University of São Paulo
"Luiz de Queiroz" College of Agriculture

Biogas and biomethane production routes in the sugar-energy sector: economic efficiency and carbon footprint

Flávio Eduardo Fava

Dissertation presented to obtain the degree of Master in Science. Area: Agricultural Systems Engineering

Piracicaba
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Bachelor in Economic Sciences

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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

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1. Vinhaça 2. Mitigação 3. Biocombustível 4. Etanol 5. Subprodutos I. Título

Dedico esta dissertação de Mestrado aos meus pais que foram exemplos de caráter e puderam demonstrar mesmo na simplicidade, o poder de buscar crescimento pessoal e profissional, com respeito ao próximo e a importância do desenvolvimento constante, sempre com conhecimento acompanhado de bom senso e de sabedoria acompanhada de humildade.

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"Aprendi o silêncio com os faladores,
a tolerância com os intolerantes,
a bondade com os maldosos;
e, por estranho que pareça,
sou grato a esses professores."

Gibran, Khalil

SUMMARY

RESUMO 8
ABSTRACT 9
1 INTRODUCTION...11
2 MATERIALS AND METHODS 15
2.1 Potential biogas production from sugar cane vinasse…………………………………….15
2.2 Comparison of scenarios for the biogas routes…………………………………………...16
2.3 Biogas as a decarbonization vector………………………………………………………19
2.4 Behavior of diesel, electricity, natural gas and Cbio prices…………………….……….20
3 RESULTS AND DISCUSSION...25
3.1 Potential for decarbonization and resource use of the routes……………………………..25
3.2 Assessment of the potential for maximizing financial results……………………………26
4 CONCLUSION 31
REFERENCES 33
APPENDIX 37
ANNEXES 39

RESUMO

Rotas de produção do biogás e biometano no setor sucroenergético: eficiência econômica e pegada de carbono

Os esforços para cumprir as metas de mitigação das mudanças climáticas por meio da substituição de combustíveis fósseis por fontes renováveis estão aumentando em todo o mundo. No Brasil, o setor sucroenergético é um dos principais responsáveis pela descarbonização da matriz energética, por meio do etanol e da cogeração de eletricidade. No entanto, novos produtos têm surgido a partir de subprodutos da destilação do etanol, como a vinhaça, que pode ser fonte de biogás e biometano. Este estudo comparou duas rotas de uso do biogás de vinhaça: cogeração de bioeletricidade e produção de biometano, por meio de análises econômicas e de mitigação de gases de efeito estufa (GEE), e desenvolveu um modelo capaz de estimar os ganhos financeiros de seu uso, comercialização, considerando a variação da pegada de carbono. As rotas consideradas foram identificadas para aumentar o lucro antes de juros, impostos, depreciação e amortização (EBITDA) dos produtores de biocombusstíveis com base nos preços projetados e nas despesas operacionais (OPEX). Eles combinaram misturas de bioeletricidade-biometano de forma complementar, levando em consideração a mitigação de carbono de cada rota. O cenário de produção máxima de biometano pode gerar um EBITDA 38% maior do que a geração máxima de bioeletricidade, no primeiro ano. Ainda assim, o desempenho estimado até 2031 seria melhor no cenário de produção máxima de biometano, crescimento de 54% contra 46% da bioeletricidade.

Palavras-chave: Vinhaça, Mitigação, Biocombustível, Etanol, Subprodutos

ABSTRACT

Biogas and biomethane production routes in the sugar-energy sector: economic efficiency and carbon footprint

Efforts to fulfill the goals of mitigating climate change by replacing fossil fuels with renewable sources are increasing worldwide. In Brazil, the sugar-energy sector is one of the main responsible for decarbonizing the energy matrix, thorugh ethanol and cogenerated electricity. However, new products have emerged using by-products of ethanol distillation, such as vinasse, which can be a source for biogas and biomethane. This study compared two routes for using biogas vinasse: bioelectricity cogeneration and biomethane production through economic and greenhouse gas (GHG) mitigation analyses and develop a model able to estimate the financial gains from their use, commercialization, considering the carbon footprint variation. The considered routes were identified to increase the earnings before interest, taxes, depreciation, and amortization (EBITDA) of producers based on projected prices and operational expenses (OPEX). They combined complementarily bioelectricity-biomethane mixes, taking into consideration the carbon mitigation from each route. The scenario with maximum biomethane production can generate an 38% higher EBITDA than the maximum generation of bioelectricity, in the first year. Yet, the estimated performance up to 2031 would be better in the scenario of maximum biomethane production, 54% growth compared to 46% for bioelectricity.

Keywords: Vinasse, Mitigation, Biofuel, Ethanol, Co-products

1. INTRODUCTION

The trend of replacing fossil fuels by biofuels and bioenergy has already become a global reality, achieving hundreds of billions of dollars annually (IEA, 2020). This is due to the reduction in energy dependence; the positive effects on the trade balance combined with the generation of added value as a function of ensuring rural job creation or maintenance; and the industrial production processes, which may generate political and economic incentives for the implementation of biofuel policies and agribusiness (Kaup, 2015).

Increased bioenergy and sustainable biomass production can provide many economic and environmental benefits. Although a bioenergy initiative produces renewable energy, the production process must harmonize with other objectives; such as: reducing emissions and optimizing sustainability indicators is critical to successfully implementing any bioenergy project (Kuo and Dow, 2017).

Sheppard et al. (2011) criticize inducing biofuel production through government policies simply to achieve suggested decarbonization targets. Since they are driven by energy security and the prospects of a future emissions-constrained economy, accelerated by domestic agricultural and innovation policies, as responses to fuel prices and electricity demand.

Regarding the reduction of environmental impacts through the adoption of technologies in industrial processes, there are development techniques that take advantage of existing processes to seek reductions in environmental impacts. For instance, the use of microalgae in biorefineries to generate biofuels (Sing and Dhar, 2019).

Another way is co-gasification, Farzad et al. (2016) explain that through controlled burning in addition to the fossil component, biomass can also be used to expand energy generation without loss of efficiency, however, in any mitigation process, it is necessary to evaluate the costs of adopting this technology.

For biorefineries, there are several strains of microalgae to propitiate processes of extraction and hydrolysis mechanisms, capable of producing liquid and gaseous biofuels. Despite the high implementation costs, they can be mitigated by the opportunity to diversify products of these biorefineries. The plants can use specific microalgae for biofertilizers, bioplastic, and health care products (pharmaceuticals compounds, cosmetics, and functional feeds) with biofuels can help to reduce the cost-associated with microalgal biorefinery, due to production flexibility (Goswami et al., 2022).

Integrated Gasification Combined Cyle plants (IGCC) can also be an alternative to minimize environmental footprints by combining fossil and biomass systems, compared to traditional thermal energy using coal. According to Sofia et al. (2013) with co-gasification it is possible to obtain, for example, H_2 (hydrogen), N_2 (nitrogen), NH_3 (ammonia), using the purpose of producing biofuels, mainly H_2, which will have a mitigation cost proportional to the raw material of low cost as waste and biomass types, a process that using up to 20% of biomass represents of 14 EUR Mg^{-1} of avoided CO_2-eq.

