International Hydrogen Ramp-up Programme – H2Uppp

Technical, Political, Regulatory, Certification, Environmental, and Animal Welfare Recommendations for a Biogas and PtX Plant in Toledo, Paraná – Brazil

Volume 1: Techno-economic assessment and Certification to export

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Executive summary

The content of the report seeks to meet the demand for essential documentation to subsidize the implementation of a green fuel project to be installed in an area located near the city of Toledo, located in the state of Paraná, in Southern Brazil. The focus is on production based on green hydrogen, obtained from the electrolysis of water and rural biogas using renewable energies and biogenic waste, more specifically, animal waste and agricultural waste. The final business goal of the project is exporting advanced e-fuels and biofuels to the European market to produce Sustainable Aviation Fuel (SAF) under mandatory requirements of Renewable Energy Directives II and III.

This report consists of two volumes. The present document, Volume 1, is the first and contains an overview of the techno-economic assessment of a biogas and PtX plant configuration in the Toledo region of Paraná, Brazil, as well as certification and sustainability analyses and recommendations. This technical analysis focuses on the feasibility assessment of green fuel production based on green hydrogen obtained from renewable energy (RE) sources and biogenic carbon, with the latter obtained from animal and agricultural wastes. Different process scenario layouts were evaluated and simplified economic assessments were conducted for each scenario. The certification and sustainability analyses explore the regulatory requirements for the produced e-fuels and biofuels to be eligible for the European market, including compliance with carbon intensity thresholds, standards for the used biomass feedstock, specifications for the process energy inputs, among others.

Volume 2 of this report contains summaries of studies conducted in the project assessment through the lenses of environmental impact, legal context, and animal well-being.

Introduction

The H2Uppp programme of the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) accompanies and supports the market ramp-up of green hydrogen (GH_2) and Power-to-X (PtX) applications in selected developing and emerging countries. Unlike other hydrogen funding initiatives, H2Uppp targets the early phase of green hydrogen project development. The Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) was commissioned to implement the programme.

The aim of H2Uppp is both to identify, prepare and accompany the implementation of projects for the production and use of green hydrogen and PtX applications, as well as to raise awareness and transfer knowledge for project development around the topic of green hydrogen. This way of working allows both the Programme and partner countries to identify economic production and use paths, map project opportunities along the value chain and develop business models.

Why Brazil?

In the face of climate change, the European Union (EU) has set specific goals for reducing greenhouse gas emissions and enhancing the share of renewable energy in its energy portfolio. Brazil's expertise in the production of biofuels, presents a compelling solution that addresses the EU's sustainability objectives and promotes the importation of biofuels with a significantly reduced carbon footprint. Brazil also has a great availability of cheap renewable energy and is geographically positioned to be an exporter to EU.

The exportation of advanced biofuels from Brazil holds a distinct advantage in terms of contributing to the EU's decarbonization targets, as the production of biofuels from waste biomass inherently circumvents concerns related to land-use change and competition with food crops, addressing key sustainability criteria set by the EU for imported biofuels. This aligns seamlessly with the EU's commitment to reducing the carbon intensity of its transportation sector, providing a strategic and eco-friendly solution to meet its renewable energy targets.

Goals of this report

It is worth noting that process configurations, economic analyses, and other aspects of the studies that support this report have their own unique advantages and disadvantages in terms of cost, yield, hydrogen, and water utilization, and are dependent on specific local conditions and requirements. Nevertheless, the goal of this report is to share knowledge that could potentially provide a frame of reference for similar future endeavours, while also offering actionable insight on how to conduct assessments of viability for biogas and PtX plants, as well paths for safe, sustainable, and economically feasible implementation and operation.

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Glossary of Acronyms/Abbreviations

CORSIA | CORSIA stands for Carbon Offsetting and Reduction Scheme for International Aviation. It is a global market-based measure established by the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations, to address greenhouse gas emissions from international aviation.

ISCC EU | ISCC EU stands for the International Sustainability and Carbon Certification system for the European Union. It is a certification scheme designed to ensure the sustainable production and use of biomass and bioenergy within the European Union.

PEM | PEM stands for Proton Exchange Membrane and in the context of this report, refers to an electrolyzer that uses PEM technology for the electrolysis process. PEM electrolysis is a method of splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using an electrolyzer cell that contains a solid polymer electrolyte membrane.

PtX | In the context of green fuel production and sustainable energy, PtX stands for *Power-to*-X. This is a concept that involves converting electrical power (often from renewable sources into various forms of energy carriers or chemicals, denoted by the "X".

RED | RED stands for Renewable Energy Directive, a legislative framework established by the European Union to promote the use of renewable energy sources and reduce greenhouse gas emissions in the energy sector.

RSB EU | The RSB EU refers to the Renewable Biomass Scheme for the European Union. It is a certification system designed to ensure the sustainability of biomass production and use within the European Union.

RWGS | RWGS stands for *Reverse Water-Gas Shift*. It is a chemical reaction that involves the conversion of carbon dioxide (CO_2) and hydrogen (H_2) into carbon monoxide (CO) and water (H_2O). This reaction is often utilized in the production of synthetic fuels or green fuels because it helps in utilizing carbon dioxide, a greenhouse gas, and hydrogen, often obtained from renewable sources.

SAF | SAF stands for Sustainable Aviation Fuel. It refers to aviation fuel that is produced from sustainable and renewable feedstocks, such as biomass, waste oils, or renewable electricity. The key characteristic of SAF is that it significantly reduces greenhouse gas emissions compared to conventional fossil-based aviation fuels.

Syngas | Syngas is short for *synthesis gas*, is a mixture primarily composed of hydrogen (H_2) and carbon monoxide (CO). It is produced through the gasification of carbon-containing materials such as coal, natural gas, biomass, or organic waste. It is a versatile intermediate product used in various industrial processes.

1 Techno-economic assessment of the biogas and PtX plant configurations

This techno-economic assessment explores process designs for two specific biogas conversion outputs: syncrude/SAF and methanol, additionally evaluating operational parameters and estimated CAPEX and OPEX for these routes. It then economically evaluates these routes in connection to green hydrogen production conditions, considering aspects such as the electrolysis plant and technology, water supply, power demand and renewable resources in the studied region, with requirements being established considering the scenarios with the best internal rate of return (IRR).

