Feasibility Study

Adding value to renewable hydrogen from wastewater plants

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Av. Graça Aranha 1, 6º Floor
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International Center for Renewable Energies (Cibiogás)
Av. Presidente Tancredo Neves, 6731
Itaipu Technology Park -– Foz do Iguaçu
https://cibiogas.org/

Sanitation Company of Paraná (Sanepar)
R. Engenheiro Rebouças,1376
80215-900 Curitiba
https://site.sanepar.com.br/

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Summary

Tables

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Abbreviations

AD - Anaerobic digestion
AFSR - Anaerobic Fluidized Sludge Reactor
ANEEL - National Electric Power Agency
ANP - National Agency of Petroleum, Natural Gas and Biofuels
Bio-H_2 - Biohidrogênio
BM Canvas - Business Model Canvas
CAPEX - Capital Expenditure
CCF - Capital Charge Factor
CEHV - Special Commission for Debating Public Policies on Green Hydrogen
CENEH - National Hydrogen Energy Reference Center
CNAE - Brazilian Classification of Economic Activities
CNPE - National Council for Energy Policy
COD - Chemical Oxygen Demand
CPE - Collective Protection Equipment
CSTR - Continuous Stirred Tank Reactor model
DF - Dark Fermentation
DRI - Direct Reduced Iron
EPE - Energy Research Company
EPE - Energy Research Office
ESG - Environmental, Social, And Governance
FCFF - Free Cash Flow to Firm
FOB - Free on Board
GDP - Gross Domestic Product
GHG - Greenhouse Gases
IEA - International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
IPHE - International Partnership for Hydrogen and Fuel Cells in the Economy
IRR - Internal Rate of Return
LCOH - Levelized Cost of Hydrogen
LH_2 - Hydrogen Laboratory
LPG - Liquefied Petroleum Gas
MCTI - Ministry of Science, Technology, and Innovation
NPV - Net Present Value
OPEX - Operational Expenditure
OSW - Organic Solid Waste
PEM - Proton Exchange Membrane
PNE - National Energy Plan
PNH - National Hydrogen Program
PNH_2 - National Green Hydrogen Program
ProBio - Biogas Production Estimation Program
ProCac - Brazilian Fuel Cell Program
PPE - Personal Safety Equipment
PSA - Pressure swing adsorption
PtX - Power-to-X
R$ - Brazilian Real
R&D+I - Research, Development and Innovation
SANEPAR - Companhia de Saneamento do Paraná
SDG - Sustainable Development Goal
SIN - National Interconnected System
SPE - Special Purpose Entity
SWOT - Strengths, Weaknesses, Opportunities and Threats
TRL - Technology Readiness Level
UASB - Upflow Anaerobic Sludge Blanket
WGS - Water Gas Shift
WWTPs - Wastewater Treatment Plants

WORKING PACKAGE 01: Analysis of technological processes for the hydrogen production in wastewater treatment plants

HIGHLIGHTS

- Renewable hydrogen is poised to become a crucial energy vector within both the Brazilian and global energy matrices, finding diverse applications in sectors undergoing complex decarbonization. This contributes to the establishment of a green economy and a just, sustainable energy transition.
- In the State of Paraná, the rich history of innovation, coupled with ongoing investments in sewage collection and treatment infrastructure, creates a conducive environment for the implementation of innovative approaches to produce biogas and renewable hydrogen in wastewater treatment plants (WWTPs).
- In contrast to the Northeast region, where solar and wind energy generation potential is significant, Paraná's energy potential is intricately linked to biomass utilization, particularly through biogas.
- Catalytic reforms emerge as prominent pathways for utilizing biogas and generating renewable hydrogen. Compared to electrolysis, catalytic reforming requires less energy and water consumption. However, for it to be deemed a viable climate-friendly alternative, it is imperative to ensure that the energy sources for steam generation originate from renewable and clean sources, thereby minimizing carbon emissions.
- The maturation of the renewable hydrogen market necessitates progress across all technological pathways. Alkaline electrolysis exhibits the highest level of technological maturity (TRL [technology readiness level] = 8 to 9[1]); however, its market establishment hinges on the expansion of the renewable electrical matrix. On the other hand, catalytic reforming routes are positioned between TRL 6 to 8, demanding increased investments in the market, alongside the development of equipment and catalyst suppliers in the Brazilian market. This process is underway and gaining strength through international cooperation efforts.

1 HYDROGEN PRODUCTION IN WASTEWATER TREATMENT PLANTS

In the last decades, the climate crisis has been the driving force behind the restructuring of production systems, particularly concerning the strengthening of the share of renewable energy sources within the global energy matrix. Concurrently, the energy crisis prompted by the war in Ukraine further evidenced how fragile the current fossil-based energy system is. These two global crises inflict major challenges in the climate and energy security areas, demanding the society to both restructure the current system and stimulate the energy and economic transition movement.

In this context, hydrogen arises as a key element of the transition to a green economy that, in addition to decreasing climate change, promises to be a driving force in economic recovery and global energy security. On the

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[1] Technology Readiness Levels (TRL) are a method of estimating the technology maturity of Critical Technology Elements (CTE) of a program during the research, development, and deployment phase of the acquisition process. TRL 1: Basic principles observed and reported; TRL 2: Technology concept and/or application formulated; TRL 3: Analytical and experimental critical function and/or characteristic proof of concept; TRL 4: Component and/or breadboard validation in laboratory environment; TRL 5: Component and/or breadboard validation in relevant environment; TRL 6: System/subsystem model or prototype demonstration in a relevant environment; TRL 7: System prototype demonstration in an operational environment; TRL 8: Actual system completed and qualified through test and demonstration; TRL 9: Actual system has proven through successful mission operations.

other hand, renewable hydrogen is an integral part of the concept “Power-to-X” (PtX), which is characterized by a series of processes aimed at converting renewable energy into a variety of products, presenting itself as an alternative and sustainable route to fossil fuels and chemicals.

According to the International Energy Agency (IEA), in 2022, the global demand for hydrogen reached 95 million tons, a 5% growth compared to the previous year. A large part of this hydrogen is absorbed by traditional applications such as the chemical industry (60%) and in petroleum refining (40%) Less than 1% is used as a natural gas substitute, energy storage, combustion engine, gas turbine and fuel cell. Forecasts predict that, in 2030, the hydrogen demand for might reach 115 Mt, with 2 Mt derived from new hydrogen applications (IEA, 2023).

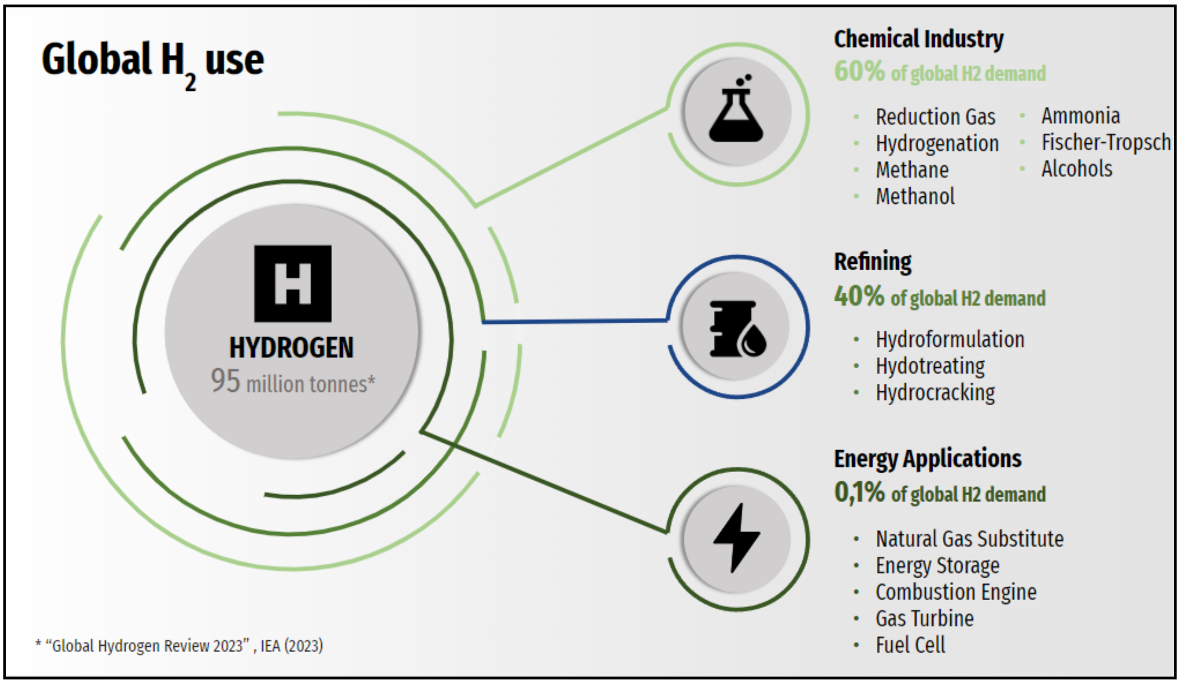

Figure 1 - Hydrogen applications and their respective demands
Source: IEA, 2023

The consolidation of the hydrogen market is related to the development of technologies and infrastructure around this energy source. Based on this, electrolysis appears as the technological route with the highest level of TRL. But to meet the large demand expected for the coming years, the market must develop other technologies that potentially lead to an increase of the supply of renewable hydrogen, even if the perspective of maturity is in the medium term.

A potentially new hydrogen production can be found in Wastewater Treatment Plants (WWTPs). Valuing the biogas produced in these locations, by transforming it into an asset with high energy density, will reinforce the development of the bioenergy chain both from Brazil and from Paraná. Regarding the environment, introducing this technology will minimize the environmental impact and the emission of two greenhouse gases (GHG).

Based on this, this working package has as purpose to develop a comparative analysis of the routes available for the hydrogen production in WWTPs, presenting the choice of the technological route to produce renewable hydrogen in Paraná's WWTPs. This analysis takes into consideration technical aspects, of scientific, economic and social development through the appreciation of the PtX chain. The result was built so that it can be replicated in other Brazilian regions with similar characteristics to those of the present case study.

2 CONTEXT OF BIOGAS PRODUCTION IN WASTEWATER TREATMENT PLANTS

The company Sanepar is responsible for providing water and sewage treatment services in the 346 municipalities of Paraná. To do so, it has 168 Water Treatment Plants (WTPs), as well as structures for capturing, preserving and distributing water and 266 Wastewater Treatment Plants (WWTPs); approximately 232 of which have an anaerobic treatment system (SANEPAR, 2021).

Among the technologies used for anaerobic treatment of sewage in the WWTPs of Paraná, there are the up-flow anaerobic sludge blanket reactors, the most used ones being the Anaerobic Fluidized Sludge Reactor (AFSR) and the Upflow Anaerobic Sludge Blanket (UASB). In Paraná, the use of UASB-type reactors stands out due to their good effluent treatment concerning removal of organic matter and solids, with low energy consumption and with no chemical products added (MIKI, 2010). However, the design of UASB reactors is constantly undergoing changes in order to achieve higher levels of efficiency to remove organic matter. In Sanepar's WWTPs, the modified UASB reactors are used to increase the communication between the three-phase separator and the decantation area; therefore, the greater distance between the synthetic canvas and the concrete promotes a change in the ascending low rate of the treated sewage, thus contributing to the development of high skim rates (ROSS, 2015).

Of the total 266 WWTPs in Paraná, 60 have modified UASB reactors, while 191 have AFSR reactors for sewage treatment. Currently, two (2) WWTPs have biogas energy usage. These WWTPs are located in Foz do Iguaçu and Curitiba and are destined to generate electricity and thermal energy for sludge drying. Between 2023 and 2024, the biogas energy usage is expected to be expanded to other 9 WWTPs, for electricity generation, recovery of dissolved methane and thermal energy for sludge drying.

Through the modified UASB reactors, based on the mean daily flow of effluents generated per day, it is estimated a production of 62,225 Nm^3 of biogas/day in Paraná's WWTPs (46,655 Nm^3 of methane/day). According to studies submitted by Sanepar, the biogas from the WWTPs has an average composition of methane between 60 and 85%, nitrogen between 10 and 25%, and carbon dioxide between 5 and 15%. The company also informs that biogas is not fully recovered in gaseous form, as a fraction of 30 to 40% remains retained in the liquid medium.

3 TECHNOLOGICAL ROUTES FOR HYDROGEN PRODUCTION

The choice of route for hydrogen production will depend on substrate availability, biogas characteristics, technological maturity level of the process and availability of suppliers in the market. In addition, environmental aspects are to be taken into consideration, such as the amount of emissions associated with a high process energy efficiency and high conversion rates.

3.1 Catalytic Routes

Thermochemical routes allow the recovery of methane (CH_4) and carbon dioxide (CO_2) of biogas through processes known as catalytic reforming, producing syngas, a mixture of H_2 and CO, which can be purified to obtain hydrogen. The applicability of biogas depends on a preliminary step of treatment to eliminate impurities, such as H_2S, NH_3 and siloxanes, which can inactivate the metallic catalysts used in the reforming process. Catalytic dry reforming, biogas steam reforming (bi-reforming) and tri-reforming stand out among the technological routes applicable to biogas.

The H_2/CO molar ratio of syngas depends on the biogas composition, the type of reforming selected, the catalyst and the operating conditions of the reaction. Finally, to obtain purified hydrogen, the syngas must undergo a purification process consisting of separating the hydrogen from the gaseous stream. Table 1 presents the particularities of each catalytic reforming route applied to biogas and Figure 2 the basic flowcharts representative of the processes, with the reaction stages and products obtained for the dry reforming, steam reforming, tri-reforming.

Table 1 - Particularities of catalytic reforming routes applied to biogas

	Dry Reforming	**Bi-Reforming**	**Tri-Reforming**
Reactions	$CH_4 + CO_2 \rightleftarrows 2H_2 + 2\,CO$	$3CH_4 + CO_2 + 2H_20 \rightleftarrows 8H_2 + 4CO$ $CH_4 + CO_2 \rightleftarrows 2H_2 + 2\,CO$	$CH_4 + ½\,O_2 \rightleftarrows H_2 + CO$ $CH_4 + CO_2 \rightleftarrows 2H_2 + 2\,CO$ $3CH_4 + CO_2 + 2H_20 \rightleftarrows 8H_2 + 4CO$
Biogas composition (CH_4:CO_2ratio)	CH_4: CO_2 = 1:1	CH_4:CO_2:H_2O = 3:1:2	CH_4/H_2O = 1 - 2.5 O_2/CH_4=0.25-0.55
Operating conditions (Temperature and Pressure)	T = 600 - 900 ºC P = 1 bar	T = 650 - 900 ºC P = 1 bar	T = 650 - 900 ºC P = 1 bar
Syngas composition (H_2:CO ratio)	1:1	2:1	2:1
Energy expenditure	High	Medium	Medium/Low
CO_2 conversion	High	Low	Medium
Advantages	● Conversion of two greenhouse gases, CH_4 and CO_2; ● Less complex reaction due to the single entry into the system (biogas); ● Research groups and pilot projects under development in Paraná.	● Syngas with H_2high content; ● Less coke deposition; ● Commercial technologies available in the European market.	● Syngas with high H_2 content; ● Low energy demand; ● Low carbon deposition on the surface of catalysts.
Disadvantages	● Catalysts under development (not commercially available); ● Low TRL; ● Syngas with low H_2 content (WGS required); ● High carbon deposition on the surface of catalysts.	● Methane-rich biogas required; ● Low CO_2 conversions;	● High complexity; ● Catalysts under development (not commercially available); ● Low TRL; ● Requires system control to balance endothermic and exothermic reactions.

Source: Prepared by the authors, 2023.

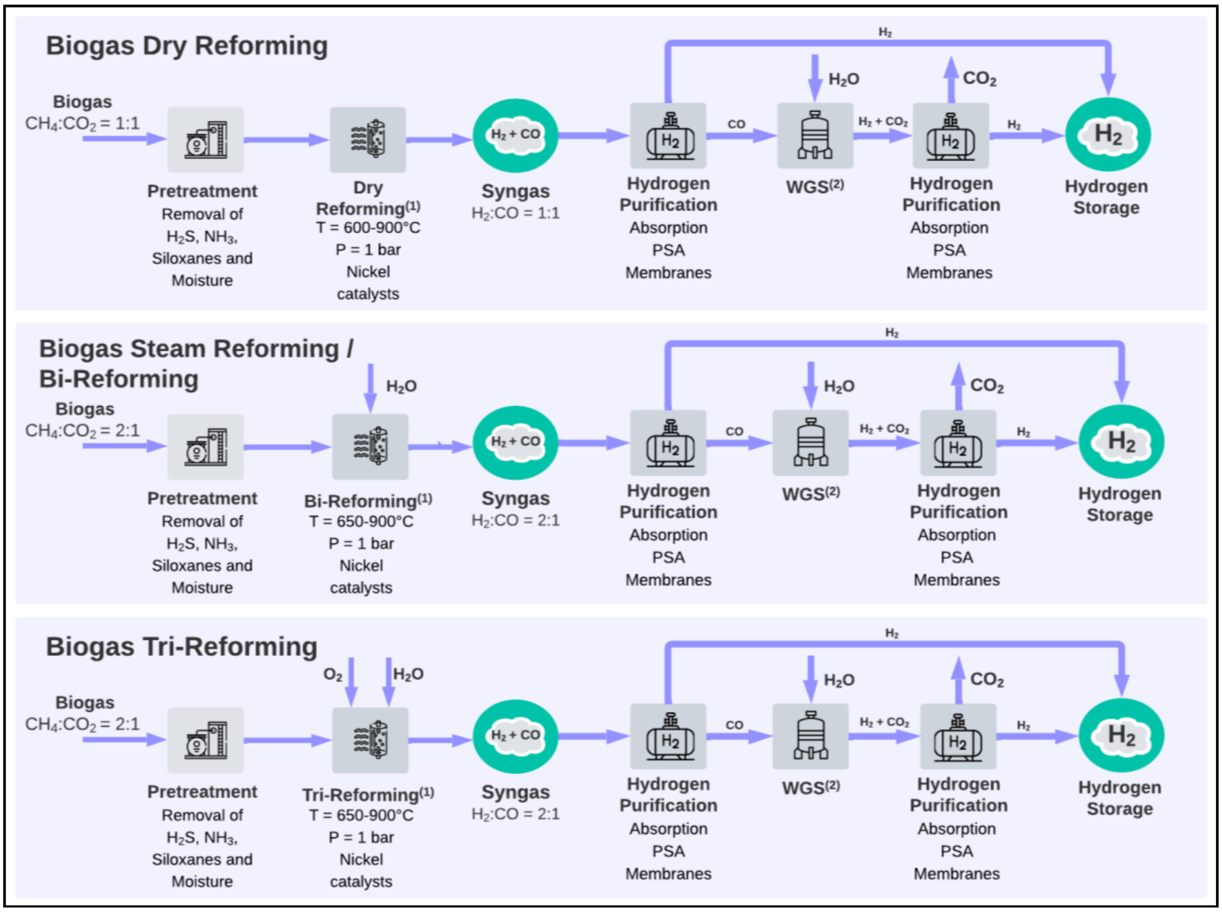

Figure 2 - Catalytic routes for hydrogen production from biogas
Source: Prepared by the authors, 2023.

3.2 Dark Fermentation

Dark Fermentation (DF) is a biological technological route to obtain bio-H_2 in wastewater from WWTPs. The process derives from intermediate steps in the anaerobic digestion (AD) route, which leads to biogas production. In the DF route, simple monomers such as carbohydrates, proteins and lipids, resulting from hydrolysis, are converted into bio-H_2, CO_2, butyrate, acetate and ethanol, by a consortium of facultative anaerobic bacteria, in the acidogenesis step.

Considering the complete AD cycle, the maximum reaction yield relative to the initial organic matter for conversion into bio-H_2 is 33%. Therefore, strains of modified microorganisms, additives or optimized reaction conditions must be applied to the process, aiming at the best DF performance and having as a goal the maximum production of bio-H_2, in relation to methane and other gases obtained in the following steps of acetogenesis and methanogenesis.

3.3 Plasmolysis

Plasmolysis is classified as a thermal process that, from wastewater or biomethane, aims to produce hydrogen and high value-added by-products. The technology consists of inserting a voltage and high-frequency field in plasma, to separate from carbon and nitrogen compounds contained in the substrate (such as urea, amino acids, nitrates and ammonium) into their elemental substances of C, N, H and O. The high frequency can be attributed to the use of renewable energies, such as solar or wind, for process sustainability, and temperatures above 5,000ºC. Inert gases are necessary for activating the plasma and ammonium and/or biomethane molecules, promoting an increase in plasma temperature from 15,000 to 20,000 ºC.

When applied to wastewater, hydrogen is recovered from the ammonia stripping, which separates substances into their elemental forms via plasmolysis. In the application for biomethane, together with electricity and acceleration of electrons, themolecule will be broken up into hydrogen and carbon (carbon black, graphene) in the plasma. Using both substrates, a source of catalyst and inert gases is required, and only plasmolysis applied to biomethane guarantees the production of graphene as high added-value by-products.

Although this technology has advantages and particularities that may be seen as a very promising route for hydrogen production in treatment plants, via effluents and/or biomethane, there are few studies found, even at research and development levels. In addition, the application of the process on a commercial scale is not practiced yet. So far, there are two pilot plants operating around the world with the technology developed by Graforce, built at the Waßmannsdorf Effluent Treatment Plant, corresponding to the Berliner Wasserbetriebe unit, in Germany (capacity of 3,000 L/h), and at the Hotel MOA Berlin, also in Germany, using natural gas as substrate.

3.4 Hydrolysis and gasification

The association of the hydrolysis and gasification processes of biomass from organic waste, including sludge from effluent treatment plants, is also an innovative route for the production of renewable hydrogen with three global steps. In a first step, carbon and steam are produced from organic materials through hydrolysis. In a second step, both products are transformed into syngases with the help of a gasification process. In a last and third step, hydrogen from the syngas is produced in a water-gas shift reaction of CO_2. The great advantage of this technology is that the process has an energy demand three to four times lower than electrolysis. It should be noted that this technology is not applicable to biogas produced in WWTPs, as the main input of the process being sludge.

There are few studies found even at research and development levels applying hydrolysis and gasification for hydrogen production. In addition, the application of the process on a commercial scale is not practiced yet, evidencing the still immature development of the route in the market. So far, BlueFLUX is the company that commercializes the technology.

3.5 Conventional route - electrolysis

Water electrolysis is the green hydrogen production process with the highest degree of technological maturity; thus, it has gained considerable space in the recent debate on the subject. Generally speaking, electrolysis separates hydrogen and oxygen from water using a renewable source of electricity. Depending on the different types of electrolytes, we can name three main types: alkaline electrolysis, PEM (Proton exchange membrane) and high temperature electrolysis.

Steam electrolysis at high temperatures has a TRL between 1 and 3, with technologies still under development and in formulation to test feasibility; PEM and alkaline electrolyzers between 9 and 10, with high technological maturity, since they are already validated and qualified for commercialization (IEA, 2023).

The main advantage shared between all electrolysis technologies is the low emission of greenhouse gases (GHG) during the process. However, this route is energetically intensive (60 to 70 kWh/kg of H_2). In addition, the water used must undergo reverse osmosis processes, consuming elevate amounts of water and energy. However, it is important to highlight the possibility of reusing the water after H2 production to reconvert into more H2. Additionally, when analyzing the life cycle of electrolysis, attention should be paid to emissions arising from the production chain of electrolyzers, which still have a considerable environmental impact (CHO et al., 2023).

4 COMPARISON AND DECISION MATRIX OF THE TECHNOLOGICAL ROUTE

The consolidation of renewable hydrogen production depends on the systemic assessment of production chains associated with available technologies, aiming to prioritize routes with lower GHG emissions and social cost, including environmental impacts and economic factors. Although electrolysis is the most widespread process, the high energy demand (60 to 70 kWh/kg of H_2) and the pure water requirement poses challenges to this route and opens up an opportunity to explore other technologies.

In the previous topics of this document, the thermal (catalytic, plasmolysis and combination of gasification and hydrolysis) and biological routes for the hydrogen production from wastewater treatment plants and their by-products (biogas) were presented. For the purposes of this study, the choice between the routes was based on the following main criteria: the characteristic of the biogas from the WWTPs, the requirements of the processes in relation to the ideal composition of the biogas and/or biomethane and the level of technological maturity, prioritizing technologies that are readily available and competitive in the market.

Catalytic routes, for instance, provide greater efficiencies in obtaining renewable hydrogen (up to 99%), with lower energy demands (10 kWh/kg of produced H_2) in comparison to electrolysis. As described, the biogas produced at Sanepar's WWTPs has a composition from 60% to 85% of CH_4 and from 5% to 15% of CO_2. Comparing the characteristics of biogas from WWTPs with the stoichiometric requirements of the two catalytic processes, we conclude that the technology must process a biogas with a high content of methane (CH_4) and low carbon dioxide (CO_2).

Therefore, in dry reforming, biogas would need to reduce the CH_4 content to achieve an ideal molar ratio for processing (CH_4:CO_2 = 1:1). Another challenge is the production of hydrogen-poor syngas (H_2:CO = 1:1); thus, additional steps of Water Gas Shift are recommended for obtaining higher yields. Furthermore, its level of technological maturity is low, as there are no commercial catalysts and industrial-grade reformers in the market. Currently, this technology is in great expansion at research and development levels, including research groups dedicated to the topic in the state of Paraná.

The tri-reforming of biogas is not consolidated in the national and international market in terms of equipment and catalysts either. The process is in full expansion in terms of research, development and innovation (R&D+I) and presents a high complexity related to the stoichiometry of the process. As evidenced by the stoichiometric requirements, purified biogas (biomethane), water and oxygen are required to produce H_2:CO syngas (2:1).

Steam reforming stands out in research and market levels for obtaining hydrogen as a route of high technological maturity, since there already is experience with reformers and catalysts destined for natural gas for the grey hydrogen production. Since the biogas from WWTPs is low in CO_2 and rich in CH_4, proper purification and treatment makes the characteristics of renewable gas similar to natural gas, allowing the application of steam reforming. Biogas treatment to remove impurities is a requirement for all catalytic routes; however, steam reforming does not require depleting the biogas with CO_2 (dry reforming) and external source of O_2 (tri-reforming), in addition to providing higher hydrogen yield.

With regard to alternative routes for the production of renewable hydrogen, dark fermentation, plasmolysis and hydrolysis, the common point between them is a greater need to develop the maturity of the technologies to be fully introduced in the market. Dark fermentation, for example, is a route that is exclusively at the R&D level. While plasmolysis and hydrolysis have limited experience from few suppliers, there is no competitive and open market for these technologies.

Dark fermentation, despite the low operational cost and toxicity for obtaining hydrogen in high molar ratios (up to 4 molH_2/mol of $C_6H_{12}O_6$), requires high concentrations of organic matter and fine-tuning of the process. With this, to enable the satisfactory production of biohydrogen in WWTPs, co-digestion with other substrates rich in organic matter, such as sludge from WWTPs or solid organic waste, which are not part of the object of study, would be essential, in addition to adequate process conditions.