Considering 11 different sources of bioenergy, Garcia et al. (2015) evaluated traditional systems, accounting their GHG reduction. The cost of avoided CO_2-eq was based on expenses (investment costs, operation and maintenance, inputs and services consumed) from revenues (obtained from energy sales), being the greatest mitigation potential the sugarcane ethanol, which carries a cost of 6.5 USD (Mg CO_2-eq) $^{-1}$, in which, even without considering biogas, it proved to be the most economically efficient mitigation alternative..

Within the context of decarbonization, there are the so-called carbon credits, for which, in a global context, one carbon credit is equivalent to 1 Mg of avoided CO_2-eq. According to Moreira et al. (2016), the fair price of credit would be around US$ 10 . This credit is traded as an asset on the Brazilian market under CBios since 2020. CBio is an instrument to achieve the goals of the biofuels national policy to reduce GHG, known as Renovabio was established in 2017 (MME, 2017). The sugar-energy sector is the primary beneficiary, as it reaches all biofuel producers based on the emissions avoided by replacing fossil fuels. So far it only considers ethanol, excluding cogenerated electricity.

Biogas and biomethane[1] production from vinasse, as bioelectricity source and fuel replacement, respectively, is gaining more importance in projects for new investments in the sugar-energy sector. Besides already having several plants attached to the 1G (first generation in which ethanol is produced from the sacarosis from sugarcane juice) distillery in operation.

A way to expand the products in the chain that are susceptible to the biodigestion process is to consider 2G (second generation in which ethanol produced from a plant fiber called cellulose) biorefineries. According to Stichnothe et al. (2016) and De Bari et al. (2020), the thermochemical and biochemical conversions of lignocellulosic biomass are promising technologies for the production of biofuels and biobased chemicals.

Lignocellulosic biomass in biodigestion process is not completely utilized,, because most anaerobes are unable to degrade lignin, however, the carbohydrate content of plant cell walls is generally useful for microbial consortia in the process, also originating biogas ex-vinasse Stichnothe et al. (2016).

[1] Details of biogas and biomethane components, and their effects, are described in Annex A.

Wikandari et al. (2019) reported that is possible make the digestion of lignocellulosic biomass more effective, with a pretreatment process to overcome the biodegradability of lignocellulose, which can be physical, chemical, thermal, and biological means. Since the cellulose, hemicellulose, and lignin which are a recalcitrant material and difficult to digest to produce biogas.

In the entire process after obtaining biogas, whether through combustion to generate bioelectricity or through purification to turn it into biomethane, the CO_2 component is rejected and released into the atmosphere, not being reused, which can currently be solved with Biofuel Carbon Capture Systems (BECCS[2]).

According to Li et al. (2017), BECCS are responsible for reducing the carbon footprint in conventional or developing industrial processes. In the future, it may allow the product or by-product obtained from a succession of steps in the industry to emit less GHG, since they may come to rely on routes that will do this capture, through physicochemical processes. With the expansion and diffusion of the technology for obtaining vinasse biogas, there is a demand to analyze the carbon footprint from a combined production, and not just each isolated route. It can provide the generation of carbon credits that can directly influence the economic model based on the use and sale of products, expanded in future scenarios.

Based on an existing 1G plant this study aimed at comparing either economically and through the GHG mitigation, two routes of use of biogas from vinasse: bioelectricity and biomethane production.

[2] Scope of Bioenergy with Carbon Capture and Storage in Annex B.

2. MATERIALS AND METHODS

2.1 Potential biogas production from sugar cane vinasse

Sugarcane provides a wide variety of products to be obtained from it, whose porportions from 1 Mg of harvested sugarcane can be observed on Figure 1.

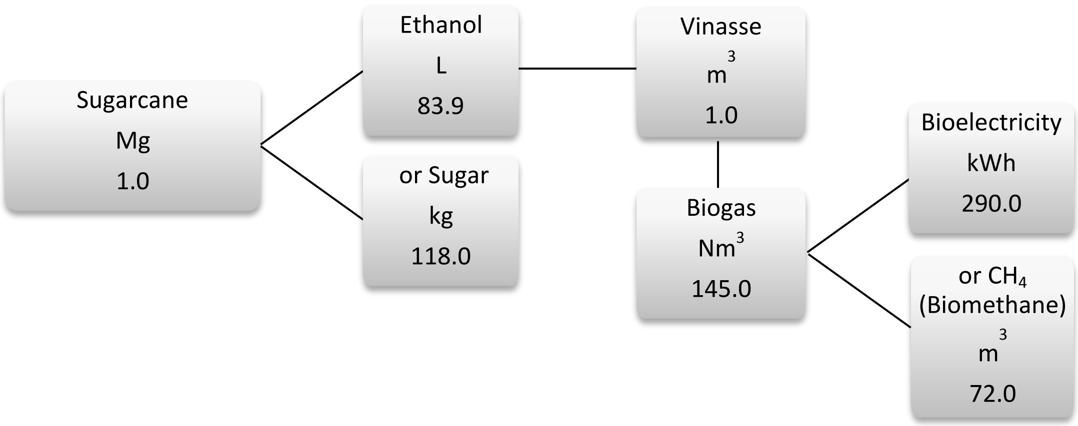

Figure 1 – Maximum product generation in Mg of processed sugarcane

The potential production of the sugar-energy plant is based on Milão et al. (2019), regarding a plant with a capacity of 4 Gigagram (Gg) annually, operating 270 days per year, processing 500 Mg h^{-1}, resulting in an ethanol productivity of 30 m^3 h^{-1}, 360 m^3 h^{-1} of vinasse, and 15 Mg h^{-1} of filter cake. For ethanol production, 19.86 Mg CO_2 h^{-1} is emited by these industrial processes. Concerning electricity consumption, this plant consumes 9.9 GWh to process 500 Mg of sugarcane. However, its electrcitity cogeneration can produce 151.7 GWh – being 141.8 GWh surplus, available for commercialization (Milão et al., 2019).

For this study, it was considered a 1G plant, with total milling of 5 Gg yr^{-1}, a generated vinasse of $2.5*10^6$ m^3, and considering a maximum production capacity of 152 GWh or $36*10^6$ m^3 of biomethane each year, which may vary according to each biogas route destination scenario. Diesel consumption is 11,715 m^3 (average 2.2 L Mg^{-1} of harvested cane). It has consumption distributed in 395 units of equipment.

The annual operation period is 270 days for ethanol production. Additionally, the biogas plant operates 24 h day^{-1} and 360 days yr^{-1}, being able to store the inputs to use in the off-season. It requires 15 employees, being five per shift.

This research was based on the economic and environmental analysis of existing processes in a production unit in São Paulo state, located at the coordinates -22.530022, -51.503793, at an altitude of 419 meters, with average temperatures between 24^{o}C and 26^{o}C, and average annual rainfall of 1,200 milimeters.

