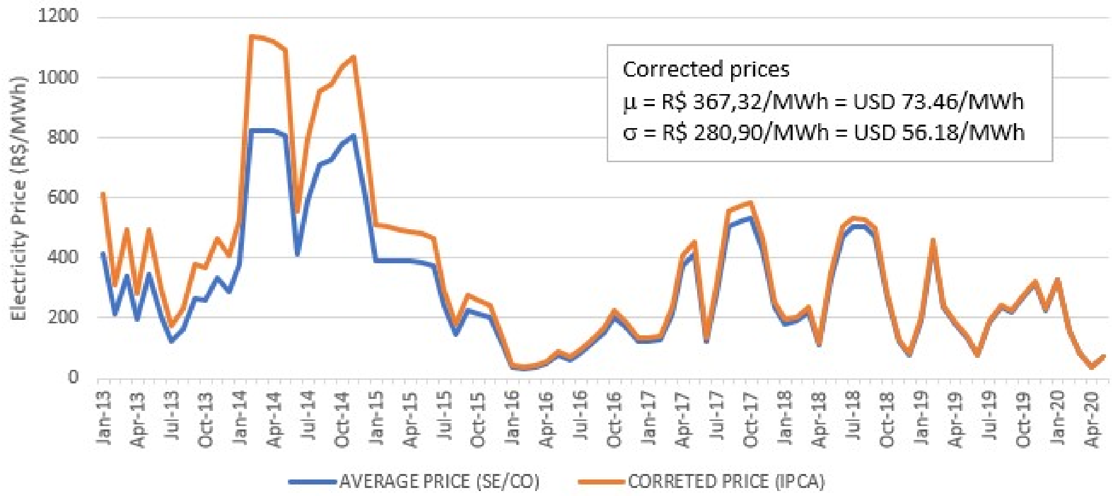
Table 24: Operational expenditure for electricity generation

OPEX (yearly)	R$/USD 5,00		Source
Electricity consumption - BIOPAQ ICX	R$ 29.203,20	$ 5.840,64	Budget from PAQUES (2019)
Electricity consumption - THIOPAQ	R$ 40.435,20	$ 8.087,04	Budget from PAQUES (2019)
NaOH consumption - BIOPAQ ICX	R$ 114.573,53	$ 22.914,71	Budget from PAQUES (2019)
NaOH consumption - THIOPAQ	R$ 275.467,50	$ 55.093,50	Budget from PAQUES (2019)
NUTRIMIX consumption - THIOPAQ	R$ 23.611,50	$ 4.722,30	Budget from PAQUES (2019)
Operator Biogas Plant (4)	R$ 68.339,38	$ 13.667,88	Budget from PAQUES (2019)
Chemical Analyst (1)	R$ 13.857,71	$ 2.771,54	Budget from PAQUES (2019)
Maintenance (BIOPAQ ICX and THIOPAQ)	R$ 477.226,80	$ 95.445,36	1,5% Capex
ICE O&M Costs (0.016USD/kWh)	R$ 1.693.440,00	$ 338.688,00	EPA (2017)
BIOGAS TO ELECTRICITY GENERATION	**R$ 2.736.154,82**	**$ 547.230,96**	

Source: elaborated by the author.

Based on these estimated values of capex and opex and on the premises presented, economic calculations were done. The results spreadsheets of the biogas use in electricity with and without tax credits considering 100% of estimated capex and electricity average price are presented in Appendix A and B, respectively. Corrected average historical price and its standard deviation from January 2013 to May 2020, presented in Figure 24.

Figure 24: Electricity price of the Southeast and Center-West regions of Brazil.

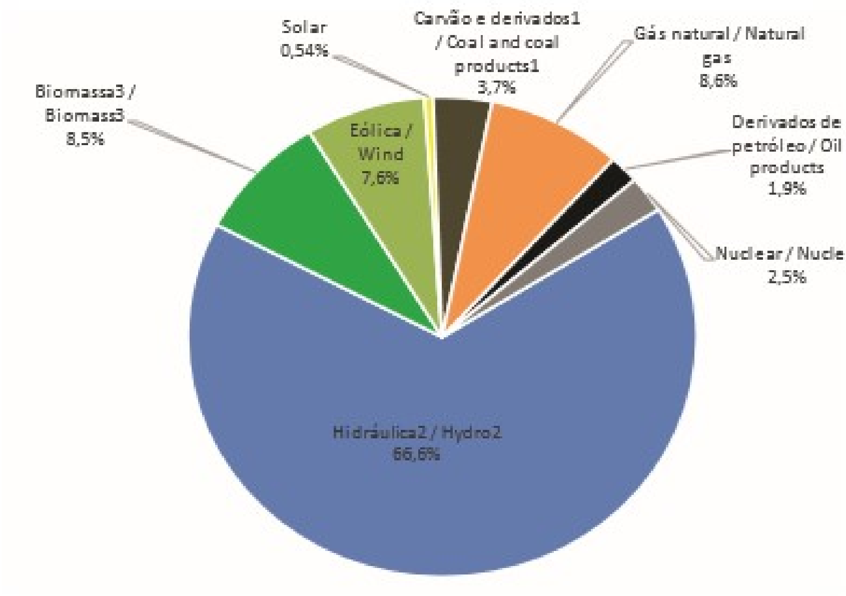


Source: Adapted from CCEE, 2020

To better understand the electricity price and its variation over time, it is important to know more about Brazilian energy matrix. The domestic electricity supply of Brazil, illustrated by Graphic 15 shows the predominance of the hydro source (around 67%), which means that the system is highly dependent of precipitation. So, it is expected that in years when the rainfall index is higher, the price of energy tends to decrease, since the production of energy from more expensive sources such as thermoelectric plants decrease. The opposite reasoning also applies, that is, when the year is drier, the price of electricity tends to increase.

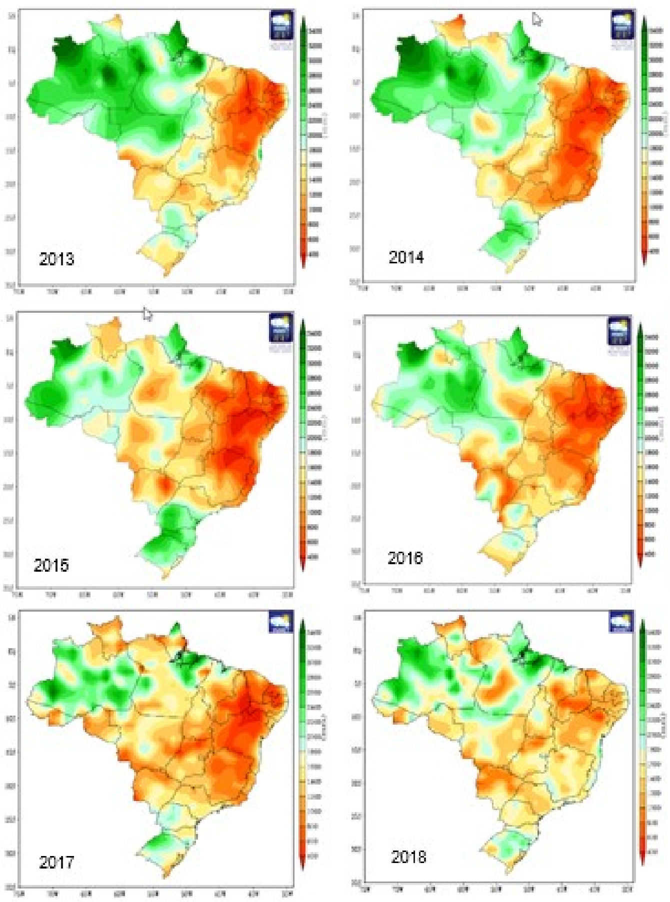
Figure 24 shows that in 2014 there was a significant increase in the price of energy followed by a decrease in 2015 and a new increase in 2016, but not returning to the level of 2014. Relating this behavior to the characteristic of the Brazilian energy matrix being highly dependent of hydroelectricity (Figure 25), it is expected that the year 2014 was a year with relatively less accumulated precipitation compared to the other years, as shown in Figure 26.

Figure 25: Domestic electricity supply of Brazil by source



Source: BEN, 2019.

Figure 26: Accumulated precipitation of Brazil



Source: Adapted from INMET, 2020.

The color scale in Figure 26 relates little precipitation to the red color, medium precipitation to the yellow color and high precipitation to the green color. It is easy to note that between the years 2013 and 2018, the year with the lowest accumulated anticipation was 2014, a period in which the price of electricity rose considerably.

The fact that the Brazilian electricity system is highly dependent on rainfall also explains the high standard deviation in electricity prices found, which brings to the sector investors a high level of uncertainty, requiring the establishment of bilateral contracts or fee-based contracts through auctions of electricity from the government that consider long terms so that the intrinsic risk to the sector can be mitigated. The high standard deviation of prices meant that the criterion of price variation for the sensitivity analysis had to be different in the case that biogas is used to generate electric energy. Variations of half a standard deviation were considered instead of one standard deviation as in the case of the other two applications of biogas.

Converting the average price and standard deviation from R$ to USD based on the exchange rate of R$ 5.00 / USD (Banco Central do Brasil, 2020) and considering the electricity price ranging from minus one standard deviation to plus one standard deviation in half standard deviation intervals, the NPV sensibility analysis was made for two different cases: with and without tax credits. The sensibility analysis was based on capex variation ranging from 85% to 125% (according FEL 2 methodology) at 10% intervals.

The results are presented in Tables 25 and 26.

Table 25: NPV sensibility analysis with tax credits (electricity generation)

	NPV WITH TAX CREDIT	ELECTRICITY PRICE (USD/MWh)				
		- 1 σ	- 1/2 σ	μ	+ 1/2 σ	+ 1 σ
	-0	$ 17,28	$ 45,37	$ 73,46	$ 101,55	$ 129,64
% CAPEX	85%	-12.666.940	-9.364.733	-6.121.849	-3.452.999	-1.181.060
	95%	-14.036.715	-10.734.508	-7.491.623	-4.581.596	-2.309.657
	105%	-15.406.489	-12.104.283	-8.861.398	-5.781.997	-3.438.254
	115%	-16.776.264	-13.474.058	-10.231.173	-7.032.999	-4.566.851
	125%	-18.146.039	-14.843.832	-11.600.948	-8.358.063	-5.695.447

Source: elaborated by the author.