Plasmolysis is characterized as a high-yield technological route for hydrogen production (4 kg of H_2/kg OF CH_4) from biomethane. The advantages of this technology are related to the lower energy demand when compared to electrolysis (one-fifth of the energy), in addition to obtaining a valuable co-product, carbon in the form of graphene. However, there are no guarantees of high purity of this by-product and the route also requires the use of catalysts, which may not yet be available on the market. The low energy consumption is validated only when the methane and/or hydrogen produced in the process are used as input for plasma activation and biomethane and/or ammonium molecules. Currently, there is only one company commercializing the technology in the market, which holds a patent on the functionality of the process. From the marketing point of view and potential replicability of this process for other WWTPs, we identified uncertainties linked to reduced competitiveness, represented by the lower number of suppliers, and the reduced scales of the pilot plants in operation in Germany.

Regarding the technological maturity level (TRL), technology readiness level and manufacturing readiness level (MRL) of the exposed routes, the steam reforming of biomethane is classified with TRL 6 to 8. It is in transition between pilot and commercial scale, with increasing commercialization by European companies and, even in the Brazilian market, evidencing the scalability of the technology from prototypes. High temperature steam electrolysis has a TRL between 1 to 3 and is among the technologies under development and formulation for feasibility testing; PEM electrolyzers between 5 and 7, in demonstration and development; and alkaline already have high technological maturity between 8 and 9, since they are already validated and qualified for commercialization. plasmolysis consolidates between 4 and 6, with some prototypes already being tested in Germany; the dark fermentation and combined process of hydrolysis and gasification between 3-4 and 3-5, respectively.

From the above, in order to implement the decision on the technological route for the production of renewable hydrogen in Paraná’s treatment plants, a comparison and decision matrix between the technologies is described in Figure 3, comparing them with electrolysis, the route of greater TRL and development in the renewable hydrogen production market. Among the catalytic processes, steam reforming was the technological process chosen for comparison purposes, since it is the only one among the described thermochemical ones (dry, steam and autothermal reforming) available in the market at commercialization level.

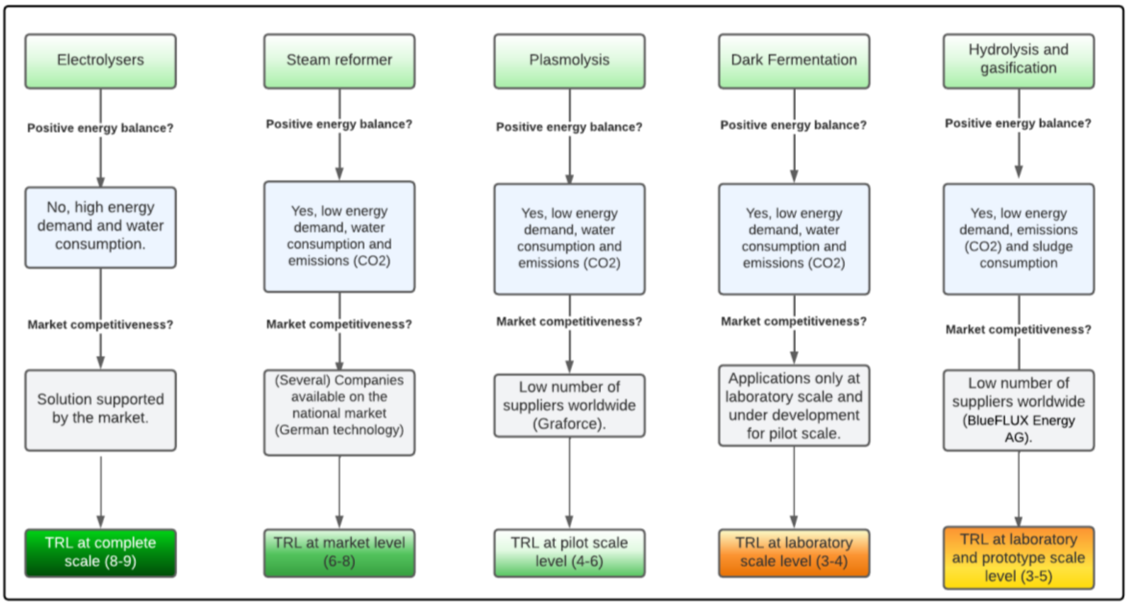

Figure 3 - Comparison matrix of technological routes for hydrogen production
Source: Prepared by the authors, 2023.

It is observed in Figure 3 that, currently, steam reforming is one of the technological routes with the greatest technological maturity and available on the market. The route has low energy consumption, low levels of greenhouse gas emissions and low water consumption when compared to electrolysis. Also, there already is commercialization of German technology of this route in the domestic market. Plasmolysis, dark fermentation and the combination of hydrolysis and gasification also stand out with low water consumption and greenhouse gas emissions; however, such technologies are not established yet in the market and present low competitiveness in relation to suppliers and large-scale applicability.

The presented criteria and the commercial availability of reformers and catalysts encourage the choice of **steam reforming** as a technological route for the hydrogen production from biogas in Paraná's WWTPs. In Europe, some companies are consolidating the steam catalytic reforming of biogas/biomethane, such as the German group BtX energy GmbH, the Swedish Metacon group and the company Helbio S.A. The Metacon group has a patent that includes a steam reformer and PSA technology for obtaining hydrogen from natural gas, biogas, liquefied petroleum gas (LPG) and ethanol. Yields presented by the technology are greater than 99.9%. The company Helbio S.A., from Greece, has patented catalysts and reformers applicable to biogas. The group's differential is the optimization of the reactors aiming at lower energy consumption and easy heat exchange during the reaction process.

To carry out the choice and evaluate the viability of steam reforming for hydrogen production in Paraná's WWTPs and at federal level, a SWOT analysis will be presented in the next section with the main information of the route. The analysis opens up discussions that encourage the leverage of this technological route in the national renewable hydrogen production matrix, since at industrial levels it is not yet applied in the country.

5 SUMMARY OF MAIN CHALLENGES AND RECOMMENDATIONS

From the information gathered in this study, a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was developed. The analysis of the SWOT matrix allows the visualization of the main competitive advantages that must be used and the main challenges to be overcome when implementing projects that aim at the use of steam reforming for the hydrogen production in Paraná's WWTPs.

In this analysis, the characteristics of the chosen technology were categorized into "strengths" and "weaknesses", which bring together internal factors in which the object of analysis has a certain influence or direct management, and "opportunities" and "threats", which bring together external factors about which the object of analysis has little or no capacity for direct influence. Table1 lists the main positive and attention points, arranged in the categories of the SWOT matrix.

Table 2 - SWOT analysis of hydrogen production from catalytic reforming of biogas

Internal factors	
Strengths	**Weaknesses**
Production of hydrogen-rich syngas (H_2:CO = up to 3:1)	High CO_2 emissions to the atmosphere (9 kg of CO_2/kg H_2 produced)*
High yields (conversion above 95%)	High cost of catalysts
Low energy cost (less than 10 kWh/kg H_2 produced)	Harmful effect of contaminants present in biogas on catalysts (e.g., H_2S, moisture and siloxanes)
Cost of producing the molecule six times lower than electrolysis	Consolidated supply chain for large scale. Small and medium scale cannot acquire inputs (example: catalysts)
Low consumption of pure water	
Does not require enrichment of biogas with CO2 and/or external source of O2	
Technology with potential application to other WWTPs in Brazil and to biogas purified from other substrates	
New distributed energy arrangements promoting decentralized hydrogen production	
Mitigation of climate impacts, contributing to the sustainable development goals (SDGs)	

Internal factors	
Strengths	**Weaknesses**
Possibility of using CO_2 and residual gases from the purification processes of biogas and hydrogen (off-gas). This compensates the process GHG (9 kg CO_2/kg H_2 produced), tending towards carbon neutral or negative*	
External factors	
Opportunities	**Threats**
High availability of biogas plants in WWTPs for the production of green hydrogen at the state level, with high concentrations of CH_4 and low CO_2 applicable to the process.	Lack of national suppliers for commercialization of technology and catalysts
Technologies and catalysts available on the international market applicable to methane-rich biogas	Low availability in the market of trained professionals for renovation technologies
Consolidated Brazilian experience in the introduction of biofuels in the national energy matrix	Low market adherence to alternatives to electrolysis for hydrogen production
Established international cooperation with holding countries and with extensive knowhow in reforming technology, such as Germany	Few cases on a large scale applicable to biogas
Presence of international companies and suppliers of equipment and catalysts for steam reforming	Development of the legal regulatory framework for hydrogen at the federal level
Diversity of research centers and laboratories in the country and in the state dedicated to the subject	There is no reference value for low-carbon hydrogen, and it is still uncompetitive with fossil hydrogen.
Legal regulatory framework for hydrogen in the state of Paraná and incentive programs	Lack of infrastructure and logistics necessary for the flow of hydrogen
	Currency changes and lack of confidence for innovative investments

* The GHGs emitted during the production process can be compensated and mitigated during the process by using CO_2.

Source: Prepared by the authors, 2023.

Regarding the internal factors, the main advantage of steam reforming is its low energy demand (10 kWh/kg H_2), when compared to electrolysis (80 kWh/kg H_2). This is a characteristic to be explored so that this technological route gains visibility in the market and consolidates it as a viable route for hydrogen production. Combined with reduced energy consumption, steam reforming offers high conversion rates, producing a hydrogen-rich syngas (H_2:CO = 3:1).

The external factors that can catalyze the implementation of the technology in Paraná are the high availability of resources related to the wide coverage of sewage treatment services and the high availability of biogas in the state's WWTPs. In addition, there is a growing political interest in the matter, both at state and federal levels, which should encourage regional initiatives regarding hydrogen. Finally, for these initiatives to be successful, the potential of international cooperation must be used as a tool for tropicalization of technologies available in the international market since Brazil lacks national suppliers of equipment and catalysts.

The issue of the competitiveness of renewable hydrogen and neutral carbon, together with the asymmetry of information and absence of normative standards, does not exist only in Brazil, but also on a global scale, and is configured as one of the most critical factors for the development of the hydrogen market. In this sense, the multilateral joint work between countries with technology, such as Germany, and countries rich in energy resources, such as Brazil, must also be strengthened in the political sphere through the socio-environmental commitment by governments and other institutions, as well as private initiative, aiming at attracting qualified investments.

In view of the challenges presented, the main recommended actions for establishing steam reforming as a route for obtaining hydrogen in the State of Paraná are highlighted below:

1 To reduce the carbon footprint of the technology, the use of renewable energy for steam generation should be predicted, preferably by using biogas. In addition to predicting routes for capturing CO2 waste, aiming at its incorporation as a by-product and making the process carbon negative.

2 Strengthening research, development and innovation (R&D + I) in the State of Paraná, by attracting investments and transferring international knowledge, aimed at developing more efficient and cheaper catalysts for processing biogas in steam reformers.

3 Training of human resources with technical knowledge on the subject and construction of a knowledge network and a database that reduces the asymmetry of information about the catalytic reforming.

4 Strengthening public policies, building a regulatory framework and providing financial instruments to leverage private investment around hydrogen in the state.

5 Stimulating the implementation of pilot projects in the state, aiming to take advantage of the effects of large-scale production as a strategy to reduce the costs of technologies, becoming a long-term strategy for increasing the competitiveness of low-carbon hydrogen in the market.

6 Promoting international cooperation as a strategy for exchanging technologies and knowledge on best practices for hydrogen production, as a strategy for standardizing industrial norms and accelerating the development of national industry.

6 FINAL CONSIDERATIONS

In order to align the peculiarities of each process with the characteristics of biogas from WWTPs, high concentration of methane and low carbon dioxide, information was gathered on the catalytic (dry reforming, steam reforming and tri-reforming), biological (dark fermentation) routes, plasmolysis and hydrolysis of hydrogen production. The level of technological development and the state of consolidation in the market of each one of them were explored.

When considering the technological maturity level, low CO_2 requirement and high CH_4 requirement, commercial availability (of reformers and catalysts on the market to obtain hydrogen), the biomethane steam reforming or bi-reforming was the technological route with greater adherence to the project demands. Thus, this catalytic route is recommended for hydrogen production from biogas in Paraná's WWTPs. A SWOT analysis of steam reforming was carried out to support this hypothesis. According to this analysis, opportunities and strengths were identified in this technology that evidence the development of a sustainable hydrogen economy, combined with numerous benefits for Brazil.

When comparing steam reforming to electrolysis (a route commonly applied to obtain hydrogen worldwide), a low energy consumption (in kWh/kg H_2) is observed, also leading to a lower cost per kg of molecule produced (1.50 - 2.00 euros/kg of H_2; electrolysis: 9 euros/kg of H_2)[2]. In addition, there is also the possibility of mitigating greenhouse gases and taking advantage of CO_2 from the process, directing the process towards neutral and/or negative carbon.

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[2] Graforce, available on: https://www.graforce.com/en/achievements/hydrogen-production

WORKING PACKAGE 02: Estimation of potential hydrogen production in wastewater treatment plants in the state of Paraná and analysis of avoided greenhouse gas emissions

HIGHLIGHTS

- Renewable hydrogen emerges as a crucial ally in the endeavor to reduce greenhouse gas (GHG) emissions, fostering the transition towards a global emission-neutral energy matrix.
- Brazil's competitive edge in the renewable hydrogen chain is evident due to its diverse opportunities for generating this energy vector, shaped by regional inclinations and the availability of raw materials.
- In the state of Paraná, biomethane steam reforming stands out as a competitive method for producing renewable hydrogen in wastewater treatment plants (WWTPs). To be deemed a viable climate-friendly alternative, it is imperative to guarantee that the energy sources for steam generation are derived from renewable and clean sources, thereby minimizing carbon emissions.
- The theoretical potential for hydrogen production through biomethane steam reforming in WWTPs in Paraná is estimated at 211,978 Nm³/day of hydrogen, from 62,225 Nm³/day of biogas. With such, there are the mitigation of 320,000 tCO2e/year;
- With the environmental attributes and practices for minimizing atmospheric emissions, using the 62,225 Nm³/day of biogas to the hydrogen production at the Paraná WWTPs, will be an annual compensation rate of 13,570,875 trees, corresponding to 40,000 hectares of forest;
- The natural gas steam reforming emits 9 kg CO_2 and demands 10 kWh of energy for each kg of produced hydrogen. Besides, using biomethane, the emissions are around 5 kg of CO_2 with an energetic demand of 1,14 kWh for each kg of renewable hydrogen produced;
- By channeling biogas towards hydrogen production, there is a potential mitigation of 320,000 tCO2e/year of greenhouse gases (GHG).

1. PRESENTATION

Currently, the supply of renewable hydrogen is limited to small projects, representing about 0.3% of world production in 2021 (IEA, 2022). The expectation is that the supply of this energy source will expand in the coming years due to its role in the climate agenda, in which it operates as an instrument to achieve the decarbonization targets set for the years 2030 and 2050.

Due to its advanced technological maturity, there is an excellent market expectation around electrolysis. However, there is a great challenge linked to increasing the installed capacity of electrolyzers, which, to meet the targets, must rise from 500 MW to 5 TW by 2050. In addition, the operation of the electrolyzers requires a high supply of renewable energy with steady generation, with an annual energy demand of 21,000 TW/h being projected (IRENA, 2023).

Achieving such ambitious goals is a great challenge for the market. It can find alternative technologies with lower energy demand as an ally, aiming to complement the future supply of renewable hydrogen and make its costs a product with high added value, bringing economic, environmental, and social value to the entire chain.

This working package aims to present the potential for hydrogen production in WWTPs in the State of Paraná and the estimate of avoided greenhouse gas (GHG) emissions through biomethane steam reforming. These two products will be detailed in two chapters, as shown in Figure 4.

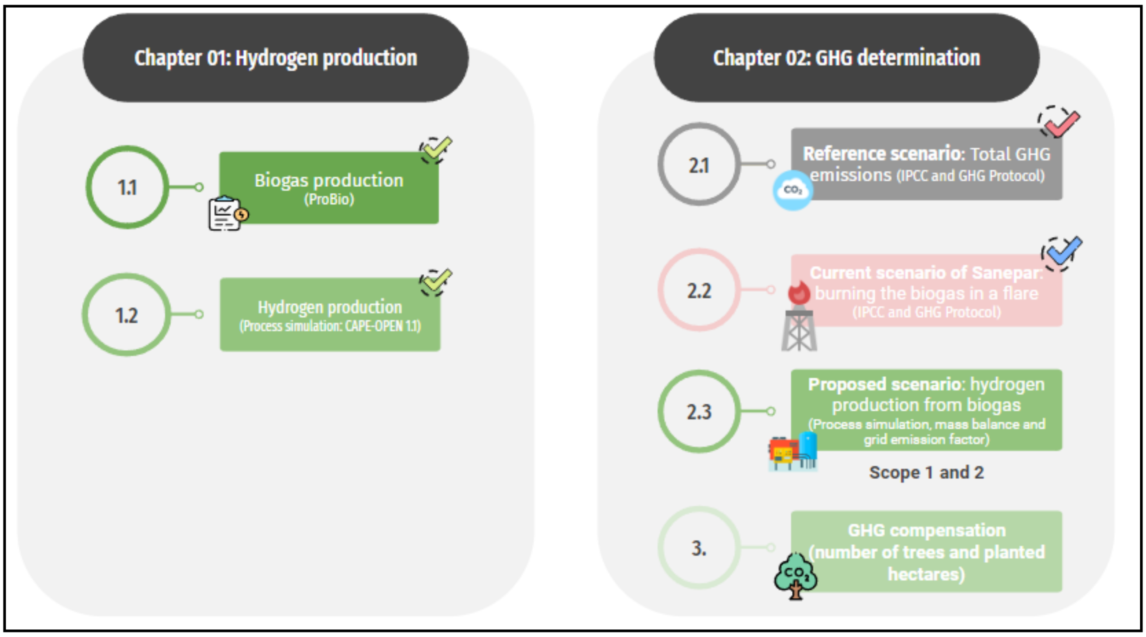

Figure 4 - Flowchart of steps involved in Chapter 1 and 2 of the study

Source: Prepared by the authors, 2023.

1.1 Chapter 1: Hydrogen production potential

This chapter aims to estimate the theoretical potential of renewable hydrogen production in WWTPs in the State of Paraná, using biomethane steam reforming as a technological route, as shown in Figure 5.

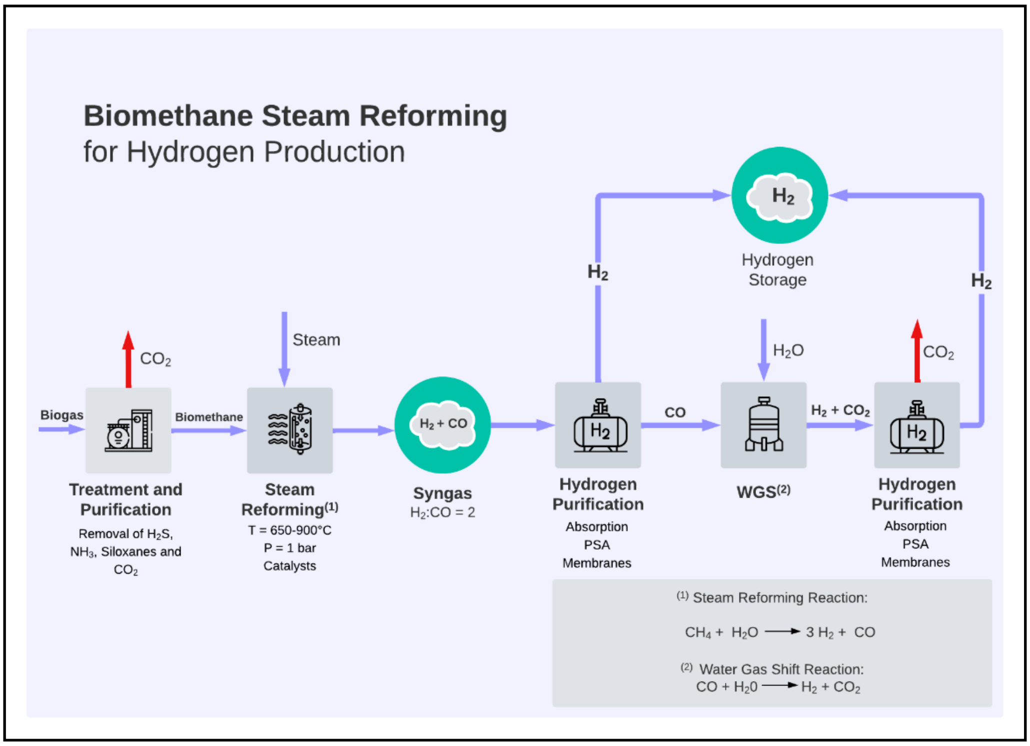

Figure 5 - Flowchart of steam reforming
Source: Prepared by the authors, 2023.

Currently, Sanepar is responsible for operating 263 sewage treatment stations in the State of Paraná, of which 231 have anaerobic effluent digestion systems with UASB[3] and ASFR[4] reactors.

First, an estimate of the theoretical potential of biogas and methane production was obtained using the computational software ProBio - Biogas Production Estimation Program[5] in UASB Reactors version 2.0, which is free and available for download. The software allows calculating the volume of biogas and methane produced in UASB and ASFR systems, having as input data: sewage flow (Nm^3/ day), chemical oxygen demand (COD, mg/L), COD removal efficiency (average value used of 75%) and average solids production coefficient of WWTPs (kg total solids/kg of COD removed).

The State of Paraná offers an excellent environment for the introduction of technologies that explore the use of biogas for the production of renewable hydrogen. Currently, Sanepar is responsible for the treatment of sewage in 266 units in the state, with configuration of UASB reactors and ASFR. Despite the different dynamics of effluent treatability, the production potential and biogas characteristics are similar in both reactors.

Based on sewage flow data (Nm^3/day), chemical oxygen demand (COD, mg/L), COD removal efficiency (average used value of 75%) and average solids production coefficient of wastewater treatment systems sewage

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[3] Upflow Anaerobic Sludge Blanket

[4] Anaerobic Fluidized Bed Reactor

[5] ProBio 2.0 is a biogas production estimation program applicable to effluents from sewage treatment plants, aimed at analyzing the available potential for energy use in reactors. The program was developed through a technical and scientific partnership between Sanepar and the Federal University of Minas Gerais (UFMG). It is an executable computational program, thus dispensing with its installation on the computer. Available for download at the following email addresses: Desa UFMG and Sanepar.

(total solid kg/kg of COD removed), the estimation of biogas and methane production rates in UASB and AFSR reactors was carried out based on the computer program “ProBio - Biogas Production Estimation Program in UASB Reactors[6]. Version 2.0 of ProBio is free and available for download[7].

The estimated biogas production in the WWTPs of the state of Paraná was of 62,225 Nm^3/ day. The state has twelve treatment plants that can produce biogas above 1,000 Nm^3/day. In addition, 150 WWTPs have an estimated potential of less than 100 Nm^3/day. This indicates that the potential for biogas production is representative of the sanitation sector. However, with the number of units spread across the state, the volume of biogas is decentralized.

The estimate of the biomethane production potential was based on the estimated volume of biogas (62,225 Nm^3/day), with a composition of 85% CH_4 and 15% CO_2, from which a mass balance was carried out for a system of biogas purification with 98% efficiency. The estimated volume of biomethane is 55,556 Nm^3/day.

Finally, the estimation of hydrogen potential used the process simulation software CAPE-OPEN 1.1 as a tool The simulation used the chemical equilibrium model of reactions as a methodology, in which a state of chemical equilibrium is assumed, such that the reaction system presents itself in its most stable composition (with lower free energy). For this, the primary assumption is that the rates of steam reforming and WGS reactions are fast enough, and the residence time is long enough to reach the chemical equilibrium state[7].

Some assumptions were also considered[8] and from the simulation of the process using data from three WWTPs, obtaining a ratio for the production of hydrogen per unit volume of processed biomethane (H_2/CH_4 = 3.82 - Nm^3/h). The coefficient was used to estimate the potential of the other WWTPs.

Based on the simulations, the estimated potential for hydrogen production in the state of Paraná from sewage and from treatment stations is 211,978 Nm^3/day, which is equivalent to about 859,689 tons per year of renewable hydrogen. According to the Energy Research Office (EPE), Brazil has eleven refineries authorized by the National Agency of Petroleum, Natural Gas and Biofuels (ANP) to produce hydrogen, with a total capacity of 76,650,000 tons per year.

Figure 6 compares the Regional Offices of Paraná about the estimated annual hydrogen production. It is observed that the regional GTESG has the most significant potential (25,144,510 Nm^3/ year), followed by GRMA (8,120,799 Nm^3/year) and GRPG (7,072,593 Nm^3/year). In these regions, municipalities with WWTPs with high potential for biogas production are concentrated, such as Curitiba, Maringá, and Ponta Grossa.

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[6] ProBio 2.0 is a biogas production estimation program applicable to effluents from WWTPs, aimed at analyzing the available potential for energy use in reactors. The program was developed through a technical and scientific partnership between Sanepar and the Federal University of Minas Gerais (UFMG). It is an executable computational program, thus dispensing with its installation on the computer.
Available for download at the following email addresses: Desa UFMG and Sanepar.

[7] The composition of the supply chain is CH4 (95%), H2O (steam) (1%) and N2 (4%). The whole process operates under pressure of 1 bar. The Reform reactor has CH4 conversion greater than 95% and the Reactor of Water Gas Shift shows CO conversion is greater than 95%.

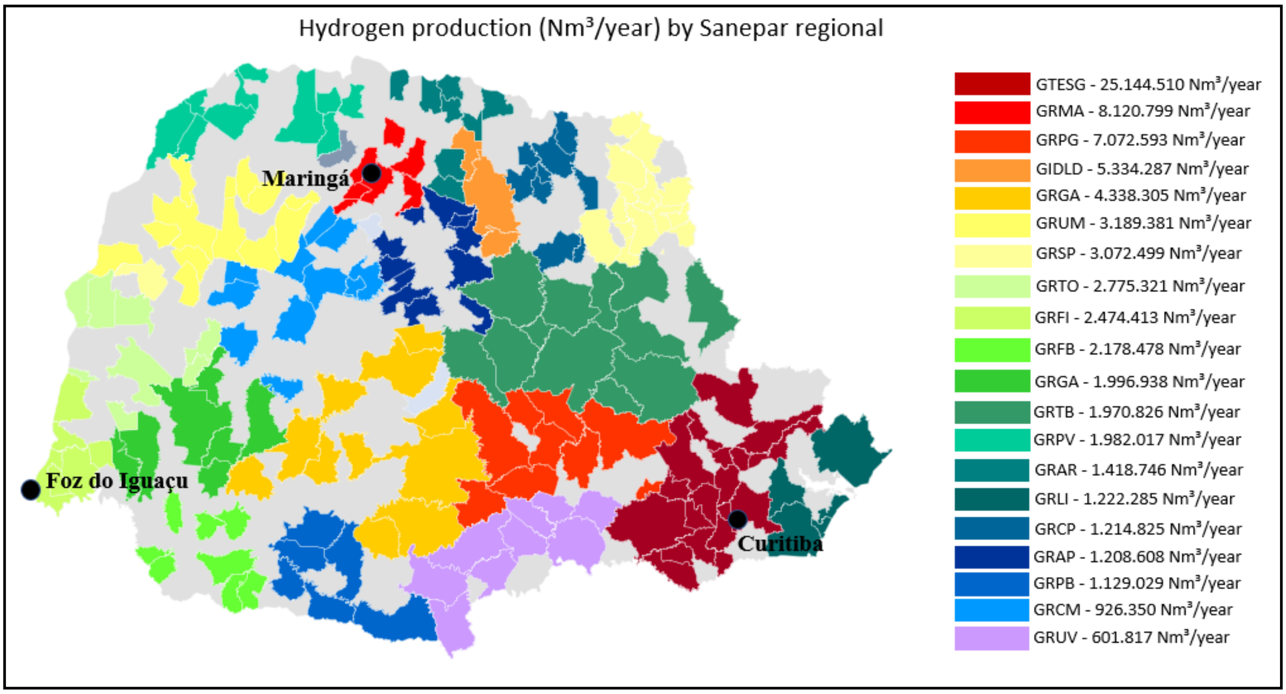

Figure 6 - Distribution of hydrogen production potential in the state of Paraná, according to Sanepar's Regional Offices

Source: Prepared by the authors, 2023.