The data were obtained directly from industrial and agricultural engineering sectors, according to the actual production and the amounts to be used for biomethane and bioelectricity productions.

Regarding expenses and operational expenditures (OPEX) linked to all the biogas equipments, a survey of all production stages for both routes, from the entry of vinasse into the system to the power and compression station.

The OPEX calculation consists of the sum of all operating expenses, such as maintenance and payroll, over a specified period, which in this study represents 30% of all revenues generated in operation.

The operation OPEX datum were validated with a main company that developed and dealt with biogas and biomethane production for use in the sugar energy-sector, which, has its management system to monitor operating costs during the process. Considering that the whole plant imposes these costs regardless the route, it is essential to analyze which production variation mitigates more efficiently, maximizing the carbon emission reduction potential, and which links a higher revenue from the credits.

2.2 Comparison of scenarios for the biogas routes

Price variations of electricity and natural gas are considered for the plant income. For the economic analysis, a calculation of revenue per biogas volume is used (Equation 1).

$$\$inc = \frac{\$_{el} + \$_{CH4} + \$_{cred}}{v_{biogas}} \tag{1}$$

In which:

$\$inc$ is the total plant income (BRL), $\$_{el}$ is the revenue from the sale of electricity from burning biogas (BRL), $\$_{CH4}$ is the revenue from the sale of biomethane (BRL), $\$_{cred}$ is the revenue from the sale of carbon credits (BRL), and v_{biogas} in which this case the biogas volume produced is $72 * 10^6$ Nm^3.

It is noteworthy that the OPEX will also be considered for comparison between the two routes and it will be composed in the margins. The revenue for both routes will come from the Sale of bioelectricity, biomethane, and carbon credit financial assets, such as CBio, with the analysis based on the current utilization limitation of the plants varying from a minimum of 0% to 100% for each route with adjustments of 1% up to the limits established by the study and involving all the variations of the biogas-biomethane mix, for discussion the results will be used with each variation of 5% from the valve combination of 25% to 75% for each route.

As a means of comparison, all indicators were also calculated for exclusive structures for biomethane and bioelectricity, 100% and 0%, in which case one excludes the other.

Based on the existence of both structures, for biomethane and bioelectricity, in the biogas plant, they must be in operation, the variation starts from the minimum utilization of 25% indicated by the producers as the threshold for each route sufficient to repay it, surpassing the breakeven concerning OPEX and generating a margin capable of protecting the industry against biofuel and electricity price variations. In this way, the maximum production is limited to to a valve variation of 75%, and there is no production above this level either for economic or environmental analyzes

In order to test the economic robustness of the two routes, the Neural Prophet algorithm (Triebe et al., 2021) contributed to estimating the price behavior for the next ten years considering inflation, which will influence the performance of the biogas routes for the same period.

Annually, the National Agency of Petroleum, Natural Gas, and Biofuels of Brazil (ANP, 2021a) provides conversion factors, densities, and lower calorific values (LCV) based on the average values obtained in the previous year. In this case, the conversion table used was the one available in 2020, based on 2019 data, where the conversion ratio of Liters of Diesel for m^3 Natural Gas Vehicles (NGV), or in the case of Biomethane, is 1:1.08, a direct replacement of 2,000 L of diesel, the equivalent is 2,160 m^3, for example. The viability of fuel replacement (VFR) is represented by the difference between the diesel cost and the non-commercialization biomethane for use in the fleet. It is as if the producing unit was acquiring its biomethane. According to Goldemberg et al. (2014), this consumption is 2.5 L Mg^{-1} harvested until milling, considering all the logistics between tractors, harvesters, and trucks, which will be replicated in m^3 of biomethane involving the same steps, and which is represented in Equation 2.

$$VFR_{MgC} = \frac{\$.D_{MgC}^{l}}{\beta_{m3}^{l}} - \$.Bm_{MgC}^{m3} \quad (2)$$

In which:

VFR_{MgC} – Agricultural yeld per megagram of processed cane (BRL Mg^{-1})

$\$.D_{MgC}^{l}$ – Diesel cost based on consumption by harvested cane (BRL Mg^{-1})

$\$.Bm_{MgC}^{m3}$ – Biomethane avoided revenue based consumption as diesel replacement consumption by harvested cane (BRL Mg^{-1})

β_{m3}^{l} – Conversion factor of liters of diesel into m^3 of biomethane (1.08)

The research considered a 10-year price variation for both fuels, in which the diesel costs that are no longer incurred generate a revenue effect for the production unit. Still, at the same time, there is an opportunity cost related to the biomethane used in the fleet that is no longer sold.

In a scenario where the whole plant produces biogas bioelectricity, there is no possibility of additional revenue in CBios, and all the energy generated will be sold on the market, considering in this case that the conventional cogeneration has already met its demand and there is no need for a surplus from biogas.

Equation 3 deals with the mix between biomethane and bioelectricity, considering, in this case, a complete system of cleaning and purifying the biogas, as well as using part to bioelectricity generation through generators. In this scenario, the proportion of biomethane and bioelectricity, in economic terms, is used to estimate how much route generates of Earnings Before Interest, Taxes, Depreciation and Amortization (EBITDA), a combination of results deducting the OPEX, represented by the model BiGMX, where "G" refers to biogas destined for electricity and "M" to biomethane, the "X" is the percentage for each of the routes.

$$BiGMX = \sum_{t=1}^{n=10} \{ \left(VFR_{MgC}\ X\ MgC_{t}^{Total} \right) + (\$Bm^{VT} + \ \$Be^{VT} + \$Cb^{VT})_{t} \} - (\$Cp_{di+in}^{Bm+be})_{t} \quad (3)$$

In which:

$BiGMX$ – Total operation EBITDA per route (BRL)

MgC_{t}^{Total} – Total cane processed (Mg);

$\$Bm^{VT}$ – Total value of biomethane commercialization (BRL);

$\$Be^{VT}$ – Total value of bioelectricity commercialization (BRL);

$\$Cb^{VT}$ – Total value of carbono credit commercialization (BRL);

$\$Cp_{di+in}^{Bm+be}$ – Direct and indirect costs of bioelectricity and biomethane production (BRL).

The scenario results in the composition of a complete biogas plant, which can take advantage of it and maximize the results according to its route, taking advantage of good moments electricity prices and high natural gas prices. This model may contain the impacts of rising diesel prices since its renewable substitute is used in its fleet. It is worth mentioning that by having biofuel generation, the plant is qualified to trade biomethane carbon credits.

Within this context, the impact of the behavior of fuel prices in recent years and the current and future levels provided the basis for the formulation of a model capable of evaluating the viability of production and using biogas in the own fleet, the opportunity cost as a substitute fuel based on the price of diesel at resale, and how much savings this generates, in addition to the revenue if it is sold, either in the form of biomethane or in the form of electricity through burning.