Technology analysis foundations: ReShift™ and RWGS

ReShift™ is a new, commercially available post-reforming technology that can bring technical and economic advantages to the reforming plant compared to conventional configurations. The focus in the use of such technology lies in the challenge of preventing carbon formation in catalytic reforming processes that contain feedstocks with a high CO_2 content, reducing energy consumption with steam usage, and adjusting the H_2/CO_2 ratios of the produced syngas. The technology applies catalytic reforming, eliminating the need for external CO conversion techniques such as RWGS (Reverse Water-Gas Shift), which requires the addition of H_2 from other sources. However, ReShift™ adoption may incur in downsides, such as increasing plant complexity; impacting the energy efficiency of the system; raising the initial investment cost of the project and requiring a significant additional amount of energy that may or may not come from renewable sources. For the purpose of this study, both paths - ReShift™ and RGWS – were assessed.

1.1 The biogas into syncrude route: processes

Three main processes configurations for converting biogas and green hydrogen into syncrude were evaluated as follows:

Process 01 | Base case (without recycles)

This process was defined as the base case for the conversion of biogas into syncrude, without considering any recycling for comparison purposes (Figure 1).

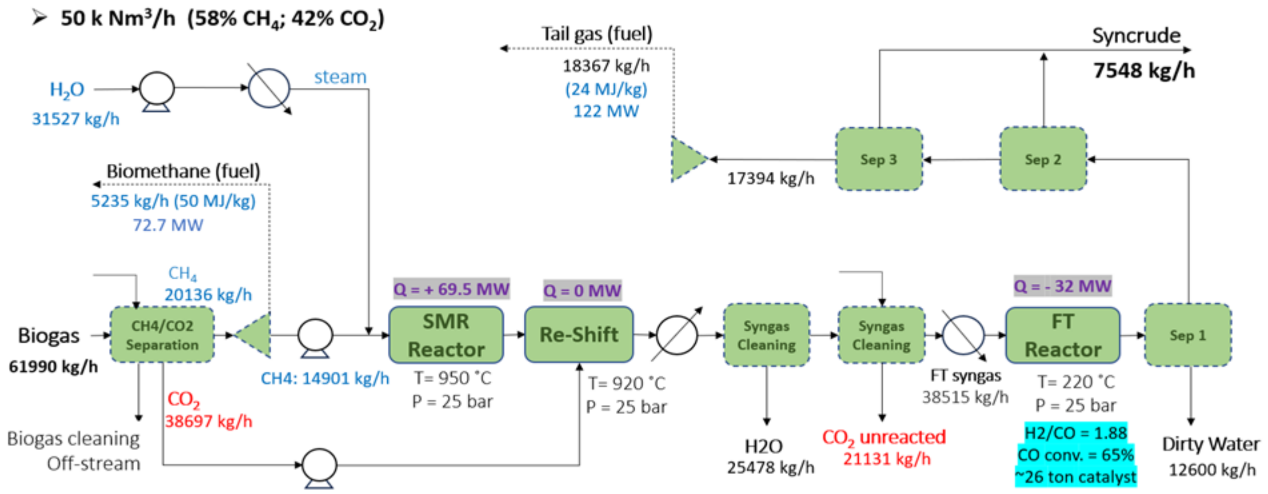

Figure 1: Process 01 | Block flow diagram for the base case process evaluated – biogas conversion to syncrude

Process 02 | Base case + recycles

Considering that in the base case a significant quantity of unreacted syngas was obtained, a second analysis configuration was proposed with tail gas recycling (Figure 2).

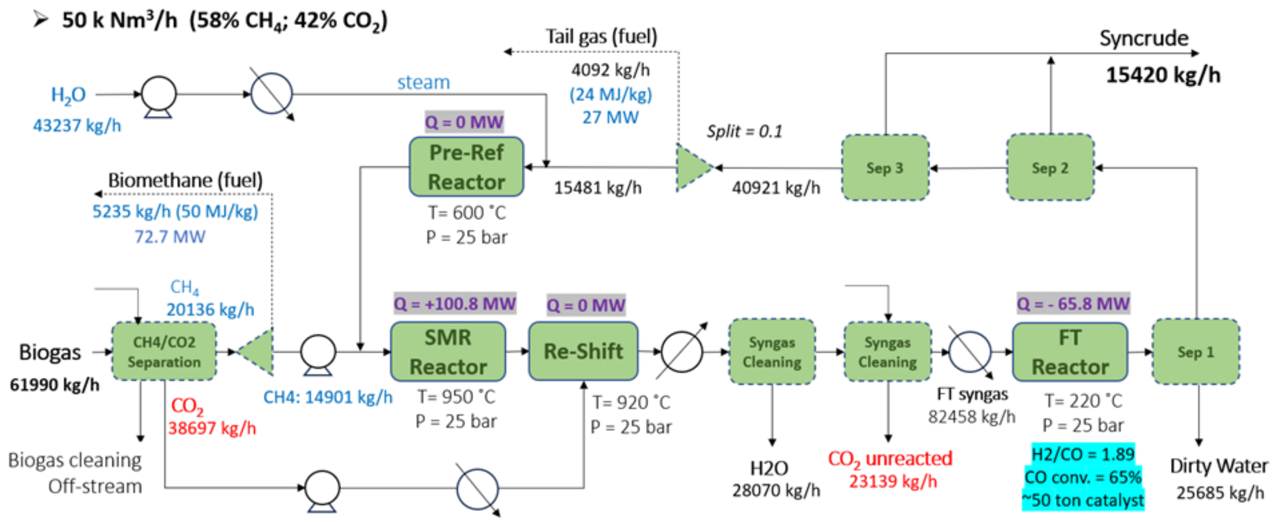

Figure 2: Process 02 | Block flow diagram for the case with tail gas partial recycling – biogas conversion to syncrude

Process 03 | Base case + recycles + RWGS

In both process 1 and 2, the unreacted CO_2 from the re-shift step needed to be removed from the syngas prior to the FT synthesis. This task was accomplished by the MEA system, but its purging of CO_2 would cause a negative impact on the process' sustainability and productivity. Process 3 addresses this issue by incorporating an additional RWGS (reverse water gas shift) reactor (Figure 3).