1.2 Chapter 2: Analysis of avoided greenhouse gas emissions

The production of renewable hydrogen is one of the allies in the decarbonization of the global economy, according to the recent publication by IRENA, "World Energy Transition Outlook 2023: 1.5ºC Pathway" hydrogen and its derivatives have the potential to contribute up to 12% of the mitigated CO_2-emissions of until 2050. Emissions from the production of H_2 from biogas are neutral, and may result in harmful emissions, according to the mitigation strategies adopted throughout the process.

In this study, the intensity of emissions produced and avoided was estimated in the renewable hydrogen production chain from the biomethane steam reforming, which includes the stages of biogas purification, steam generation from biogas, production, and hydrogen purification. In addition, GHGs referring to a hypothetical reference scenario (baseline) were also estimated, where biogas would be directly released into the atmosphere without treatment and a biogas flare scenario[8]. Figure 6 exemplifies the analyzed scenarios and emission points.

GHG emissions were also classified according to their nature, which can be direct (Scope 1, from sources that belong or are controlled by Sanepar) or indirect (Scope 2, resulting from activities that occur in sources owned or controlled by another organization).

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[8] Techniques currently performed by Sanepar.

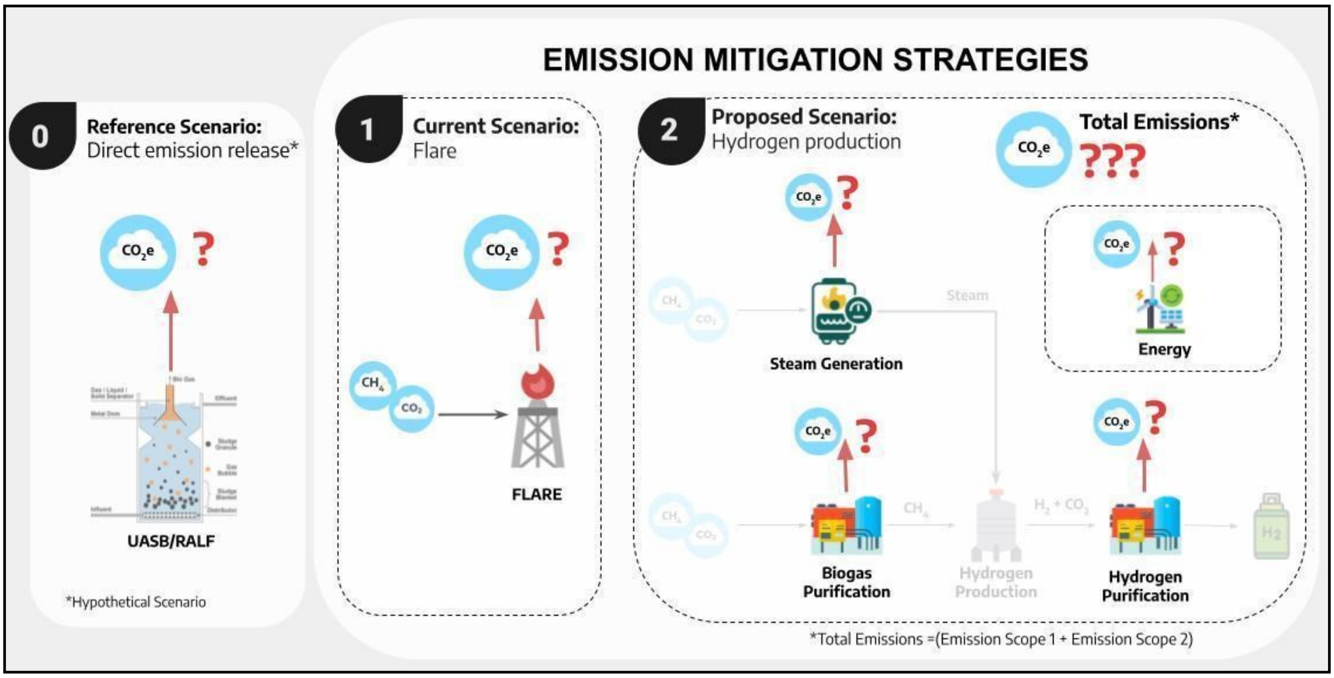

Figure 7 - Greenhouse gases mitigation with different scenarios

Source: Prepared by the authors, 2023.

Definition of calculation borders

The calculation boundaries for GHG estimation were determined between the **biogas production and hydrogen production**, taking as reference the peculiarities of the technological route of biomethane steam reforming. Based on this scope, the limits determined "from cradle to gate" for calculation boundaries, are from biogas to hydrogen[9].

The portions of direct emissions associated with each stage of the process of obtaining hydrogen were analyzed: (1) biogas production and steam generation, (2) biogas purification, and (3) hydrogen production and purification. Scope 2 emissions related to electricity demand were calculated based on National Interconnected System (SIN) data. Finally, the avoided emissions were obtained from the total emissions associated with the hydrogen production process, as shown in Figure 7.

The results referring to the mitigated emissions in the hydrogen-obtaining chain were compared to the biogas burning system in Flare, currently adopted in Sanepar's WWTPs. The methodologies used for calculations were based on the Intergovernmental Panel on Climate Change (IPCC), Brazilian GHG Protocol Program and mathematical process simulation. Table 3 presents the assumptions and calculation methodology used for each point in Figure 7.

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[9] Emissions related to ASFR treatments not related to UASB and RALF reactors (example: aerobic treatment of effluents, WWTP treatment of sewage sludge, shallow aerobic lagoons, facultative lagoons, anaerobic filters, pits and ditches, aerated lagoons, aerobic systems with anaerobic sludge digestion), were not considered in the carbon balance.

Table 3 - Scopes of CO2e emissions

	Stages	Assumptions	Calculation methodology
Scope 1	1. Biogas production and steam generation from the thermal energy produced	1. Biogas production in UASB/ASFR reactors, with the composition: 60 to 85% methane; 5 to 15% carbon dioxide, 10 to 25% nitrogen, 0 to 2% oxygen, and 1000 to 5000 ppm hydrogen sulfide. 2. Part of the biogas is used to generate steam used in biomethane reform.	Proprietary spreadsheet based on the IPCC (2019) and GHG Protocol (2013).
	2. Purification of biogas into biomethane	3. Purification of biogas to produce biomethane with 95% purity using a system with 98% efficiency.	Proprietary spreadsheet, performing the mass balance of the purification system.
	3.Hydrogen production and purification	4. Biomethane steam reforming (95% CH_4). 5. Hydrogen purification using systems such as Pressure Swing Adsorption (PSA) (GHG emissions will be accounted for - CO2e).	Proprietary spreadsheet, using the results of the process simulation in the *Software* CAPE-OPEN.
Scope 2	4. Demand for electricity from the biogas purification system and the hydrogen production system	6. Emissions from the electrical energy of the grid demanded by the process. The regulated energy market serves all of Sanepar's WWTPs.	Proprietary spreadsheet using the emission factor of the Brazilian grid.
		The portfolio of Companhia Paranaense de Energia Elétrica (COPEL) indicates that the grid is composed of: 79% hydroelectric, 17% wind, and 4% thermoelectric (Information shared by Sanepar).	

Source: Prepared by the authors, 2023.

Greenhouse gases (Scope 1)

Biogas production and steam generation

The estimated emissions of tons of carbon dioxide equivalent (tCO_2e) were first determined in the biogas production stage, based on the volume produced in the WWTPs (22,712,125 Nm^3/year), biogas composition (85% methane) and physicochemical characteristics of methane (density: 0.00067 t/m^3). The second step was determining the emissions associated with biogas as a thermal energy source for steam generation. The steam demand of the reforming and Water Gas Shift was calculated according to the stoichiometry of the reaction and, from it, the energy demand and the necessary flow of biogas to feed the steam generation system were calculated. The input parameters of the calculation considered fugitive emissions and flaring efficiency of 10 and 90%, respectively.

With the mentioned data, the production value of CH_4 was obtained (t CH_4/year) at baseline, which was converted into carbon dioxide equivalent (CO_2e) through an emission factor 28 times higher than that of CO2[10], the fugitive emissions (tCO2e/year) and emissions from burning efficiency (tCO_2e/year), thus identifying the total amount of avoided emissions (tCO_2e/year).

Biogas purification

In the biogas purification to reach 95% methane purity for steam reforming, emissions were estimated through mass balance in a hypothetical system. Purification efficiency was considered for 98%, estimated biogas volume for one year (22,712,125 Nm^3/year) and initial biogas composition with 85% CH_4, 15% CO_2 and energy efficiency (1.65 Nm^3/kWh).

The data were the basis for calculating biomethane production (Nm^3/year) and direct emissions of CO_2 at the off gas produced in the purification system (tCO_2e/year).

Hydrogen production and purification

The estimate of CO_2 emitted in the production and purification of hydrogen considered the results obtained in the simulation of the process using the Software CAPE-OPEN 1.1. The process was calculated considering the chemical equilibrium model of the reactions.

Greenhouse gases (Scope 2)

Indirect GHG emissions from electricity consumption for hydrogen production were accounted for in Scope 2. These emissions are considered indirect, as they refer to the source of electrical energy obtained and generated in locations outside the geographic limits of the WWTPs.

To calculate Scope 2 emissions, the electricity demand for the biogas purification process, hydrogen production, and the grid factor were considered. The grid factor represents the emission factor of CO_2 for the generation of electricity in the National Interconnected System of Brazil and was obtained from data provided by the Ministry of Science, Technology, and Innovation (MCTI). It considers the average of the months of the base year of 2021 (MCTI, 2021). The amount of electricity on the grid consumed in the considered activity was 145 MWh/year, according to the demand of all WWTPs and the grid factor of 0.5985 tCO_2/MWh.

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[10] GHG Protocol.

Results (GEE)

GHG emissions data were presented for the scenario and related to Sanepar's 2022 inventory (IGEE). Sanepar's total IGEE emissions were **986,793 tCO_2e/year**, related to raw methane from WWTPs. Of this total, **835,413 tCO_2e/year** are related to the UASB and ASFR reactors (Figure 8). Reflecting the current reality of the company that burns biogas from anaerobic reactors in flare, emissions were **577,615 tCO_2e/year** and GHG mitigation **257.798 tCO_2e/year**. This reduction in emissions obtained by burning biogas through burners in anaerobic reactors and in sludge biodigesters is estimated at 26.42% of gross emissions. In the biogenic form, arising from the use of this device **3,355 tCO_2e/year were issued**. This shows that even though they have 50% efficiency, not all biogas arrives in the flare for burning as part of it is dissolved. These emissions are related to the number of WWTPs equipped with burners with automatic ignition, the percentage of methane losses in the liquid medium, the efficiency of burning the burners that is applied to the rate of methane recovered, and the time the equipment has been running when it was not stopped, under maintenance.

Reflecting the estimated biogas scenario using the Software ProBio, referring to the volume available for energy use and hydrogen production, if all biogas produced in UASB/ ASFR reactors were released directly into the atmosphere[12], GHG emissions would be 344,177 tCO_2e/ year. With the estimate of the current scenario that considers emissions related to the use of flare, these correspond to 273,762 tCO_2e/year. Comparing this value with the reference scenario, the avoided emissions are 70,415 tCO_2e/year (Figure 8).

Referring to the production of hydrogen, the GHG emission would be 17,825 tCO_2e/year. This value includes emissions related to: steam generation from biogas (6,312 tCO_2e/year), purification of biogas (2,727 tCO_2e/year) and catalytic reforming of biomethane and purification of hydrogen (8,786 tCO_2e/year). As regards the indirect GHG emissions resulting from the supply of energy for the production of hydrogen, these were calculated in 82,720 tCO_2e/year. Comparing the emissions of the hydrogen production chain (17,825 tCO_2e/year) with the reference scenario (344,177 tCO_2e/year), the mitigation of emissions would be 325,701 tCO_2e/year. These data demonstrate an opportunity for the Paraná sanitation sector, aiming at a low-carbon energy transition. The results align with Sanepar's objectives, which have been developing studies and research to consolidate biogas as a profitable energy asset for the company.

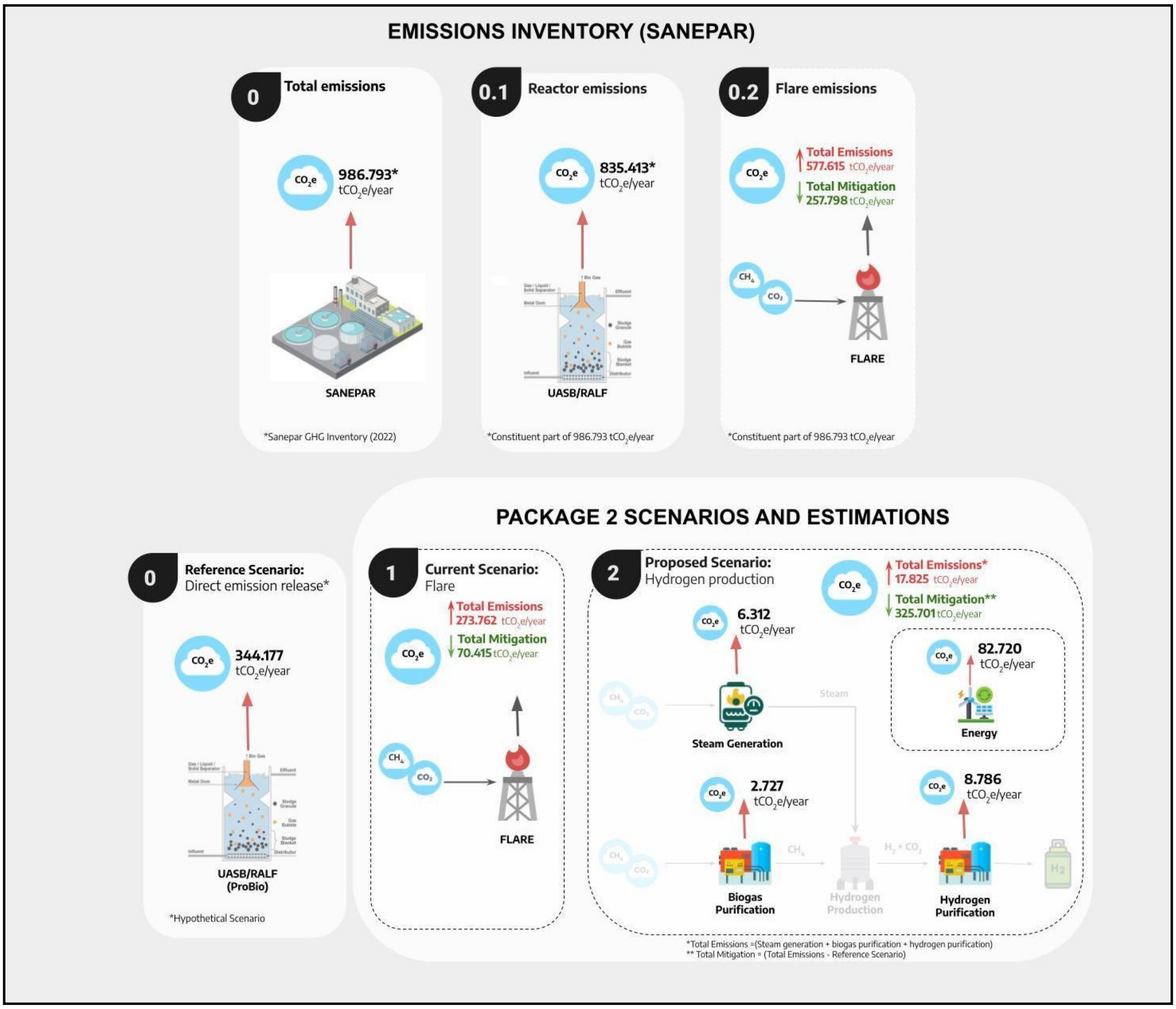

Figure 8 - Emissions associated with the evaluated scenarios (tCO2e/year)

Source: Prepared by the authors, 2023.

If all WWTPs adopted steam reforming technology for biogas, emissions of CO_2 of Sanepar could be drastically reduced, reaching mitigations of approximately 325 thousand tCO_2e/year. That is, more CO_2 would be removed than is produced during the catalytic reforming of biogas to obtain hydrogen. The most significant reductions would be linked to Scope 2 (82.8%), followed by the catalytic reforming process (8.3%), steam production from biogas (6.3%), and purification of biogas to biomethane (2.7%), as shown in Figure 9. The significant reductions linked to Scope 2 are related to the characteristic of the process for obtaining hydrogen from catalytic reforming, which emits low amounts of greenhouse gases.

Compared to the catalytic reforming of natural gas, which reduces a maximum of 60% of GHG emissions when obtaining grey hydrogen, the hydrogen production process from biogas stands out for using a renewable source for steam generation and reducing 100% of emissions.

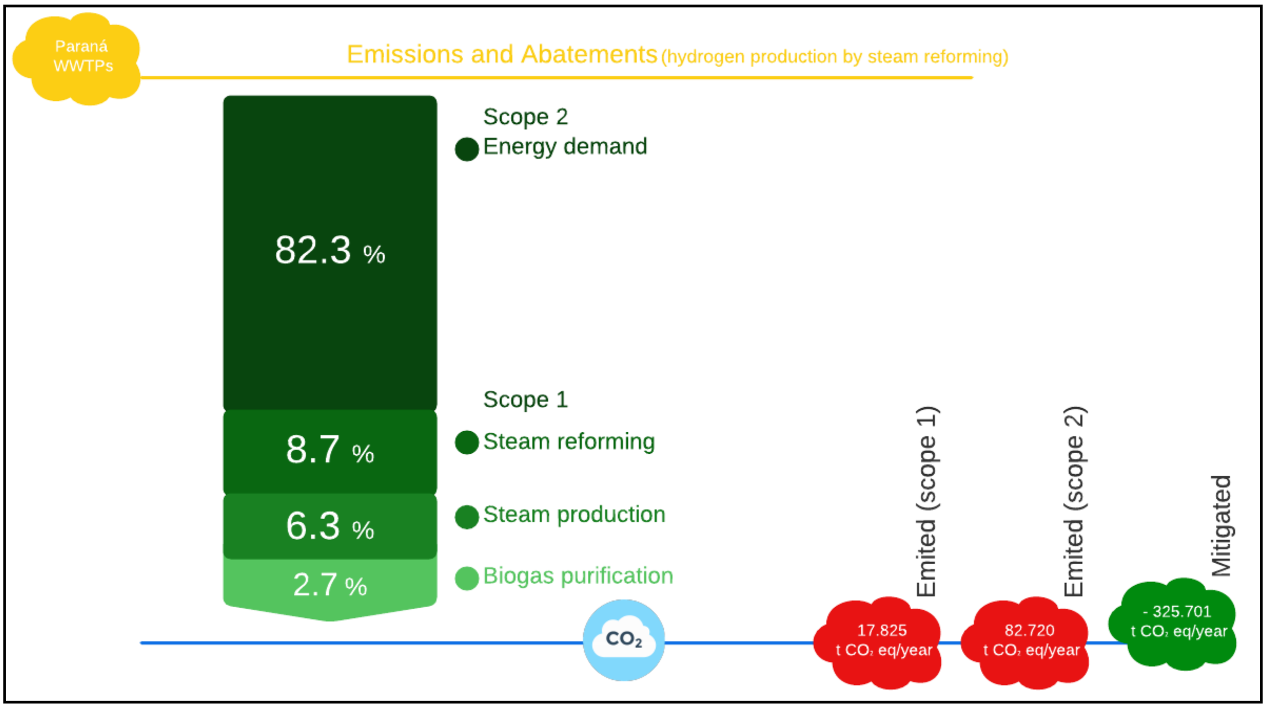

Figure 9 - CO2 emissions and mitigated emissions associated with the hydrogen production process

Source: Prepared by the authors, 2023.

Comparing the estimated numbers of GHG reductions in the hydrogen sector at the WWTPs in Paraná, with the number of trees, to offset the total GHG emissions of the WWTPs, around 14,340,713 trees are needed, equivalent to 43,065 hectares of forests. However, with the current biogas flaring systems there is an equivalent annual compensation rate of 2,933,960 trees, corresponding to 8,811 hectares of planted forests. If hydrogen production were adopted in all treatment plants in the state of Paraná, the corresponding proportion in mitigated GHG would increase by 13,570,875 trees, making up approximately 40,000 hectares of trees in integrated systems.

2. FINAL CONSIDERATIONS

From the adoption of steam reforming as a technological process for hydrogen production in WWTPs, the following data were estimated:

1. Annual hydrogen production of approximately 77,372,000 Nm^3/year.
2. Mitigation of around 325,000 tCO$_2$e/year. This provides the equivalent of -5.38 kg CO$_2$/kg H$_2$ produced, requiring 1.14 kWh/kg H$_2$.
3. Average annual offsets of 13,000,000 trees, equivalent to about 40,000 hectares of forests.

With the data presented, it is evident that steam reforming is a satisfactory technology for producing hydrogen from biogas produced in WWTPs, since it can increase the current GHG mitigations of the Paraná sanitation company, with significant hydrogen production.

WORKING PACKAGE 03: Analysis of the Legal Regulatory Framework and the Renewable Hydrogen Market in Paraná with Identification of Potential Customers

HIGHLIGHTS

- Brazil's unique position in the development of a hydrogen market is attributed to its advantages stemming from abundant natural resources and a well-established renewable energy and electricity matrix. This positions the country as a potential producer of renewable hydrogen.
- The approval of a comprehensive legal framework for hydrogen in Brazil, as demonstrated by Resolution No. 6 of June 23, 2022, establishing the National Hydrogen Program and creating the National Hydrogen Program Steering Committee, underscores the country's commitment to the energy transition. This move positions Brazil as a significant player in the global hydrogen market.
- In the state of Paraná, the relevance of Law No. 21,454 lies in its establishment of incentive parameters for the use of renewable hydrogen, especially in terms of preparing tax and credit instruments. However, the law lacks clarity regarding the timeframe and manner of implementation, without providing an applicability forecast.
- Harmonizing legal and regulatory conditions at the state, national, and global levels is identified as a pivotal step in expanding the commercialization of hydrogen.
- Within the state of Paraná, 305 companies have been identified as potential hydrogen buyers for their production or commercial processes, spanning both manufacturing and trade segments.
- The Sanepar Sewage Management (GTESG), located in the metropolitan region of Curitiba, the capital of Paraná, stands out with the highest representation in the number of identified companies and the highest geographic density in the state.

1. PRESENTATION

1.1 Overall Purpose

The working package presents an analysis of the current hydrogen regulatory framework in Brazil, highlighting public programs and policies at the federal and state levels to promote the development of the renewable hydrogen market in the country, as well as an overview of the hydrogen market in Paraná. The main aim of this study is to identify opportunities for renewable hydrogen obtained from the Sewage Treatment Stations (WWTPs) in the state of Paraná.

1.2 Specific Purposes

- Present public policies under development in Brazil, regarding hydrogen, including its insertion in the context of WTPs;
- Evaluate the hydrogen market panorama within the scope of the state of Paraná;

- Identify the sectors and number of potential companies that might acquire hydrogen in the state of Paraná, according to the Regional Management Units of SANEPAR.

2. INTRODUCTION

In recent years, the economic agenda has been increasingly linked to the environmental agenda, engaging various *stakeholders,* such as economic agents, international organizations and governments in investing in new technologies and infrastructure to establish new markets with a strong environmental and climate perspective. This articulation is another step towards achieving the commitment made in the Paris Agreement (2015) to keep the global temperature increase below 2°C in relation to pre-industrial levels, seeking to limit this increase, preferably, to 1.5°C (GIZ, 2021).

The scope of this commitment involves increasing energy efficiency and expanding the use of renewable energy sources. However, these measures alone will not be enough to contain global warming. In this scenario, the energy and industrial use of renewable hydrogen (H_2) and its derivatives emerges, motivated by the insertion of these products as decarbonization instruments in sectors with difficult emission abatement and where electrification is difficult, such as in the steel industry, some industry segments and aviation fuel and transport over long distances. H_2 has versatility of use and energy storage capacity, promoting a broad and decentralized competitive dynamics to couple different market segments.

The relevance of hydrogen in the energy transition agenda is reflected in the rapid dissemination of national and regional strategies for its development in several countries, unprecedented in recent years. This political movement aims to boost a new global value chain for renewable hydrogen, making it an export commodity and reconfiguring the energy geopolitics, positioning countries with a large supply of renewable energy resources as producers and exporters of hydrogen and derivatives, aiming to complement supply in countries whose demand exceeds domestic production capacity.

In this scenario, Brazil occupies a prominent position as a potential producer and exporter of hydrogen, due to its consolidated renewable electricity matrix, with excellent capacity factors, a robust energy transmission structure and transport logistics with several ports and cargo storage areas (ENERGY ASSETS DO BRASIL, GESEL/UFRJ and PUC-RIO, 2023)[11]. The wide availability of natural resources for producing hydrogen by different routes, the supply of low-priced and safe renewable electricity and Brazil's extensive coastline favoring export tend to make the Levelized Cost of Hydrogen (LCOH) competitive in the medium and long term, bringing the Brazilian LCOH close to USD 1.50/kg H_2 in 2030 (OLIVEIRA, 2022). In 2020, the amount of energy available domestically in the country reached 287.6 million tons of oil equivalent (Mtoe), with a 48.4% share coming from renewable sources. Brazil has one of the energy profiles with the lowest impacts on the environment, where the contribution of biomass derived from

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[11] All references mentioned in this document are available in the market and regulatory deliverables of working package 3

sugarcane (19.1% of the total amount of energy available domestically) and biodiesel is combined with the historical presence of hydroelectric power (12.6%), in addition to the growing use of wind and solar energy (ENERGY ASSETS DO BRASIL, GESEL/UFRJ and PUC-RIO, 2023).

However, the limited experience of the renewable hydrogen market impacts the maturity of the regulation of this energy source, in the same way that the increase in production capacity is still linked to the advancement of policies, incentive programs and credit facilities to subsidize and offer security to the investment in large projects.