2.3 Biogas as a decarbonization vector

Electricity is the form of energy that most demands a response to environmental and emissions issues, especially in the global context since natural gas and petroleum derivatives mainly generate it, and coal-fired power plants (Ghasemian et al., 2020). Concerning fuels, diesel oil represents, on average, 63% of energy consumption and 31% of total GHG emissions from the sugarcane ethanol production chain used in Brazil (Silva, 2009). According to the Brazilian energy balance (EPE, 2021), diesel consumption in the transport sector represents 44% of all other fuels used.

To determine the mitigations, the concept of Energy-Environmental Efficiency Score (EEES), used by MME (2011) to recognize the differences in carbon intensity in equivalent fuels, and demonstrates the emission of CO2eq MJ^{-1} of biogas which is 25.0 $gCO_2eq\ MJ^{-1}$ (Luca et al., 2018) and biomethane 4.4 $gCO_2eq\ MJ^{-1}$ (MME, 2017) and its main fossil equivalents, being for the first one, the thermoelectric plants with 148.4 $gCO_2eq\ MJ^{-1}$ (Miranda, 2012), generating 123.4 $gCO_2eq\ MJ^{-1}$, and for the second one, the diesel oil which has a carbon intensity of 86.6 $gCO_2eq\ MJ^{-1}$ (Sheehan et al., 1998), generating 123.4 $gCO_2eq\ MJ^{-1}$ of EEES by renewable bioelectricity and 82.2 $gCO_2eq\ MJ^{-1}$ for biomethane.

Based on data from the Energy Cogeneration Industry Association (COGEN, 2015), even without considering a BECCS, the combination of 1st Generation (1G) ethanol with the biodigestion of waste and diesel substitution at the industry can classify biofuel as “zero emissions,” precisely because it reduces the carbon footprint, reducing all GHG emissions from sugarcane ethanol by 95%.

According to Souza et al. (2013), when it comes to local and regional development, the production of biofuels close to the place of consumption offers several advantages, such as reduced marketing costs, transport, and storage, another point of consideration are the environmental benefits of biofuels compared to fossil substitutes, such as reduction of gas emissions, soot, and smoke.

2.4 Behavior of diesel, electricity, natural gas and CBio prices

To evaluate the price behavior of the fossil fuel used by the industry, the S10 Diesel type was considered, the price was based in the last ten years based at the ANP (2021b) data, which calculates an average of 17,702 gas stations/year, which were able to provide an average price in the period of 3.21 BRL L^{-1} in the period, considering the resale price, which is the closest to what the plants have as cost per liter, since they make purchases in large quantities, both for the agricultural fleet and for the heavy-duty fleet.

Between 2012 and 2021, the fuel had a constant increase of 107%, reaching a peak of 4.63 BRL L^{-1} in 2021, the only year of decline was in 2020, where it fell about 4.5% compared to previous year, but the following year the price had a correction of 32%, reaching the highest level of the series.

Electricity is a product of the biorefinery that has become an important strategic ally in sustaining the margins and performance of the sugar-energy sector units; however, at the same time that this product has this relevance, its generation in most companies occurs for self-consumption, highlighting those that have cogeneration to sell the surplus directly on the power grid.

The commercialization occurs with pricing in a few ways, through energy auctions mediated by the National Agency for Electrical Energy (ANEEL), between suppliers and distributors with the winner committing to supply all the agreed energy at a previously agreed price for a certain period of time, usually long-term contracts, and there is also the trading in the free energy market, between supplier and distributor, without the presence of the regulatory agency.

The electricity spot market price from 2012 to 2021, Figure 2, was used as a reference for remuneration to the power plants, since most of the contracts signed by them with distributors, respect this model, with pricing based on the Electric Energy Trading Chamber (CCEE).

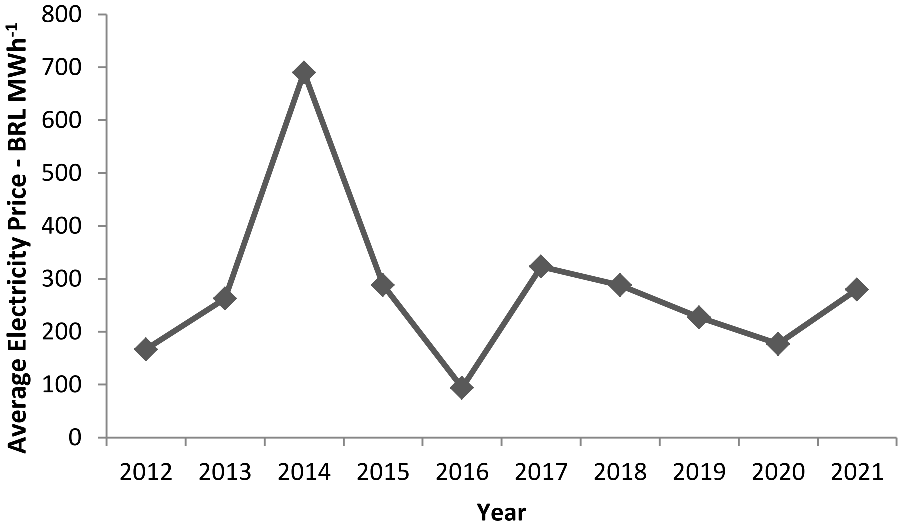

Figure 2 - Average electricity price in the spot market. Adapted from CCEE (2022)

Energy prices peaked soon after in the third year of the series, reaching 689.98 BRL MWh^{-1} in 2014, up 163% compared to 2013, within a scenario of water scarcity in important energy-demanding regions, such as Sao Paulo, which is why thermoelectric plants had to be put into operation to supply the demand, together with an election year scenario linked to public policies of not transfer prices to final consumers, such tax adjustments in subsequent years were intense even with reservoirs recovered that contributed to the price of MWh reach its lowest level in 2016.

The years after 2016, registered price maintenance kept prices closer to the series average of 279.58 BRL MWh^{-1}, and based on 2021, prices are at a cumulative high of 59% to that found in 2012, the beginning of the ten-year series.

Regarding the pricing of natural gas by volume, Figure 3 shows the variation as a function of price from 2012 to 2021. The series considers the discount in pricing through the LCV of biomethane in relation to its fossil equivalent, natural gas, for the New Gas Market, with prices provided by MME (2022).