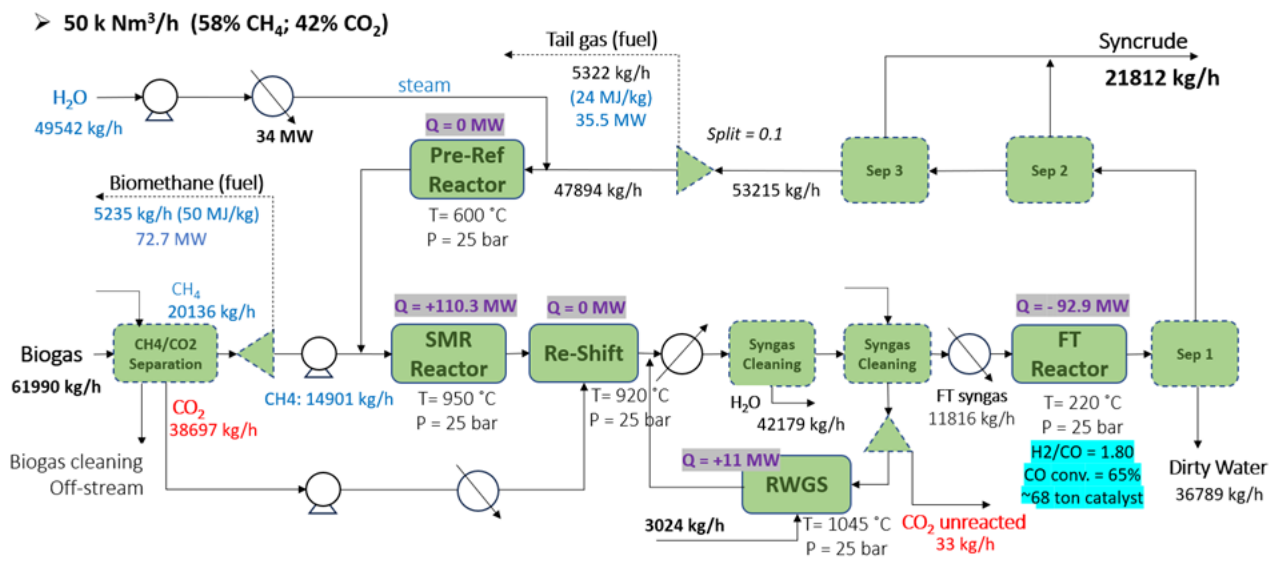

Figure 3: Process 03 | Block flow diagram for the case with tail gas partial recycling and additional rWGS of CO_2 with green H_2 – biogas conversion to syncrude

1.1.1 Biogas intro syncrude processes: comparison

1.1.1.1 Operational parameters comparison

Table 1: Analysed operational parameters for comparison among the configurations

Parameter	Process 01	Process 02	Process 03
Syncrude production	7,548 kg/h	15,396 kg/h	21,802 kg/h
H2/CO molar ratio	1.88	1.88	1.80
S/C molar ratio	1.92	1.10	1.12
Unreacted CO2	21,131 kg/h	23,145 kg/h	33 kg/h

1.1.1.2 CAPEX estimates comparison

CAPEX estimative was performed for these three cases evaluated using two Order-of-Magnitude Estimate methods, as presented in Tables 2 and 3. Another quick methodology to make an order-of-magnitude estimate of plant cost is to scale it from the known cost of an earlier plant that used the same technology or vendors published data. This requires no design information other than the production rate. The capital cost of a plant is related to capacity by the scale equation, as indicated in Table 3 applied for those three different processes evaluated for syncrude production from biogas.

Table 2: Estimated CAPEX for the proposed configurations using Method 1: Order-of-Magnitude Estimate (based on the Method of Hill) (Seider et al., 2017)

Parameter	Process 01	Process 02	Process 03
Module Cost	$15,630,811.65	$21,990,495.07	$32,948,157.04
Total bare-module Investment	$51,701,915.45	$72,737,791.38	$108,982,365.60
Direct Permanent Investment	$113,744,214.00	$160,023,141.03	$239,761,204.32
Total Permanent Investment	$170,616,321.00	$240,034,711.54	$359,641,806.49
Total Capital Investment (CAPEX)	$196,208,769.15	$276,039,918.27	$413,588,077.46

Table 3: Estimated CAPEX for the proposed configurations using Method 2: Order-of-Magnitude Estimate (based on plant scales) (Towler & Sinnott, 2021)

Plant/Base process	Process 01	Process 02	Process 03
ExxonMobil FT Plant	503 MM US$	777 MM US$	997 MM US$
GTL Plant	332 MM US$	368 MM US$	473 MM US$
Method 1 (Table 3.2)	196 MM US$	276 MM US$	414 MM US$
Total Capital Costs (Suggested range)			
Minimum Cost Suggested	196 MM US$	276 MM US$	414 MM US$
Maximum Cost Estimated	503 MM US$	777 MM US$	997 MM US$

Note: All these numbers must be considered with +/- 50% accuracy.

Different CAPEX estimation methodologies, as can be seen from Table 3, produce significantly different results, in relative terms. These estimates should not be used outside their context and should not be mixed with other estimates of other methodologies. CAPEX estimates conducted for the economic comparison presented in paragraph 1.5 uses the same common methodology, a factorial methodology based on main plant components and layout, and is not to be compared with the preliminary results shown in this current paragraph.

1.1.1.3 OPEX estimates comparison

An initial estimate for the operational costs (OPEX) was conducted for the three scenarios. It considered electricity consumption for pumps and compressors, the acquisition of raw materials (in this case, exclusively biogas), the water supply and the utility costs associated with heat exchangers. It is worth noting that the heat exchangers potentially involved in heat integration schemes were not included into this utility estimation. Prices for water and electricity were based on rates from suppliers in Paraná state at the time of the study and the exchange rate applied to the calculations (US Dollar to Brazilian Real) was 5.05 USD/R$ and the biogas price was estimated at 0.6 R$/kg.

The pre-heated water stream resulting from the three processes could be considered, for example, for steam generation, to be either used internally in the process or to be sold to improve process economics. This steam generation could be performed in a boiler with some remaining amount of tail gas or biomethane from the process. Steam selling was not considered at this point. The general results obtained for the three process scenarios are summarized in Table 4.

Table 4: OPEX Comparison for biogas to syncrude processes

Scenario	Unit	Process 01	Process 02	Process 03
Electricity Consumption	MW	3.67	3.63	3.63
Electricity Costs	$/h	266.22	263.10	263.10
Water Consumption (process)	tons/h	0.72	0.72	0.72
Water Costs (process)	$/kg	1.58	1.58	1.58
Water Consumption (utility)	tons/h	160.57	316.94	358.89
Water Costs (utility)	$/h	352.42	696.51	788.40
HP Steam Consumption (utility)	tons/h	-	18.47	24.14
HP Steam Costs (utility)	$/h	-	40.46	52.88
Biogas Cost	$/h	7365.17	7365.17	7365.17
OPEX	$/h	$7,985.38	$8,326.35	$8,418.24
OPEX (without raw material)	$/h	$620.22	$961.18	$1,053.07

Considering all the proposed scenarios, scenario 02 (which involves a percentage of tail gas recycle, but not the use of CO_2 in a new RWGS section) can be recommended to produce syncrude in this specific context, due to less complexity relative to the other scenarios and to the relation CAPEX/productivity.