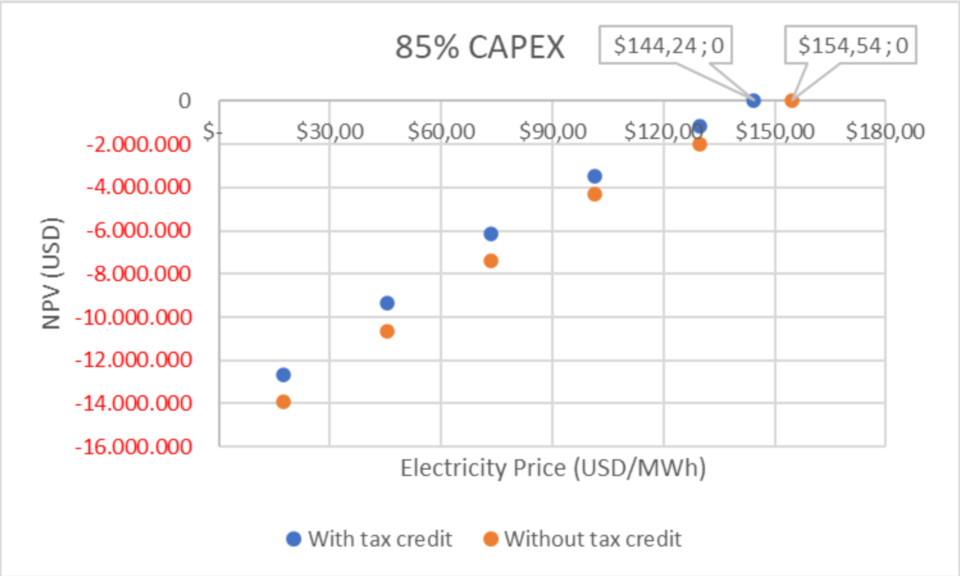
Table 26: NPV sensibility analysis without tax credits (electricity generation)

NPV WITHOUT TAX CREDIT		ELECTRICITY PRICE (USD/MWh)				
		- 1 σ	- 1/2 σ	μ	+ 1/2 σ	+ 1 σ
	0	$ 17,28	$ 45,37	$ 73,46	$ 101,55	$ 129,64
% CAPEX	85%	-13.929.425	-10.627.218	-7.384.333	-4.286.239	-2.014.300
	95%	-15.447.727	-12.145.521	-8.902.636	-5.659.751	-3.240.925
	105%	-16.966.029	-13.663.823	-10.420.938	-7.178.053	-4.467.550
	115%	-18.484.332	-15.182.125	-11.939.241	-8.696.356	-5.694.175
	125%	-20.002.634	-16.700.428	-13.457.543	-10.214.658	-6.971.773

Source: elaborated by the author.

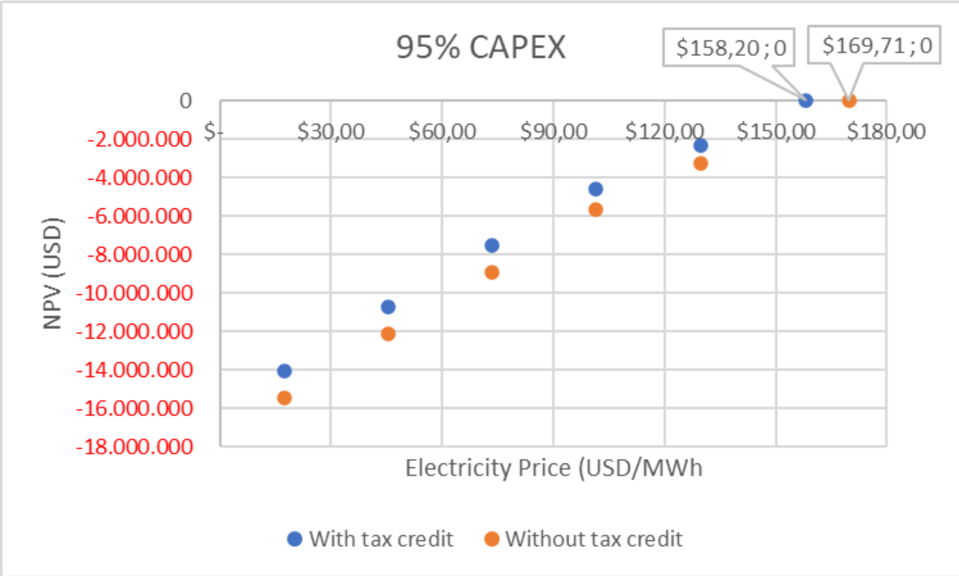
Figures 27 to 31 illustrate the same information adding the break-even point, where the NPV=0.

Figure 27: NPV values for Electricity Generation considering 85% capex.



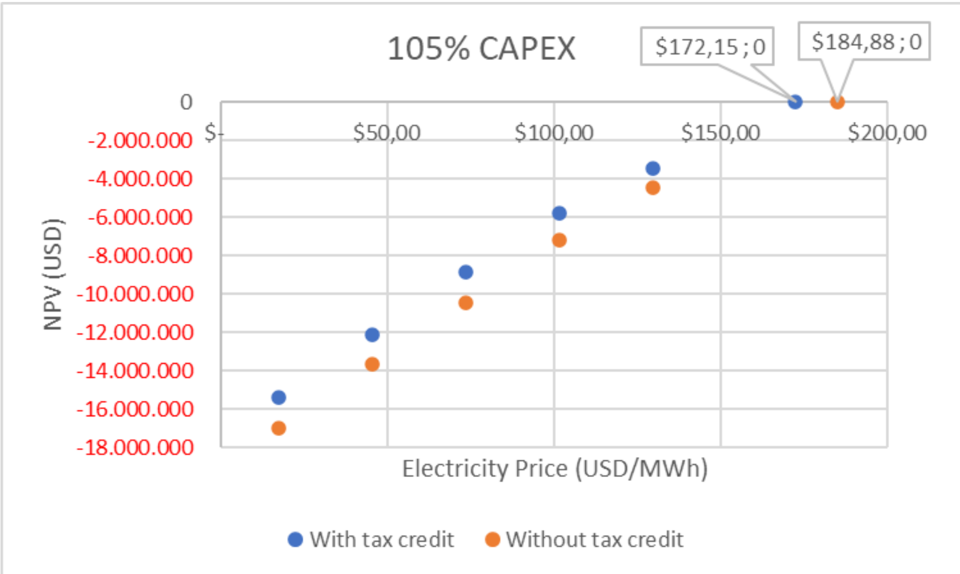
Source: elaborated by the author.

Figure 28: NPV values for Electricity Generation considering 95% capex.



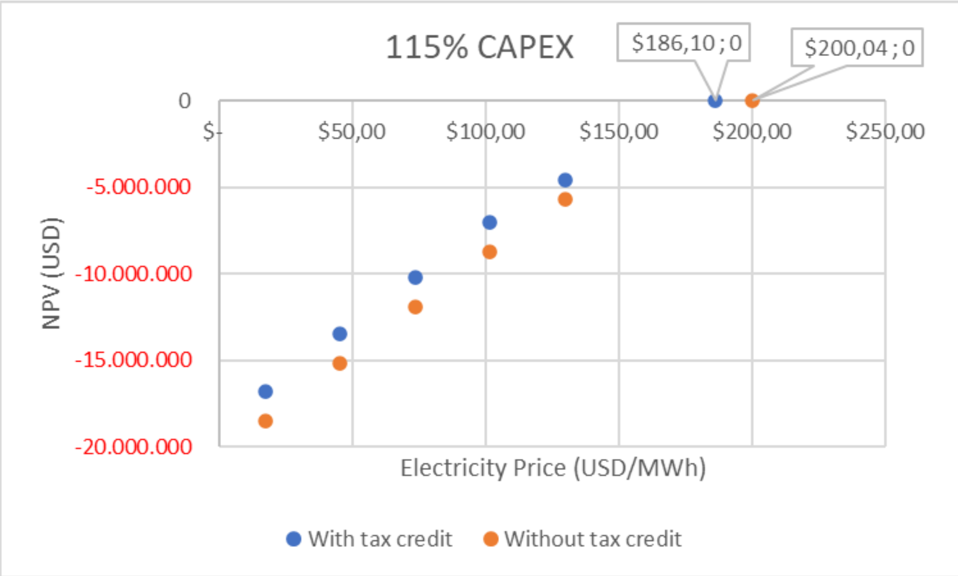
Source: elaborated by the author.

Figure 29: NPV values for Electricity Generation considering 105% capex.



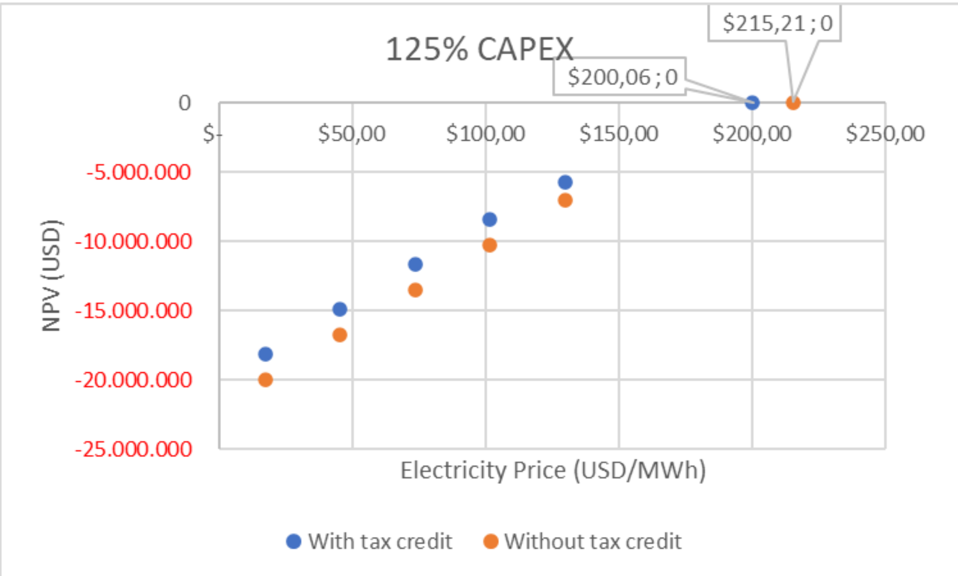
Source: elaborated by the author.

Figure 30: NPV values for Electricity Generation considering 115% capex.



Source: elaborated by the author.

Figure 31: NPV values for Electricity Generation considering 125% capex.



Source: elaborated by the author.

Based on the calculated NPVs, biogas calculations made by this author for electricity generation proved viable for energy prices ranging from USD 144.24 / MWh (85% of the estimated capex) to USD 200.06 / MWh (125% of the estimated capex) for cases with tax credits. For the simulations that did not consider tax credits, calculations made by this author of biogas for electricity generation proved viable for energy prices ranging from USD 154.54 / MWh

(85% of the estimated capex) to USD 215.21 / MWh (125 % of estimated capex).

Considering that the price of energy sold at the 2016 A-5 auction by UTE Bonfim was USD 50.20 / MWh (R$ 251,00 / MWh; R$ 5.00 / USD), whose corrected value for May 2020 would be USD 65.09 / MWh, NPV would be negative for all cases, indicating that the project would not be economically viable considering the assumptions adopted. Also considering that the average historical price of energy sold was USD 73.46 / MWh (R$ 367,32 / MWh; R$ 5.21 / USD), still NPV would be negative for all cases, reinforcing that the project would not be economically viable considering the assumptions adopted.

In 2018, the Ministry of Mines and Energy published Ordinance No. 65/2018 establishing new VREs (Specific Reference Values) for the following technologies: biogas, dedicated biomass, residual biomass, natural gas cogeneration, wind, SHP, urban solid waste and solar photovoltaic. In this ordinance, the specific reference value for biogas was established at R$390/MWh (EPE, 2023), equivalent to USD78/MWh, which also does not make the project economically viable considering the assumptions made.

7.1.2 Transport fuel

To analyze the sustainability of biogas use in transport fuel, both environmental and social impacts were converted in economic values to compose the economic analysis. Based on FEL methodology and budgets from supplier companies, capital and operational expenditures were estimated and are presented in Tables 27 and 28.