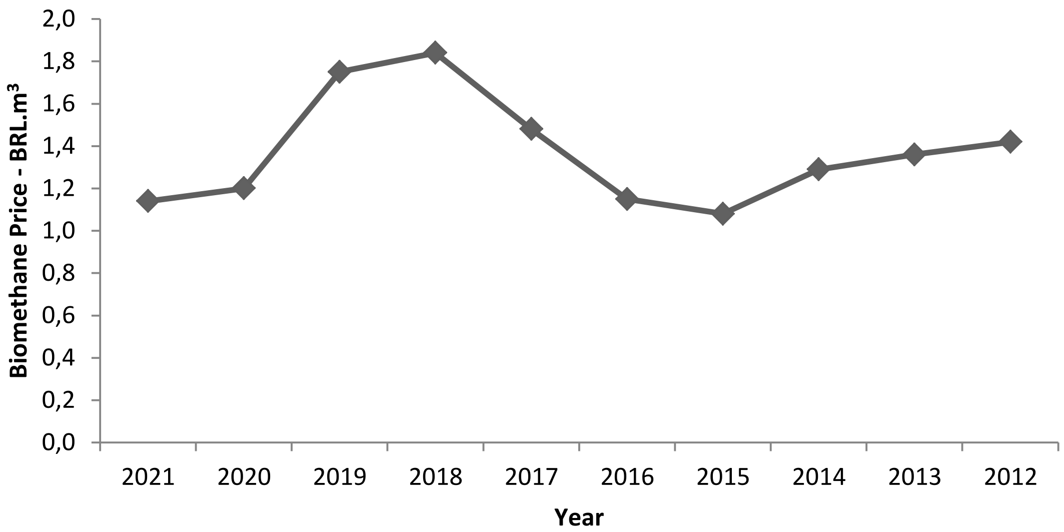

Figure 3 - Suggested pricing based on the biomethane LCV relative to natural gas

The LCV forces the distributor, which according to EPE (2019), is responsible for 17% of the price composition to the final consumer, to purchase more biomethane to supply the entire demand of the gas chain, the difference in the LCV was based on the Brazilian Standard (NBR) 15213, provided by the Brazilian Association of Technical Standards (ABNT, 2008), where the biofuel has an LCV of 35.8 GJ m^{-3}, while natural gas has 39.5 GJ m^{-3}, the difference about 10%, was applied to prices, bringing a better analysis for the injection of biomethane in the gas grid and its remuneration.

The financial asset linked to decarbonization, the CBio, the main Brazilian instrument for reaching the carbon dioxide emission reduction targets, with its negotiation history in Figure 4, since the beginning of transactions on the B3 - The Brazilian Stock Exchange.

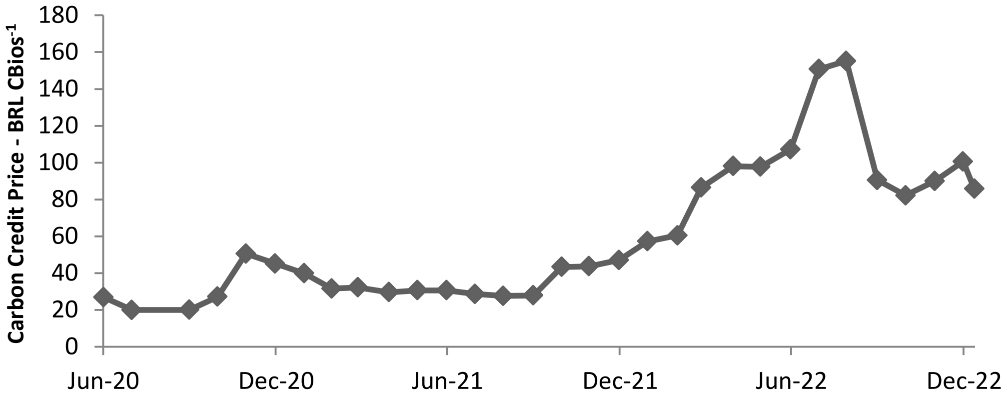

Figure 4 – Price of carbon credits in the Brazilian market since the beginning of negotiations

The carbon credits currently have high price volatility due to issues involving the review of the target set in 2022, as well as the relaxation of the obligation of fossil fuel distributors. The asset reached the maximum traded price of 209.50 BRL, a difference of 781% since the beginning of negotiations. To aggregate the possible financial volumes of transactions involving carbon credits in obtaining the research results, the average of the period of 60.12 BRL was considered, close to the value pointed out by Moreira et al. (2016).

3. RESULTS AND DISCUSSION

3.1 Potential for decarbonization and resource use of the routes

According to UNICA (2022), considering that each m^3 of biomethane has 36.2 MJ and attenuates 2.97 kg of CO_2, for each 337 m^3, there will be one Mg ton of CO_2 avoided, if all the biogas production were turned to biomethane, it would prevent 106,824 Mg of CO_2.

In bioelectricity generation, each Nm^3 of biogas, according to Andriani et al. (2015), has 20 MJ and attenuates 2.47 kg of CO_2. To mitigate one Mg CO_2, 405 Nm^3 of biogas are required, each generation of 0.8 MWh. It is possible to avoid 1 Mg CO_2-eq and reach 177,777 Mg if production is dedicated entirely to this purpose.

To evaluate the decarbonization potential within the scenarios, these indicators will be distributed according to each volume of biogas and biomethane routes, as follows in Table 1.

Table 1 – CO_2 mitigation potential by biogas routes

Route Composition		**Mitigation**
Electr.	**CH4**	**Gg CO_2-eq**
25%	75%	124.6
30%	70%	128.1
35%	65%	131.6
40%	60%	135.2
45%	55%	138.8
50%	50%	142.3
55%	45%	145.8
60%	40%	149.4
65%	35%	152.9
70%	30%	156.5
75%	25%	160.0

The variations of the biogas-biomethane mix, indicated the CO_2 mitigation of all possible valve combinations, ranging from 25% bioelectricity and 75% biomethane to 25% biomethane and 75% bioelectricity, already based on the carbon intensity of each combination. For the CO_2 mitigation was possible to observe that the more the electric energy production increases in the system, and consequently the biomethane production is reduced, the amount of CO_2 avoided increases from 124.6 Gg to 160.0 Gg, an increase of 28.5%, demonstrating a better potential contribution to GHG reduction.

In biorefineries that use only the biomethane structure, the maximum mitigation obtained is 106.9 Gg CO_2-eq, while those that use all the biogas for bioelectricity can mitigate

177.7 Gg CO_2-eq, with an average mitigation cost based on 2022 prices of 156.6 BRL/MgCO_2-eq.

3.2 Assessment of the potential for maximizing financial results

Based on the series of diesel prices, energy, biomethane, and carbon credit, represented by CBios, projections were made for the next ten years to demonstrate scenarios that provide constancy in behavior. Not only specific moments of attractiveness, points that must be considered in particular decision-making may also involve decisions about future routes investments.

The current performance and the future projections provide indicators that can guide decision-making that, according to each moment, can make more sense in the face of uncertain scenarios that involve conjuncture and also future objectives of the biorefinery or biogas production unit itself.

Checking how much each product unit represents in biogas plant revenue is fundamental for an initial analysis of the product in which time, labor, and other costs directly or indirectly related to the activity are being spent. Table 2 shows how much biogas production adds value per m^3 in each route over ten years.