1.2 The biogas and GH_2 into methanol route

An alternative pathway for biogas utilization involves its conversion to methanol via a three-step process: steam methane reforming, water-gas shift, and methanol synthesis. This method features a high 91% recycle of unreacted components, like the syncrude production process.

1.2.1 Biogas and GH_2 into methanol: the process

This process initially separates CO_2 and CH_4 streams from biogas through a water scrubber or similar technologies, with CH_4 then being mixed with water and then blended with the CO_2, with this mixed stream then converted in the RWGS reactor, achieving a CO_2 conversion of 55%. The obtained syngas, mixed with a stream of green hydrogen then passes through heat exchangers for further dehydration. Subsequently, the syngas is sent to the methanol reactor. Post-reactor, a heat exchanger takes on the role of cooling the system and condensing water and methanol. Subsequently, the chilled mixture is directed into a distillation column. The distillation process removes 98.5% of the water in the bottom stream. However, the inclusion of a partial condenser results in the generation of two distinct product streams.

The vapor stream, laden with unreacted syngas, CO_2, CH_4, and trace amounts of methanol, is reintroduced into the system to enhance the conversion of methanol synthesis. This stream undergoes compression to 70 bars, achieving an impressive 91% recycle rate. Meanwhile, the liquid stream, comprising water, methanol, and dissolved CO_2, undergoes additional processing. A strategically placed valve expands the mixture, facilitating the removal of CO_2. A flash tank separates the remaining water and CO_2 from the purified methanol, yielding a main product with a purity of 98.5%.

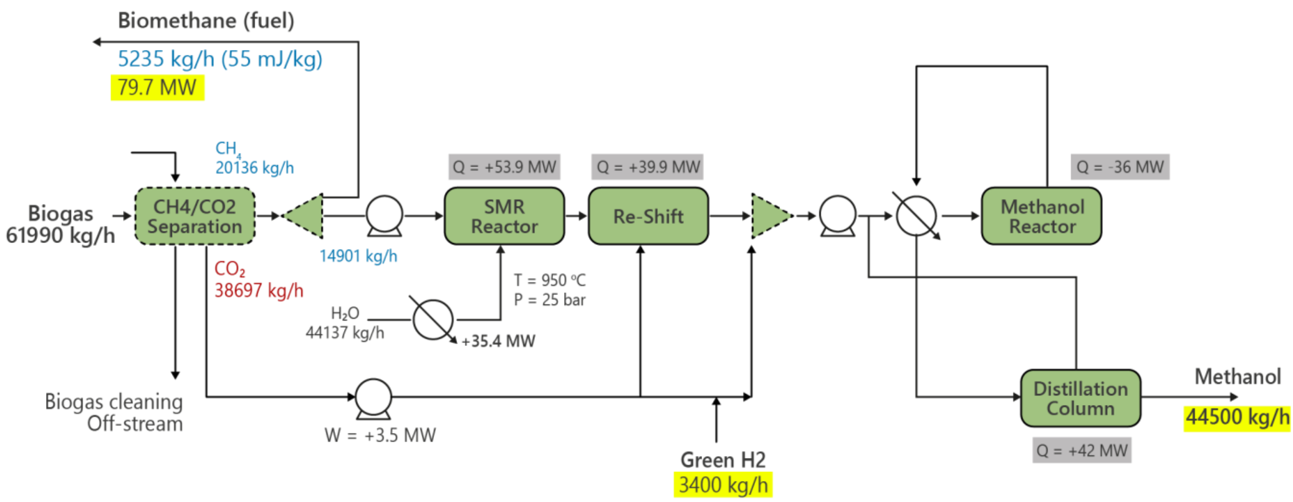

Figure 4: Block flow diagram for the conversion of biogas to methanol

1.2.2 Biogas into methanol: CAPEX estimates

For the methanol plant case, a more refined CAPEX estimate is conducted employing the factorial methodology developed by Guthrie (1974). Each cost associated with the Total Invested Capital (C_{TCI}) is described individually as follows. *Total Module Cost (C_{TBM})*

C_{TBM} sums up bare-module costs for every process equipment element, from tanks and machinery to computers and software. The bare-module cost of each equipment (C_{BM}) starts with the base price of the equipment (C_{FOB}), then adds in the cost of materials and labor needed to install it (direct field costs), and finally includes additional expenses like shipping, insurance, and overhead (indirect expenses).

$$C_{BM} = C_{FOB} \cdot F_M$$

C_{FOB} is the cost of the equipment calculated with freight and insurance separately, as the transportation of the goods is the responsibility of the buyer. This cost is calculated using the correlations and values established by Guthrie (1974) and Seider et al. (1999), correlations which are different for each piece of equipment. In addition, F_M is the module factor for correcting this FOB cost and varies according to the unit operations

Table 5: Module factors for different equipment

Equipment	F_M
Horizontal reactors	4.3
Columns	4.3
Heat Exchangers	3.3
Centrifugal Pumps	3.4
Compressors	3.5

Note: Adapted from: (Seider et al., 2009).

The module prices are calculated and estimated in dollars for a CE index equivalent to 560.4 at the end of 2010. Therefore, it is necessary to correct these values using the following relationship:

$$C_{2023} = C_{2010} \cdot \frac{CE_{2023}}{CE_{2010}}$$

For 2023, the Chemical Engineering Plant Cost Index used was 798.7. This value is available on Chemengonline, of Chemical Engineering (https://toweringskills.com/financial-analysis/cost-indices/). Also, a safety factor of 20% was added in the total bare-module cost.

Site Cost (C_{site})

Site preparation and development costs (C_{site}) can be significant for new plants (grass-roots plants), ranging from 10 to 20% of the total bare-module cost of the equipment (C_{TBM}). However, for an expansion of an existing integrated facility, the cost is typically much lower, falling between 4% and 6% of the C_{TBM}. For the present case, 20% of total bare-module cost has been used.

Buildings Cost ($C_{buildings}$)

The cost of process buildings can be initially estimated at 10% of C_{TBM}. For new plants (grass-roots plants), non-process buildings can be preliminarily estimated at 20% of C_{TBM}. However, for expansions of existing integrated complexes, non-process buildings are typically lower at around 5% of C_{TBM}.

Facilities Cost ($C_{facilities}$)

Offsite facilities encompass utility plants (if the company manages its own utilities), pollution control systems, ponds, waste treatment facilities, offsite tankage, receiving and shipping infrastructure. Additionally, an estimated 5% of C_{TBM} can be allocated for other offsite facilities.