Table 27: Capital expenditure for transport fuel

CAPEX	R$/USD 5,00				Source
Anaerobic Treatment - Biodigester BIOPAQ ICX (2 x 5,400m^3)	R$	19.980.000,00	$	3.996.000,00	Budget from PAQUES (2019)
Design and Execution of Civil Works	R$	2.450.000,00	$	490.000,00	Budget from PAQUES (2019)
Burner (Flare)	R$	428.120,00	$	85.624,00	Bernal et al. (2017)
Gasometer (43.7 USD/m^3)	R$	527.000,00	$	105.400,00	Bernal et al. (2017)
Compressor (242.8 USD/m^3)	R$	2.930.000,00	$	586.000,00	Bernal et al. (2017)
Pipeline (121.4 USD/m) – 380m	R$	240.000,00	$	48.000,00	Bernal et al. (2017)
BUP2300 + H_2S Removal system ($H_2S \leq$ 80ppm)	R$	12.245.000,00	$	2.449.000,00	Budget from ACESA (2020)
Freight equipment Germany and insurance, DDU Porto SP	R$	766.000,00	$	153.200,00	Budget from ACESA (2020)
Cold and chilled water system	R$	250.000,00	$	50.000,00	Budget from ACESA (2020)
Chromotograph	R$	250.000,00	$	50.000,00	Budget from ACESA (2020)
Odorizer	R$	365.000,00	$	73.000,00	Budget from ACESA (2020)
Nitrogen for start up	R$	50.000,00	$	10.000,00	Budget from ACESA (2020)
Chromatograph helium	R$	5.000,00	$	1.000,00	Budget from ACESA (2020)
Detailing engineering	R$	608.000,00	$	121.600,00	Budget from ACESA (2020)
Electromechanical assembly BUP	R$	284.200,00	$	56.840,00	Budget from ACESA (2020)
Assembly of cooling / chilling and nitrogen system	R$	171.500,00	$	34.300,00	Budget from ACESA (2020)
Electrical transformer assembly into the BUP	R$	232.000,00	$	46.400,00	Budget from ACESA (2020)
Crane	R$	27.810,00	$	5.562,00	Budget from ACESA (2020)
Connection to a natural gas network (121.4 USD/m) – 5km	R$	3.035.000,00	$	607.000,00	Bernal et al. (2017)
02 Compression systems (IODM 115-4 compressor with cab)	R$	2.827.959,00	$	565.591,80	Budget from ASPRO (2020)
02 Control panels with frequency inverter	R$	-	$	-	included in the compression system
02 AS-120G dispensers for filling	R$	-	$	-	included in the compression system
18 cylinders for storage (125 liters each)	R$	150.000,00	$	30.000,00	Budget from ASPRO (2020)
Mechanical and electrical installation	R$	163.798,26	$	32.759,65	Budget from ASPRO (2020)
Vehicles conversion (278units)	R$	13.640.000,00	$	2.728.000,00	Budget Convergas (2020)
Others*	R$	6.162.638,73	$	1.232.527,75	10% Capex
BIOGAS AS VEHICLE FUEL (A+C+E+F)	**R$**	**67.789.025,99**	**$**	**13.557.805,20**	

Note: Including taxes and considering required area = 2,000m² (50m x 40m) available (no investment required).

* Others: Civil work, electrical supply, gounding, lightning, closing areas (screens, doors and gates), condensate destination and treatment and offgas treatment.

Source: elaborated by the author.

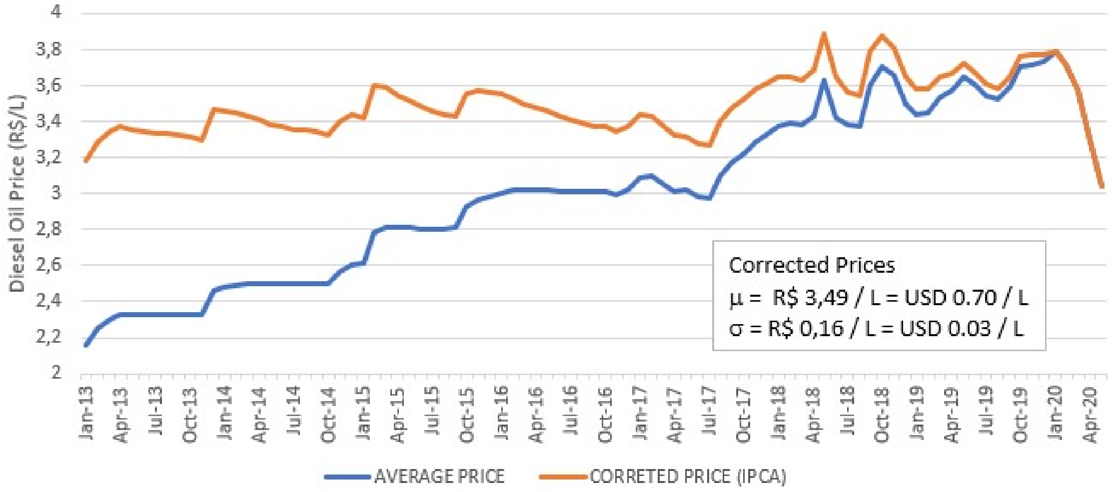
Table 28: Operational expenditure for transport fuel

OPEX (yearly)	R$/USD 5,00				Source
Electricity consumption - BIOPAQ ICX	R$	29.203,20	$	5.840,64	Budget from PAQUES (2019)
NaOH consumption - BIOPAQ ICX	R$	114.573,53	$	22.914,71	Budget from PAQUES (2019)
Activated carbon - BUP	R$	69.900,00	$	13.980,00	Budget from ACESA (2020)
Operator Biogas Plant (4)	R$	68.339,38	$	13.667,88	Budget from PAQUES (2019)
Chemical Analyst (1)	R$	13.857,71	$	2.771,54	Budget from PAQUES (2019)
Operation - BUP	R$	373.800,00	$	74.760,00	Budget from ACESA (2020)
Labor supply contract (ASPRO)	R$	48.000,00	$	9.600,00	Budget from ASPRO (2020)
Maintenance	R$	1.016.835,39	$	203.367,08	1,5% Capex
BIOGAS TO ELECTRICITY GENERATION	**R$**	**1.734.509,21**	**R$**	**346.901,84**	

Source: elaborated by the author.

Based on these estimated values of capex and opex and on the premises presented, economic calculations were done. The results spreadsheets of the biogas use in transport fuel with and without tax credits considering 100% of estimated capex and diesel oil average price are presented in Appendix C and D, respectively. Corrected average historical price and its standard deviation from January 2013 to May 2020, presented in Figure 32.

Figure 32: Historical average diesel oil price of the São Paulo State, Brazil.



Source: Adapted from ANP, 2020.

The standard deviation of historic diesel prices represents 4.6% of the average price for the period, which seems to be a reasonable variation. Brazil broke a diesel import record in 2021, the country imported 14.4 million cubic meters of diesel A (pure, without biodiesel), a volume 20.4% greater than the previous year. It was the highest result since 2000, when the historic series began. The share of diesel sold in the country with foreign origin rose from 20.9% in 2020 to 23.2% in 2021, the second highest in the historical series (BEN, 2022).

Converting the average price and standard deviation from R$ to USD based on the exchange rate of R$ 5.00 / USD (Banco Central do Brasil, 2020) and considering the diesel oil price ranging from minus two standard deviations to plus two standard deviations in one standard deviation interval, the NPV sensibility analysis was made for two different cases: with and without tax credits. The sensibility analysis was based on capex variation ranging from 85% to 125% (according FEL 2 methodology) at 10% intervals.

The results are presented in Tables 29 and 30.

Table 29: NPV sensibility analysis with tax credits (transport fuel)

	NPV WITH TAX CREDIT	DIESEL PRICE (USD/L)				
		- 2 σ	- 1σ	μ	+ 1 σ	+ 2 σ
	0	$ 0,64	$ 0,67	$ 0,70	$ 0,73	$ 0,76
% CAPEX	85%	742.927	1.168.347	1.593.768	2.019.188	2.444.608
	95%	-264.863	160.558	585.978	1.011.398	1.436.819
	105%	-1.272.652	-847.232	-421.812	3.609	429.029
	115%	-2.280.442	-1.855.022	-1.429.601	-1.004.181	-578.761
	125%	-3.288.232	-2.862.811	-2.437.391	-2.011.971	-1.586.550

Source: elaborated by the author.

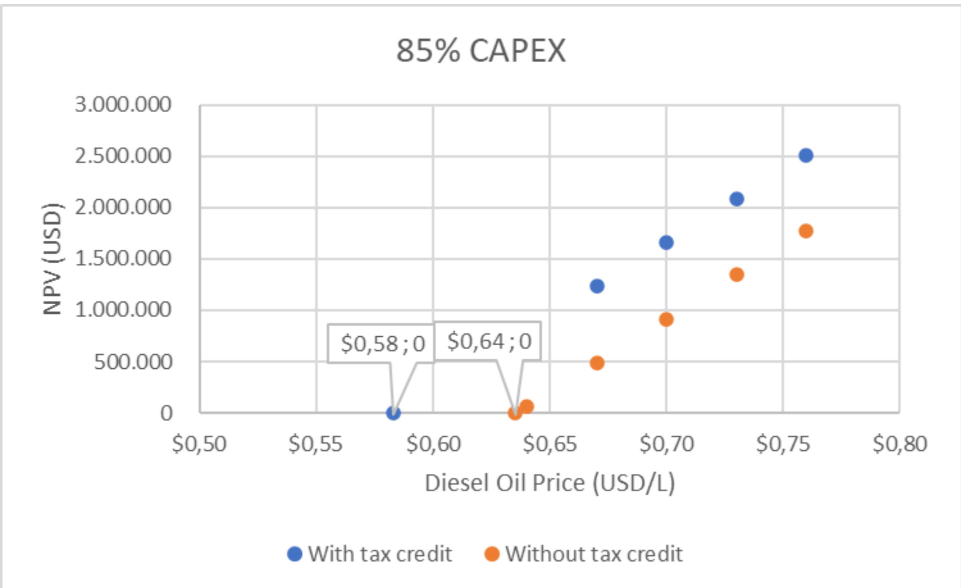
Table 30: NPV sensibility analysis without tax credits (transport fuel)

	NPV WITHOUT TAX CREDIT	DIESEL PRICE (USD/L)				
		- 2 σ	- 1σ	μ	+ 1 σ	+ 2 σ
	0	$ 0,64	$ 0,67	$ 0,70	$ 0,73	$ 0,76
% CAPEX	85%	-1.121	424.299	849.719	1.275.140	1.700.560
	95%	-1.096.446	-671.026	-245.606	179.815	605.235
	105%	-2.191.771	-1.766.351	-1.340.930	-915.510	-490.090
	115%	-3.287.096	-2.861.676	-2.436.255	-2.010.835	-1.585.414
	125%	-4.382.421	-3.957.000	-3.531.580	-3.106.160	-2.680.739

Source: elaborated by the author.