Table 2 – Aggregate revenue in biogas

Route Composition		**Revenue**									
Electr.	**CH_4**	**BRL m^{-3} – Year**									
		2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
0%	100%	1.25	1.36	1.46	1.69	1.80	1.90	2.01	2.24	2.34	2.45
25%	75%	1.14	1.22	1.30	1.57	1.65	1.73	1.81	2.08	2.16	2.25
30%	70%	1.11	1.19	1.27	1.55	1.62	1.70	1.77	2.05	2.13	2.21
35%	65%	1.09	1.16	1.23	1.52	1.59	1.66	1.73	2.02	2.09	2.16
40%	60%	1.07	1.13	1.20	1.50	1.56	1.63	1.70	1.99	2.06	2.12
45%	55%	1.04	1.11	1.17	1.47	1.53	1.60	1.66	1.96	2.02	2.08
50%	50%	1.02	1.08	1.13	1.45	1.50	1.50	1.50	1.93	1.99	2.04
55%	45%	1.00	1.05	1.10	1.42	1.48	1.48	1.48	1.90	1.95	2.00
60%	40%	0.98	1.02	1.07	1.40	1.45	1.45	1.45	1.87	1.92	1.96
65%	35%	0.95	0.99	1.04	1.37	1.42	1.42	1.42	1.84	1.88	1.92
70%	30%	0.93	0.97	1.00	1.35	1.39	1.39	1.39	1.81	1.85	1.88
75%	25%	0.91	0.94	0.97	1.33	1.36	1.36	1.36	1.78	1.81	1.84
100%[3]	0%	1.13	1.12	1.11	1.46	1.45	1.44	1.42	1.77	1.76	1.75

[3] In a scenario with exclusive electricity production, 152 GWh is reached, and the carbon intensity is higher (+66.4%) compared to biomethane. When considering this difference, the carbon credit effect on revenue is increased.

The remuneration obtained for each m^3 used, it is possible to assess that the biomethane operation has a greater capacity to add value, reaching a 97% increase throughout the evaluated period, independent of the biogas route. Still, it is worth mentioning that the 25/75 valve position is the one that maximizes these results, already not considering possible carbon credit results from electric energy, since the CBios are generated only to the biofuels that substitute diesel, in this case, CH_4, considering an amount 106,824 carbon credits.

In scenarios with exclusive production, the highest remuneration occurs in production focused on biomethane, starting a series with a 10% advantage over the m^3 of biogas destined for bioelectricity, and reaching 28% in 2031.

If it were possible to add carbon credits in the same existing structure of CBio, in the generation of electric energy by biogas, an amount 177,777 carbon credits could be created annually, there would be a potential to add value in each production route over the ten years, with the capacity to add value to the m^3 above 4% in the first three years, considering the valve in the position of 75% of the biogas used for electric energy, with this potential reducing over the series but still reaching a level close to 2.35% in the last year analyzed.

The VFR of the operation also becomes a reference in decision-making, especially involving biomethane, a direct diesel substitute, in agricultural and logistical operations until the sugarcane destination at the distillery. In Figure 5, it is possible to verify the impact of the prices of both diesel and biomethane in the processes of substitution by biofuels per megagram of harvested sugarcane.

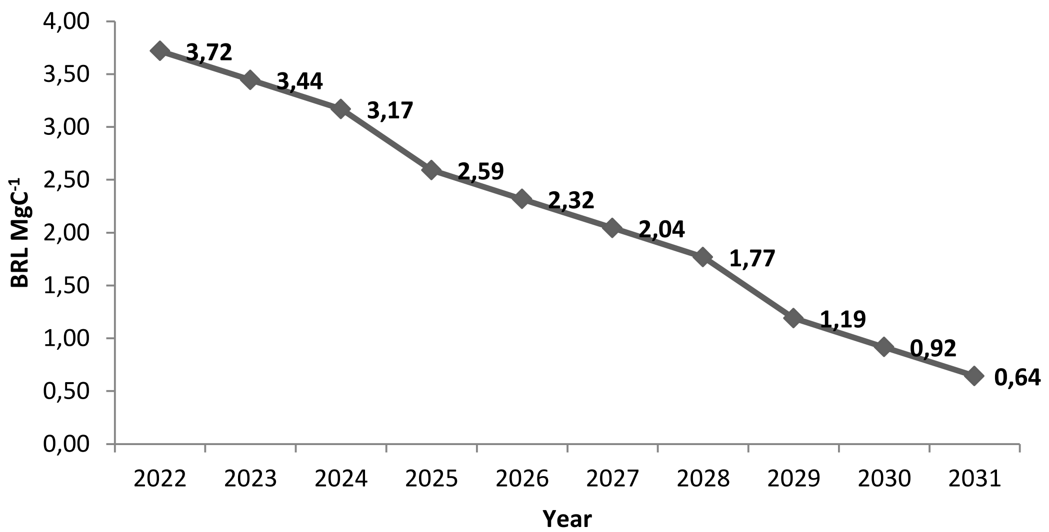

Figure 5 – Aggregate revenue for each megagram using biomethane

There is an 83% decrease in the VFR by the end of the ten years. This decrease has, as factors, the maintenance of diesel prices throughout the series and the appreciation of biomethane in the same period, which may demonstrate a trend to fossil fuel consumption to its direct substitute. Analyzing only the substitution from the perspective VFR, it may become negative at some point. For decision-making, it is better to sell biomethane than to use it in the fleet.

The OPEX composes the complete scenarios to calculate the EBITDA and the study allowed, with an equivalence of 30% on revenue, to determine the distribution of these costs throughout the biogas process, proportionally to the investment in each project stage in the same production conditions as the industry analyzed according Table 3.

Table 3 - Structure for complete biogas plant[4]

Structure for complete biogas plant	Qty.	Total OPEX.year^{-1}
		%
Buffer Lagoon	2	7.75
Horizontal Biodigester	4	8.85
Filter Cake Silos	4	6.64
Vertical Biodigester	2	22.12
Desulfurization Plant	1	25.44
Purification Plant	1	6.64
Gasometer	1	4.42
Flare	1	2.13
Generators	4	5.53
Compression Station	1	5.97
Power Station	1	4.42

In the financial performance scenario the valve variations, combined with the Neural Prophet price projection algorithm, a scenario involving all the variables in the model is obtained, including revenues, VFR, and production expenditure.

The biogas was allocated proportionally to the routes over time, as demonstrated in Table 4. A maximum financial result can be obtained in each one and thus influencing the most appropriate choices according to the decision-makers strategies.

[4] In order to obtain a biogas plant of the same size as the research, investments of $250*10^6$ BRL are required, with 10% of this volume representing fixed production costs included in the OPEX. Structure for production, as described in Annex C.