Table 6: CAPEX investment costs for the methanol route

Description	Value (US$)
Total Module Cost (C_{TBM})	$ 350,762,624.87
Working Capital Cost (C_{WC}, equation 35)	$ 52,521,011.63
Site Cost (C_{site})	$ 52,614,393.73
Buildings Cost ($C_{buildings}$)	$ 70,152,524.97
Facilities Cost ($C_{facilities}$)	$ 114,478,376.73
Total Capital Invested Cost (C_{TCI}, equation 32)	$ 746,370,357.58
CAPEX from renewable plants	$ 652,000,000.00
Total CAPEX Investment Costs	$ 1,398,370,357.58

1.2.3 Biogas into methanol: OPEX estimates

Table 7: OPEX investment costs for the methanol route

Description	Value (US$)
Raw Material Costs	$ 58,815,407.58
Utilities Costs	$ 100,981,048.20
Labor-Operations Costs	$ 341,141.30
Maintenance	$ 62,446,441.14
Depreciation	$ 44,701,188.91
Taxes and Insurance	$ 6,938,493.46
Total OPEX Costs	$ 233,275,085.94

1.2.4 Biogas into methanol: sensitivity analysis

To provide a more comprehensive understanding and better evaluation of the methanol process, a sensitivity was conducted, considering the methanol selling price as USD 1500/ton, and the MeOH production as 31,5 tons/h, totalling a gross annual revenue of USD 374.397.130,80. Considering factors such as annual depreciation and production costs, the assessment provided an estimate internal rate of return (IRR). This hypothetical discount rate, based on projected cash flow, helps determine if the investment is financially viable. The analysis (Table 8) considered scenarios where either production volume or selling price fluctuated. For economic viability, either a minimum production of 23,4 tons/h of methanol or a minimum selling price of USD 1113,7/ton is necessary. This ensures zero profit or loss, deeming the process economically feasible.

Table 8: Estimated IRR for methanol production

Case Description	IRR
Methanol Cost: 1000 US$/ton	-3,87 %
Methanol Cost: 1200 US$/ton	2,91 %
Methanol Cost: 1500 US$/ton	12,92 %

1.2.5 Biogas into methanol: viability analysis

To enhance the understanding of the bio-methanol production analysis, four distinct scenarios were examined, each based on a different data source: NIRAS (Scenario C1), MeLe (Scenario C2), 50% uncertainty (Scenario C3), and the most recent improved NIRAS analysis (Scenario C4).

It is important to highlight that the Total CAPEX used in the calculations includes the CAPEX of the Biogas Plant. A fourth scenario was developed to integrate various revenue streams based on insights from the MeLe report (i.e., fertilizer and carbon credits sale, among others). Updated CAPEX values were sourced from market data and NIRAS' references and a more precise Weighted Average Cost of Capital (WACC) was chosen (11%) to improve the accuracy of the financial assessment.

Viability analysis is shown in Table 9 below, with the results of the four scenarios considered for the construction of the Biorefinery intended for bio-methanol production. The results indicate that all scenarios are feasible from a technical, economic, and financial standpoint, presenting attractive indicators in terms of Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period.

The reasons for these results, compared to scenarios for Syncrude/SAF production, lie in the lower complexity of construction and operation processes, as well as the market price being lower than the levelized price. The simplicity of technological processes, higher production capacity, and current market price make this option the most viable among those considered.

Table 9: Analysis of the viability of four scenarios

Indicator	Scenario C1 NIRAS Data	Scenario C2 MeLe Data	Scenario C3 Uncertainty Data 50%	Scenario C4 NIRAS latest improved financial analysis
Net Present Value (NPV) (Millions €)	€ 160	€ 333	€ 500	€ 371
Internal Rate of Return (IRR) (%)	5,72%	6,99%	8,57%	14,65%
Payback (years)	17,2 years	15,0 years	13,0 years	12,3 years

1.3 Considerations on syncrude and methanol financial and economic analysis

Based on the results of the analyses conducted for this economic and financial feasibility study of the projects in question, we can affirm that the Biogas Central Project of 45 units demonstrates viability and is highly attractive in terms of financial return and environmental benefits. The choice of the Biomethanol production chain is technically less complex than that of Syncrude/SAF, resulting in reduced associated economic risks and providing greater flexibility. Studies demonstrate an attractive feasibility for this approach.

As much as the economic and financial feasibility analysis reflect conservative scenarios, it presents uncertainties due to the need for improvement in detailing the technologies employed. Therefore, further refinement is recommended as the studies progress.

We express a highly favorable opinion on the realization of this investor partnership in the projects, highlighting that the project benefits from intrinsic support from public, private, and academic institutions, making it of great importance for regional, state, and national development towards sustainability. Furthermore, this initiative strengthens ties between Brazil and Germany, providing mutual benefits in terms of environmental, economic, and social aspects for both countries, including positive impacts on local and global decarbonization.

1.4 Biogas and GH_2 into syncrude vs. biogas and GH_2 into methanol routes: recommendation & limitations

Results suggest that with an optimized process design, both green fuel production routes are economically feasible. However, it appears that the CAPEX investment necessary for a SAF (Sustainable Aviation Fuel) plant is higher with respect to a methanol plant, with the latter process route potentially offering a higher degree of flexibility for future investments and changes. In conclusion, it is advised to select a single process scenario for thorough evaluation.

Limitations

Though the provided cost figures provide a glimpse of potential expenses, it is important to note that production and sales at the selected site for the methanol plant may vary considerably. Costs associated with electricity, raw materials, labour, equipment, and utilities are particularly vulnerable to change. This uncertainty, coupled with natural error margins in the cost estimations, underscores the need for flexibility in planning. Additionally, the simulations conducted in this assessment aimed to demonstrate technical feasibility and provide input data for economic analysis. Consequently, due to time constraints, optimizations related to process efficiency and heat integration were not carried out, therefore, it is recommended that further exploration of process optimization routes are conducted.

1.5 Green Hydrogen Production

The next step in the study involved the assessment of the electrolysis plant and technology, water supply, power demand and renewable resources in the studied region, with requirements being established for both the syncrude/SAF and methanol routes and considering the scenarios that presented the best IRR results (Table 9).

Table 10: Basic requirements considered for green hydrogen in each scenario

Requirements	Syncrude/SAF	Methanol	Units
Fuel Productivity	15.4	31.5	tons/h
Green Hydrogen demand	395	3400	kg/h
Power (electrolysis) – PE	24	205	MW
Power (compression) – PC	9	45	MW
Deionized water for electrolysis (DW)	4	34	m^3/h
Water for electrolysis cooling (CW)	6	51	m^3/h
Treated water for electrolysis (DW+CW)	10	85	m^3/h
Treated water for fuel synthesis (FW)	43.3	84	m^3/h
Total treated water (TW=DW+CW+FW)	53.3	169	m^3/h
Total Raw Water Withdrawal (river: TW+40%)	74	237	m^3/h

1.5.1 Water & power supplies: resources and requirements

To ensure resources that meet the plant requirements, the study recommends the design of a design an intermediate hydrogen storage system (buffer) in both syncrude and methanol scenarios, as well as a compression system to ensure compatibility between the green hydrogen plant gas outlet and the synthetic fuel plant's gas inlet pressure.