Thus, government initiatives and public policies must be created based on the specificities of each country and/or region, taking into account the available resources and the necessary infrastructure. According to the International Energy Agency (IEA), the development of this market is linked to five main spheres: establishing goals and long-term policy signals; policies to support the creation of demand for low-emission hydrogen; policy strategies to mitigate project investment risks; promotion of research and development (R&D) projects, innovation and strategic demonstration and sharing of knowledge; and, establishment of regulatory structures, standards and certification systems (IEA, 2022).

The growing attention around hydrogen in recent years is evident, in view of major political articulations, announced projects and the launch and implementation of national hydrogen strategies in several countries (WEC, 2020). Brazil is taking the first steps in designing public policies and the regulatory framework for the renewable hydrogen market, as some states in the country have already launched their energy strategies, such as Paraná, which is the object of study in this work.

Law 11.445/2007 establishes the national guidelines for basic sanitation and has as one of its fundamental principles the promotion of energy efficiency and the reuse of effluents (art. 2, XIII), thus, the use of sludge from WTPs for the production of biogas, and consequently of renewable hydrogen, complies with the norm. Therefore, it is extremely important that the laws related to hydrogen are in harmony with those related to basic sanitation in order to effectively develop the market.

Accordingly, this summary gathers the analysis on the hydrogen market potential in Paraná and the regulatory context and incentive policies for renewable hydrogen, aiming to identify opportunities to promote the production of hydrogen from WWTPs in the state of Paraná. To do so, it presents an overview of the current context of the hydrogen market in Paraná, identifying the sectors and companies that tend to become consumers (offtakers) of hydrogen produced in the state, contrasting the forecast information of the hydrogen supply from Sanepar's WWTPs with the geographical position of the companies. In this way the market balance obtained regionally tends to minimize the problems of energy outflow. In order to analyze the policies and regulatory framework, the study presents the overviews of Brazil and of Paraná state. Additionally, the current regulatory framework that guides the activities of Wastewater Treatment Plants (WWTPs) in the state of Paraná is presented, seeking to identify opportunities and weaknesses for the development of projects to incorporate renewable hydrogen as a product of the sanitation system.

3. BRAZILIAN REGULATORY HYDROGEN PANORAMA

In Brazil, the programs and policies agenda related to hydrogen began as a result of the oil crisis in 1970, through the creation of the program to study and develop alternative fuels. In 1975, the Hydrogen Laboratory (LH_2), linked to the Physics Institute of the State University of Campinas, was created to research the hydrogen production and its use in combustion engines (BNDES, 2022).

In 1998, the Ministry of Science and Technology (MCTI) established the National Hydrogen Energy Reference Center (CENEH). In 2002, this ministry launched the Brazilian Fuel Cell Program (ProCaC), with the participation of research entities and the private sector. In 2003, it became a member of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), created by the US Department of Energy. ProCaC, in 2005, was renamed the Science, Technology and Innovation Program for the Hydrogen Economy [Programa de Ciências, Tecnologia e Inovação para a Economia do Hidrogênio] ($ProH_2$), with the aim of promoting actions to boost the national development of hydrogen and fuel cell technologies.

In 2005, the MME published the Roadmap for Structuring the Economy in Brazil. The goals are for 20 years and point to: the importance of technological routes that provide competitive advantages for Brazil; the role of natural gas in the energy transition towards the predominance of green hydrogen; and, the diffusion in distributed generation markets, isolated regions and urban buses.

In this perspective, the following intermediate horizons, associated with the hydrogen production targets, were presented: 1) 2015 Horizon: production of commercial hydrogen from natural gas; 2) 2020 Horizon: production of hydrogen from the electrolysis of water; 3) 2025 Horizon: production of hydrogen from biomass and ethanol reform; 4) 2030 Horizon: production of hydrogen from alternative processes. However, such goals were not achieved. To date, not even the first stage related to that roadmap has been reached, which demonstrates the urgent need to articulate public policies that encourage the production and commercialization of renewable hydrogen in Brazil.

Hydrogen was included in the Science, Technology and Innovation Plan for renewables and biofuels in 2018, which indicated actions for the development of its use as an energy source. In 2020, the National Energy Plan 2050 (PNE 2050) identified hydrogen as a disruptive technology and as an element of interest in the context of decarbonizing the energy matrix. The Plan listed various uses and applications[12], in addition to bringing public policy recommendations for the energy transition, among which we can list the appropriate design of the legal-regulatory framework that encourages the penetration of technologies applicable to the hydrogen energy chain as a whole (production, transport, storage and consumption), as well as the need to work in an articulated and coordinated way with international institutions (MME, 2021, pg. 6)

Brazil co-leads the United Nations High-level Dialogue on Energy. In 2021, it presented the energy pact on hydrogen. The voluntary commitments signed in the pact aim to accelerate the fulfillment of goal 7 of the Sustainable

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[12] For example, hydrogen in fuel cell electric vehicles.

Development Goal (SDG 7), which deals with universal access to clean energy. With regard to hydrogen, the pact aims to encourage the development of the industry by consolidating knowledge about this energy vector in Brazil based on following pillars: research, development, and innovation policies; qualification and training; creation of a platform to consolidate and spread knowledge about hydrogen in the country.

In the same year, a determination was submitted to the National Council for Energy Policy (CNPE) for the establishment of the National Hydrogen Program (PNH_2), which has some guiding principles: valuing the national potential of energy resources, recognizing the different sources for obtaining hydrogen, renewable or not; being encompassing, valuing the diversity of energy sources and alternatives for production, logistics, storage and use of hydrogen; valuing and encouraging national technological development with a view to training and technological autonomy and the development of the national productive system; and recognizing the contribution of the national industry, since Brazil has an industrial base and services capable of contributing to the hydrogen economy (BRAZIL, 2021f) (BNDES, 2022, pg. 16).

Also, in 2021, the CNPE published two resolutions with positive implications for the development of hydrogen in the country: no. 2/2021, which establishes guidelines on research, development and innovation in the energy sector; and no. 6/2021, which determines the carrying out of a study to propose guidelines for the National Hydrogen Program. The program was instituted in 2022 through Resolution No. 6 of the MME, in six axes, as shown below: 1) Strengthening of technological bases; 2) Training and human resources; 3) Energy planning; 4) Legal-Regulatory framework; 5) Market growth and competitiveness; and 6) International cooperation. It is important to emphasize that one of the principles of the PNH_2 is to seek synergies and links with other countries, this activity being extremely important for serving the global hydrogen market, especially imports.

In axis 4, referring to the legal and regulatory-normative framework, the program aims to map existing national legislation and regulations to subsidize the inclusion of Hydrogen as an energy vector and fuel in the Brazilian energy matrix. Thus promoting regulation, through government agencies, on the production, transport, quality, storage and use of hydrogen and its technologies (PNH, 2021, pg. 17).

In this perspective, such a regulatory framework should encompass the various technological alternatives for production, as well as the diversity of sources for the production of renewable hydrogen. This regulatory framework is expected to catalyze the appreciation and encouragement of the national technological development in order to make the reform of biomethane from the WWTPs a competitive route in the market.

3.1 Legislation and programs

The Federal Constitution provides in its art. 22, IV[13], that legislating on energy is an exclusive competence of the Federal Government (BRASIL, 1987). At the federal level, Brazil is still lacking regulations regarding the hydrogen

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[13] Art. 22. It is the Federal Government's private responsibility to legislate on: IV - water, energy, informatics, telecommunications and broadcasting (BRAZIL, 1987).

market, but Bill 725/2022 is being processed, and its summary includes: Disciplines the insertion of hydrogen as an energy source in Brazil and establishes incentive parameters for the use of sustainable hydrogen. With the approval of the bill, hydrogen will be introduced as a source of energy in Brazil, with the Federal Government having exclusive competence to legislate on the matter.

The following resolutions are in force: CNPE Resolution No. 2/2021, which guides the National Electric Power Agency (ANEEL) and the National Petroleum, Natural Gas and Biofuels Agency (ANP) to prioritize the allocation of R&D resources to the hydrogen theme; and No. 6/2021, which determines the carrying out of a study to propose guidelines for the National Hydrogen Program, instituted by Resolution No. 6 of the MME. Some legislation and programs that were in force, or in the project phase, in Brazil in June 2023 will be presented and discussed below.

3.1.1 Bill 725/2022

Bill (PL) No. 725/2022, drafted by Senator Jean Paul Prates (PT/RN) has the disciplinary scope of inserting hydrogen as an energy source in Brazil and establishes parameters to encourage the use of sustainable hydrogen. This project is being processed in the Federal Senate, afterwards it will go to the Federal Chamber for voting and, finally, presidential sanction.

Article 1 of the bill addresses the aim to establish “mechanisms for the inclusion of hydrogen in the national energy sector and establishes parameters to encourage the use of sustainable hydrogen" (BRAZIL, PL 725/2022). This bill basically modifies two pieces of legislation:

- Law No. 9,478, of August 6, 1997 - Provides for the national energy policy, activities related to the oil monopoly, establishes the National Energy Policy Council and the National Petroleum Agency, and makes other provisions.
- Law No. 9,847, of October 26, 1999 - Provides for the inspection of activities related to the national fuel supply, dealt with in Law No. 9,478, of August 6, 1997, establishes administrative sanctions and other measures.

The prediction of such changes is in the sense of including hydrogen as an energy vector for the transition to a low-carbon economy, as well as bringing some concepts.

> XXXII – Hydrogen: pure hydrogen that remains in the gaseous state under normal conditions of temperature and pressure, collected or obtained from various sources, through the use of specific technical processes or as a by-product of industrial processes.
> XXXIII - Sustainable hydrogen: hydrogen produced from solar, wind, biomass, biogas, and hydraulic sources (BRASIL. PL 725/2022)

If the Bill is approved, the ANP will be responsible for promoting the regulation, contracting and inspection of the economic activities that are part of the hydrogen industry, as well as the inspection of activities related to the *production, import, export, storage, standards for use and injection at hydrogen delivery points or exit points* (BRAZIL. PL 725/2022) Finally, the project provides for the compulsory addition of hydrogen:

> Art. 4 The addition of hydrogen at the delivery point or exit point in transport gas pipelines will follow mandatory minimum percentages in volume, in the following progression:
> I - 5% as of January 1, 2032;
> II - 10% as of January 1, 2050;
> Paragraph 1: The volume referred to in the caput must contain a mandatory proportion of sustainable hydrogen of at least 60%, in the case of item I, and at least 80%, in the case of item II.
> Paragraph 2: The percentage referred to in the caput may be scaled incrementally in installments, according to the transport and supply security capacity (BRASIL. PL 725/2022)

There is no mention or definition in the document of who will be the agents required to inject hydrogen into the pipelines. Also, it does not inform what will be the basis for arriving at such a percentage, whether by production, amount of gas conducted in the gas pipeline or production, for example. In addition, this project only mentions the transport pipeline, that is, there is no obligation to inject the distribution pipelines.

3.1.2 Projects of Laws and Political Initiatives of National Scope in Proceedings

On 03/14/2023, the Special Commission for Debating Public Policies on Green Hydrogen (CEHV) was created in the Federal Senate, "with the purpose of debating, within two years, public policies on green hydrogen, in order to encourage the scaling of this clean energy generation technology and evaluate public policies that promote green hydrogen technology (CEHV, 2023).

In the analysis of renewable hydrogen projects the Aneel opened a public call for the Research, Development and Innovation Program (PDI), which focus is to boost projects that promote the production of hydrogen using the energy generated by renewable sources of electricity, such as hydro, biomass, wind and solar. This public consultation, nº 018/2023, was available for contributions between 06/07/2023 and 07/24/2023.

3.2 State Legislation Initiatives: the state of Paraná

The Federal Constitution attributed private legislative competence to the Union to legislate on energy. In this perspective, the states are entitled to supplementary legislation, as well as, in the absence of a federal law, general rule on the subject. Thus, the states have full competence to legislate on the subject, as this is the case of hydrogen. However, the supervenience of federal law on general rules suspends the efficacy of state law, insofar as it is contrary to it.

> Art. 24. The Federal Government, the States and the Federal District are responsible for legislating concurrently on:
> Paragraph 2. The Federal Government's responsibility to legislate on general rules does not exclude the supplementary responsibility of the States.
> Paragraph 3. In the absence of a federal law on general rules, the States will exercise full legislative responsibility, observing their peculiarities.
> Paragraph 4. The supervenience of federal law on general rules suspends the efficacy of state law, insofar as it is contrary to it (BRAZIL, 1987)

Thus, due to the lack of a federal law that addresses the hydrogen, it is up to the states to address the issue. In this perspective, some states anticipated and enacted laws on the subject. The negotiations of the state of Paraná are set out below.

In 2023, the State of Paraná published Law 21.454, which provides for incentive parameters for the use of renewable hydrogen in the state. The rule brings some concepts described in the following article of the resolution:

> Art. 2. The following are taken into account for the purposes of this Law:
> I – renewable hydrogen: element obtained from renewable sources through a process with low carbon emissions;
> II – renewable hydrogen production chain: undertakings and productive arrangements linked to each other and that are part of sectors of the economy that provide services and use, produce, generate, industrialize, distribute, transport or commercialize renewable hydrogen and products derived from its use, which necessarily include the search for carbon credits when the economic and financial viability of the certification process is proven.

Regarding such concepts, it is important to highlight item II, of art. 2, which determines that the hydrogen production chain must necessarily include the search for carbon credits, given that in Brazil, currently, there is no regulated carbon credit market. Thus, it is understood, at this moment, that such a legislative determination would be reckless, given that the determinations do not converge (the need for the hydrogen production chain to be linked to the search for carbon credit).

The law defines the following objectives:

> Art. 3 The objectives of this Law are:
> I – increasing the share of renewable hydrogen in the State's energy matrix;
> II – stimulating:
> a) the use of renewable hydrogen in its various applications and, in particular, as an energy source and production of agricultural fertilizers;
> b) technological development aimed at the production and application of renewable hydrogen, oriented towards the rational use and protection of natural resources;
> c) the development and training of productive, commercial and service sectors related to hydrogen-based energy systems;
> III – contributing to reducing the emission of greenhouse gases and, therefore, to tackling climate change in line with a low-carbon economy;
> IV – stimulating, supporting and fomenting the production chain of renewable hydrogen in the State of Paraná;
> V – establishing rules, administrative instruments and incentives that help the development and fostering the production chain of renewable hydrogen;
> VI – increasing in economic, social and environmental bases the participation of the uses of green hydrogen in the energy matrix;
> VII – promoting incentives, supervision and support to the renewable hydrogen production chain in the State;
> VIII – providing synergy between sources of renewable energy generation; and
> IX – attracting investments in infrastructure for the production, distribution and commercialization of renewable hydrogen.

To do so:

> Art. 4 In order to achieve the objectives dealt with in this Law, the public authorities may promote, among others, the following actions:

> I – carry out studies and establish goals, norms, programs, plans and procedures aimed at increasing the share of hydrogen energy in the State's energy matrix;
> II – carry out studies:
> a) for the elaboration of fiscal and credit instruments that encourage the production and acquisition of equipment and materials used in hydrogen production and application systems;
> b) for the allocation of financial resources in the budgetary legislation to fund activities, programs and projects aimed at the objectives of this campaign;
> III – enter into agreements with public and private institutions and finance research and projects aimed at:
> a) technological development and cost reduction of energy systems based on renewable hydrogen;
> b) the qualification of human resources for the development, installation and maintenance of energy systems projects based on renewable hydrogen;
> IV – encourage the use of renewable hydrogen in public transport, industry and agriculture;
> V – promote studies in the regulatory sandbox, to develop a production plant and services for hydrogen with low carbon production, for the implementation of solutions and technological innovations.

The actions defined by the norm are relevant for the development of the hydrogen chain in the state, mainly with regard to carrying out studies for the elaboration of fiscal and credit instruments. Such law does not provide the period or form by which it will occur, therefore, it does not bring predictability of such application. The norm is a great advance for the expansion of renewable hydrogen in the state, but it fails to effectively define the form for such implementation, or period for it.

4. MARKET SCENARIO FOR THE HYDROGEN CHAIN IN PARANÁ

It is appropriate to highlight the state of Paraná as an important potential producer of renewable hydrogen, mainly due to its economic characteristics. The state is the fifth largest economy in Brazil. Its good economic performance is related to the agro-industrial profile, mainly of soy, corn and wheat producing sectors and the vegetable oil, dairy and animal protein industry, especially for poultry. In exports, the state has been regularly positioning itself among the ten main exporters in the country, with emphasis on the soy, meat and automobile sectors (IPARDES, 2023). In addition, Paraná has about 5.64% of the country's total population, corresponding to 11.443.208 people (IBGE, 2023).

The agro-industrial profile that fosters the state's economy is relevant to the hydrogen market, since, as argued by the literature and already presented previously in this summary, industrial activities are the largest potential buyers of hydrogen, whether for the replacement of hydrogen of fossil origin or innovative insertion in its production process, aiming the decarbonization (BNDES, 2022; IEA, 2022).

4.1 Potential sectors and companies demanding hydrogen in Paraná

Accordingly, in order to meet the objective of this research, which consists of identifying opportunities for hydrogen from the WWTPs in the state of Paraná, the companies operating in the state and that might[14] use hydrogen in their production processes were identified[15]. The database was obtained from the Brazilian Federal Revenue Office, and medium and large companies were selected.

In total, 305 companies were identified as possible offtakers of hydrogen for their production or commercial processes. These were divided in two large sections, that is, the manufacturing industry and the commerce, which accounts for about 85.9% and 14.1% of companies, respectively. Manufacturing industries are characterized by transforming a raw material into a new product, either for the final consumer or as part of a new process to be transformed into another product. The commerce section, on the other hand, refers to the wholesaler who is defined as the reseller of new or used goods, without transformation, to several agents, such as: retailers, professional, institutions, commercial, agricultural and industrial agents, in addition to other wholesalers; or can also act as a commercial agent or trade broker (purchase or sale) of goods to these users (IBGE, 2023).

Figure 10 (a) shows Sanepar's regional management units according to the number of companies identified in the research, while Figure 10 (b) shows the estimated hydrogen production by the biomethane steam catalytic reforming process[16] in each of them.

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[14] There is no disclosure in open media of the volume of hydrogen demanded by the companies, so it was necessary to classify them according to the productive sector. Thus, the confirmation of the actual use of hydrogen in the production processes is only possible based on primary market research, which is not the objective of this project.

[15] Considering the sectors pointed out by the literature on the subject.

[16] Estimates and methodologies data were presented in working package 2, delivered in June 2023.

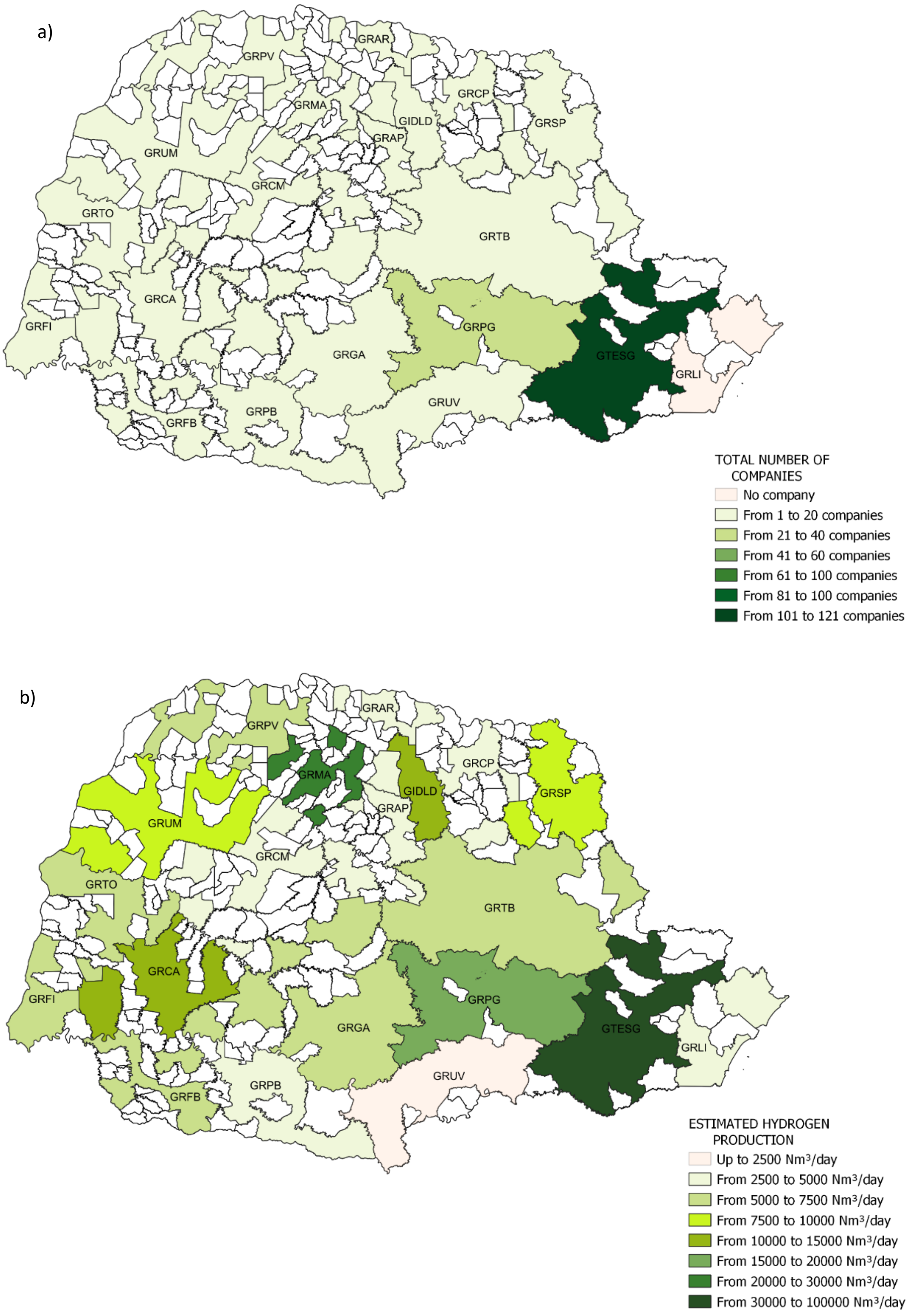

Figure 10 - Identified companies (a) and potential for daily hydrogen production via catalytic steam reforming (b), according to regional management
Source: Prepared by the authors, 2023.

Figure 10 (a) shows that the largest concentration of companies identified is in the Sewage Management unit (GTESG), in the metropolitan region of Curitiba. Of the total companies, 38% are located in this region, with emphasis on the municipalities of Curitiba, Araucária and São José dos Pinhais. The other regional management units did not present significant numbers in the total number of companies identified.

After identifying the location of the companies mentioned in the study, it was necessary to identify whether this concentration occurs in regional managements units that have great potential for hydrogen production. By crossing this information, it is possible to see a market balance, that is, a scenario in which the supply of hydrogen is able to meet all demand. Considering that the values referring to the volume demanded are not known, this balance analysis will consider only the total number of companies and the forecast of hydrogen production, according to the regional managements.

Figure 10 (a) and (b) indicates that the concentration of companies and estimated hydrogen production happens more intensely in the Sewage Management unit (GTESG), that is, part of the hydrogen demand in this location tends to be met at a more competitive price[17], since the costs related to the transport of the asset will not be significant components in the total costs of the business. If the volume demanded is greater than that offered in the locality, the region will tend to be an importer of the asset from the other regions of the state, but in these cases, transport costs would be higher and, in some situations, commercialization could be made unfeasible by the logistical factor.

Otherwise, some regional managements showed little representation in companies demanding hydrogen, not being highlighted in a sectoral way for any trade or industry activity framed in this research[18]. However, the forecast of hydrogen production in the WWTPs located there is higher than most of the state, such as, for example, in the regional managements of Cascavel (GRCA), Umuarama (GRUM) and Santo Antônio da Platina (GRSP). In this sense, it can be assumed that these regions tend to market the asset outside the region, thus becoming possible exporters of the product.

Most identified companies were from the industrial sector,[19] totaling 262, which are split into 7 Brazilian Classification of Economic Activities (CNAE) divisions, as shown in Figure 11.

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[17] It is not part of the work plan of this report to assess the production cost, including the distance factor.

[18] As the volume demanded by the companies is not known, this statement takes into account only their number, that is, if only one company has a high demand for hydrogen as a productive characteristic, this analysis should be changed.

[19] In Brazil, the manufacturing industry has 24 CNAE divisions, and in this research companies split into 7 divisions only were identified.

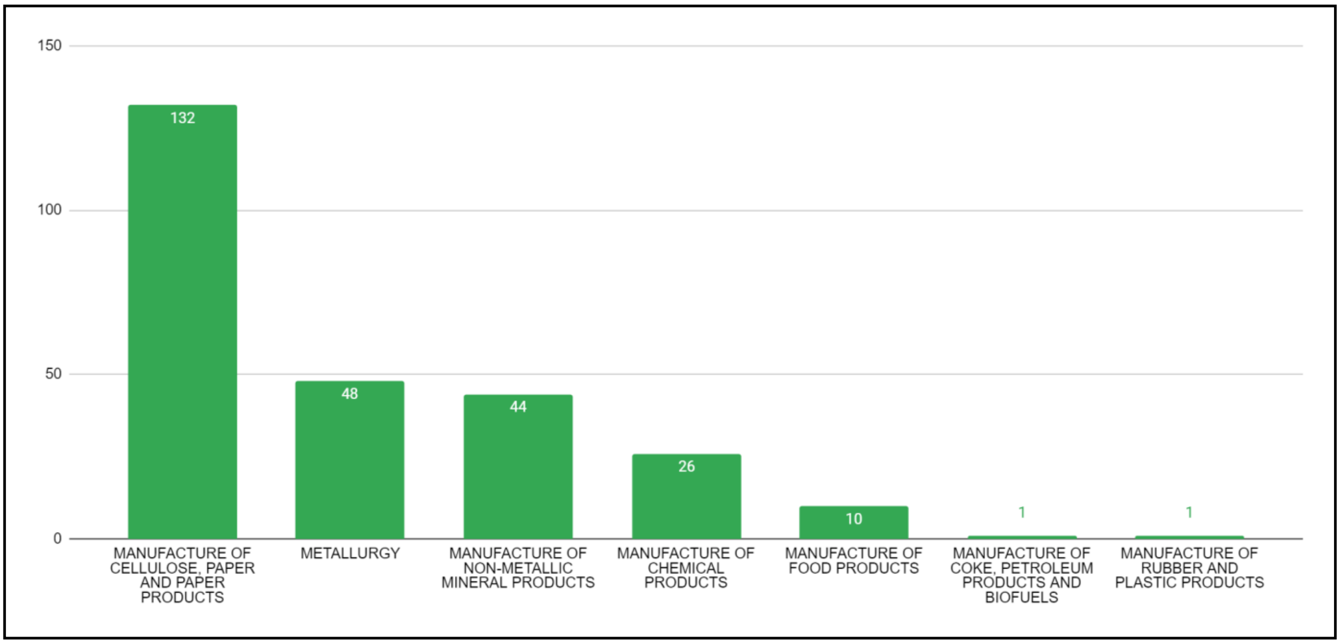

Figure 11 - Number of manufacturing companies, according to the CNAE division
Source: Prepared by the authors, 2023.