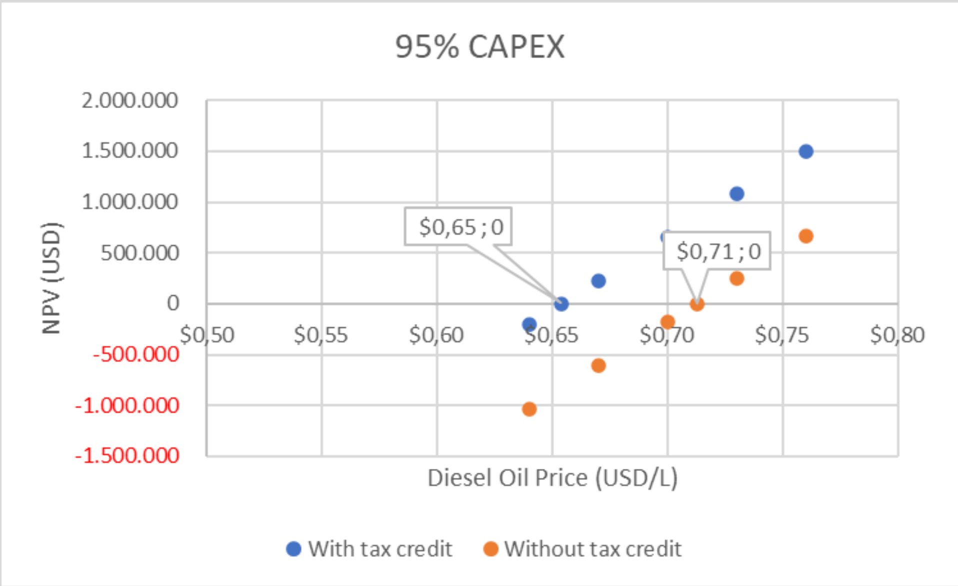
Figure 33 to 37 illustrate the same information adding the break-even point, where the NPV=0.

Figure 33: NPV values for Diesel Oil replacement considering 85% capex.



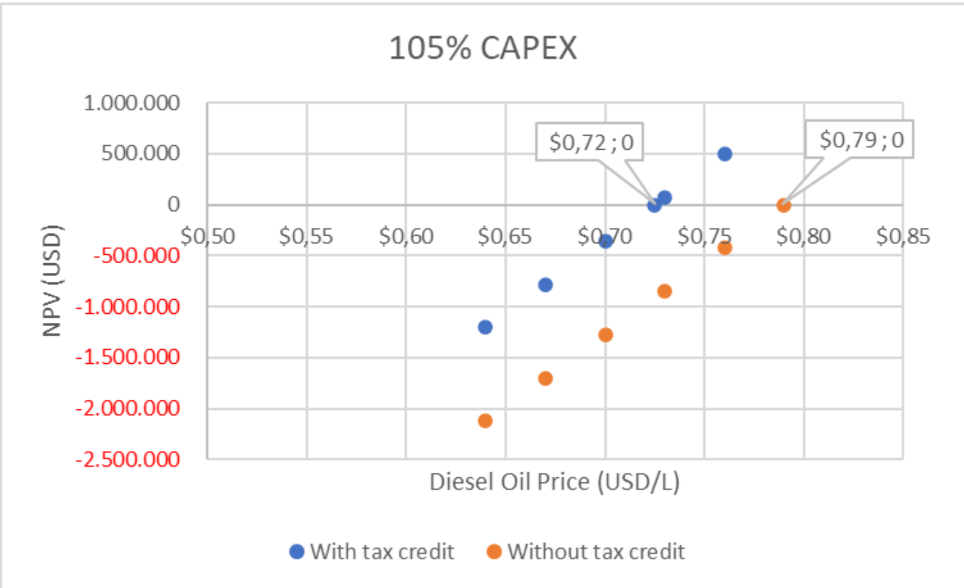
Source: elaborated by the author.

Figure 34: NPV values for Diesel Oil replacement considering 95% capex.



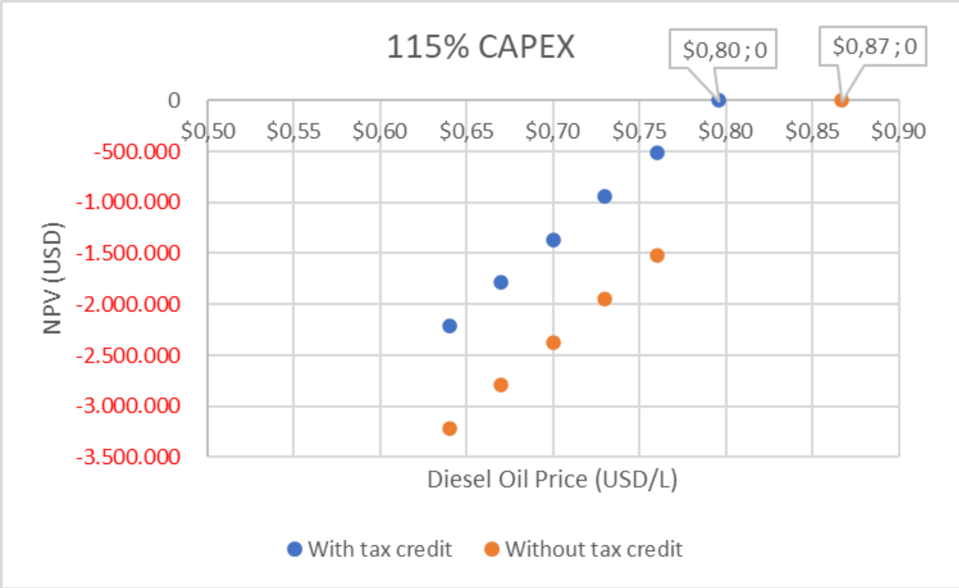
Source: elaborated by the author.

Figure 35: NPV values for Diesel Oil replacement considering 105% capex.



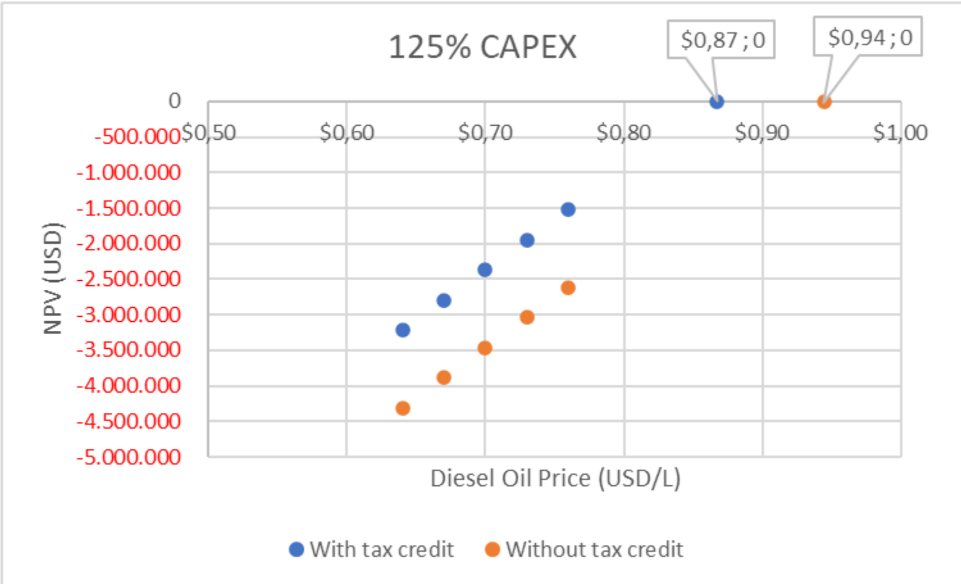
Source: elaborated by the author.

Figure 36: NPV values for Diesel Oil replacement considering 115% capex.



Source: elaborated by the author.

Figure 37: NPV values for Diesel Oil replacement considering 125% capex.



Source: elaborated by the author.

Based on the calculated NPVs, biogas calculations made by this author for diesel oil replacement proved viable for energy prices ranging from USD 0.58 / L (85% of the estimated capex) to USD 0.87 / L (125% of the estimated capex) for cases with tax credits. For the simulations that did not consider tax credits, calculations made by this author of biogas for electricity generation proved viable for energy prices ranging from USD0.64 / L (85% of the estimated capex) to USD 0.94/ L (125 % of estimated capex). The greatest difference found between cases with and without tax credits is justified by the higher capex for the use of biogas replacing diesel oil, that is, the greater the investment, the greater the difference that the existence of tax credits will make once that such taxes are based on invested capex.

Considering that the average historical price of diesel oil was USD 0.70 / L (R$ 3,49 / L; R$ 5.00 / USD), NPV would be positive for the cases in which the capex is around 90% of the estimated value without tax credits and around 100% of the estimated value with tax credits, indicating that the project would be economically viable in part of the cases considering of the assumptions adopted.

7.1.3 Natural gas substitutive

To analyze the sustainability of biogas use in natural gas substitution, both environmental and social impacts were converted in economic values to compose the economic analysis. Based on FEL methodology and budgets from supplier companies, capital and operational expenditures were estimated and are presented in Tables 31 and 32.

Table 31: Capital expenditure for natural gas substitutive.

CAPEX	R$/USD 5,00		Source
Anaerobic Treatment - Biodigester BIOPAQ ICX (2 x 5,400m^3)	R$ 19.980.000,00	$ 3.996.000,00	Budget from PAQUES (2019)
Design and Execution of Civil Works	R$ 2.450.000,00	$ 490.000,00	Budget from PAQUES (2019)
Burner (Flare)	R$ 428.120,00	$ 85.624,00	Bernal et al. (2017)
Gasometer (43.7 USD/m^3)	R$ 527.000,00	$ 105.400,00	Bernal et al. (2017)
Compressor (242.8 USD/m^3)	R$ 2.930.000,00	$ 586.000,00	Bernal et al. (2017)
Pipeline (121.4 USD/m) – 380m	R$ 240.000,00	$ 48.000,00	Bernal et al. (2017)
BUP2300 + H_2S Removal system ($H_2S \leq 80$ppm)	R$ 12.245.000,00	$ 2.449.000,00	Budget from ACESA (2020)
Freight equipment Germany and insurance, DDU Porto SP	R$ 766.000,00	$ 153.200,00	Budget from ACESA (2020)
Cold and chilled water system	R$ 250.000,00	$ 50.000,00	Budget from ACESA (2020)
Chromotograph	R$ 250.000,00	$ 50.000,00	Budget from ACESA (2020)
Odorizer	R$ 365.000,00	$ 73.000,00	Budget from ACESA (2020)
Nitrogen for start up	R$ 50.000,00	$ 10.000,00	Budget from ACESA (2020)
Chromatograph helium	R$ 5.000,00	$ 1.000,00	Budget from ACESA (2020)
Detailing engineering	R$ 608.000,00	$ 121.600,00	Budget from ACESA (2020)
Electromechanical assembly BUP	R$ 284.200,00	$ 56.840,00	Budget from ACESA (2020)
Assembly of cooling / chilling and nitrogen system	R$ 171.500,00	$ 34.300,00	Budget from ACESA (2020)
Electrical transformer assembly into the BUP	R$ 232.000,00	$ 46.400,00	Budget from ACESA (2020)
Crane	R$ 27.810,00	$ 5.562,00	Budget from ACESA (2020)
Others*	R$ 4.180.963,00	$ 836.192,60	10% Capex
Connection to a natural gas network (121.4 USD/m) – 50km	R$ 30.350.000,00	$ 6.070.000,00	Bernal et al. (2017)
BIOGAS TO INJECTION INTO NATURAL GAS GRID	**R$ 76.340.593,00**	**$ 15.268.118,60**	

Note: Including taxes and considering required area = 2,000m² (50m x 40m) available (no investment required).