Table 4 – Evaluation of the scenarios for Ebitda generation[5]

Route compostition		EBITDA									
Electr.	CH_4	BiGMX Year – 10^6 BRL									
		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
0%	100%	83.63	87.54	91.46	100.16	104.06	107.98	111.90	120.60	124.50	128.42
25%	75%	74.61	77.31	80.01	90.80	93.50	96.20	98.90	109.69	112.39	115.09
30%	70%	64.75	75.58	78.04	89.25	91.71	94.16	96.62	107.83	110.29	112.75
35%	65%	53.05	73.85	76.07	87.70	89.91	92.13	94.34	105.97	108.19	110.40
40%	60%	51.56	72.13	74.10	86.14	88.12	90.09	92.06	104.11	106.09	108.06
45%	55%	50.08	70.40	72.13	84.59	86.33	88.06	89.78	102.25	103.98	105.72
50%	50%	48.60	68.67	70.16	83.04	84.53	83.16	81.79	100.39	101.88	103.37
55%	45%	47.11	66.95	68.18	81.41	82.74	81.37	79.99	98.53	99.78	101.03
60%	40%	45.60	65.22	66.22	79.93	80.95	79.58	78.20	96.66	97.68	98.68
65%	35%	44.14	63.49	64.24	78.38	79.15	77.78	76.41	94.80	95.57	96.34
70%	30%	42.66	61.77	62.27	76.83	77.36	75.99	74.61	92.94	93.47	93.99
75%	25%	41.17	60.04	60.30	75.28	75.57	74.20	72.82	91.08	91.37	91.65
100%	0%	60.36[6]	59.43	58.47	75.54	74.62	73.69	72.73	89.30	88.88	87.95

EBITDA = Earnings Before Interest, Taxes, Depreciation and Amortization

For the route with the total biogas destined for biomethane, the best financial and EBITDA results are obtained, if compared with all valve combinations. In exclusive productions for bioelectricity through biogas, in addition to bringing inferior results, there is an increase in operational cost, as it is necessary to purchase of biomethane for use in the agricultural operation considered in the model, there is a 38% performance of biomethane over bioelectricity in 2022, reaching 32% in 2031.

The operation that allocates the most significant biogas quantity to produce biomethane for commercialization, even considering the demand for the substitution of diesel in agricultural operations, is the one that most efficiently remunerates the industry, the valve in the top biomethane position, in this case, 75%, leaving the rest for electric energy generation, is capable of providing an 81% higher result in the first year compared to the opposite scenario.

On the other hand, this combination has the lowest growth potential until the end of the projected series, which is 54% by 2022. Despite a relevant growth, the combination of

[5] All scenarios presented are not considering any productive investments, only using the production of an already installed capacity.

[6] Exclusive production scenarios should always be analyzed in isolation and not as a sequence of mixed production. In the case of exclusive bioelectricity production, there is a higher Ebitda at the beginning of the series due to the fact that the VFR is not considered, since there is no production of biomethane to mitigate the use of diesel. If, for example, the biorefinery had its entire fleet powered by biomethane, when needing to purchase this biofuel, 2022 would start with 24.14*10^6 BRL, and in the case of using diesel oil, the result would reduce to 8.22*10^6 BRL.

production with 75% of electricity and the rest in biomethane starts the series with the lowest added value. Still, it has the highest growth potential, which reaches 123% and can contribute to decision-making based on short and long-term planning.When considering the effect of carbon credits, the scenarios improve margins by an average of 2.73%. However, with a less significant improvement in the combinations with higher biomethane quantity, an average of 2.66%. In comparison, varieties with higher biogas directed to bioelectricity bring an average improvement of 2.85%.

The representativeness of CBio is lower in the scenarios with more biomethane in the system over the years of the series compared to the majority of bioelectricity routes, making biomethane less dependent on carbon credit to project higher results.

4. CONCLUSION

The insertion of the biogas industry in the sugar-energy sector is capable of promoting the mitigation of GHGs, industrial waste, and costs, as well as emerges as an alternative to be explored in the sector, promoting the improvement in results, the optimization of sustainability indicators, and consequently the viability of new processes involving biogas, as an energy alternative.

Maximizing the EBITDA of the biogas routes is still a challenge, given the uncertainties of the macroeconomic scenarios, which directly influence the decision-making of industries that have long-term strategic planning and are exposed to a series of variables that can change demand, supply, and price projections at any time.

It is possible, with the results from the applied model, to measure and project impacts of the vinasse-biogas utilization in the composition of financial results, but also for relevant reductions of the carbon footprint, in the sugar-energy sector. The carbon credits generated through avoided CO_2 can benefit all production systems, which can acquire the assets as a way of offsetting their emissions

The flow of generation and use of biogas presented in the analyzed biorefinery can be replicated to the others, with volumes proportional to its ethanol production capacity. The use in the form of biomethane. In turn, it will depend on the opportunity cost in relation to the price of diesel oil, this substitution can also be replicated in other sectors that may use the generation of biomethane from the digestion of biomass from other sources.

The research limited the routes based on the minimum and maximum production parameters indicated by the industry, but according to the parameters used, it also simulated single-product routes. Still, due to the potential for generating additional financial results in the biomethane maximization route, one can evaluate possible new biogas generation units focused only on biofuel production, leaving the electric energy route out at this moment, being able to consider, when exclusive production, that there is a need to purchase biomethane in the market, when the fleet is adapted, otherwise there is the equivalent in diesel oil.

About the carbon credits in the Brazilian market, due to the recent history, with negotiations beginning less than three years ago, it is a market with a large learning curve, and that tends to develop over the evaluated period and can bring greater representativeness within each route, and make a difference in decisions over the period, with the possibility of route adjustments each year, maximizing results.

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APPENDIX

Appendix A – Author's consideration

The demand for renewable energy sources should increase over time, increasing the need for investments in biogas and biomethane production technology from sugarcane, which should work in parallel with processes aimed at capturing CO_2, which use biomass as an energy source, such as BECCS.

In this study, from the moment that biomethane is generated in the system, a maximum production capacity was considered, not investigating the inefficiency in the chosen routes, which may overestimate the results obtained from the proposed model.

The inflation attributed to the period, based on the broad national consumer price index (IPCA), represented 50% in the projection and formation of future prices, with the remaining 50% of the behavior determined in the prices of biofuel, bioelectricity or equivalent fossil fuel, with other variables such as interest rates, exchange rates and other indices that may influence prices disregarded.

In the case of the model already developed, the BiGMX , in addition to the formation of the analyzes and generation of research results, it is possible to adapt other variables to also understand the inefficiencies of this productive system and the limitations in the projection of prices.

Regarding projected prices, instead of using an algorithm to predict inflation behavior for the next 10 years, based on the history of recent years, projections can be made based on deflated prices in the same period, which can contribute to less optimistic scenarios regarding the perspectives of results until 2030, and correction alternatives may also be considered, such as the General Price Index - Market (IGP-M) or Internal Availability (IGP-DI) .

For new studies involving the biogas structure in the sugar-energy sector, as well as its economic efficiency, in addition to a revised BiGMX model of the use of the plant, complementary analyzes can be taken into account, such as stochastic simulations, in order to promote risk analyzes and map scenarios, as well as the probabilities that they occur.

Simulations of scenarios with bioelectricity and biomethane production should be developed, also taking the production of ethanol and the production mix with sugar over the years, it is also worth considering the Capital Expenditure (CAPEX) for the investment decision in a biogas plant in the biorefineries, and the impact of the scenarios presented, for net present value, internal rate of return, and payback over time.