The paper and cellulose sector constitute the most companies in the state. In this sector, hydrogen is commonly used to generate heat which represents about 50.38% of them, followed by metallurgy (18.32%), manufacture of non-metallic mineral products (16.79%), manufacture of chemicals (9.92%), manufacture of food products (3.82%), manufacture of coke, petroleum products and biofuels (0.38%) and manufacture of rubber and plastic products (0.38%).

In addition to identifying the sectors that may become hydrogen consumers, it is also important to identify the location of the related companies, since the proximity to the regional managements units whose WWTPs will be the source of supply of the asset tends to reduce transport costs. Figure 12 shows the location of the companies identified.

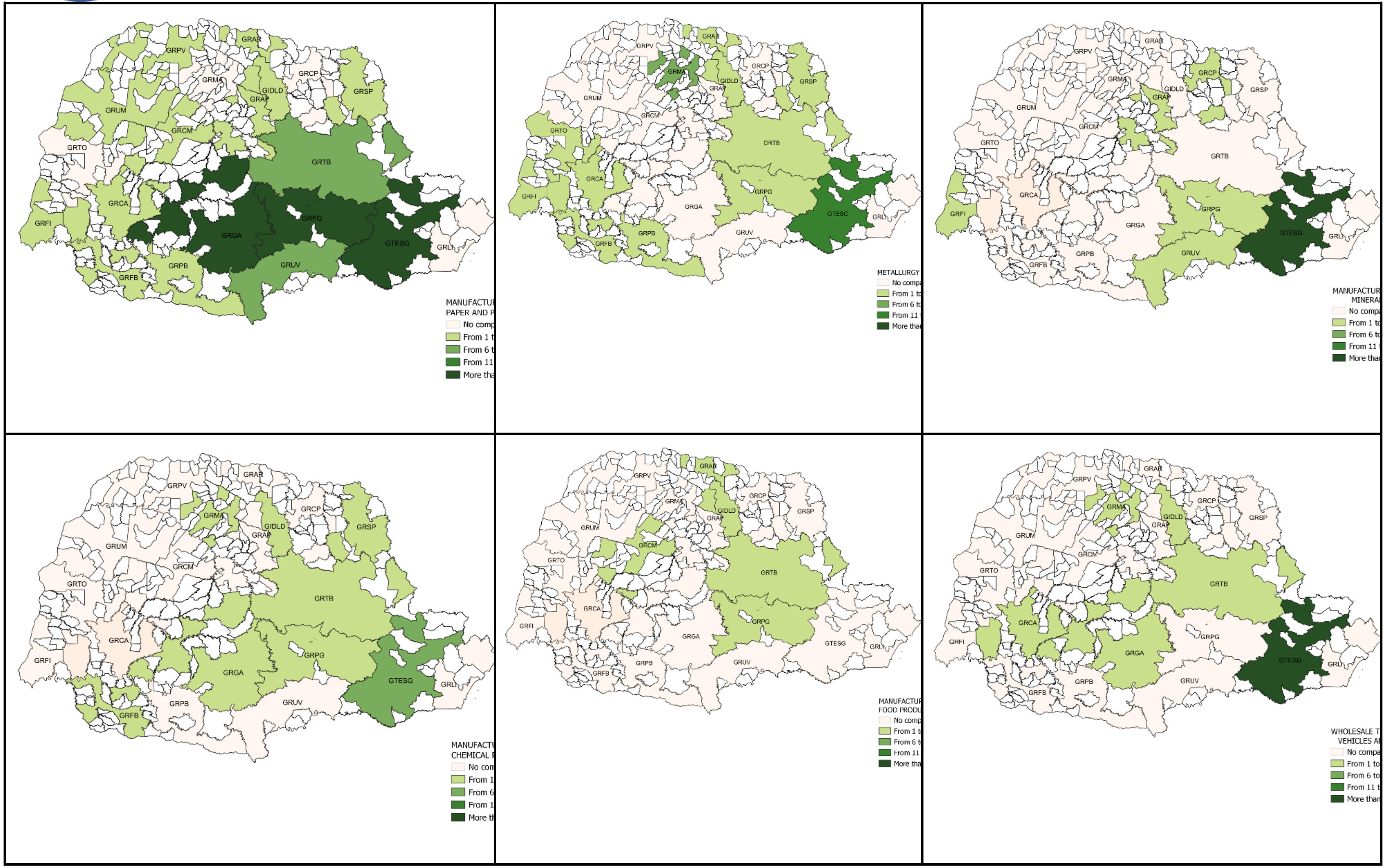

Figure 12 - Location of companies, according to CNAE division and regional management
Source: Designed by the authors, 2023.

It is observed that the Sanepar Sewage Management unit (GTESG) is representative in number of companies identified for most sectoral divisions, with the exception of the manufacture of food products. Others gain representation only in some cases, such as the Regional Management of Maringá (GRMA) in metallurgy and the Regional Management of Umuarama (GRUM) which presents companies only for the manufacture of paper, pulp and paper products.

These results support the thesis that, if in these locations the supply of hydrogen from the WWTPs is not absorbed by local companies, these regions tend to be exporters of hydrogen to other regions of the state, and even the country, unless production is made unfeasible by transport costs, so it is essential to identify potential customers and volumes demanded.

In this research, the companies were not classified as current or future users of hydrogen, nor was it possible to identify the actual volume demanded and used in their production processes. Access to this type of information can only be obtained by a primary market research that includes direct contact with the companies. In this sense, it can be said that this information, when obtained, can change the results of this research.

To conclude, it was observed that the State of Paraná has several characteristics that tend to position it as an important region in the development of the hydrogen market, since there is the possibility of working both alongside supply and demand, which can be verified by linking the possible buyers with the estimated production of hydrogen through the analyzed WWTPs.

5. FINAL CONSIDERATIONS

From this work, it was possible to understand that the hydrogen market is on the rise in the country, even though prices are variable, as they depend mainly on the source of hydrogen, degree of maturity of the market, available technologies, supply, demand for the product and even the regulatory framework of each region. Brazil has a wide availability of renewable energy sources distinctly distributed amongst the country. In this sense, each location will have greater or lesser potential for hydrogen production taking into account its regional characteristics.

As can be seen from the legislation being voted on and published, the alignment of legal and regulatory conditions at Paraná state, Brazil and even worldwide, emerge as one of the main procedures for expanding the commercialization of this energy vector. Therefore, efficient procedures for planning, approval, and standardization of certification systems must be established for the proper management of renewable hydrogen at all levels (use and commercialization).

The hydrogen market in Paraná has potential demand from different sectors of the economy. 305 potential hydrogen demanding companies were identified, sectored between the industrial processing and commercial branches, corresponding to 85.9% and 14.1%, respectively of the total amount of identified companies and containing several subclasses ranging from chemicals to food, including gas and fuel trade.

The supply of hydrogen from the sanitation, in this case, of Sanepar's WWTPs in Paraná has an estimated hydrogen production potential of 77,372,000 Nm³/year from **the steam reforming of the biogas**[20]. The greatest potential was found in the metropolitan region of the state capital.

With regard to the geographical distribution of the identified companies, they also have a greater concentration in GTESG and this result is in line with the geographic-economic distribution of the state, with this region as the most expressive in terms of gross domestic product (GDP) and population. This relationship with the estimated production of biogas in the WWTPs being higher in the same management (GTESG) tends to reduce the logistics’ costs.

Therefore, Paraná’s characteristics establish it as an important player in the developing hydrogen market, considering that it has the 5th largest economy in the country and its agro-industrial profile with great availability of feedstocks for the production of biogas. Due to these advantages, the state has potential to become a relevant producer and even a possible exporter of renewable hydrogen.

A point of attention is that the approval of a legal regulatory framework for hydrogen in Brazil demonstrates the country's commitment to the energy transition, benefiting the country as an important player in this global market. However, while a lack of positioning remains, investments can be put at risk due to uncertain standardization for use and commercialization. It is worth mentioning that the current lack of a legal position shall influence the definition of the business model and will limit the possibility of offtakers for hydrogen from WWTPs, either to ensure the traceability of the renewable attribute, commercialization or transport in pipelines.

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[20] Data reported in the deliverable ‘working package 02’

WORKING PACKAGE 04: Business Model Structuring

HIGHLIGHTS

- Four distinct business models have been crafted for sanitation companies, encompassing two models tailored specifically for Sanepar and two generic models applicable to sanitation companies throughout Brazil. Both models revolve around harnessing biogas for the generation of renewable hydrogen within Wastewater Treatment Plants (WWTPs).
- The initial business model developed for Sanepar proposes a special purpose entity (SPE) in collaboration with a technology company for renewable hydrogen production. Under this arrangement, Sanepar generates biogas, selling it to the SPE for refinement and subsequent renewable hydrogen production.
- The second business model for Sanepar involves an SPE partnership with a gas distribution company. In this scenario, Sanepar's collaborator contributes its customer base, along with distribution and sales logistics.
- The third business model, applicable as a generic framework for sanitation companies in Brazil, advocates for the autonomous production and commercialization of renewable hydrogen by the sanitation company, without forming partnerships with other entities throughout the production or commercialization processes.
- Similarly, the fourth generic business model suggests renewable hydrogen production for self-consumption by the sanitation company, with electricity as the ultimate product generated.
- These proposed models showcase various avenues for the valorization of biogas extracted from WWTPs, enabling the production of renewable hydrogen for either commercialization, self-consumption, or as a means of electricity generation.
- The establishment of a robust regulatory framework and the provision of economic incentives specifically tied to renewable hydrogen are integral elements crucial for enhancing the reliability of these business models.

1. PRESENTATION

1.1 Overall Purpose

The overall aim is to propose a strategic management for the inclusion of renewable hydrogen as a new environmentally friendly product in the operation of WWTPs, focusing on encouraging a new sustainable value chain. This new sustainable value chain is based on the proposal of business models through the generation and commercialization of renewable hydrogen (H_2) and derivatives, contributing to the decarbonization of productive activities.

1.2 Specific Purposes

- Construction of two business models aligned with Sanepar's commercial strategies;
- Construction of two generic business models applicable to sanitation companies throughout Brazil.

2. INTRODUCTION

Creating strategic business models for renewable hydrogen is becoming increasingly important. Through these models, companies can anticipate opportunities to strategically position themselves in the market for this sustainable asset. This includes addressing their energy needs and deriving value from their involvement in the renewable hydrogen sector. For this type of business, it is necessary to consider the potential energy, the available technology, the economic feasibility, the environmental and social impact, in addition to the regulation and public policies on this topic (BIOGAS PORTAL, 2023).

The methodology applied in this work was the "*Business Model Innovation"*, based on the book *Business Model Generation*, adding concepts of strategy and innovation. This method will be described by applying the following tools: I) 4 Questions; II) Value Proposal; III) Partners' Value; IV) Partners' Radar; and V) Business Model Canvas *(BM Canvas*)[21], which presents a system of interdependent activities that encompass a focal company and which may include activities carried out by its partners, suppliers and customers, seeking a way to create and capture value.

Considering this, it is important to note that Brazil does not have federal legislation regarding renewable hydrogen so far. Nevertheless, the Brazilian government has presented some initiatives to promote its development. For example, on November 28, 2023, Bill (PL) 2308/2023 was approved in the Federal Chamber of Deputies, establishing the legal framework for low-carbon hydrogen. Currently, this bill has been sent for analysis and voting in the Federal Senate. In this perspective, if Bill 2308/2023 is voted in favor, without any modification, it will be approved or vetoed by the President of the Republic of Brazil.

In addition, in 2022, the Ministry of Mines and Energy (MME) published the National Green Hydrogen Plan (PNH2), which aims to address conceptual and fundamental aspects for the construction of the Brazilian hydrogen strategy, as well as the development of the economy of this energy in the country, allowing harmony with other sources of the energy mix. Implementing policies and legislation for renewable hydrogen is crucial to realizing and putting into practice business models. This is essential as it provides the security that investors require for their ventures.

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[21] All the tools used had the *templates* adapted from businessmakeover.eu.

3. BUSINESS MODEL PROPOSALS

The deliveries previously made in this project (Chapter 01, 02 and 03) established the bases for structuring the business models. On working package 1 steam reforming was chosen as a technology for hydrogen production in WWTPs; the results obtained in working package 2 estimated the production of H_2 from Sanepar's WWTPs and emissions reduction. The results obtained in working package 3 showed the importance of regulation in promoting the development of the entire H_2 production value chain. The alignment of legal and regulatory conditions at state, national and global levels to achieve this objective, in addition to the need to establish efficient procedures for planning, approval and standardization of certification systems, both for use and for the commercialization of renewable H_2 were highlighted. Within this framework, the absence of a clear positioning, which could potentially jeopardize investments in the sector, was emphasized. This is mainly due to uncertainties surrounding the standardization of renewable hydrogen. The concerns extend to aspects such as ensuring traceability of the renewable attribute, establishing commercialization methods, and addressing transportation through pipelines.

These results directly impact the business model for hydrogen, and therefore, the regulatory agent (which would be responsible for legislating, regulating and supervising regulatory and public policy issues specific to the sector) will not be considered in this delivery. Likewise, other revenues, such as premium or credit for the use of H_2 of renewable origin were not considered in the business models, as it also does not have a legislative provision yet. However, it may become an important factor for the greater employability of this feedstock in the future.

For the H_2 market in Paraná, there are 305 potential companies demanding H_2, sectorized in the industrial branches of processing industry and commerce. The geographical distribution of these companies is mostly located in the metropolitan region of Curitiba, whose result is in line with the geographical and economic distribution of Paraná state so as with the maximum estimate of biogas production in the WWTPs. This convergence has the potential to decrease the logistical costs associated with the process. Consequently, the results indicate a promising market potential for the proposed business models.

In this context, to integrate renewable hydrogen as a new product for the operation of Sanepar's Sewage Treatment Plants (WWTPs), a Business Model Workshop took place at the company's headquarters on October 16, 2023 in Curitiba, Paraná State. During this workshop, various business possibilities involving hydrogen were thoroughly discussed. These discussions played a crucial role in establishing the foundations for models tailored to the company's specific needs and provided valuable insights that will be reflected in the demonstration of more generic models.

3.1 PREMISES OF SANEPAR'S BUSINESS-ORIENTED MODELS

The premises established in the workshop are as follows: Sanepar aims to avoid implementing new processes and areas, such as developing its own infrastructure for the production, commercialization, and logistics of H_2. Instead, the plan is to forge partnerships with companies specialized in these sectors. To facilitate this, the formation of a Special Purpose Entity (SPE)[22] between two companies is considered, introducing potential business models that generate revenue beyond Sanepar's usual scope of services. Moreover, such partnerships contribute to reducing carbon emissions. In these proposed models, Sanepar would not act as the majority partner in the SPE, thereby avoiding potential impacts on the water bill. As a public utility company, Sanepar can only derive ancillary revenue[23] if there is a corresponding reduction in water tariffs for consumers[24]. Therefore, Sanepar's participation in the SPEs is envisioned to be 49%.

The selection of the future partner and the formation of each SPE would require Sanepar to conduct a public call. This process ensures that the chosen partner meets the predefined conditions. The eligible partners may include national or foreign companies, provided they possess the Brazilian tax registration (CNPJ).

The initial business model proposal involves a partnership with a company possessing the technology for H_2 production. Conversely, the second model suggests a collaboration with a company specializing in the distribution of special gases. In both scenarios, Sanepar assumes the roles of producing and commercializing biogas for the SPE. The SPE, in turn, will utilize the biogas for hydrogen production, following a technological pathway determined by the purification of Sanepar's biogas — a responsibility delegated to the SPE.

Another crucial premise is that the SPE will be required to acquire land for the H_2 plant, and the selection of its location will depend on the logistics intricacies of the process. Optimal proximity to the WWTPs is preferable to minimize the cost of transporting biogas. As part of this analysis, the construction of a low-pressure pipeline dedicated to biogas is deemed necessary. This pipeline will establish an interconnection between Sanepar (the producer) and the SPE (the consumer), with the associated costs borne by the SPE. Both business models assume the need for a fixed storage system for H_2, which falls under the responsibility of the SPE. This storage system is essential until the hydrogen is sold and subsequently withdrawn or delivered to companies that demand H_2. The transportation of H_2 is envisioned to be conducted by road using tank trucks operated by specialized

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[22] A Special Purpose Entity (SPE) is a model of business organization through which a new company is established, either as a limited liability company or a corporation, with a specific purpose. In other words, its activities are highly restricted, and in some cases, it may have a predetermined lifespan (SEBRAE, 2021).

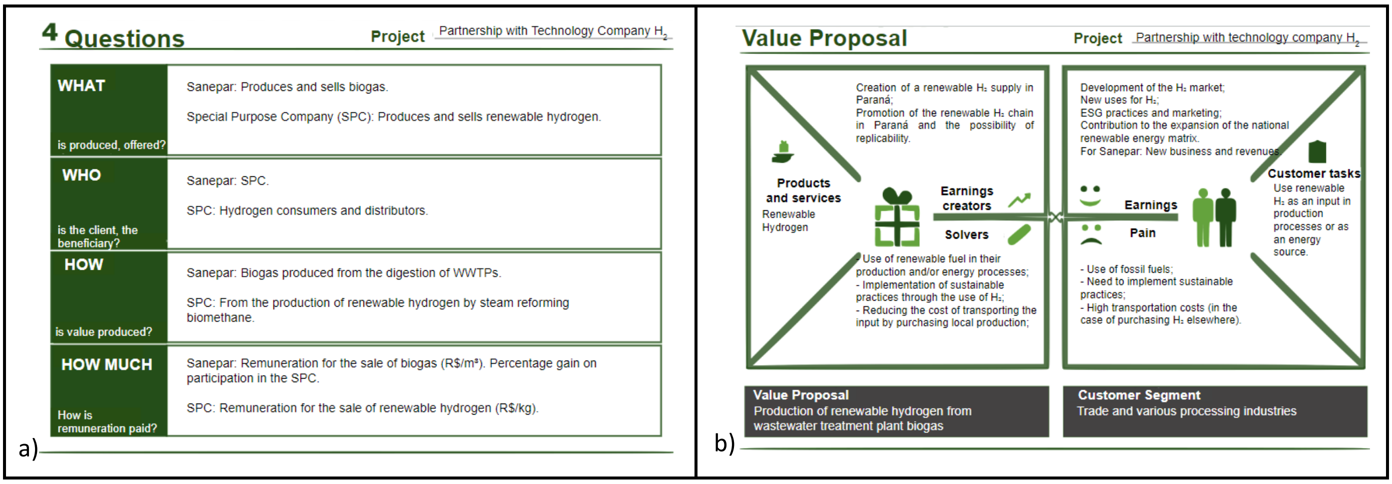
[23] Ancillary revenues are gains that the service provider may receive due to the provision of additional services beyond what is specified in the terms of the contract.

[24] The amount collected from the sale of biogas (R$/Nm³) to be marketed to the SPE will have this effect.

companies, preferably those utilizing renewable fuels. Importantly, the cost of transportation will be the responsibility of the companies demanding H_2. Therefore, a Free on Board (FOB) freight arrangement will be considered, placing all responsibilities, risks, and associated costs of transportation on the customer.

3.1.1 Business Model Proposal 1 - Partnership between Sanepar and Technology Company

The first business model proposed is a partnership between Sanepar[25] and a company that owns the technology to produce renewable H_2. Sanepar will be the biogas supplier and participant on the SPE. To formulate this model, the initial tool employed was the "4 questions," as illustrated in Figure 13.a). According to this framework, it is presumed that Sanepar will undertake the production and commercialization of biogas for the SPE, which, in turn, will be responsible for producing renewable H_2. The primary customers or beneficiaries of these products include, firstly, the SPE, acting as Sanepar's direct customer in the sale of biogas. Subsequently, the customers of the SPE are the ultimate consumers of H_2 or gas distributors, as determined by the outcomes of working package 3 in the analysis of potential customers. The economic value of this business model is generated through the sale of biogas by Sanepar, which the SPE will use to produce renewable H_2. Remuneration for these processes is determined by the sale price per cubic meter (R$/m³) of biogas for Sanepar and the sale price per kilogram (R$/kg) of renewable H_2 for the SPE. Additionally, as partners in the SPE, Sanepar and the technology supplier will also receive compensation through a percentage of the revenues generated by the SPE's processes.



4 Questions **Project** Partnership with Technology Company H_2

WHAT is produced, offered?	Sanepar: Produces and sells biogas. Special Purpose Company (SPC): Produces and sells renewable hydrogen.
WHO is the client, the beneficiary?	Sanepar: SPC. SPC: Hydrogen consumers and distributors.
HOW is value produced?	Sanepar: Biogas produced from the digestion of WWTPs. SPC: From the production of renewable hydrogen by steam reforming biomethane.
HOW MUCH How is remuneration paid?	Sanepar: Remuneration for the sale of biogas (R$/m³). Percentage gain on participation in the SPC. SPC: Remuneration for the sale of renewable hydrogen (R$/kg).

a)

Value Proposal **Project** Partnership with technology company H_2

Products and services
Renewable Hydrogen

Earnings creators
Creation of a renewable H_2 supply in Paraná;
Promotion of the renewable H_2 chain in Paraná and the possibility of replicability.

Solvers
- Use of renewable fuel in their production and/or energy processes;
- Implementation of sustainable practices through the use of H_2;
- Reducing the cost of transporting the input by purchasing local production;

Earnings
Development of the H_2 market;
New uses for H_2;
ESG practices and marketing;
Contribution to the expansion of the national renewable energy matrix.
For Sanepar: New business and revenues.

Pain
- Use of fossil fuels;
- Need to implement sustainable practices;
- High transportation costs (in the case of purchasing H_2 elsewhere).

Customer tasks
Use renewable H_2 as an input in production processes or as an energy source.

Value Proposal
Production of renewable hydrogen from wastewater treatment plant biogas

Customer Segment
Trade and various processing industries

b)

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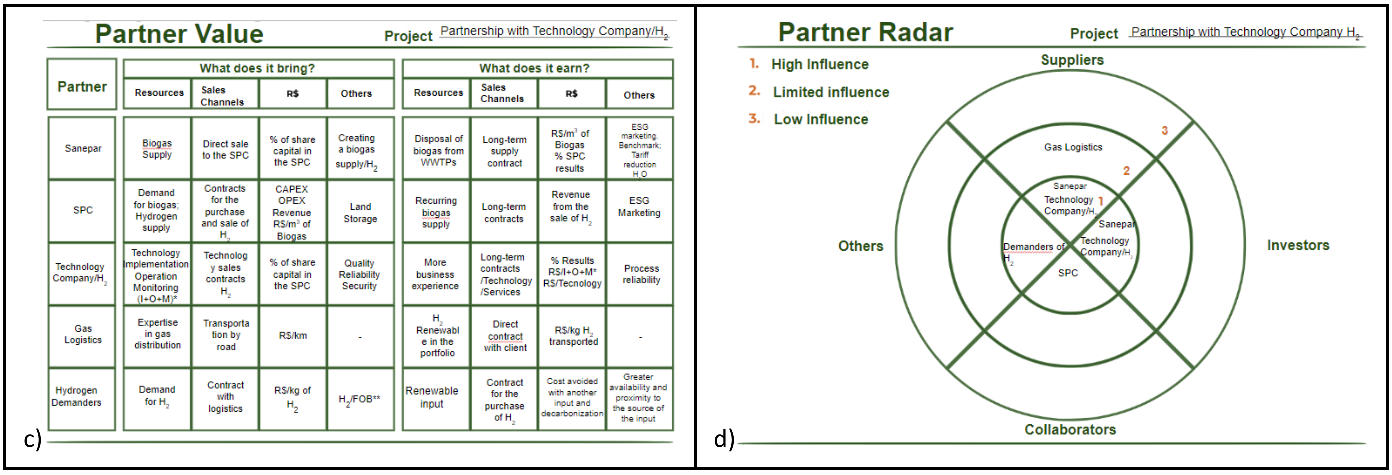
[25] The way in which this company will take place by Sanepar, for example, if Sanepar creates another legal entity to participate in the SPE with its new National Register of Legal Entities (CNPJ) is at the discretion of Sanepar itself, considering the indication of ancillary revenues already mentioned above.



Partner Value Project Partnership with Technology Company/H_2

Partner	What does it bring?				What does it earn?			
	Resources	Sales Channels	R$	Others	Resources	Sales Channels	R$	Others
Sanepar	Biogas Supply	Direct sale to the SPC	% of share capital in the SPC	Creating a biogas supply/H_2	Disposal of biogas from WWTPs	Long-term supply contract	R$/m³ of Biogas % SPC results	ESG marketing. Benchmark; Tariff reduction H_2O
SPC	Demand for biogas; Hydrogen supply	Contracts for the purchase and sale of H_2	CAPEX OPEX Revenue R$/m³ of Biogas	Land Storage	Recurring biogas supply	Long-term contracts	Revenue from the sale of H_2	ESG Marketing
Technology Company/H_2	Technology Implementation Operation Monitoring (I+O+M)*	Technology sales contracts H_2	% of share capital in the SPC	Quality Reliability Security	More business experience	Long-term contracts /Technology /Services	% Results R$/I+O+M* R$/Tecnology	Process reliability
Gas Logistics	Expertise in gas distribution	Transportation by road	R$/km	-	H_2 Renewable in the portfolio	Direct contract with client	R$/kg H_2 transported	-
Hydrogen Demanders	Demand for H_2	Contract with logistics	R$/kg of H_2	H_2/FOB**	Renewable input	Contract for the purchase of H_2	Cost avoided with another input and decarbonization	Greater availability and proximity to the source of the input

Figure 13 - Business model tools for the Partnership between Sanepar and the technology company

Source: Prepared by the authors, 2023.

Figure 13.b) illustrates the "Value Proposal" tool for the initial business model assessed for Sanepar. This model proposes the production of renewable H_2 from biogas derived from WWTPs. The value proposition is centered around addressing concerns related to the use of fossil fuels, the imperative to adopt sustainable practices, and the potential high costs associated with transporting H_2 from distant sources. As a value generator for this model, the key aspects include establishing a supply of renewable H_2 in Paraná, promoting the entire production chain, and creating a replicable model. The anticipated gains encompass the development of the renewable H_2 market, exploration of new applications for H_2, adherence to environmental, social, and governance (ESG) practices by the partner companies of the model and contributing to the expansion of the national renewable energy mix. The customers of this model belong to the trade and distribution segments, as well as to various manufacturing industries, in line with the results of working package 3[26]. These have the potential to use of renewable H_2 as a feedstock in production processes or its distribution replacing other sources.