* Others: Civil w ork, electrical supply, gounding, lightning, closing areas (screens, doors and gates), condensate destination and treatment and offgas treatment.

Source: elaborated by the author.

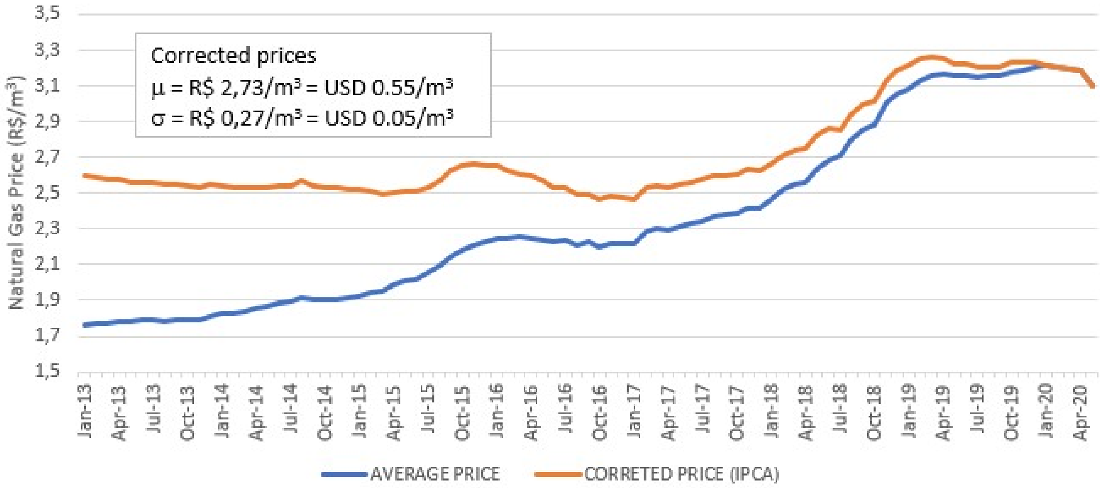
Table 32: Operational expenditure for natural gas substitutive.

OPEX (yearly)	R$/USD 5,00		Source
Electricity consumption - BIOPAQ ICX	R$ 29.203,20	$ 5.840,64	Budget from PAQUES (2019)
NaOH consumption - BIOPAQ ICX	R$ 114.573,53	$ 22.914,71	Budget from PAQUES (2019)
Activated carbon - BUP	R$ 69.900,00	$ 13.980,00	Budget from ACESA (2020)
Operator Biogas Plant (4)	R$ 68.339,38	$ 13.667,88	Budget from PAQUES (2019)
Chemical Analyst (1)	R$ 13.857,71	$ 2.771,54	Budget from PAQUES (2019)
Operation - BUP	R$ 373.800,00	$ 74.760,00	Budget from ACESA (2020)
Labor supply contract (ASPRO)	R$ 48.000,00	$ 9.600,00	Budget from ASPRO (2020)
Maintenance	R$ 1.145.108,90	$ 229.021,78	1,5% Capex
BIOGAS TO ELECTRICITY GENERATION	**R$ 1.862.782,72**	**R$ 372.556,54**	

Source: elaborated by the author.

Based on these estimated values of capex and opex and on the premises presented, economic calculations were done. The results spreadsheets of the biogas use in natural gas substitution with and without tax credits considering 100% of estimated capex and natural gas average price are presented in Appendix E and F, respectively. Corrected average historical price and its standard deviation from January 2013 to May 2020, presented in Figure 38.

Figure 38: Historical average natural gas price of the São Paulo State, Brazil.



Source: Adapted from ANP, 2020.

Not as high as the standard deviation found for the case of electricity generation, the standard deviation of historic natural gas prices still draws attention as it represents 10% of the average price for the period. This fact can be at least partly explained by the fact that Brazil's external dependence on natural gas is relatively high, having reached 43.5% in 2014 (BEN, 2019).

Converting the average price and standard deviation from R$ to USD based on the exchange rate of R$ 5.00 / USD (Banco Central do Brasil, 2020) and considering the natural gas price ranging from minus two standard deviations to plus two standard deviations in one standard deviation interval, the NPV sensibility analysis was made for two different cases: with and without tax credits. The results are presented in Tables 33 and 34. The sensibility analysis was based on capex variation ranging from 85% to 125% (according FEL 2 methodology) at 10% intervals.

Table 33: NPV sensibility analysis with tax credits (natural gas substitutive)

NPV WITH TAX CREDIT	NATURAL GAS PRICE (USD/m³)				
	- 2 σ	- 1σ	μ	+ 1 σ	+ 2 σ
-0	$ 0,45	$ 0,50	$ 0,55	$ 0,60	$ 0,65
% CAPEX 85%	1.666.618	2.910.537	4.154.456	5.398.375	6.642.294
95%	531.696	1.775.615	3.019.534	4.263.453	5.507.372
105%	-603.227	640.693	1.884.612	3.128.531	4.372.450
115%	-1.738.149	-494.230	749.690	1.993.609	3.237.528
125%	-2.873.071	-1.629.152	-385.232	858.687	2.102.606

Source: elaborated by the author.

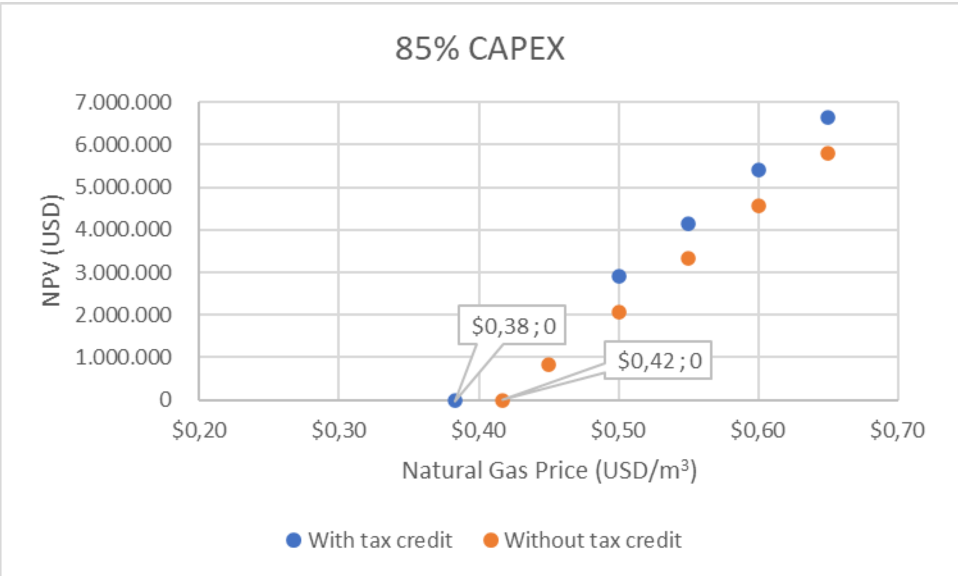
Table 34: NPV sensibility analysis with tax credits (natural gas substitutive)

NPV WITHOUT TAX CREDIT	NATURAL GAS PRICE (USD/m³)				
	- 2 σ	- 1σ	μ	+ 1 σ	+ 2 σ
0	$ 0,45	$ 0,50	$ 0,55	$ 0,60	$ 0,65
% CAPEX 85%	828.708	2.072.627	3.316.546	4.560.465	5.804.384
95%	-404.792	839.127	2.083.046	3.326.965	4.570.884
105%	-1.638.292	-394.373	849.546	2.093.465	3.337.385
115%	-2.871.792	-1.627.872	-383.953	859.966	2.103.885
125%	-4.105.291	-2.861.372	-1.617.453	-373.534	870.385

Source: elaborated by the author.

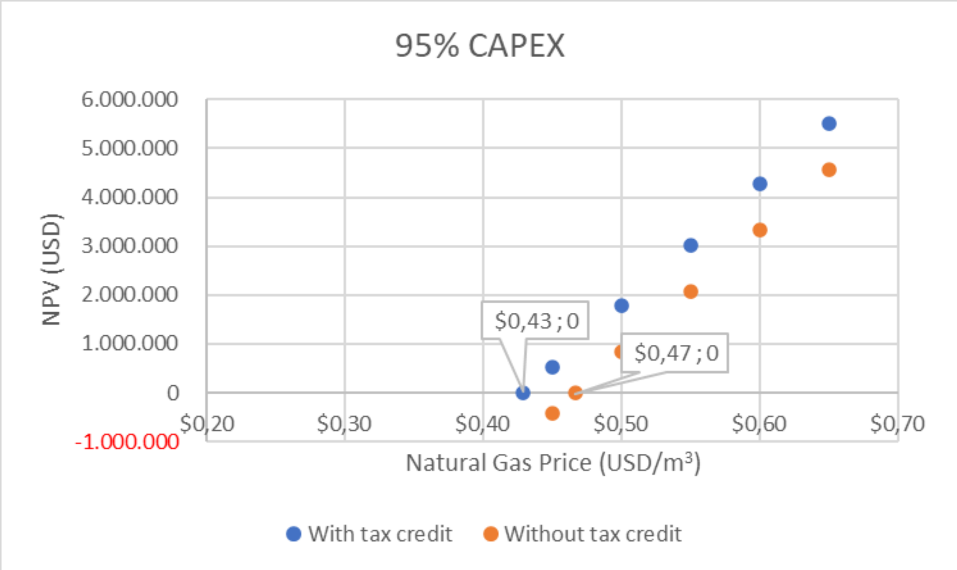
Figures 39 to 43 illustrate the same information adding the break-even point, where the NPV=0.

Figure 39: NPV values for Natural Gas replacement considering 85% capex.



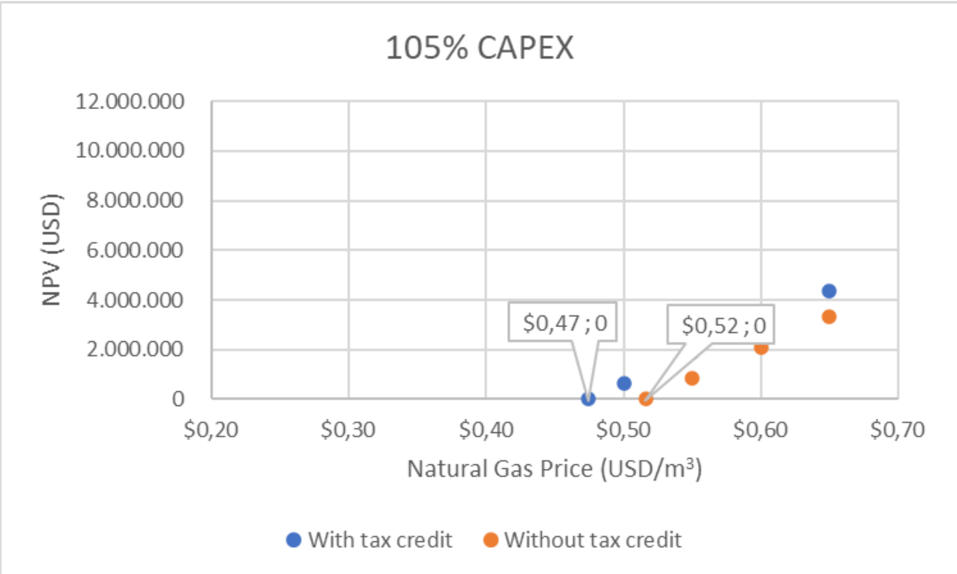
Source: elaborated by the author.