ANNEXES

Annex A – Biogas and biomethane compounds

Table A.1 – Biogas/biomethane specifications and effects of its impurities

Compounds	Biogas Composition	Biomethane Specification	Effects on Biomethane
CH_4	55–65 (% mol)	Min 90 (%mol)	–
CO_2	35–45 (% mol)	Max 3 (%mol)	Reduction of calorific value, corrosion.
H_2O	<5 (% mol)	–	Reduction of calorific value, corrosion (reaction with H_2S, NH_3 and CO_2) and possible condensation at high pressures.
H_2S	20–20,000 (ppmv)	Max 10 (mg/ m^3)	Corrosion, toxicity (>5 cm^3/ m^3) and possible formation of SO_2 and SO_3.
N_2	<2 (% mol)	–	–
NH_3	<500 (ppmv)	–	Corrosion.
H_2	0–0.02 (% mol)	–	–
Total Sulfur	–	Max 70 (mg/ m^3)	–
$CO_2 + O_2 + N_2$	–	Max 10 (%mol)	–

Moreira et al. (2022).

Annex B – BECCS

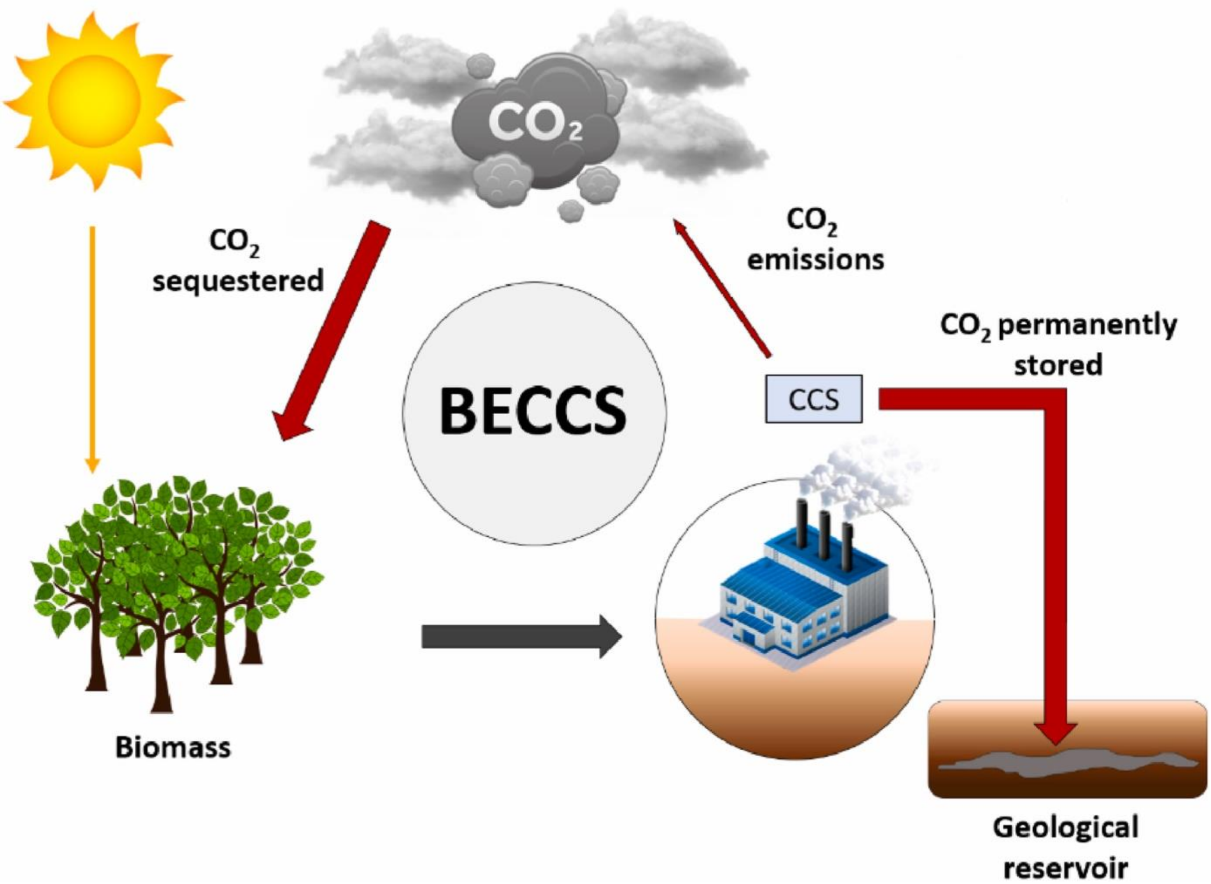

Figure B.1 – Scope of Bioenergy with Carbon Capture and Storage (Almena et al., 2022).

Annex C – Production structure for biogas routes

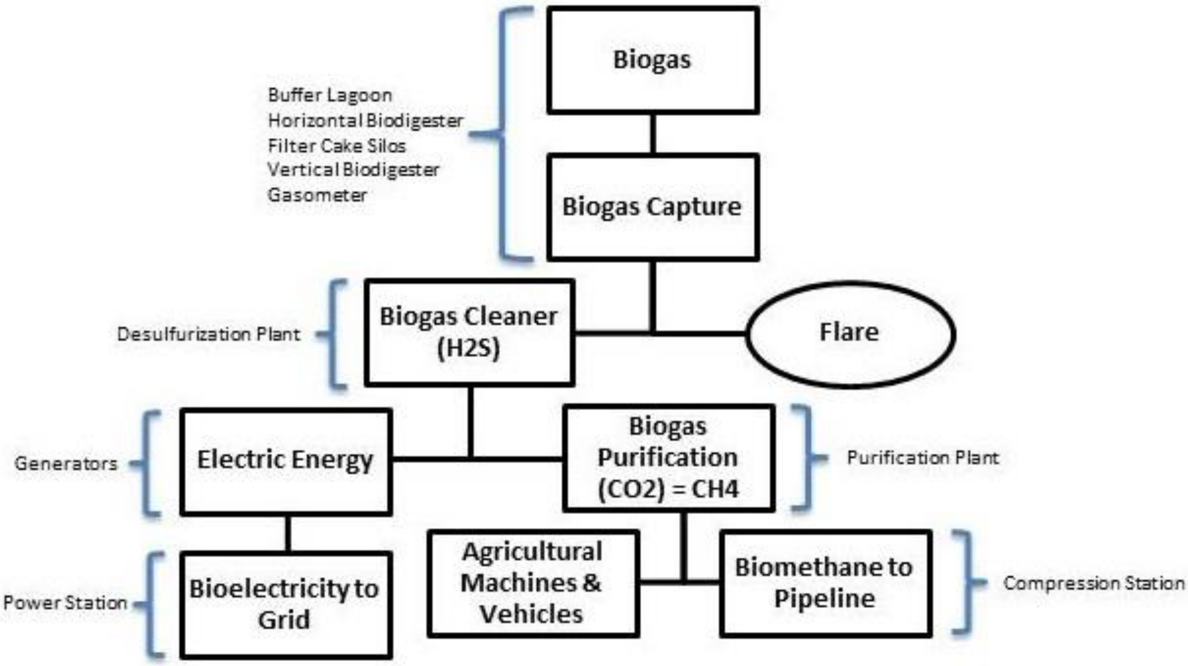

Figure C.1 - Biogas utilization routes, adapted from Coelho (2018).