In short, considering these aspects, the following components should be present in the green hydrogen plant.

An electrolysis plant that uses electrical energy and water to produce hydrogen

Based on a broader outlook and cost forecasts, a PEM-based Electrolysis plant (Figure 5) with high-lifetime stacks guarantee might be a solution slightly better for projects such as this one, which requires flexibility, additional renewable power, and more importantly, is impacted by the potential opportunity cost of emerging markets for hydrogen derivatives due to fast deployment time.

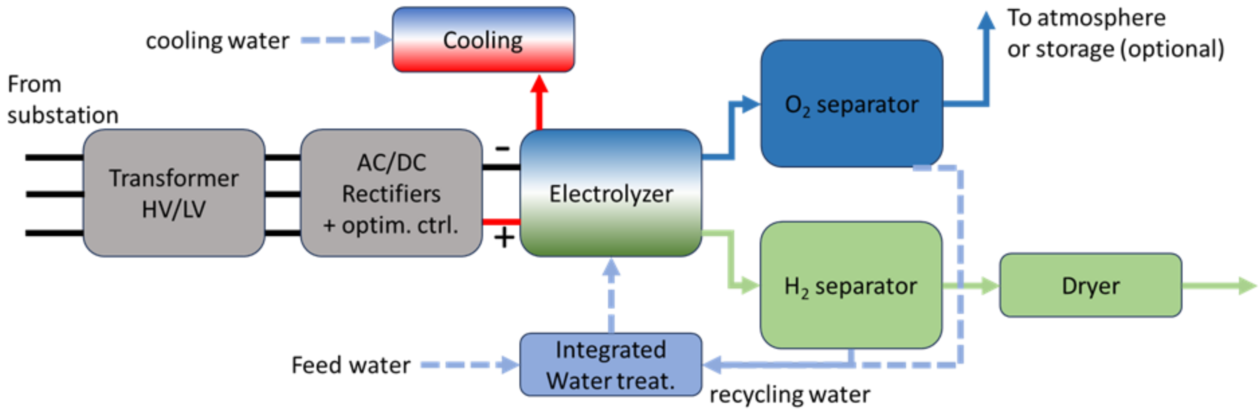

Figure 5: Electrolysis plant basic concept flowchart

A water collection and treatment plant for the electrolysis process

With water being also key not only for electrolysis, but also for processes such as cooling and steam generation, the study assessed the water demand for both the syncrude/SAF and methanol routes, resulting in a total raw water withdrawal of ~74tons/hfor syncrude/SAF and ~237 tons/h for methanol (Figure 6).

Additionally, the study surveyed the availability of water close to the potential plant location, considering nearby surface and groundwater permits and concluding that further assessment is worth conducting in a specific sub-basin, as it has a greater flow available for capture and is in closer in proximity to the area.

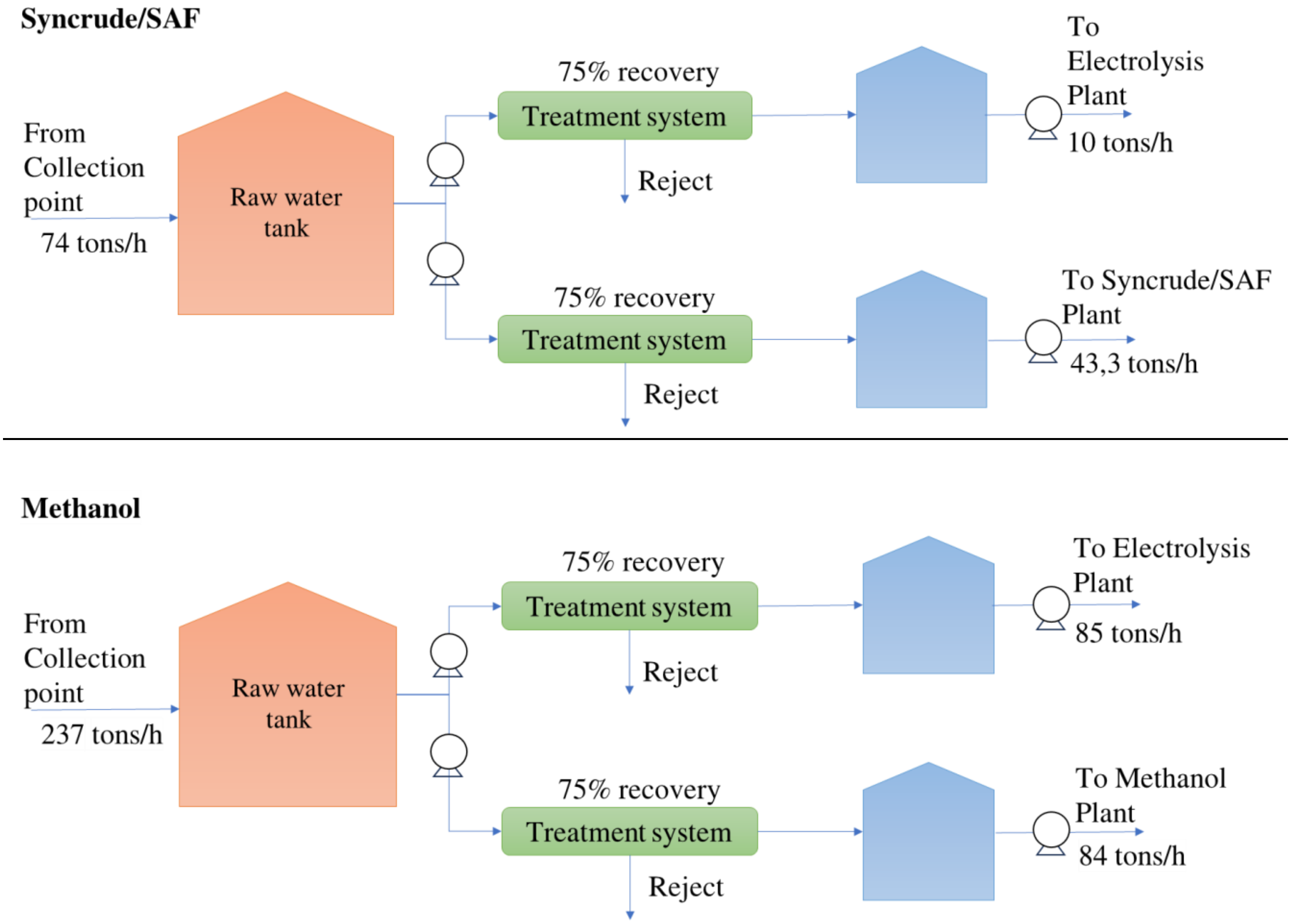

Figure 6: Water flowchart from collection to processes

A power supply system that meets the specifications and certifications required for the products of the industrial complex

To ensure compliance with international certification standards and the Renewable Energy Directive (RED II, which will soon be revised in RED III), it is essential to prioritize the lowest possible carbon footprint from the certification of the synthesized products, considering the impact of each stage of the production process. Therefore, it is suggested to size the energy supply of the electrolyzers in a way that meets the criteria for sustainability, greenhouse gas emissions reduction, and compliance with the criteria defined for RFNBO (Renewable Fuels of Non-Biological Origin) as well.