Figure 40: NPV values for Natural Gas replacement considering 95% capex.



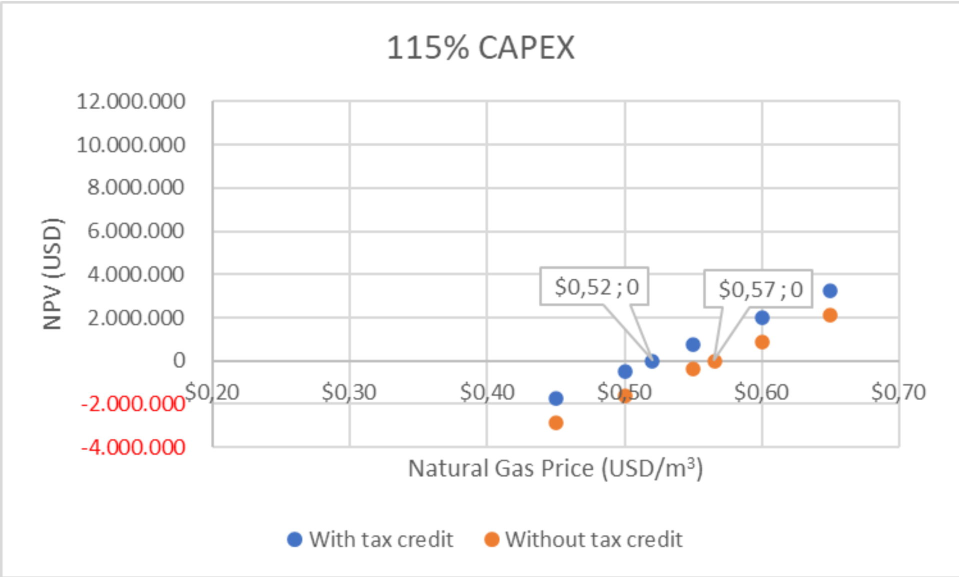
Source: elaborated by the author.

Figure 41: NPV values for Natural Gas replacement considering 105% capex.



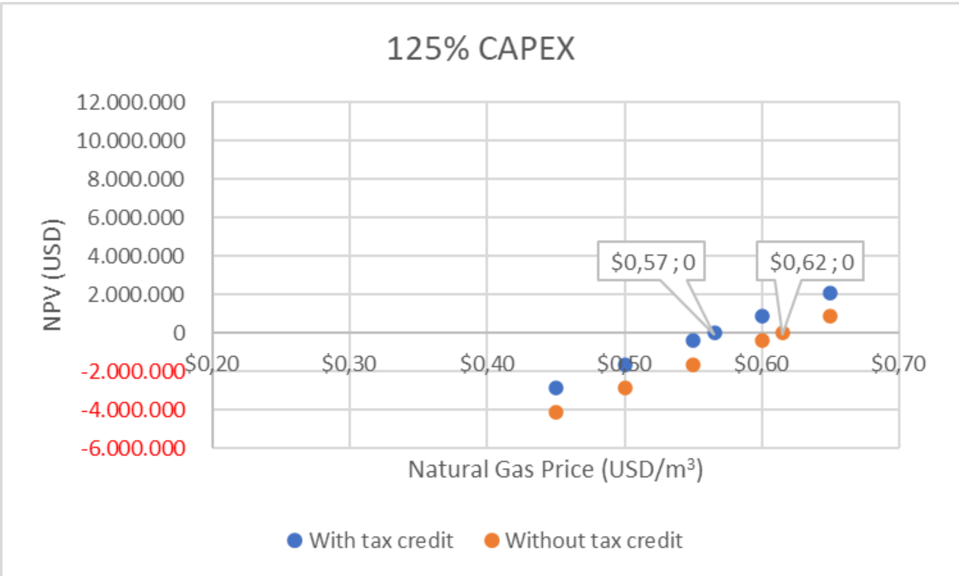
Source: elaborated by the author.

Figure 42: NPV values for Natural Gas replacement considering 115% capex.



Source: elaborated by the author.

Figure 43: NPV values for Natural Gas replacement considering 125% capex.



Source: elaborated by the author.

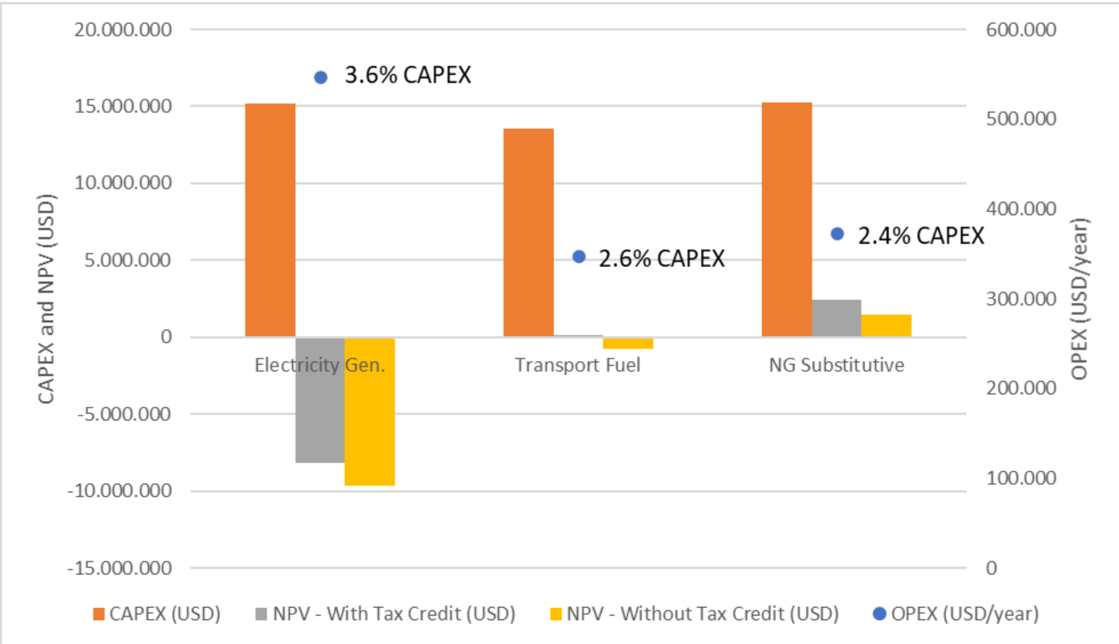
Based on the calculated NPVs, biogas calculations made by this author for injection into natural gas grid proved viable for energy prices ranging from USD 0.38 / m^3 (85% of the estimated capex) to USD 0.57 / m^3 (125% of the estimated capex) for cases with tax credits. For the simulations that did not consider tax credits, calculations made by this author of biogas for electricity generation proved viable for energy prices ranging from USD 0.42 / m^3 (85% of the estimated capex) to USD 0.62 / m^3 (125 % of estimated capex).

Considering that the average historical price of natural gas was USD 0.55 / m^3 (R$ 2,73 / m^3; R$ 5.00 / USD), NPV would be positive for half cases, indicating that the project could be economically viable considering the assumptions adopted.

7.2. Comparison of economic analysis

From a comparative point of view, Figure 44 illustrates the economic results of the three biogas utilizations studied. The orange columns show the 100% of the capital expenditure, the blue dots (whose axis is shown on the right) illustrate the operational expenditure, the grey columns show the NPV with tax credits and the yellows ones the NPV without tax credits.

Figure 44: Comparison of economic analysis.



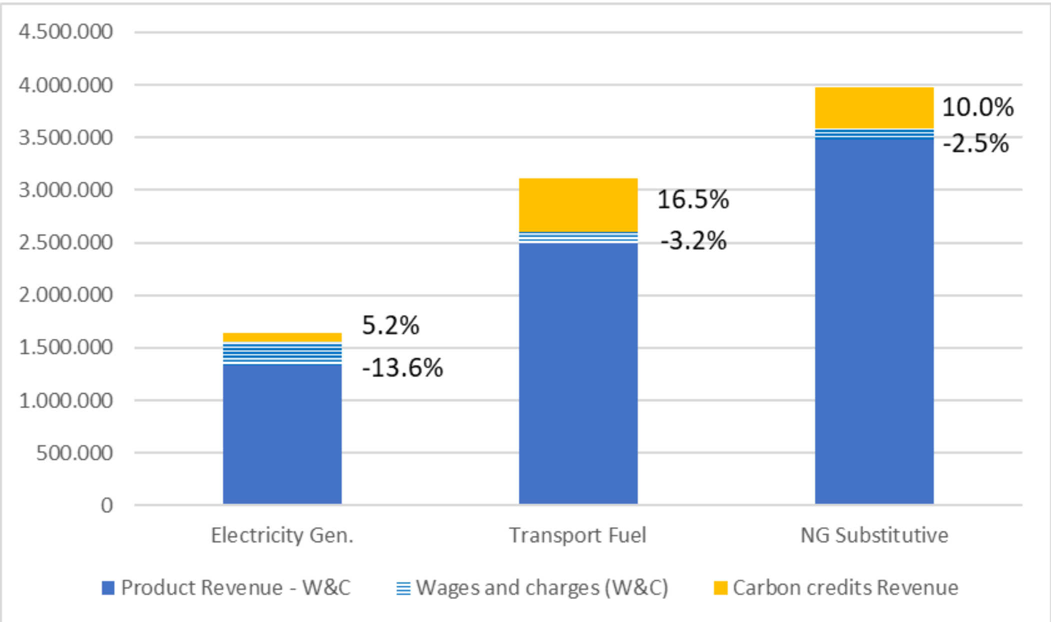
Source: elaborated by the author.

As it is possible to notice the higher is percentage of OPEX based on CAPEX, the lowest is the NPV, as it is expected. Additionally, comparing the biogas utilization in electricity generation and in natural gas substitution, although the CAPEX values are very similar, the results in terms of NPV are very different, indicating that besides the OPEX impact, the product revenue brings positive impact in the second case. In the case of the biogas utilization in transport fuel, it can be said that the impact of tax credits is crucial for the feasibility of this alternative because NPV is slightly positive in the case with tax credits and negative without them.

7.3. Environmental and social analysis

To better understand the environmental and social impacts in the economic results, a comparative analysis was made. Environmental impact was calculated based on the sale of carbon credits and, therefore, it enters as a positive value in the cash flow. In contrast, social impact was calculated based on the wages and charges of the jobs created, entering as a expense value in the cash flow. Figure 45 illustrates the environmental and social impacts in the total revenue for each biogas utilization considering the average price and 100% capex. The blue solid columns represent the product (electricity/diesel oil/natural gas) revenues discounting the wages and charges, represented by the blue and white striped columns. The yellow columns show the carbon credits revenues adding value to the total revenue that is illustrated by the sum of the three columns.