The "Partners' Value" tool in Figure 13.c) outlines the key partners for this business model, including Sanepar, the SPE, the technology supplier company, the gas logistics supplier, and H_2 consumers. In examining the partner matrix for the business, Sanepar contributes the primary feedstock for renewable H_2 production, namely, biogas. Additionally, it provides monetary value through its percentage share (%/R$) in the capital of the SPE. Sanepar stands to gain environmentally by ensuring the proper disposal of biogas from the WWTPs, being monetized by the sale of biogas. The revenue sources include the sales price per cubic meter of biogas (R$/m³), a percentage of results

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[26] The sectors that could use hydrogen in their processes were divided through the National Classification of Economic Activities (CNAES), and wholesale trade, which were divided into subclasses: wholesale trade of industrial gases; fuel importer; asphalt industry; chemical industry; manufacture of hydrogenated vegetable fats; automation technology; metal mechanics and oleo chemistry; the manufacturing industry sector is comprised of the divisions: chemicals manufacturing; manufacture of pulp, paper and paper products; manufacture of rubber and plastic products; manufacture of food products; manufacture of non-metallic mineral products; metalworking; and manufacture of coke, petroleum products and biofuels.

based on its participation in the SPE, and gaining adherence to Environmental, Social, and Governance (ESG) practices, potentially establishing itself as a market reference. Sanepar may also pioneer efforts in this segment. Moreover, there is an indirect benefit for Sanepar's water consumers, who stand to gain from a reduced water tariff resulting from the sale of biogas by Sanepar.

The technology company supplies the necessary technology (equipment, machines, parts, etc.) for the establishment and operation of the H_2 plant. It contributes expertise in deploying, operating, and maintaining this technology, ensuring quality and reliability throughout the process. The technology company also provides monetary value (R$) through its percentage share in the capital of the SPE, as one of its partners.

The SPE partners, consisting of Sanepar and the technology partner, contribute resources to the business model. They act as the demand for biogas, ensuring the supply of renewable H_2. This offering is connected to customers through the sales channel established by contracts for the purchase and sale of renewable H_2. The SPE also provides monetary value (R$) in the form of resources required for the operation of the renewable H_2 plant, including Capital Expenditure (CAPEX) and Operational Expenditure (OPEX)[27], this includes the purchase of land for the plant and management of storage, which is funded through capital contributions from both partners (Sanepar and the technology partner). Additionally, the SPE will pay in Brazilian reais per cubic meter (R$/Nm^3) of biogas purchased from Sanepar.

As gains, the SPE secures the recurring provision of biogas (sourced from Sanepar) as a resource. In terms of monetary gains (R$), the SPE accrues revenue from the sale of renewable H_2. The technological partner holds a crucial role in the business model, not only for bringing the necessary technology for renewable H_2 production but also for instilling confidence in equipment quality. The partner's expertise in implementation, equipment operation, and maintenance ensures that the H_2 plant can achieve high levels of quality, efficiency, and productivity. As the responsible entity for operational processes and the "owner" of the business operations, the technological partner's performance directly impacts its revenue. In recognition of its contribution, the technological partner gains monetarily (R$) through payments for services provided during the implementation, operation, and maintenance of the plant. Additionally, compensation is earned for the use of technology in the process. As a partner of the SPE, the technology company will also receive a share of the revenues generated by the SPE. The partners demanding H_2, which can either be the final consumers who will

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[27] CAPEX can be considered as capital expenditures or investments in capital goods, it is a cost to create, maintain or even expand the scope of a company's operations, such as, for example, expenses with the construction of a new factory. OPEX are the operating expenses and expenditures, as well as in the maintenance of the company equipment, such as the expenses of the company's routine activities, such as tax expenses, employee expenses, accounts and equipment maintenance (SUNO, 2023).

use H_2 in their production processes or distributors/traders[28] of this feedstock will bring the demand for renewable H_2. Thus, these will bring as a monetary value (R$) to the business model the payment in R$/kg of renewable H_2, as the revenue of the SPE. The requesting companies also bring the contract with the logistics partner, which is considered FOB in this model. For the companies demanding H_2, the gains come from having a renewable feedstock resource. In monetary value (R$), these gains include the avoided cost associated with another energy feedstock and the decarbonization factor, allowing them to include the use in emissions inventory. Additionally, there's an advantage in terms of greater availability and proximity to the origin of the feedstock, especially if considering the H_2 production market and consumers in Paraná.

The partner responsible for gas logistics contributes valuable expertise in gas distribution, leveraging existing knowledge from non-renewable H_2 transportation, particularly through road transport. This partner gains the advantage of incorporating renewable H2 into its portfolio, with sales channels established through direct contracts with demanding companies. Consequently, the partner earns in Brazilian reais per kilogram (R$/kg) of renewable H_2 in the flow.

A crucial aspect to consider in this model is the necessity for the SPE to structure a customer portfolio and proactively engage in sales efforts by identifying and offering the product to potential customers. This requires strategic efforts to establish and cultivate relationships with future clients.

To comprehensively assess the performance and influence of each partner in this business model, the "Partner Radar" tool, depicted in Figure 13.d), was employed. The SPE emerges as a collaborative partner with high influence, given that the processes for producing renewable H_2 from Sanepar's WWTPs commence with its creation. Sanepar, being a major contributor to the SPE's share capital, is both a supplier (as the producer of biogas) and an investor, and thus, holds high influence in these aspects. The technology company partner functions as a supplier of both technology and services, and it also assumes the role of an investor. Consequently, its participation in these two capacities is considered highly influential. The gas logistics partner, responsible for distributing H_2 between the SPE and demanding companies, is regarded as a supplier with limited influence in this model. Its role is essential and necessary, however, given that multiple logistics partners may provide similar services, its influence is considered limited. The renewable H_2 demanding companies are deemed to have high influence in the model, as they are both beneficiaries and revenue generators for the SPE. Their role is pivotal in shaping the success and effectiveness of the proposed business model. Thus, from the four tools explained above, Figure 14 shows the Business Model (*BM Canvas*) structure as a whole, demonstrating the key and strategic points of the entire process.

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[28] The activity of the distributors considered includes the acquisition, storage, bottling (when necessary), transportation, commercialization, as well as technical assistance to the consumer of special gases.

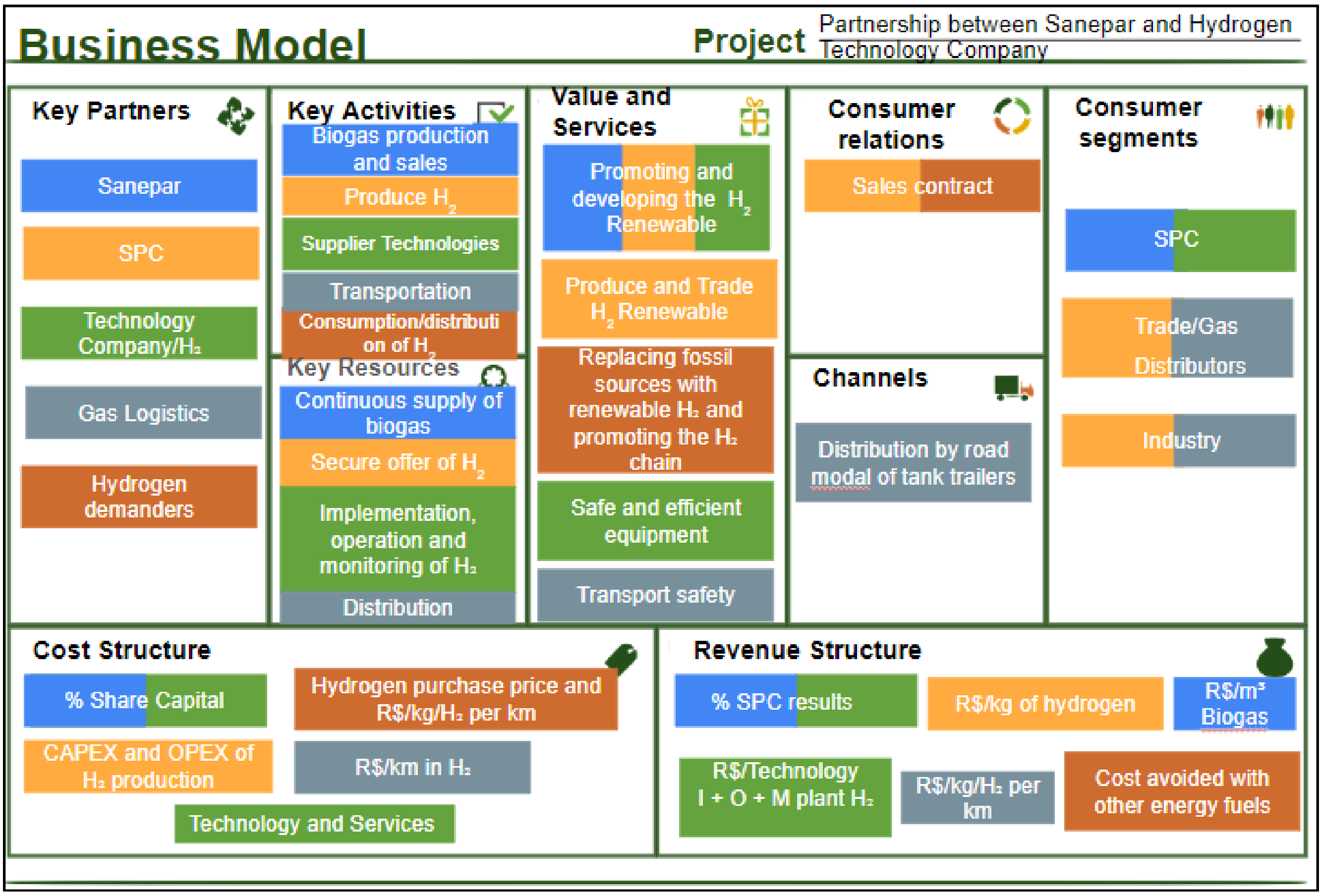

Figure 14 - BM Canvas tool for business model 1: Partnership between Sanepar and the technology company
Source: Prepared by the authors, 2023.

In this model, Sanepar, as a partner, is primarily engaged in the production and sale of biogas to the SPE, with the SPE itself as its consumer. The cost structure[29] involves the percentage of participation in the share capital of the SPE. Revenues are derived from the percentage of results related to the SPE's business and the Brazilian real (R$) per cubic meter of biogas sold to the SPE. Sanepar's value in this model lies in its role as a promoter and developer of the renewable H_2 chain, alongside all partners. The technology partner focuses on providing technologies for H_2 production, with key resources being implementation, operation, and maintenance services for the plant, serving the SPE as its customer. The cost structure includes the percentage of participation in the share capital of the SPE, technology costs, and human resources related to the provided services. Revenues come from a percentage share of the SPE's results, payments for the technology used, and services related to the implementation, operation, and maintenance of the plant. The value of the technology partner in this model is evident through the provision of secure and efficient H_2 technology and expertise in

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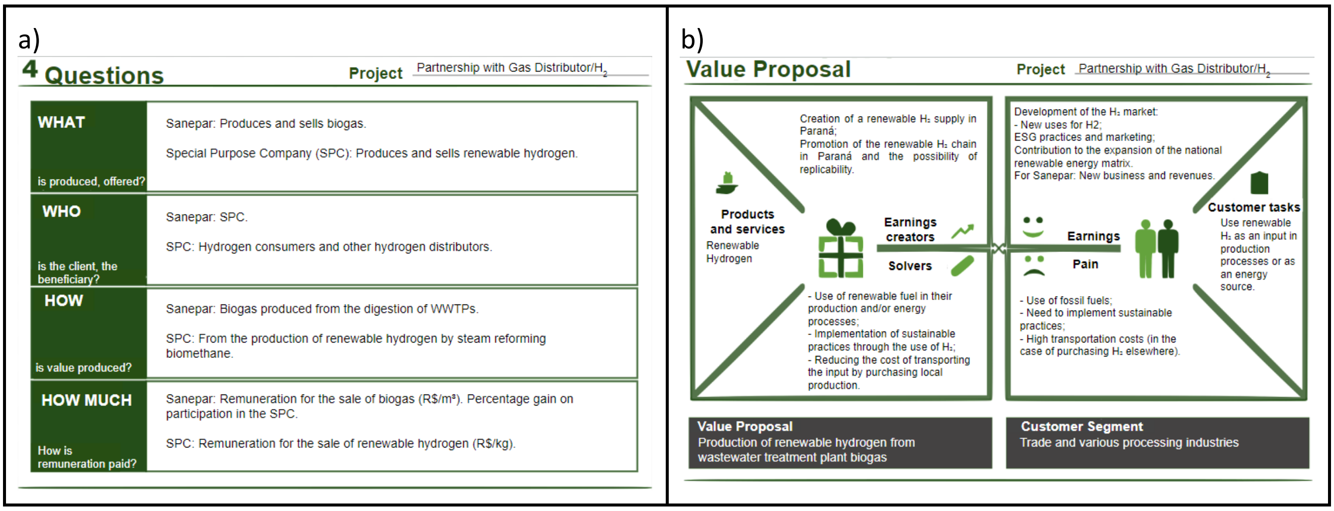
[29] It is assumed that Sanepar already produces biogas, and these business propositions of working package 4 are for the use of the biogas produced. Thus, the costs linked to the production of biogas by Sanepar are already contained in the company's current business model and therefore are not considered in this report.

services. The SPE's primary activity is the production of renewable H_2, relying on a secure H_2 supply as a key resource. Relationships with commercial segments, including distributors and the manufacturing industry, are established through purchase and sale agreements. The cost structure encompasses CAPEX and OPEX for renewable H_2 production, while revenues are generated through the commercialization in R$/kg of renewable H_2. The value of the SPE in this model is associated with its production and commercialization of H_2. The logistics partner specializes in the transport of H_2, relying on distribution logistics, with the same consumer segment as the SPE's demanding companies. This relationship is facilitated through the distribution channel via road modal using tanker trucks. The cost structure involves R$/km traveled for H_2 distribution, while revenues are generated per R$/kg of H_2, considering the distance in kilometers. The value of this partner lies in providing the necessary security for the transport of this renewable input. Finally, H_2 demanding companies, engaged in the consumption or distribution of H_2, interact with the SPE through purchase and sale agreements. Their cost structure includes the price for purchasing renewable H_2 and transportation costs (R$/kg/$H_2$ - considering the distance). Revenues are perceived as avoided costs with the replacement of other productive inputs. The value of these companies in the model is in replacing fossil sources with renewable H_2 consumption, promoting the development of the renewable H_2 chain, and, for distributors, the possibility of using it in carbon emissions inventories.

3.1.2 Business Model Proposal 2 - Partnership between Sanepar and Gas Distribution Company

The second business model proposed is a partnership between Sanepar and a gas distribution company[30], established in the form of a SPE. The "4 Questions" tool guiding the business model is illustrated in Figure 15.a).



a)

4 Questions **Project** Partnership with Gas Distributor/H_2

WHAT is produced, offered?	Sanepar: Produces and sells biogas. Special Purpose Company (SPC): Produces and sells renewable hydrogen.
WHO is the client, the beneficiary?	Sanepar: SPC. SPC: Hydrogen consumers and other hydrogen distributors.
HOW is value produced?	Sanepar: Biogas produced from the digestion of WWTPs. SPC: From the production of renewable hydrogen by steam reforming biomethane.
HOW MUCH How is remuneration paid?	Sanepar: Remuneration for the sale of biogas (R$/m³). Percentage gain on participation in the SPC. SPC: Remuneration for the sale of renewable hydrogen (R$/kg).

b)

Value Proposal **Project** Partnership with Gas Distributor/H_2

Creation of a renewable H_2 supply in Paraná;
Promotion of the renewable H_2 chain in Paraná and the possibility of replicability.

Products and services
Renewable Hydrogen

Earnings creators

Solvers

- Use of renewable fuel in their production and/or energy processes;
- Implementation of sustainable practices through the use of H_2;
- Reducing the cost of transporting the input by purchasing local production.

Development of the H_2 market:
- New uses for H2;
ESG practices and marketing;
Contribution to the expansion of the national renewable energy matrix.
For Sanepar: New business and revenues.

Earnings

Pain

Customer tasks
Use renewable H_2 as an input in production processes or as an energy source.

- Use of fossil fuels;
- Need to implement sustainable practices;
- High transportation costs (in the case of purchasing H_2 elsewhere).

Value Proposal
Production of renewable hydrogen from wastewater treatment plant biogas

Customer Segment
Trade and various processing industries

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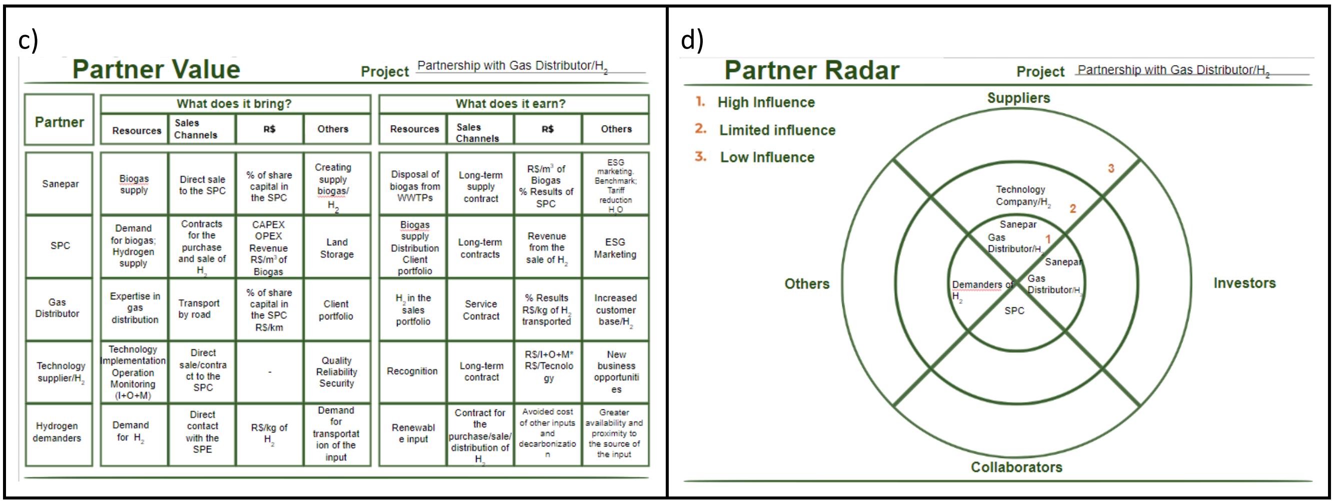
[30] The activity of the distributors considered includes the acquisition, storage, bottling (when necessary), transportation, commercialization, as well as technical assistance to the consumer of special gases.



c)

Partner Value Project Partnership with Gas Distributor/H_2

Partner	What does it bring?				What does it earn?			
	Resources	Sales Channels	R$	Others	Resources	Sales Channels	R$	Others
Sanepar	Biogas supply	Direct sale to the SPC	% of share capital in the SPC	Creating supply biogas/ H_2	Disposal of biogas from WWTPs	Long-term supply contract	R$/m³ of Biogas % Results of SPC	ESG marketing. Benchmark; Tariff reduction H_2O
SPC	Demand for biogas; Hydrogen supply	Contracts for the purchase and sale of H_2	CAPEX OPEX Revenue R$/m³ of Biogas	Land Storage	Biogas supply Distribution Client portfolio	Long-term contracts	Revenue from the sale of H_2	ESG Marketing
Gas Distributor	Expertise in gas distribution	Transport by road	% of share capital in the SPC R$/km	Client portfolio	H_2 in the sales portfolio	Service Contract	% Results R$/kg of H_2 transported	Increased customer base/H_2
Technology supplier/H_2	Technology Implementation Operation Monitoring (I+O+M)	Direct sale/contract to the SPC	-	Quality Reliability Security	Recognition	Long-term contract	R$/I+O+M* R$/Tecnology	New business opportunities
Hydrogen demanders	Demand for H_2	Direct contact with the SPE	R$/kg of H_2	Demand for transportation of the input	Renewable input	Contract for the purchase/sale/ distribution of H_2	Avoided cost of other inputs and decarbonization	Greater availability and proximity to the source of the input

Figure 15 - Business model tools for the partnership between Sanepar and gas distribution company
Source: Prepared by the authors, 2023.

From the tool, in a similar way to the previous model, Sanepar will produce biogas in the WWTPs to serve as an input in the production of renewable H_2 carried out by the SPE. The primary beneficiaries of these products will be the SPE itself, acting as a consumer of the biogas purchased from Sanepar. Subsequently, the demanding companies of H_2 (final consumers and other potential distributors) will benefit from the renewable H_2 offered by the SPE.

In this model, the distributor will bring its own customer portfolio. As in the previous model, the value in this business will come from the commercialization of biogas by Sanepar and the production of H_2 by the SPE. The SPE will pay for the biogas and will receive revenues from the H_2 sold.

Figure 15.b) illustrates the "Value Proposal" for the second business model evaluated for Sanepar, indicating gains and issues for the model partners. This model assumes the creation of a SPE from Sanepar and a Gas Distribution Company, analogous to the value proposal of the first business model (involving Sanepar and a Technology Company to create the SPE), with the difference being the segment of the SPE partner. The foundation of this model is based on the production of renewable H_2 from biogas originating from Sanepar's WWTPs. The goal is to mitigate the use of fossil fuels in favor of renewables, aligning with the growing trend of companies adopting sustainable and decarbonization practices. The supply of renewable H_2 generates gains such as providing a renewable H_2 supply within Paraná state, fostering greater development of the supply chain, and offering the possibility of replicating this business. Therefore, one of the gains is the expansion of the country's renewable energy mix and the exploration of new possibilities for using renewable H_2.

In the "Partners' Value" tool, the crucial partners in the model are Sanepar, the SPE, the Gas Distribution Company, the technology provider, and the H_2 demanding companies, as shown in Figure 15.c). The difference between the first and the second business model is that, now, Sanepar's partner to form the SPE will be a company that has expertise in special gas distribution and has a portfolio of customers to share. The SPE therefore brings in the demand for biogas and the supply of renewable H_2 as a resource, with H_2 purchase and sales contracts serving as a distribution channel. In this sense, it is up to Sanepar to decide which model seems more viable according to its capabilities and needs.

The SPE brings to the model the responsibility for CAPEX and OPEX costs on the renewable H_2 plant, including the land. It also brings revenue to Sanepar regarding the purchase of biogas (R$/Nm³). As gains, the SPE has the recurring provision of biogas by Sanepar and, already in its business, the distribution of H_2, as well as the customer portfolio for commercialization. Additionally, it obtains revenues from the sale of renewable H_2.

Sanepar, as a partner in the SPE, continues with the same contributions and gains compared to business model 1, bringing as a resource the recurring supply of biogas and contributing a percentage value to the SPE's equity. Sanepar earns in R$/m³ of biogas sold to the SPE and its corresponding share of the share capital in the SPE's results. It also benefits from environmentally sustainable destination practices for the biogas from the WWTPs, ESG practices, benchmarking, and provides its water consumers with a tariff reduction due to the sale of biogas.

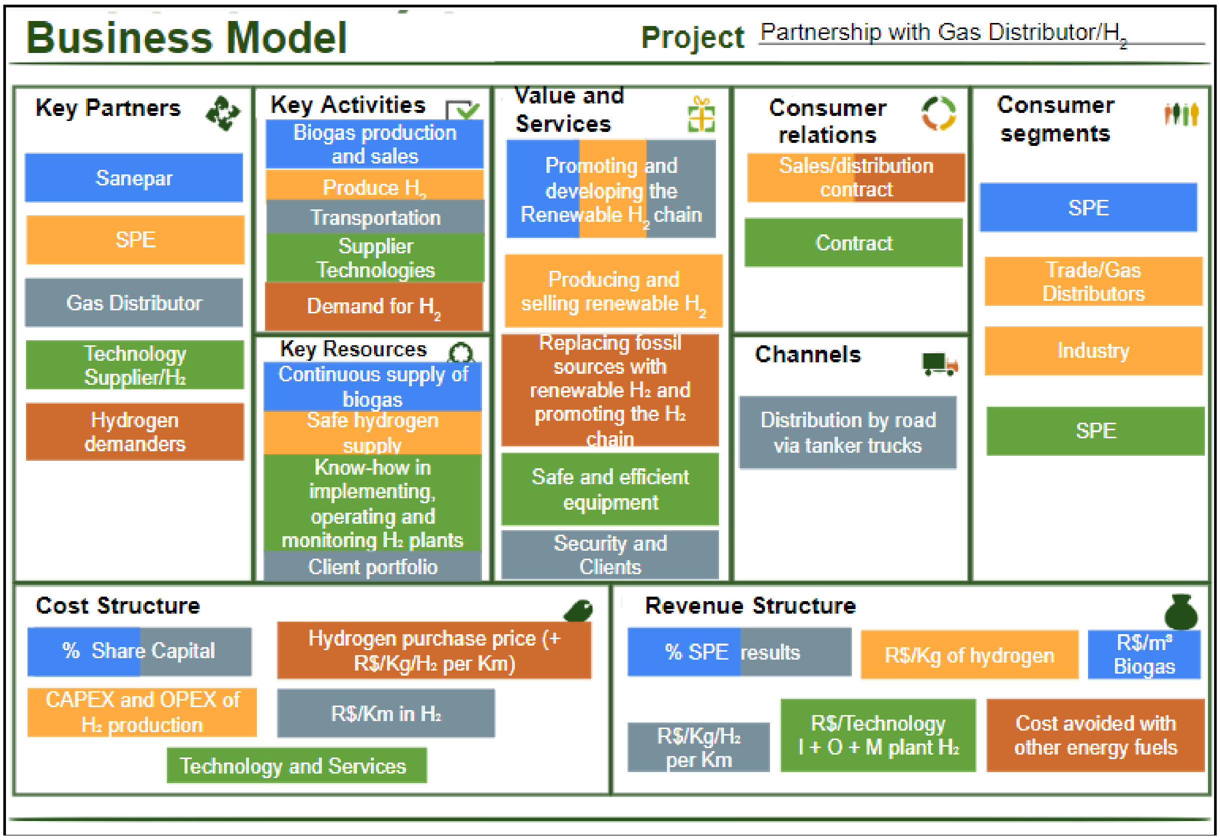
The gas distributor, in this model, is the other partner of the SPE and, therefore, also contributes with a portion of its capital stock. Thus, it brings the know-how of the gas distribution chain and the flow (R$/km), which is the sales channel of this model. Furthermore, the partner also contributes with its customer portfolio, one of the differentials in this business model. With respect to gains, the distribution partner will have the advantage of the availability of renewable H_2 for sale in its portfolio, allowing an increase in its portfolio by acquiring new customers for the business. Additionally, it receives a percentage share in the results of the SPE and an amount in R$/kg of distributed renewable H_2.

With regards to the technology supplier, the SPE will need to seek a partner in the national and international market that brings quality and safety in the operation, aiming at contracting a product and services with a long-term agreement. In addition to providing the necessary technology to produce H_2 from biogas, the selected partner should also be capable of implementing, operating, monitoring, and performing maintenance on the plant. Therefore, the costs related to CAPEX and OPEX of the plant will need to be budgeted in the market and will also be the responsibility of the SPE, derived from the capital stock contributed by its two partners. The technology supplier will obtain revenue (R$) related to these processes and has the possibility of generating new business and being recognized for such achievement.