Considering that the plant's potential location is in the south submarket of the Brazilian electrical system, a region that has met 90% of the renewable share target consistently over the last 10 to 12 years, the study assessed various power supply alternatives and concluded that PPAs (Power Purchase Agreements) for electricity are the most recommended paths if the principles of renewability, additionality, temporal, and geographic correlation are upheld.

To enhance operational security, a flexible connection scheme is recommended (Figure 7). This would involve building new renewable generation plants that are linked to the industrial complex. The scheme should also enable the complex to be connected to the grid, allowing for the import of energy via PPAs from the generation plant located in areas that offer better conditions for renewable energy production.

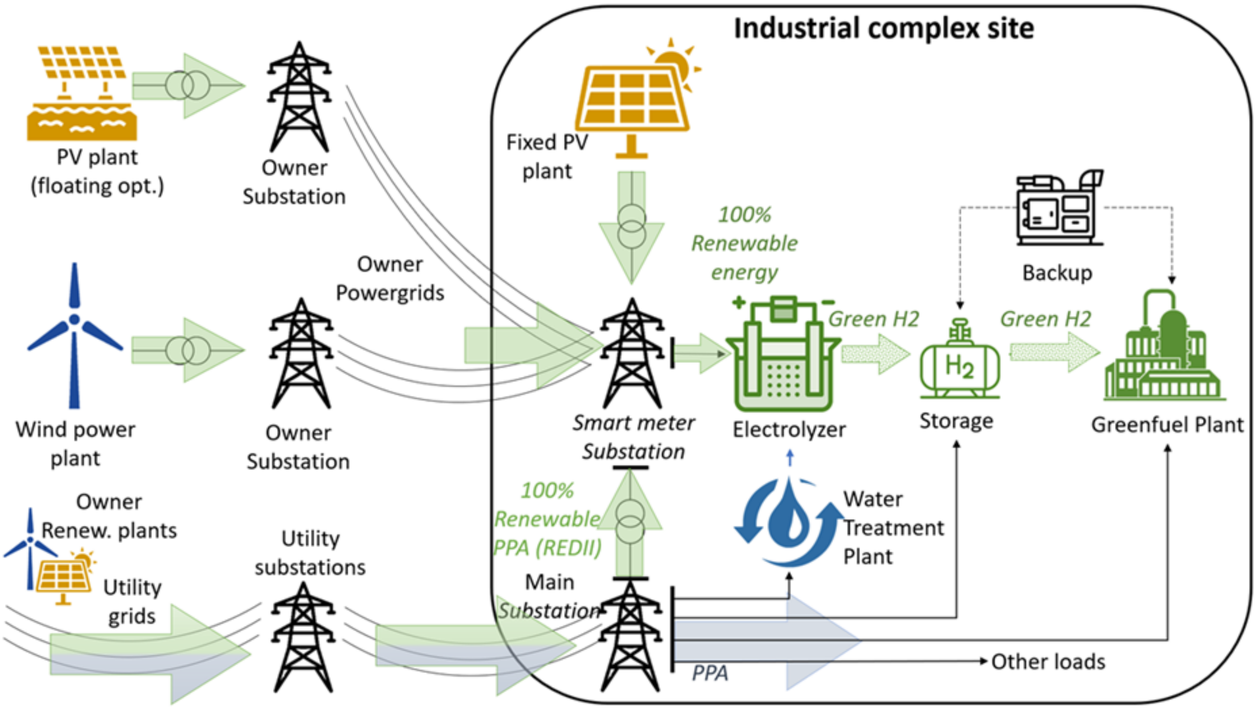

Figure 7: Standard power supply scheme for both direct and indirect connection alternatives

Solar and wind alternatives were also evaluated for the power supply analysis. While options are available in both fronts, they would allow the operational regime of the industrial complex to be met in only 67% of the available operational period. The option to increase the installed capacity of renewable plants would increase the amount of energy in excess of the plant's demand.

1.6 Business case: route comparison and recommendations

Final product (syncrude or methanol) yield in mass per hour terms is shown below (Table 11), with the study's baseline process excluded from this analysis due to its inferior performance.

Table 11: Summary of the process layouts yields

Scenarios	Product Yield	Green H_2 requirement
Process Scenario 2: Syncrude	15200 kg/h (syncrude)	395 kg/h (for Hydrocracker)
Process Scenario 3: Syncrude	23500 kg/h (syncrude)	3700 kg/h (for rWGS & Hydrocracker)
Process Scenario 4: Methanol (from Syngas)	44500 kg/h (methanol)	3400 kg/h (for correct syngas composition)

A simple business case analysis is shown in below (Figure 8), offering an economical comparison of the different processes. For comparison to actual market price standards, it is hypothesized that all the syncrude is hydrocracked to SAF, for which a market price is more easily identifiable.