Figure 45: Environmental and social impacts in the total revenue (in USD/year).



Source: elaborated by the author.

Regarding the quantification of environmental impacts in the case of electricity generation, it can be said that the economic point of view does not reflect the expected qualitative benefits, only 5.2% of total revenue is related to the environmental benefits, largely due to the assumptions for converting electric energy into carbon equivalent and for the valorization of such product in the market. The contribution of the application of biogas in the generation of electric energy is shown to be relatively minor because a large part of the electric energy in Brazil is already of renewable origin. Unlike the case where biogas was used for electricity generation, the economic quantification of environmental impacts in the case of transport fuel and natural gas substitution reflects the expected qualitative benefits, corresponding to 16.5% and 10.0% of total revenue, respectively.

Related to the social indicator, job generation, although only nine additional jobs would be created in the case of electricity generation, the operators of the powerhouse have higher salaries which implies in an higher relative impact comparing to the others two biogas utilizations: 13.6% (electricity generation) versus 3.2% (transport fuel) and 2.5% (natural gas substitution). The job creation number of each biogas utilization may not be very relevant locally, but in terms of the potential for job creation in the sector, it may prove to be significant. Considering that about 28.5 million cubic meters of ethanol are produced per year, equivalent to 381.9 million cubic meters of vinasse per year, 3,182 jobs could be created by the cases of electricity generation and natural gas substitution and 4,596 jobs could be created in the of transport fuel by the partial substitution of diesel oil.

7.4. Political and strategic dimensions

Concerning to political analysis and the implications of government subsidies in making projects like this feasible, the results presented here reinforce what was said by Fubara et al. (2017): the use of subsidies to support an energy policy creates an artificial price for a product and may affect the development of a sector in various ways. When subsidies exist and are considered to make projects viable, a heavy dependency is created that can put the operation at risk if such subsidies cease due to policy changes. When subsidies are entirely not considered in the planning phase, the system should be optimized on this basis searching for maximize the combined NPV and GHG savings through innovative technological routes. If successful, any introduction of subsidies during its operation will only further improve its profitability and enhance its economic robustness. It should be emphasized that, the improved economic viability identified by planning without subsidies is at the cost of a significant reduction in the level of biogas/biomethane penetration.

Especially thinking about the social impacts, although job generation, health and life quality tend to increase with these kind of projects, social aspects are expenses in the project bringing negative economic impacts. Policies that offer benefits for projects with positive social aspects can bring an additional incentive to investors.

Subsidy policies can only be guaranteed in the long term, reducing project risks, when governments understand that such subsidies are strategic tools towards a sustainable future. The search for economic, environmental, and social sustainability necessarily passes through the political and strategic spheres in order to materialize. Initiatives such as RenovaBio, the Metano Zero Program and the bill "Incentive Program for the Production and Use of Biogas, Biomethane and Associated Coproducts (PIBB)" may become landmarks for biogas in Brazil.

Figure 46 illustrates the present author's view on how each of the sectors (academic, financial, public, and private) can contribute to the success of projects such as those studied here.

Figure 46: Scheme representing the different sectors and their contributions.

Source: elaborated by the author.

8 CONCLUSIONS

The critical analysis of the utilization of biogas from sugarcane vinasse focusing on electricity production, transport fuel and natural gas substitution based on the results obtained from a specific case allowed to say that the biogas injection into natural gas grid seems to be the better sustainable option among the three studied applications. In addition to the economic result being the only favorable one in the current economic conditions, its environmental and social results are intermediaries to the other two alternatives studied. Considering the other two applications studied, the option of using biogas as a partial replacement for diesel in heavy vehicles is highlighted, since the environmental and social results were the best among the three alternatives and the economic result was close to the breakeven point, that is, in an economic scenario of rising diesel prices, it is possible that this application will be attractive. The option of generating electricity, even in a scenario of rising energy prices, proved to be far from reaching a reversal of negative economic results and proved to be the worst alternative from an environmental and social point of view.

Analyzes have shown results that reinforce the need for a closer look both from the academic community in efforts to increase efficiency and governments through policies to encourage such initiatives, especially in the case of electricity generation. Government incentives can also help to reduce Brazil's external dependence on natural gas and diesel oil. The environmental and social benefits are relevant but marginal and only through incentive policies on the part of governments can be realized and make the search for sustainability a strategic differential for nations. Initiatives such as RenovaBio, the Metano Zero Program and the bill "Incentive Program for the Production and Use of Biogas, Biomethane and Associated Coproducts (PIBB)" may become landmarks for biogas and biomethane in Brazil.

It can be cited as difficulties encountered in conducting this work the adaptation of traditional academic analysis tools in order to be understood and easily replicated by companies that are interested in investing in such projects.

It is believed that although this difficulty has arisen, the present author has been successful in serving both publics: academic and private.

This work deepened and expanded the analyzes conducted so far and offered subsidies to decision makers to make viable and perpetuate the projects in operation and under evaluation. The case study, designed to be close to most ethanol producing units in the State of São Paulo, expanded the potential applicability of the results obtained here.

9 FUTURE STUDIES

As opportunities for future studies, it can be mentioned:

- the application of the LCA (Life Cycle Assessment) method to the projects studied here to broaden the understanding of environmental impacts.
- the application of the S-LCA method (Social Life Cycle Assessment) to the projects studied here to broaden the understanding of social impacts.
- the understanding of the reason why most of the biogas projects in Brazil have been made focusing on the use in electricity generation, since this application proved to be the alternative with the lowest economic return.
- the analysis of the practical consequences of the Brazilian government's initiatives, more specifically the “RenovaBio” and “Metano Zero” programs.

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APPENDIX A

SPREADSHEET OF ELECTRICITY GENERATION WITH TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	
Electricity sale	MWh/year	0	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	
CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		**0**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**21.116.098**
(+) Receipts (sale of electricity)	USD	0	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	23.325.019
(+) Receipts (sale of carbon credits)	USD	0	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	1.289.831
(-) Sales taxes	USD		-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-3.498.753
OUTPUTS (TOTAL COST)	**USD**	**0**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-8.208.464**
(-) OPEX	USD	0	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-8.208.464
TAX CREDITS	**USD**	**0**	**368.188**	**368.188**	**368.188**	**368.188**	**140.443**	**140.443**	**140.443**	**140.443**	**140.443**	**140.443**	**0**	**0**	**0**	**0**	**0**	**2.315.411**
(+) ICMS Credit	USD	0	227.745	227.745	227.745	227.745	0	0	0	0	0	0	0	0	0	0	0	910.981
(+) PIS / COFINS Credit	USD	0	140.443	140.443	140.443	140.443	140.443	140.443	140.443	140.443	140.443	140.443	0	0	0	0	0	1.404.430
GROSS PROFIT	**USD**	**0**	**1.228.697**	**1.228.697**	**1.228.697**	**1.228.697**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**15.223.044**
(-) Depreciation	USD	0	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	0	0	0	0	0	-15.183.024
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	**USD**	**0**	**-289.605**	**-289.605**	**-289.605**	**-289.605**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**40.020**
(-) Income Tax	USD	0	0	0	0	0	0	0	0	0	0	0	-292.573	-292.573	-292.573	-292.573	-292.573	-1.462.865
NET PROFIT	**USD**	**0**	**-289.605**	**-289.605**	**-289.605**	**-289.605**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**-517.351**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**-1.422.845**
(+) Depreciation	USD	0	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	0	0	0	0	0	15.183.024
OPERATING CASH FLOW	**USD**	**0**	**1.228.697**	**1.228.697**	**1.228.697**	**1.228.697**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**13.760.179**
TOTAL NET INVESTMENT	**USD**	**-15.183.024**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-15.183.024**
CAPEX	USD	-15.183.024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-15.183.024
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	**USD**	**-15.183.024**	**1.228.697**	**1.228.697**	**1.228.697**	**1.228.697**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**1.000.952**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**-1.422.845**
ACCUMULATED NET CASH FLOW	**USD**	**-15.183.024**	**-13.954.327**	**-12.725.630**	**-11.496.932**	**-10.268.235**	**-9.267.283**	**-8.266.331**	**-7.265.380**	**-6.264.428**	**-5.263.476**	**-4.262.524**	**-3.694.588**	**-3.126.652**	**-2.558.716**	**-1.990.781**	**-1.422.845**	
VPL (USD)	**-8.176.511**																	
TIR	**-1,40%**																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.

APPENDIX B

SPREADSHEET OF ELECTRICITY GENERATION WITHOUT TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Electricity sale	MWh/year	0	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168	21.168

CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		**0**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**1.407.740**	**21.116.098**
(+) Receipts (sale of electricity)	USD	0	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	1.555.001	23.325.019
(+) Receipts (sale of carbon credits)	USD	0	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	85.989	1.289.831
(-) Sales taxes	USD		-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-233.250	-3.498.753
OUTPUTS (TOTAL COST)	**USD**	**0**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-547.231**	**-8.208.464**
(-) OPEX	USD	0	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-547.231	-8.208.464
TAX CREDITS	**USD**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
(+) ICMS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(+) PIS / COFINS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GROSS PROFIT	**USD**	**0**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**12.907.633**
(-) Depreciation	USD	0	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	-1.518.302	0	0	0	0	0	-15.183.024
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	**USD**	**0**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**-2.275.391**
(-) Income Tax	USD	0	0	0	0	0	0	0	0	0	0	0	-292.573	-292.573	-292.573	-292.573	-292.573	-1.462.865
NET PROFIT	**USD**	**0**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**-657.794**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**-3.738.256**
(+) Depreciation	USD	0	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	1.518.302	0	0	0	0	0	15.183.024
OPERATING CASH FLOW	**USD**	**0**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**11.444.768**
TOTAL NET INVESTMENT	**USD**	**-15.183.024**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-15.183.024**
CAPEX	USD	-15.183.024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-15.183.024
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	**USD**	**-15.183.024**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**860.509**	**567.936**	**567.936**	**567.936**	**567.936**	**567.936**	**-3.738.256**
ACCUMULATED NET CASH FLOW	**USD**	**-15.183.024**	**-14.322.515**	**-13.462.006**	**-12.601.497**	**-11.740.988**	**-10.880.480**	**-10.019.971**	**-9.159.462**	**-8.298.953**	**-7.438.444**	**-6.577.935**	**-6.009.999**	**-5.442.063**	**-4.874.128**	**-4.306.192**	**-3.738.256**	
VPL	**-9.661.787**																	
TIR	**-3,61%**																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.