Figure 15.d) presents the "Partners Radar" tool, indicating the degree of influence of each business partner for the model focused on meeting the premises established by Sanepar. As a biogas producer and also an investor contributing to the capital stock in the SPE, Sanepar is considered a

highly influential partner. In the same category are classified: 1) the gas distributor, also as an investor (by contributing capital stock to the SPE) and responsible for transportation and distribution logistics of the model, 2) the SPE itself, for producing H_2, and 3) the H_2 demanding companies, for bringing this demand for the feedstock. In this model, the technology company has limited influence, as there may be several companies willing to offer the expected products and services to the business.

The Business Model tool (BM Canvas), shown in Figure 16 places each item mentioned above and demonstrates how each partner can contribute and earn value from the business.



Business Model **Project** Partnership with Gas Distributor/H_2

Key Partners
Sanepar
SPE
Gas Distributor
Technology Supplier/H_2
Hydrogen demanders

Key Activities
Biogas production and sales
Produce H_2
Transportation
Supplier Technologies
Demand for H_2

Key Resources
Continuous supply of biogas
Safe hydrogen supply
Know-how in implementing, operating and monitoring H_2 plants
Client portfolio

Value and Services
Promoting and developing the Renewable H_2 chain
Producing and selling renewable H_2
Replacing fossil sources with renewable H_2 and promoting the H_2 chain
Safe and efficient equipment
Security and Clients

Consumer relations
Sales/distribution contract
Contract

Channels
Distribution by road via tanker trucks

Consumer segments
SPE
Trade/Gas Distributors
Industry
SPE

Cost Structure
% Share Capital
Hydrogen purchase price (+ R\$/Kg/H_2 per Km)
CAPEX and OPEX of H_2 production
R\$/Km in H_2
Technology and Services

Revenue Structure
% SPE results
R\$/Kg of hydrogen
R\$/m³ Biogas
R\$/Kg/H_2 per Km
R\$/Technology I + O + M plant H_2
Cost avoided with other energy fuels

Figure 16 - BM Canvas tool for business model 2: Sanepar and a Gas Distribution Company
Source: Prepared by the authors, 2023.

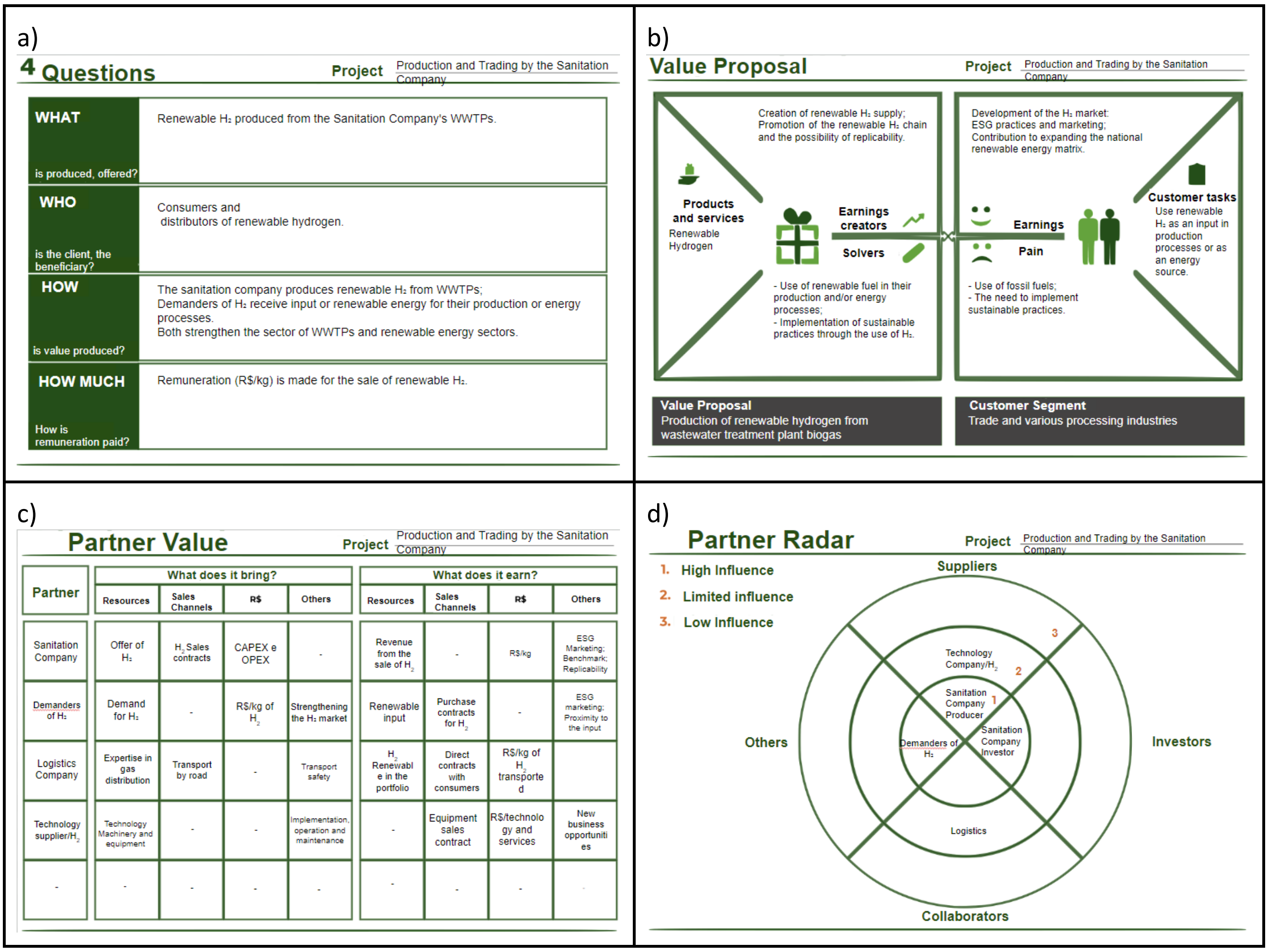
This second business model proposal involves the same partners as in the first model, but the contributions and actions change for the technology supplier and the gas distributor in terms of their relationship with the SPE. In this sense, the key partner Sanepar continues with its primary activity of producing and selling biogas to the SPE. The costs linked to its relationship with the model include the amount it needs to contribute to the SPE as share capital. Sanepar earns both the sale price of biogas (R\$/m³) and revenues from the percentage of participation in the SPE. Thus, the value presented by Sanepar is generated according to its contribution to the promotion and development of the renewable H_2 chain, and this value is also perceived by the other partners of the model. The SPE acts as a producer of renewable H_2, and the consumer relationship takes place through a purchase contract, including distribution. Its costs are related to the CAPEX and OPEX of these processes, and its revenue occurs through the sale in R$/kg of renewable H_2. The gas distribution partner, in this model, brings the key activities of transport and the customer portfolio, respectively. Its customers are the same as the SPE, considering that this relationship with the consumer will take place between the SPE and the demanding companies, including the cost of transport, carried out by road in tanker trucks. Thus, its cost structure includes the percentage value of participation in the SPE, in addition to its cost in transportation services, with revenue in R$/kg considering H_2 logistics, and it also participates in the results of the SPE. A comparative advantage of the business is that the gas distribution company includes renewable H_2 in its portfolio from WWTPs, in addition to the reduction of logistic costs in cases where the demanding companies for this renewable feedstock are located in the vicinity of the SPE production plant, as presented in the results of working package. The technology partner provides the technologies necessary for the production of H_2 and brings expertise in services for the implementation, maintenance, and operation of the H_2 plant, with the SPE as its customer, relating through a contract. Its costs are focused on the technology offered and the services provided, and its revenue comes from the payment for these products and services (R$). On the other hand, the demanding companies for renewable H_2 have the demand for this feedstock as their key activity related to its supplier (SPE) through a contract for the purchase, sale, and distribution of this H_2. Therefore, their cost structure for this process is the price to be paid for renewable H_2 (R$/kg, considering the logistics cost), and revenue is assumed as the cost avoided when replacing other feedstocks with renewable H_2 and the possibility of using it in emissions inventory, which is the value they bring to the model, also promoting the chain of this renewable product.

3.2 PREMISES OF THE GENERIC BUSINESS MODELS APPLICABLE TO THE SANITATION SECTOR IN BRAZIL

The generic models proposed are for WWTPs that have biogas as a product obtained from sewage treatment, applicable to sanitation companies throughout Brazil. These companies might have its own specificities, so each type of company, whether public or private, must follow its own rules regarding its business.

3.2.1 Business Model Proposal 3 - Sanitation Company producing and trading H_2

In this business model the production and commercialization of H_2 is carried out by the Sanitation Company itself (COMPANY), under its full responsibility. Hence, the "4 questions" tool provides a pragmatic overview of the proposal, as illustrated in Figure 17.a).



a)

4 Questions **Project** Production and Trading by the Sanitation Company

WHAT is produced, offered?	Renewable H_2 produced from the Sanitation Company's WWTPs.
WHO is the client, the beneficiary?	Consumers and distributors of renewable hydrogen.
HOW is value produced?	The sanitation company produces renewable H_2 from WWTPs; Demanders of H_2 receive input or renewable energy for their production or energy processes. Both strengthen the sector of WWTPs and renewable energy sectors.
HOW MUCH How is remuneration paid?	Remuneration (R$/kg) is made for the sale of renewable H_2.

b)

Value Proposal **Project** Production and Trading by the Sanitation Company

Products and services
Renewable Hydrogen

Earnings creators
Creation of renewable H_2 supply;
Promotion of the renewable H_2 chain and the possibility of replicability.

Solvers
- Use of renewable fuel in their production and/or energy processes;
- Implementation of sustainable practices through the use of H_2.

Earnings
Development of the H_2 market:
ESG practices and marketing;
Contribution to expanding the national renewable energy matrix.

Pain
- Use of fossil fuels;
- The need to implement sustainable practices.

Customer tasks
Use renewable H_2 as an input in production processes or as an energy source.

Value Proposal
Production of renewable hydrogen from wastewater treatment plant biogas

Customer Segment
Trade and various processing industries

c)

Partner Value **Project** Production and Trading by the Sanitation Company

Partner	What does it bring?				What does it earn?			
	Resources	Sales Channels	R$	Others	Resources	Sales Channels	R$	Others
Sanitation Company	Offer of H_2	H_2 Sales contracts	CAPEX e OPEX	-	Revenue from the sale of H_2	-	R$/kg	ESG Marketing; Benchmark; Replicability
Demanders of H_2	Demand for H_2	-	R$/kg of H_2	Strengthening the H_2 market	Renewable input	Purchase contracts for H_2	-	ESG marketing; Proximity to the input
Logistics Company	Expertise in gas distribution	Transport by road	-	Transport safety	H_2 Renewable in the portfolio	Direct contracts with consumers	R$/kg of H_2 transported	
Technology supplier/H_2	Technology Machinery and equipment	-	-	Implementation, operation and maintenance	-	Equipment sales contract	R$/technology and services	New business opportunities
-	-	-	-	-	-	-	-	-

d)

Partner Radar **Project** Production and Trading by the Sanitation Company

Figure 17 - Business model tools for the production and sales by the sanitation company
Source: Prepared by the authors, 2023

In this model, the Sanitation Company is presumed to be the entity responsible for both the production and commercialization of renewable H_2 derived from its WWTPs, positioning itself as the primary agent in the framework. The clientele of this company encompasses entities requiring H_2, either for direct consumption or as intermediaries such as gas distributors. The inherent value generated in this model lies in the Sanitation Company's capacity to produce renewable H_2 from its WWTPs, thereby facilitating a reliable supply chain for the consuming or commercializing entities and reinforcing the renewable H_2 ecosystem. The compensation mechanism involves remuneration through the sale of renewable H_2, measured in Brazilian Reais per kilogram (R$/kg).

Figure 17.b) illustrates the "Value Proposal," delineating the benefits and challenges for the partners involved in this model. It is discernible from this depiction that the value proposition in this business model encompasses the production of renewable H_2 derived from the biogas of the WWTPs, as opposed to relying on fossil fuels, aligning with the imperative to adopt sustainable practices. Assuming these priorities as primary considerations for "customers," the devised solutions center around the effective utilization of renewable H_2 and the implementation of sustainability measures.

This engenders value gains through the provision of renewable H_2 and the fortification of the associated supply chain. These gains are reflected in the expansion of the market and the contribution to the nation's renewable solutions matrix. The customer segments comprise entities involved in trade, distribution, and various processing industries that seek to substitute fossil sources, feedstocks, or distribution methods with renewable H_2, thereby promoting its usage. Thus, in all three models discussed, there is an appreciation of biogas as a byproduct of sewage treatment activities. Instead of merely flaring or utilizing it for energy purposes, there is a concerted effort towards the production of renewable H_2, thereby enhancing its overall value proposition.

The "Partners' Value" tool identifies key stakeholders in this business model, including the Sanitation Company, H_2 demanding companies, logistics company, and technology supplier company, as outlined in Figure 17.c). The partners' value matrix elucidates that the Sanitation Company assumes responsibility for the entire production process, contributing resources such as the supply of renewable H_2, as well as covering the associated CAPEX and OPEX costs of the plant. The company further commercializes the product through a purchase and sale contract with customers, thereby generating revenue from the sale of renewable H_2 in R$/kg. Additionally, the Sanitation Company stands to benefit from environmental, social, and governance (ESG) practices, potential recognition as a benchmark, and the prospect of business replicability for other WWTPs.

The involvement of H_2 demanding companies in the model entails their consumption of renewable H_2 and payment for the product in R$/kg, contributing to the strengthening of the market. These companies gain access to a renewable feedstock through a purchase and sale agreement, potentially reducing costs if the feedstock source is in proximity to the consumption site. Furthermore, consumers benefit from ESG practices by utilizing a renewable source.

The logistics company, leveraging its expertise and safety measures in gas distribution by road, gains access to renewable H_2 in its portfolio. The transport contract is established directly with the H_2 demanding companies, with compensation in R$/kg for the transported H_2.

The technology company, engaged by the Sanitation Company, provides the necessary technology for the H_2 plant, along with implementation, operation, and maintenance services. This entity earns revenue for the technology and services rendered, potentially utilizing this engagement as a springboard for other business opportunities.

Figure 18.d) has the “Partner Radar” tool for this model. Highly influential partners include: 1) the Sanitation Company that will be responsible for the production of H_2 (supplier) and the investor of the entire production process so as 2) the end consumers for bringing the feedstock demand and its revenue. The technology company as a supplier has limited influence, in the same way as the company responsible for gas logistics, assuming several players in these segments.

Ultimately, Figure 18 shows the Business Model (BM Canvas) with the structure of the business model as a whole, with key and strategic points.

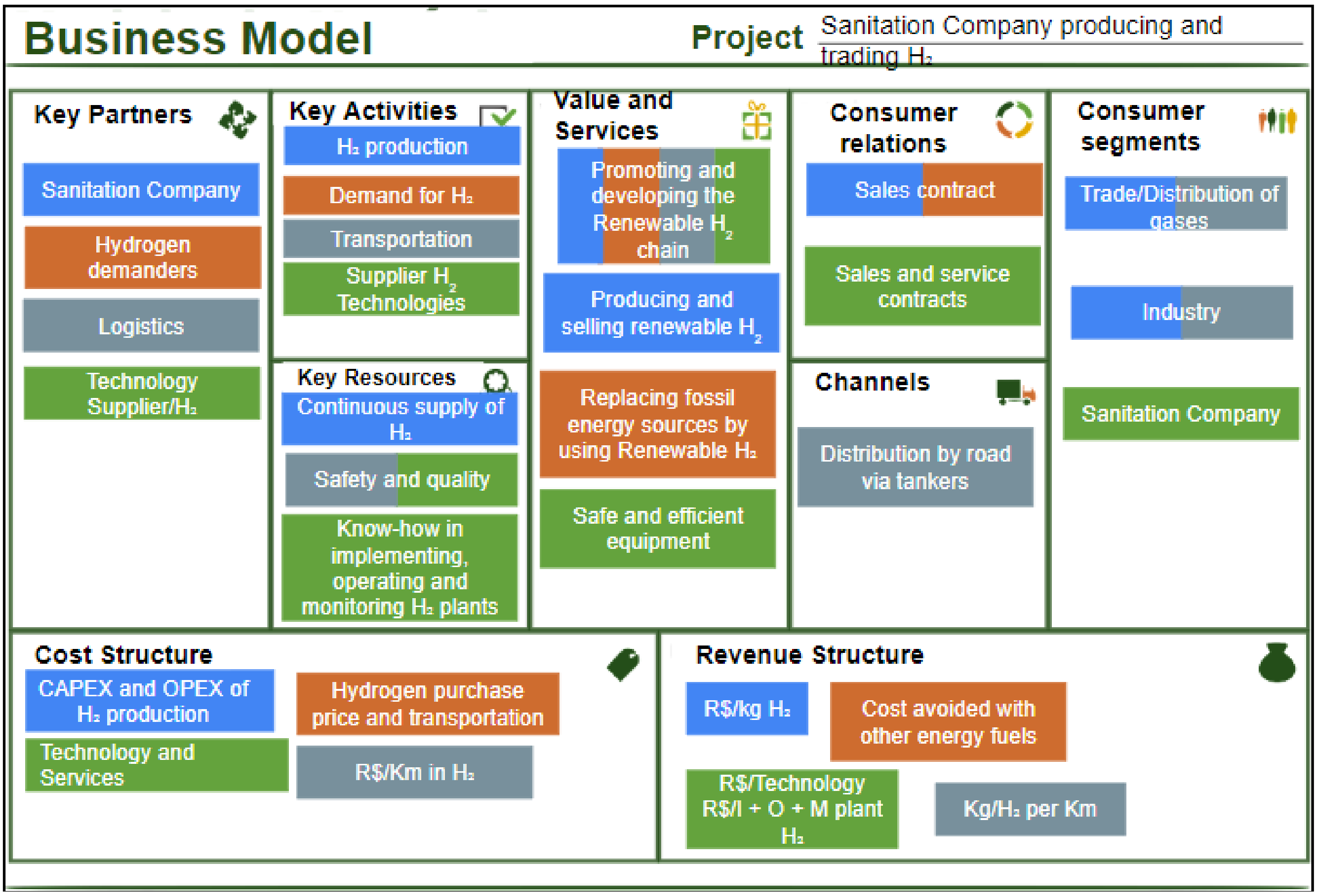


Figure 18 - BM Canvas tool for business model 3: production and commercialization business by the sanitation company

Source: Prepared by the authors, 2023.

In contrast to development models aligned with Sanepar's guidelines, the absence of a shareholders society characterizes the current model. The Sanitation Company assumes a pivotal role with a key activity focused on the continuous production of H_2. It manages the entire supply chain and reaches customers through a purchase and sale agreement. Consequently, the CAPEX and OPEX costs associated with the H_2 plant fall under its responsibility, as does the revenue generated from the sale of renewable H_2 in R$/kg.

The renewable H_2 demanding companies play a central role in driving demand for the product. Their costs are incurred through the purchase price of H_2 and its transportation. Conversely, their revenue is derived from cost savings and replacement of other fuels and/or feedstocks.

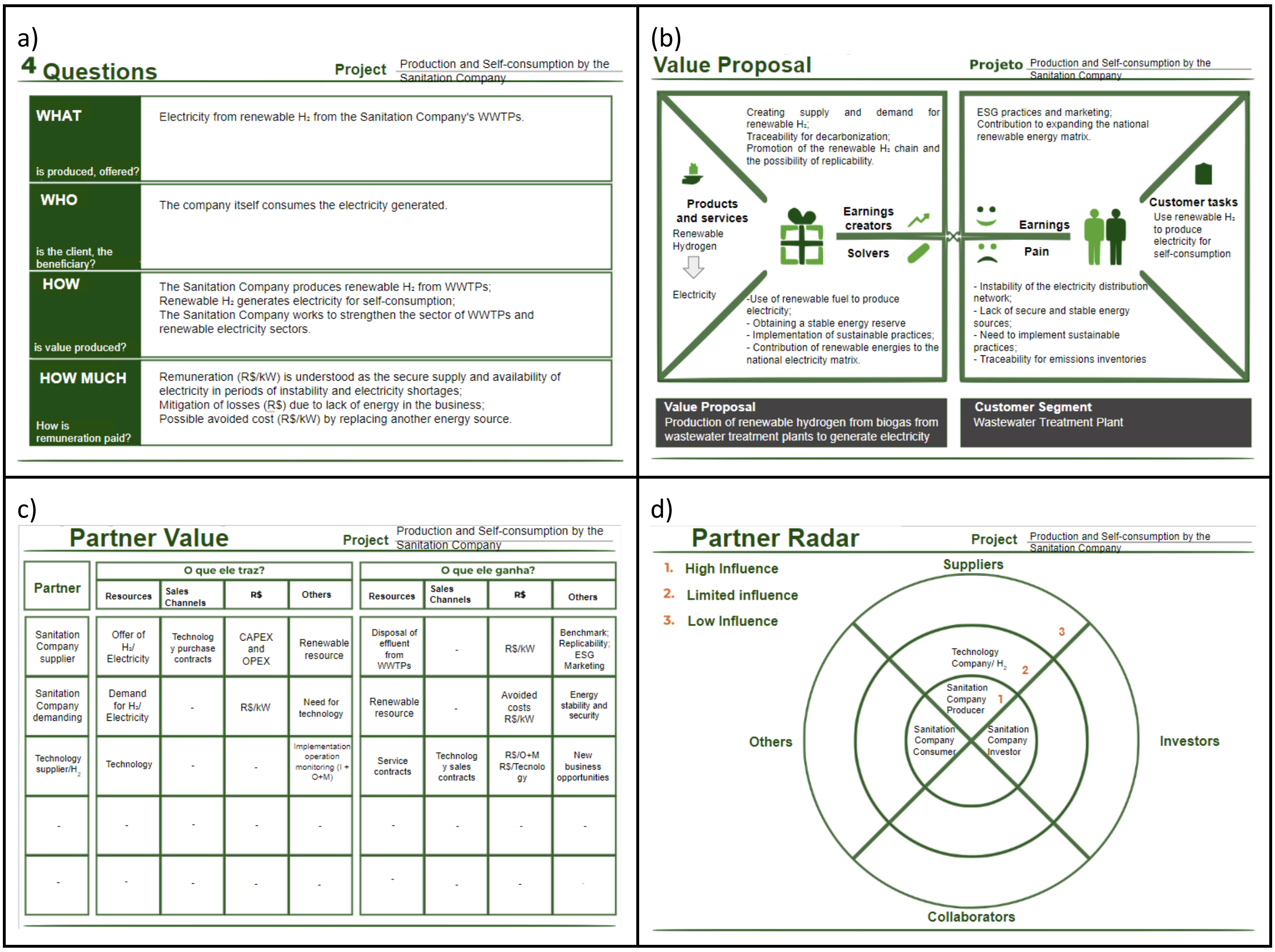
The logistics partner specializes in road transportation via tank trucks, catering to the same customer segments that purchase from the Sanitation Company and subsequently engage their services. Costs for the logistics partner are determined on a R$/km per H_2 drained basis, while revenue is calculated in kg/H_2, accounting for the distance between the product's origin and the final customer/destination.

The technology supplier's primary activity lies in providing comprehensive technology essential for the H_2 plant's operation, ensuring safety and quality in the process. The supplier leverages its know-how for implementation, operation, and monitoring. The Sanitation Company serves as its customer, and the relationship is formalized through a purchase and sale and service contract. Consequently, the technology supplier's costs are associated with applied technologies and services rendered, while revenues are defined in terms of R$/technology and R$/implementation, operation, and maintenance of the H_2 plant.

3.2.2 Business Model Proposal 4 - Production for Self-Consumption of the Sanitation Company

In this model, the Sanitation Company assumes the role of both the producer and consumer of renewable H_2 derived from Sewage Treatment Plants (WWTPs), utilizing it to generate electricity during periods of instability and electricity shortages. It is noteworthy that a significant portion, ranging from 15% to 40%, of operating costs in wastewater treatment is allocated to electricity consumption, representing the second-highest expenditure for the plant (METCALF et al., 2016; SNIS, 2019). This underscores the critical importance of ensuring a reliable and stable electricity supply. Given the utilization of H_2 within the same production area, regulatory and transport logistics agents have been omitted from this business model. Consequently, the entire process of renewable H_2 production and consumption falls under the purview of the Sanitation Company.

This consolidation of responsibilities is considered advantageous for decarbonization efforts, as the entire process cycle can be meticulously traced, resulting in tangible reductions in the Sanitation Company's emission inventories, without additional certifications for third parties. Figure 19.a) introduces the "4 Questions" tool, designed to identify the primary characteristics of the H_2 production and self-consumption model.



a)

4 Questions **Project** Production and Self-consumption by the Sanitation Company

WHAT is produced, offered?	Electricity from renewable H_2 from the Sanitation Company's WWTPs.
WHO is the client, the beneficiary?	The company itself consumes the electricity generated.
HOW is value produced?	The Sanitation Company produces renewable H_2 from WWTPs; Renewable H_2 generates electricity for self-consumption; The Sanitation Company works to strengthen the sector of WWTPs and renewable electricity sectors.
HOW MUCH How is remuneration paid?	Remuneration (R$/kW) is understood as the secure supply and availability of electricity in periods of instability and electricity shortages; Mitigation of losses (R$) due to lack of energy in the business; Possible avoided cost (R$/kW) by replacing another energy source.

(b)

Value Proposal **Projeto** Production and Self-consumption by the Sanitation Company

Creating supply and demand for renewable H_2;
Traceability for decarbonization;
Promotion of the renewable H_2 chain and the possibility of replicability.

Products and services
Renewable Hydrogen
Electricity

Earnings creators

Solvers

-Use of renewable fuel to produce electricity;
- Obtaining a stable energy reserve
- Implementation of sustainable practices;
- Contribution of renewable energies to the national electricity matrix.

ESG practices and marketing;
Contribution to expanding the national renewable energy matrix.

Earnings

Pain

Customer tasks
Use renewable H_2 to produce electricity for self-consumption

- Instability of the electricity distribution network;
- Lack of secure and stable energy sources;
- Need to implement sustainable practices;
- Traceability for emissions inventories

Value Proposal
Production of renewable hydrogen from biogas from wastewater treatment plants to generate electricity

Customer Segment
Wastewater Treatment Plant

c)

Partner Value **Project** Production and Self-consumption by the Sanitation Company

Partner	O que ele traz?				O que ele ganha?			
	Resources	Sales Channels	R$	Others	Resources	Sales Channels	R$	Others
Sanitation Company supplier	Offer of H_2/ Electricity	Technology purchase contracts	CAPEX and OPEX	Renewable resource	Disposal of effluent from WWTPs	-	R$/kW	Benchmark; Replicability; ESG Marketing
Sanitation Company demanding	Demand for H_2/ Electricity	-	R$/kW	Need for technology	Renewable resource	-	Avoided costs R$/kW	Energy stability and security
Technology supplier/H_2	Technology	-	-	Implementation operation monitoring (I + O+M)	Service contracts	Technology sales contracts	R$/O+M R$/Tecnology	New business opportunities
-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-

d)

Partner Radar **Project** Production and Self-consumption by the Sanitation Company

Figure 19 - Business model tools for the production for self-consumption of the sanitation company
Source: Prepared by the authors, 2023.