Process Scenario A: Syncrude (SAF)

Capex			
complexity factor		1	
H2 electr		US$ 25.1M	36 MW
Equipment Total		US$ 430M	
Engineering (10%)		US$ 43 M	
BoP (15%)		US$ 64.5M	
TCI= Contingency (20%) + land and others		**US$ 752M**	
Opex			
	H2	**Compressors**	
size kWh	36,410.4	9000	45,410.4
el price $/kWh	0.063	0.063	
Lifetime	25y		
operative cost	2,851.8$/h		
operativeness	0.95		
operational year	8117h/y		
operative cost	23.1 MUS$/y		
Maintenance (3%)	15.3 MUS$/y		
Depreciation	20.4MUS$/y		
Interest (4%)	20.4MUS$/y		
H2	5,184,840.96kg/y		
O2	41,478,727.68kg/y		
O2 to sell	-154038964kg/y		
Mini Business Case			
Cost per year	106MUS$/y		
SAF Produced	123,139,972.8kg/y		
LCOSAF	**860.16US$/ton**		
SAF Price	1400US$/ton		
IRR	7%		

Process Scenario B: Syncrude (SAF)

Capex			
complexity factor		1	
H2 electr		US$ 150M	218 MW
Equipment Total		US$ 730M	
Engineering (10%)		US$ 73 M	
BoP (15%)		US$ 109 M	
TCI= Contingency (20%) + land and others		**US$ 1.28b**	
Opex			
	H2	**Compressors**	
size kWh	218,100.0	9,000	227,100
el price $/kWh	0.063	0.063	
Lifetime	25y		
operative cost	14,261.9$/h		
operativeness	0.95		
operational year	8117h/y		
operative cost	116MUS$/y		
Maintenance (3%)	28.2MUS$/y		
Depreciation	37.7MUS$/y		
Interest (4%)	37.7MUS$/y		
H2	31,057,440kg/y		
O2	248,459,520kg/y		
O2 to sell	-9903144kg/y		
	256MUS$/y		
	190,744,800kg/y		
	1343.11US$/ton		
	1400US$/ton		
	-10%		

Process Scenario C: Methanol

Capex			
complexity factor		1	
H2 electr		US$ 142M	205 MW
Equipment Total		US$ 399M	
Engineering (10%)		US$ 40 M	
BoP (15%)		US$ 59.9	
TCI= Contingency (20%) + land and others		**US$ 698 M**	
Opex			
	H2	**Compressors**	
size kWh	205,620	45,000	250,620
el price $/kWh	0.063	0.063	
Lifetime	25y		
operative cost	15,738.9$/h		
operativeness	0.95		
operational year	8117h/y		
operative cost	128MUS$/y		
Maintenance (3%)	13.9MUS$/y		
Depreciation	20.7MUS$/y		
Interest (4%)	18.5MUS$/y		
H2	29,280,288kg/y		
O2	234,242,304kg/y		
O2 to sell	38724612kg/y		
Mini Business Case			
Cost per year	207MUS$/y		
Methanol Produced	359,614,824kg/y		
LCOMethanol	**576.26US$/ton**		
e/bio-Methanol Price	800US$/ton		
IRR	11%		

Figure 8: Simplified economic estimations for the analyzed processes

1.6.1 The economically preferrable process scenario

Results suggest that methanol production via the syngas route emerges as the economically preferred process scenario. The Process Scenario 2, which considers the conversion of biogas to syncrude with a RWGS reactor, is potentially economically feasible, but would require optimization to reduce CAPEX and/or enhance productivity. In contrast, Process Scenario 3 proves economically unfeasible under the SAF price assumed for the study. Additionally, the methanol process layout exhibits the highest IRR under the lowest product price scenario, indicating its economic feasibility. However, the assessment's sensitivity analysis also reveals that the methanol process is the most susceptible to fluctuations in product price, which could be considered a potential drawback.

In summary, the methanol process layout presents an intriguing option from an economic standpoint, but its sensitivity to both electricity and product selling point prices, particularly compared to Process 2 syncrude/SAF, cannot be overlooked. Process 2 syncrude/SAF emerges as a robust business case for SAF prices ranging from $1400 to $2400 per ton, and its resilience to electricity price variations stems from its lower reliance on green hydrogen.

2 Certification studies for export

For the produced (e+bio) fuels to be eligible for export to the mandatory European market, several regulatory requirements must be met, including the system's compliance with carbon intensity thresholds, standards for the used biomass feedstock, specifications for the process energy inputs, among others. These requirements shall also affect the process potential of being certified as a sustainable fuel, which influences its ability of commercialization in Europe.

As the project involves exporting advanced biofuels to the mandatory European market to produce Sustainable Aviation Fuel (SAF), it must align with the regulations of this market, obtaining certification under systems recognized by each of the regulations governing it.

2.1 Key regulatory aspects to consider

When exporting this biofuel to the European market, it is necessary for it to be aligned with various requirements outlined in the RED II Directive (EU) 2018/2001 regulation, governs biofuels, bioliquids, and biomass consumption within the European Union.

Considering that these biofuels intended use in producing SAF, it is crucial to incorporate into the analysis the regulations concerning the product. The SAF production process should comply with the Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM D7566), and if assuming the consumption of SAF within Europe, adherence to the REFuel Aviation EU regulation might also be necessary.

If the project involves the integration of renewable hydrogen in its production process, the renewable portion of the fuel produced must only align with the RED II Directive (EU) 2018/2001 Art 25-30, that includes specifications for Renewable Fuels of Non-Biological Origin (RFNBOs).

CORSIA, an international voluntary initiative that establishes various emission targets for operators of aircraft belonging to participating member states, is an additional regulation that might or might not impact the project, depending on the preferences of the off-takers. If the off-takers of the SAF intended for delivery to European countries wish to utilize it as a method for achieving carbon emissions offsetting set by CORSIA, it would additionally be necessary for this product to align with the requirements imposed under this scheme.

The Brazilian law and the standard currently under development in Brazil for low-carbon hydrogen is very incipient.

2.2 Certification systems applicable to the project

To identify the certification systems applicable to the project according to the regulations underscored in the previous section, an analysis of existing global certification systems was carried out.

For a product solely targeting the European RED II regulation for advanced biofuels (for biofuels and SAF markets), excluding the CORSIA market, it is advisable to consider certifications that offer simpler requirement frameworks, easing product production and future certification. This approach is recommended because there is no guarantee that there will be a market price that justifies compliance with all the social and environmental sustainability criteria proposed by the more complex certification systems. Systems like ISCC EU, 2BSvs, and REDcert align with this approach.

If CORSIA SAF regulations become internationally mandatory, and the producer aims to supply an off-taker looking to enter this CORSIA SAF market, early certification, and verification of compliance with the CORSIA requirements become crucial. This guarantees future SAF off-takers that the product could be commercialized. Therefore, utilizing RSB EU certification for advanced biofuels is advisable, since it is the only scheme that allows coverage of additional sustainability criteria such as those of CORSIA SAF in the project's initial stages (before exporting to Europe for SAF production).

2.2.1 Certification for export: recommended approach

Among all evaluated certification systems and considering the current stage of the project, ISCC EU stands out due to its extensive experience and presence in Brazil. Moreover, ISCC EU covers all the regulations analysed through its diverse certifications, potentially streamlining certification implementation by maintaining consistent interaction with the same institution and stakeholders.

Nevertheless, the optimal certification strategy heavily relies on regulation evolution and application, as well as the adaptability and scope of different certifications during these changes. Remaining attentive and flexible, closely observing regulatory and market evolutions, is crucial for making informed and strategic certification decisions when necessary.