APPENDIX C

SPREADSHEET OF TRANSPORT FUEL WITH TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	
Biomethane	m^3	0	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	
CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		**0**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**2.607.101**	**39.106.513**
(+) Receipts (sale of electricity)	USD	0	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	38.969.173
(+) Receipts (sale of carbon credits)	USD	0	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	5.982.716
(-) Sales taxes	USD		-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-5.845.376
OUTPUTS (TOTAL COST)	**USD**	**0**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-346.902**	**-5.203.528**
(-) OPEX	USD	0	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-5.203.528
TAX CREDITS	**USD**	**0**	**328.777**	**328.777**	**328.777**	**328.777**	**125.410**	**125.410**	**125.410**	**125.410**	**125.410**	**125.410**	**0**	**0**	**0**	**0**	**0**	**2.067.565**
(+) ICMS Credit	USD	0	203.367	203.367	203.367	203.367	0	0	0	0	0	0	0	0	0	0	0	813.468
(+) PIS / COFINS Credit	USD	0	125.410	125.410	125.410	125.410	125.410	125.410	125.410	125.410	125.410	125.410	0	0	0	0	0	1.254.097
GROSS PROFIT	**USD**	**0**	**2.588.976**	**2.588.976**	**2.588.976**	**2.588.976**	**2.385.609**	**2.385.609**	**2.385.609**	**2.385.609**	**2.385.609**	**2.385.609**	**2.260.199**	**2.260.199**	**2.260.199**	**2.260.199**	**2.260.199**	**35.970.550**
(-) Depreciation	USD	0	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	0	0	0	0	0	-13.557.805
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	**USD**	**0**	**1.233.195**	**1.233.195**	**1.233.195**	**1.233.195**	**1.029.828**	**1.029.828**	**1.029.828**	**1.029.828**	**1.029.828**	**1.029.828**	**2.260.199**	**2.260.199**	**2.260.199**	**2.260.199**	**2.260.199**	**22.412.745**
(-) Income Tax	USD	0	-419.286	-419.286	-419.286	-419.286	-350.142	-350.142	-350.142	-350.142	-350.142	-350.142	-768.468	-768.468	-768.468	-768.468	-768.468	-7.620.333
NET PROFIT	**USD**	**0**	**813.909**	**813.909**	**813.909**	**813.909**	**679.687**	**679.687**	**679.687**	**679.687**	**679.687**	**679.687**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**14.792.412**
(+) Depreciation	USD	0	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	0	0	0	0	0	13.557.805
OPERATING CASH FLOW	**USD**	**0**	**2.169.689**	**2.169.689**	**2.169.689**	**2.169.689**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**28.350.217**
TOTAL NET INVESTMENT	**USD**	**-13.557.805**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-13.557.805**
CAPEX	USD	-13.557.805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-13.557.805
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	**USD**	**-13.557.805**	**2.169.689**	**2.169.689**	**2.169.689**	**2.169.689**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**2.035.467**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**1.491.731**	**14.792.412**
ACCUMULATED NET CASH FLOW	**USD**	**-13.557.805**	**-11.388.116**	**-9.218.426**	**-7.048.737**	**-4.879.048**	**-2.843.581**	**-808.113**	**1.227.354**	**3.262.821**	**5.298.288**	**7.333.755**	**8.825.486**	**10.317.218**	**11.808.949**	**13.300.680**	**14.792.412**	
VPL (USD)	**82.083**																	
TIR	**12,12%**																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.

APPENDIX D

SPREADSHEET OF TRANSPORT FUEL WITHOUT TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	
Biomethane	m^3	0	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	
CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		0	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	2.607.101	39.106.513
(+) Receipts (sale of electricity)	USD	0	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	2.597.945	38.969.173
(+) Receipts (sale of carbon credits)	USD	0	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	5.982.716
(-) Sales taxes	USD		-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-389.692	-5.845.376
OUTPUTS (TOTAL COST)	USD	0	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-5.203.528
(-) OPEX	USD	0	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-346.902	-5.203.528
TAX CREDITS	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(+) ICMS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(+) PIS / COFINS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GROSS PROFIT	USD	0	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	33.902.985
(-) Depreciation	USD	0	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	-1.355.781	0	0	0	0	0	-13.557.805
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	USD	0	904.418	904.418	904.418	904.418	904.418	904.418	904.418	904.418	904.418	904.418	2.260.199	2.260.199	2.260.199	2.260.199	2.260.199	20.345.180
(-) Income Tax	USD	0	-307.502	-307.502	-307.502	-307.502	-307.502	-307.502	-307.502	-307.502	-307.502	-307.502	-768.468	-768.468	-768.468	-768.468	-768.468	-6.917.361
NET PROFIT	USD	0	596.916	596.916	596.916	596.916	596.916	596.916	596.916	596.916	596.916	596.916	1.491.731	1.491.731	1.491.731	1.491.731	1.491.731	13.427.819
(+) Depreciation	USD	0	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	1.355.781	0	0	0	0	0	13.557.805
OPERATING CASH FLOW	USD	0	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.491.731	1.491.731	1.491.731	1.491.731	1.491.731	26.985.624
TOTAL NET INVESTMENT	USD	-13.557.805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-13.557.805
CAPEX	USD	-13.557.805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-13.557.805
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	USD	-13.557.805	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.952.697	1.491.731	1.491.731	1.491.731	1.491.731	1.491.731	13.427.819
ACCUMULATED NET CASH FLOW	USD	-13.557.805	-11.605.108	-9.652.412	-7.699.715	-5.747.018	-3.794.322	-1.841.625	111.072	2.063.769	4.016.465	5.969.162	7.460.893	8.952.625	10.444.356	11.936.087	13.427.819	
VPL	-793.268																	
TIR	10,84%																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.

APPENDIX E

SPREADSHEET OF NATURAL GAS SUBSTITUTIVE WITH TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	
Biomethane	m^3	0	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	
CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		**0**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**51.642.085**
(+) Receipts (sale of electricity)	USD	0	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	53.716.905
(+) Receipts (sale of carbon credits)	USD	0	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	5.982.716
(-) Sales taxes	USD		-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-8.057.536
OUTPUTS (TOTAL COST)	**USD**	**0**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-5.588.348**
(-) OPEX	USD	0	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-5.588.348
TAX CREDITS	**USD**	**0**	**370.252**	**370.252**	**370.252**	**370.252**	**141.230**	**141.230**	**141.230**	**141.230**	**141.230**	**141.230**	**0**	**0**	**0**	**0**	**0**	**2.328.388**
(+) ICMS Credit	USD	0	229.022	229.022	229.022	229.022	0	0	0	0	0	0	0	0	0	0	0	916.087
(+) PIS / COFINS Credit	USD	0	141.230	141.230	141.230	141.230	141.230	141.230	141.230	141.230	141.230	141.230	0	0	0	0	0	1.412.301
GROSS PROFIT	**USD**	**0**	**3.440.501**	**3.440.501**	**3.440.501**	**3.440.501**	**3.211.479**	**3.211.479**	**3.211.479**	**3.211.479**	**3.211.479**	**3.211.479**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**48.382.125**
(-) Depreciation	USD	0	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	0	0	0	0	0	-15.268.119
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	**USD**	**0**	**1.913.689**	**1.913.689**	**1.913.689**	**1.913.689**	**1.684.667**	**1.684.667**	**1.684.667**	**1.684.667**	**1.684.667**	**1.684.667**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**33.114.006**
(-) Income Tax	USD	0	-650.654	-650.654	-650.654	-650.654	-572.787	-572.787	-572.787	-572.787	-572.787	-572.787	-1.043.885	-1.043.885	-1.043.885	-1.043.885	-1.043.885	-11.258.762
NET PROFIT	**USD**	**0**	**1.263.035**	**1.263.035**	**1.263.035**	**1.263.035**	**1.111.880**	**1.111.880**	**1.111.880**	**1.111.880**	**1.111.880**	**1.111.880**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**21.855.244**
(+) Depreciation	USD	0	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	0	0	0	0	0	15.268.119
OPERATING CASH FLOW	**USD**	**0**	**2.789.847**	**2.789.847**	**2.789.847**	**2.789.847**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**37.123.363**
TOTAL NET INVESTMENT	**USD**	**-15.268.119**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-15.268.119**
CAPEX	USD	-15.268.119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-15.268.119
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	**USD**	**-15.268.119**	**2.789.847**	**2.789.847**	**2.789.847**	**2.789.847**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.638.692**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**21.855.244**
ACCUMULATED NET CASH FLOW	**USD**	**-15.268.119**	**-12.478.272**	**-9.688.425**	**-6.898.579**	**-4.108.732**	**-1.470.040**	**1.168.653**	**3.807.345**	**6.446.037**	**9.084.730**	**11.723.422**	**13.749.787**	**15.776.151**	**17.802.515**	**19.828.880**	**21.855.244**	
VPL (USD)	**2.452.073**																	
TIR	**15,12%**																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.

APPENDIX F

SPREADSHEET OF NATURAL GAS SUBSTITUTIVE WITHOUT TAX CREDITS (100% CAPEX AND AVERAGE PRICE)

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Biomethane	m^3	0	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140	6.511.140

CASH FLOW		**Ano 0**	**Ano 1**	**Ano 2**	**Ano 3**	**Ano 4**	**Ano 5**	**Ano 6**	**Ano 7**	**Ano 8**	**Ano 9**	**Ano 10**	**Ano 11**	**Ano 12**	**Ano 13**	**Ano 14**	**Ano 15**	**Total**
ENTRIES (NET RECEIPTS)		**0**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**3.442.806**	**51.642.085**
(+) Receipts (sale of electricity)	USD	0	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	3.581.127	53.716.905
(+) Receipts (sale of carbon credits)	USD	0	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	398.848	5.982.716
(-) Sales taxes	USD		-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-537.169	-8.057.536
OUTPUTS (TOTAL COST)	**USD**	**0**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-372.557**	**-5.588.348**
(-) OPEX	USD	0	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-372.557	-5.588.348
TAX CREDITS	**USD**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
(+) ICMS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(+) PIS / COFINS Credit	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GROSS PROFIT	**USD**	**0**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**46.053.737**
(-) Depreciation	USD	0	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	-1.526.812	0	0	0	0	0	-15.268.119
(-) Financial expenses	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INCOME BEFORE INCOME TAX	**USD**	**0**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**1.543.437**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**3.070.249**	**30.785.618**
(-) Income Tax	USD	0	-524.769	-524.769	-524.769	-524.769	-524.769	-524.769	-524.769	-524.769	-524.769	-524.769	-1.043.885	-1.043.885	-1.043.885	-1.043.885	-1.043.885	-10.467.110
NET PROFIT	**USD**	**0**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**1.018.669**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**20.318.508**
(+) Depreciation	USD	0	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	1.526.812	0	0	0	0	0	15.268.119
OPERATING CASH FLOW	**USD**	**0**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**35.586.627**
TOTAL NET INVESTMENT	**USD**	**-15.268.119**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**-15.268.119**
CAPEX	USD	-15.268.119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-15.268.119
Incoming financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amortization financing	USD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NET CASH FLOW	**USD**	**-15.268.119**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.545.480**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**2.026.364**	**20.318.508**
ACCUMULATED NET CASH FLOW	**USD**	**-15.268.119**	**-12.722.638**	**-10.177.158**	**-7.631.677**	**-5.086.197**	**-2.540.716**	**4.764**	**2.550.245**	**5.095.725**	**7.641.205**	**10.186.686**	**12.213.050**	**14.239.415**	**16.265.779**	**18.292.144**	**20.318.508**	
VPL	**1.466.296**																	
TIR	**13,84%**																	
DEMONSTRAÇÃO PAGAMENTO DE JUROS																		
(+) Liberações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Amortizações	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Dívida acumulada	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(-) Juros sobre o saldo anterior	R$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: elaborated by the author.