The ultimate product in this business model is electricity, generated through the conversion of renewable H_2 produced by the Sanitation Company into fuel cells for application during periods of electricity shortages. The inherent value of this model is centered around the production of renewable H_2 specifically tailored for electricity generation for self-consumption. This not only fortifies the sector and contributes to the renewable electricity matrix but also presents opportunities for ESG practices and facilitates the decarbonization of the company. The values embedded in this model encompass the secure supply and availability of electricity during periods of instability and electrical scarcity, measured in R$/kW. This contributes to the mitigation of losses (measured in R$) resulting from operational disruptions due to the lack of electricity. Furthermore, each unit of H_2 produced and consumed serves to proportionally displace an equivalent amount of energy from another source, potentially purchased. This displacement may lead to the avoidance of acquisition costs associated with alternative energy sources.

The use of motor-generator sets to produce electricity from biogas, even though shows a low-cost to implement, has a high operating cost. Motor-generator requires maintenance every 200 hours of use, and the overall efficiency of the process is around 30 to 40%, due to the energy loss involved in converting the chemical energy of the gases into mechanical energy and then electrical energy. In addition, as the use of biogas is low, there is a large volume of GEE associated with the burning of biogas. In this context, fuel cells stand out as highly efficient alternatives for producing electricity. The only residue of the process is water and, depending on the type of cell, efficiencies of up to 90% can be achieved, since the use of these devices directly converts the chemical energy of hydrogen and/or syngas into electrical energy. Fuel cells also have low operating costs, since their useful life can reach up to 80,000 hours.

Besides, hydrogen fuel cells offer several advantages over batteries, including: 1) Range and refueling (hydrogen fuel cells typically offer longer range compared to batteries, making them suitable for applications where extended range is crucial, such as long-haul transportation. Additionally, can take several hours to refuel a battery; 2) Energy Density and Weight (hydrogen fuel cells have a high energy density, meaning they can store more energy per unit weight compared to batteries); 3) Durability and Lifespan: Fuel cells tend to have a longer lifespan than batteries, resulting in greater durability and fewer replacements over time; 4) Versatility of Applications (Hydrogen fuel cells can be used in a wide range of applications, including transportation, stationary power generation, and portable electronics); 5) Emissions (applying hydrogen in fuel cells, the only byproduct is water, making them environmentally friendly and contributing to reduced greenhouse gas emissions compared to fossil fuel combustion); 6) Temperature Tolerance: Fuel cells can operate at a wide range of temperatures, including extreme cold and hot conditions, without significant loss of performance.

Figure 19.b) introduces the "Value Proposal" tool, delineating the production of renewable H_2 from biogas from WWTPs for electric power generation for self-consumption. The framework is built upon addressing issues related to the instability of the electric power distribution network, the absence of secure and stable energy sources, the imperative to implement sustainable practices, and the demand for traceability to enhance emission inventories.

The proposed solutions include leveraging renewable energy for electricity generation, establishing a stable energy reserve, implementing sustainable practices, and contributing renewable energy to the national electricity matrix. This model generates value by providing a renewable H_2 supply and meeting demand, ensuring traceability for decarbonization efforts, fostering the growth of the renewable H_2 chain, and presenting potential for business replicability. The gains in this model extend to ESG practices and marketing benefits, and a tangible contribution to the expansion of the national renewable energy mix.

The "Partners' Value" tool (Figure 19.c) outlines the key partners in the model, considering their contributions and gains within the business. In this model, the primary partners are the Sanitation Company and the technology supplier.

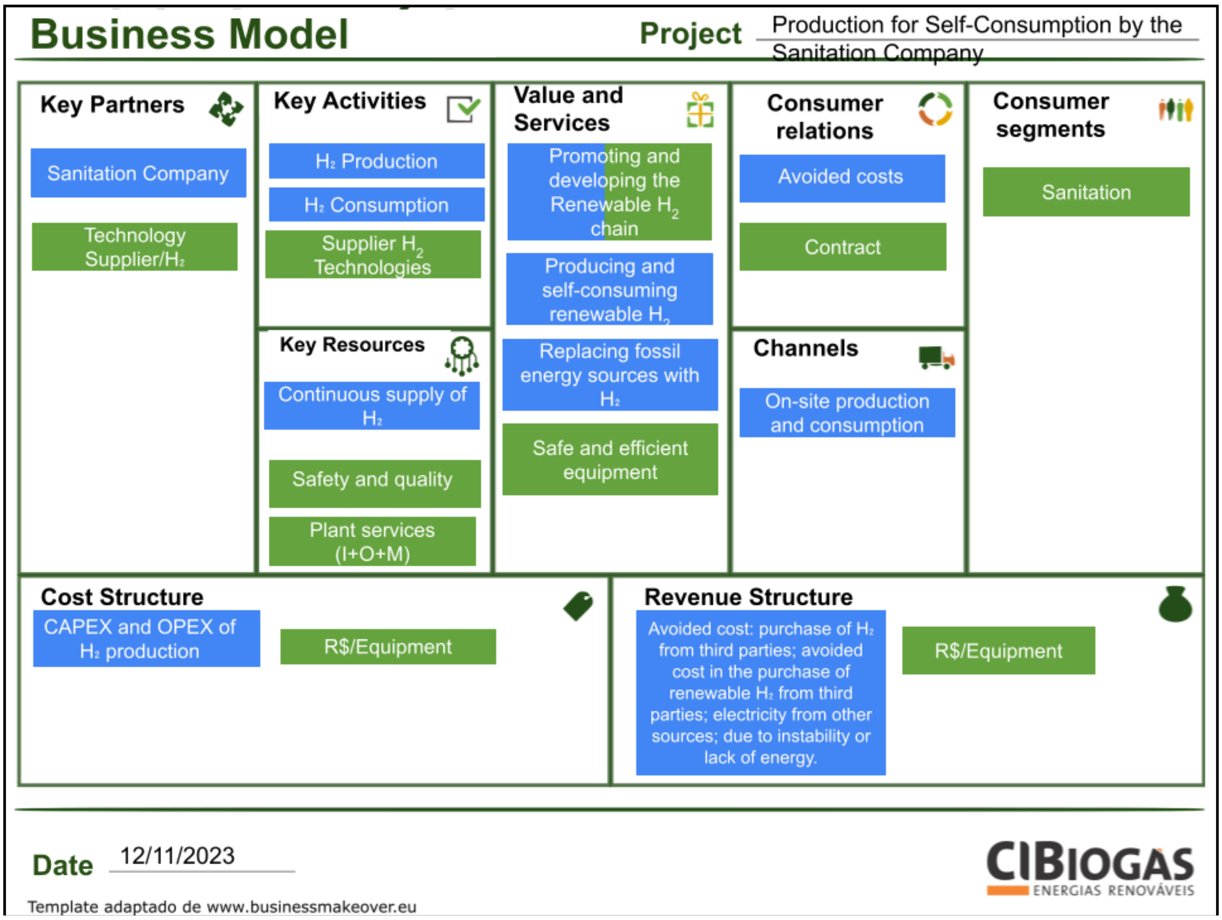
From one perspective, the Sanitation Company operates as the supplier, providing renewable H_2 as a sustainable energy source. It bears the financial responsibility for the entire production process of renewable H_2, covering CAPEX and OPEX costs until it becomes available as a source of electricity. The Sanitation Company's gains include the utilization of effluent from the WWTPs, translating into revenue measured in R$/kW of offered energy. Additionally, the company benefits from ESG practices and has the potential to become a benchmark case for replication.

Conversely, the Sanitation Company also functions as a demanding entity for electricity derived from renewable H_2, contributing monetary resources measured in R$/kW and requiring technologies for this purpose. Its gains encompass access to a renewable resource, while revenue is perceived through cost avoidance achieved by utilizing electricity from other sources (measured in R$/kW). The Sanitation Company mitigates losses (measured in R$) stemming from electricity shortages, achieving stability and energy security.

The technology company provides the essential technology for electricity generation through renewable H_2, encompassing implementation, operation, and monitoring of the plant. The company is contracted for the purchase and sale of the utilized technologies and services, with values specified in R$ (Brazilian reais) for each of these contracts. Additionally, the technology company has the prospect of generating new business opportunities within this segment.

In Figure 19.d), the “Partners' Radar” tool highlights the degree of influence each partner holds within the business model. The Sanitation Company emerges with high influence, serving as the producer of H_2, the primary investor in the entire production process, and the ultimate consumer by generating demand for the product. Conversely, the technology company exhibits limited influence, assuming a role within the supplier category.

The Business Model (BM Canvas) is shown in Figure 20. This tool positions each element of the model, illustrating how each partner contributes and gains within the overarching business framework.



Business Model

Project Production for Self-Consumption by the Sanitation Company

Key Partners
- Sanitation Company
- Technology Supplier/H_2

Key Activities
- H_2 Production
- H_2 Consumption
- Supplier H_2 Technologies

Key Resources
- Continuous supply of H_2
- Safety and quality
- Plant services (I+O+M)

Value and Services
- Promoting and developing the Renewable H_2 chain
- Producing and self-consuming renewable H_2
- Replacing fossil energy sources with H_2
- Safe and efficient equipment

Consumer relations
- Avoided costs
- Contract

Channels
- On-site production and consumption

Consumer segments
- Sanitation

Cost Structure
- CAPEX and OPEX of H_2 production
- R$/Equipment

Revenue Structure
- Avoided cost: purchase of H_2 from third parties; avoided cost in the purchase of renewable H_2 from third parties; electricity from other sources; due to instability or lack of energy.
- R$/Equipment

Date 12/11/2023

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Figure 20 - BM Canvas tool of the business model 4: production for self-consumption of the sanitation company
Source: Prepared by the authors, 2023.

In this model, the Sanitation Company assumes key activities involving both the production and consumption of renewable H_2, ultimately converted into electricity as the final product. The emphasis lies on ensuring a continuous supply of H_2 through on-site production and consumption. The revenue structure of this model is closely tied to cost avoidance, encompassing the procurement of renewable H_2 from third parties, the provision of electricity from alternative sources, and addressing issues related to the instability or lack of energy.

As a result, this business model is specifically tailored for locations characterized by electricity supply instability and precariousness. This scenario is particularly relevant in regions where hydroelectric plants serve as the primary energy source, and during times of water scarcity, there is an inherent risk of energy shortages. Consequently, the North and Northeast Regions of Brazil are identified as strategic targets for this model, offering a storable, safe, and stable energy source. Given the evolving market dynamics and the exploration of new applications for H_2, electricity generation emerges as a promising avenue within this context.

4. FINAL CONSIDERATIONS

This work has endeavored to construct four distinct business models tailored for sanitation companies, with a specific focus on two models customized for Sanepar and two generic models applicable to sanitation companies across Brazil, emphasizing the utilization of biogas in the generation of renewable H_2 within WWTPs.

The first business model contemplates a partnership between Sanepar and a technology company, established within the framework of a SPE. The technology partner contributes the necessary expertise for producing renewable H_2 through biomethane steam reforming, offering not only the technology but also services encompassing the implementation, operation, monitoring, and maintenance of the renewable H_2 plant. The distinctive feature of this model lies in the comprehensive processes introduced by the technology supplier, functioning as both a technology provider and an operational partner, with an inherent investment role, enhancing the overall performance of the venture.

The second business model designed for Sanepar involves a partnership with a gas distribution company, also structured within an SPE with Sanepar. In contrast to the first model, the key distinction here lies in the fact that the distribution company brings its existing customer portfolio to the partnership, along with distribution and sales logistics. While the technology supplier remains responsible for selling both technology and services related to the renewable H_2 plant, it does not function as an integral part of the SPE.

In the generic model applicable to sanitation companies in Brazil (third model), the sanitation company independently oversees the production and commercialization of renewable H_2, without the need for an SPE. This model places the advantage on the sanitation company for handling the CAPEX and OPEX structure, creating the customer portfolio, and engaging technology and operations suppliers. It positions the sanitation company as the primary driver of ESG practices and the potential benchmark for other industry peers.

The fourth model, also generic, advocates for the production and self-consumption of renewable H_2 by the sanitation company itself. The distinctive feature of this model is the generation of electricity for self-consumption derived from renewable H_2, ensuring a secure supply and availability of electricity during periods of instability and scarcity of feedstock. This model mitigates financial losses resulting from the lack of electricity in business operations during specific periods or regions with limited distribution network infrastructure.

These proposed models show the diversity of possibilities in developing businesses centered around the production, commercialization, and self-consumption of renewable H_2 for various applications. These models are adaptable to other sanitation companies, considering the unique characteristics of each entity. Importantly, they contribute to environmental and economic sustainability, support decarbonization efforts, reduce emissions, and foster the development of the renewable H_2 chain, ultimately contributing to a more diversified and sustainable energy mix.

WORKING PACKAGE 05: Preliminary Feasibility Analysis

HIGHLIGHTS

- The feasibility analysis encompassed four scenarios within sewage treatment plants (WWTPs), considering three different biogas production sizes: small (Quati I STP), medium (Padilha Sul STP), and large (Belém WWTP[31]). As shown in Table 4, three scenarios were considered with the reformer available in the domestic market (Hytron) and one scenario with imported technology.

Table 4 - Summary of the economic feasibility of the evaluated scenarios

Item	Quati I Hytron NEA	Padilha Sul Hytron NEA	WWTP Belém Hytron NEA	WWTP Belém Metacon
Production capacity (Nm^3/h)	50	100	200	250
Hydrogen production (kg/day)	22	43	262	331
CAPEX (€)	3.785.162	5.316.035	16.218.130	19.416.819
OPEX (€/year)	155.566	169.864	332.991	361.167
Electricity consumption (€/kg)	5	4	1	1
LCOH (€/kg)	17	12	6	5

Source: Prepared by the authors, 2023.

- Hydrogen production at the smallest scale of evaluated STP (Quati) has implementation costs of approximately €4 million and operation costs of 830 thousand/year[32] (€156 thousand/year), respectively. The LCOH in this scenario has an approximate production cost of €17/kg H_2.
- At the medium scale STP (Padilha Sul), the approximate costs of implementation are €5 million and the operation of the plant is €170 thousand/year. The LCOH was about €12/kg H_2.
- In the largest scale unit (WWTP Belém), in the case of national technology, the implementation costs are €16 million and LCOH estimated at approximately €6/kg H_2. For *Metacon*, the implementation costs are of €19 million and estimated LCOH of €5/kg H_2.
- It was possible to identify some challenges of the development of renewable hydrogen in Brazil and the solution to them. For this, strategies were developed to strengthen the new energy vector in the country.
- Despite the challenges pointed out and the substantial investments required, the implementation of pilot projects for the production of renewable hydrogen in WWTPs provides an opportunity for the development of this sector.

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[31] Formerly CS Bioenergia

[32] Considering the euro price quotation of 5.34 on November 22, 2033 [*sic*].

1. PRESENTATION

1.1 Overall Purpose

Preliminarily analyze the economic feasibility associated with the implementation and operation of renewable hydrogen production plants in sewage treatment plants (WWTPs).

1.2 Specific Purposes

- Define technology arrangements for the production of renewable hydrogen through the biomethane steam reforming, at different production scales (small, medium and large);
- Demonstrate the economic indicators of the project by cash flow;
- Determine the levelized cost of renewable hydrogen (LCOH) production from biomethane for the scenarios evaluated in the scales determined by Sanepar[33].
- Evaluate the impact of the reformer's technological import on the feasibility analysis in the scenario with the greatest potential.

2. INTRODUCTION

The hydrogen market is on the rise worldwide. However, its production cost is influenced by different factors, which include the production technology, availability of suppliers, price of renewable energy, supply and demand ratio and a regulatory environment that provides investment security and financing lines for hydrogen projects. Thus, it is important to define financial indicators that assist in decision making, offering a clear view of the main profitability vectors of a hydrogen production unit.

The results of the feasibility analysis allow a structured and coherent diagnosis of the investment and must be expressed based on the estimate of implementation costs (CAPEX), operating expenses (OPEX) and revenues. From these inputs, the following financial indicators are calculated: Net Present Value (NPV), Internal Rate of Return (IRR), Payback and the levelized cost of hydrogen (LCOH), which will assist in decision-making on the selection of the technological arrangement and the product application.

Therefore, the proposal of this working package is to present a preliminary economic feasibility analysis, associated with the implementation of hydrogen production projects via biomethane steam reforming[34] in WWTPs in Paraná. The financial indicators demonstrated the effect of scale and import

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[33] WWTP Belém, Padilha Sul STP, Quati I STP, as pre-established by Sanepar

[34] The development of the economic and technological feasibility study includes information on deliverables 1 and 2 (determination of the technology route of production of renewable hydrogen and estimation of hydrogen production. In addition, the design of the work considers the business models developed and presented in deliverable 4 and that will be described throughout the document.

on the cost of hydrogen production, which, linked to the costs of fixed capital and operation, should be strong allies in taking strategies for the economic feasibility of projects of this nature.

3. TECHNICAL PREMISES

The premises considered in the economic feasibility analysis include Sanepar's business models, presented in working package 4, which are listed below:

- The feasibility analysis will be conducted for four scenarios: three of them with the reformer available in the domestic market and one with imported technology.
- The sensitivity analysis will be conducted for two variables: hydrogen sales price and CAPEX of the implementation, considering NPV of 10 and 20 years.
- The evaluation on the impact of the implementation of an imported reformer on the technological arrangement and the feasibility analysis will be conducted for the largest scale[35].
- For foreign technologies, the import tax considered was 70%[36].
- Biogas was considered an operating cost (OPEX) and Sanepar shall be deemed the supplier of this product.
- The transport of the biogas to the hydrogen production plant must be within a maximum radius of 2 km.
- The biogas should be delivered with a maximum nitrogen concentration between 3 to 5%, to ensure a purification efficiency of 95%.
- The average composition of the biogas produced in UASB reactors in WWTPs is 60-80% of CH_4, 5-15% CO_2, and N_2 up to 5%.
- The capacity factor of the hydrogen production units is 95% (345 days), considering the downtime and maintenance period, with 24 hours a day for production.
- The expected application of hydrogen is to be compressed and stored in tank trucks for distribution and commercialization in road mode[37].
- The profits from the sale of kilograms (kg) of renewable hydrogen should be divided among the companies composing the SPE. The division of profits must be agreed between the parties, and this division is not established in this study.

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[35] Due to availability of the supplier's budget and specifications.

[36] This percentage may vary according to the acquisition period and new import lines.

[37] In Brazil, there is no regulation for the injection of hydrogen into the natural gas network, and there is also no dedicated gas pipeline.

4. SELECTION OF STEAM REFORMING TECHNOLOGY

4.1 National reformer

The selection of biomethane steam reforming technology in the Brazilian market considered the availability of European suppliers operating in Brazil, due to the experience and quality of the projects developed. From this premise, the technology provided by Hytron Energia e Gás, a company of the German group Neuman & Esser (Hytron NEA), was selected. Table 5 shows the models of the reformers available by the company in the national market and their respective minimum processing capacities of biomethane and hydrogen production.

Table 5 - Models of biomethane reformers available in Brazil

Model	**Biogas requirement (Nm^3/h)***	**Biomethane requirement (Nm^3/h)**	**Maximum hydrogen production capacity (Nm^3/h)**
HYREF 50-10	38	22	50
HYREF 100-10	74	43	100
HYREF 200-10	148	86	200

* Considering overall efficiency of 95% of the biogas refining system in biomethane.

Source: Prepared by the authors, 2023.

Based on the choice of national technology and its technical specifications, the plants with the potential to implement these technologies and the technological arrangement required to treat and purify biogas were defined, aiming to meet the ideal biomethane specifications for the reformer.

4.2 Imported Reformer

To measure the impact of import on investment costs in a project, a feasibility analysis for the larger technological arrangement was considered, due to the availability of budgets for this scale, in which reform technology is imported from Europe. The selection of European reform technology was supported by project partner Bluemove Consulting. The solution provided by the company Metacon was selected.

Based on the technical specifications of the HHG-250 reformer available, with a production capacity of 250 Nm^3/h of H_2, the plant with the potential to implement this technology was defined. Costs and technical data that were not publicly available were considered similar to Hytron NEA's HYREF-200-10 model.

5. DEFINITION OF THE TECHNOLOGICAL ARRANGEMENT

5.1 Selection of WWTPs

One of the premises defined by Sanepar was to carry out the feasibility analysis for three different production scales, in order to present the effect of the scale on the cost of hydrogen (LCOH). Based on this premise and the processing capabilities of Hytron NEA's three steam reformer models (Table 5) and Metacon's HHG-250 reformer capacities, it was possible to identify the units eligible for the implementation of the proposed technology. Of Sanepar's 263 WWTPs, 15 WWTPs were identified that deliver a minimum potential flow of 37 Nm³/h of biogas.

From these units, three sizes of WWTPs were indicated by Sanepar for the feasibility analysis: Quati I STP and Padilha Sul STP, aiming to meet the small and medium scale, respectively. As indicated by the sanitation company, it was defined that the analysis for the large scale would be carried out for the sewage sludge and organic solid waste (OSW) receiving and treatment unit, WWTP Belém. For the WWTP Belém scenario, the definition of the technological arrangement and the feasibility analysis were made using the national and imported reform technology.

Thus, the technological arrangements were built and the costs of capital expenditure (CAPEX), operational expenditure (OPEX) and other economic indices for the production of renewable hydrogen in the following three biogas production units were evaluated:

- Small scale: Quati I STP located in Cascavel (estimated flow of biogas: 38 Nm³/h)[38].
- Medium scale: Padilha Sul STP, located in Curitiba (estimated flow of biogas: 86 Nm³/h)[39].
- Large scale: WWTP Belém, located in Curitiba (estimated flow of biogas: 450 Nm³/h)[40].

5.2 Technological Arrangements

The biogas production units selected for the analysis have two distinct technological arrangements, using different substrates and biodigestion technologies. Quati I STP and Padilha Sul STP use modified UASB reactors for sewage treatment, producing a biogas with higher concentrations of methane (60 to 80%), but with considerable nitrogen contents (5 to 25%). Whereas the biodigestion system used in WWTP Belém consists of a CSTR (Continuous Stirred Tank Reactor model), which conducts the co-digestion of sanitary sludge and organic solid waste (OSW). In this system, the methane concentration is lower (~60%), and the nitrogen contents are insignificant.

This difference in the composition of the biogas produced by the systems implies different technologies for treatment and purification (Figure 21). At WWTP Belém, the biogas produced has

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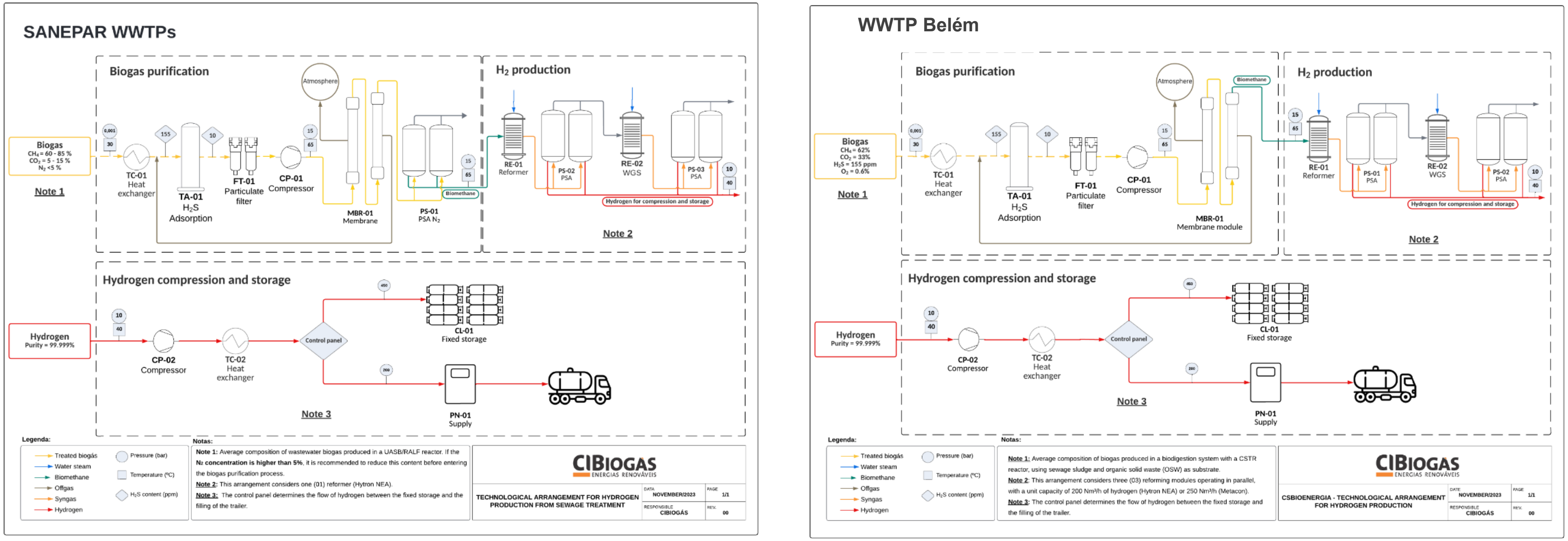
[38] Flow calculated with the aid of ProBio 2.0 Software (results presented in the working package 2 deliverable).
[39] Flow calculated with the aid of ProBio 2.0 Software (results presented in the working package 2 deliverable).
[40] Flow rate informed by Sanepar according to measurement data.

negligible nitrogen content, which requires only the membrane module for purification. In the WWTPs, the nitrogen content is very high, which requires an additional Pressure swing adsorption (PSA) system, in addition to the membranes, to reduce the content of this element.



Note 1: Average composition of wastewater biogas produced in a UASB/RALF reactor. If the **N_2 concentration is higher than 5%**, it is recommended to reduce this content before entering the biogas purification process.

Note 2: This arrangement considers one (01) reformer (Hytron NEA).

Note 3: The control panel determines the flow of hydrogen between the fixed storage and the filling of the trailer.

TECHNOLOGICAL ARRANGEMENT FOR HYDROGEN PRODUCTION FROM SEWAGE TREATMENT

Note 1: Average composition of biogas produced in a biodigestion system with a CSTR reactor, using sewage sludge and organic solid waste (OSW) as substrate.

Note 2: This arrangement considers three (03) reforming modules operating in parallel, with a unit capacity of 200 Nm³/h of hydrogen (Hytron NEA) or 250 Nm³/h (Metacon).

Note 3: The control panel determines the flow of hydrogen between the fixed storage and the filling of the trailer.

CSBIOENERGIA - TECHNOLOGICAL ARRANGEMENT FOR HYDROGEN PRODUCTION

Figure 21 - Difference in the technological arrangements for the production of hydrogen in the units

Source: Prepared by the authors, 2023.

6. COST SURVEY

The CAPEX and OPEX estimates presented in this topic were obtained from direct contact with suppliers and from the CIBiogás database. The values refer to the costs for implementation, operation, and maintenance of the four scenarios previously presented.

6.1 Costs for implementation (CAPEX)

The capital costs of goods are presented below in Table 6.

Table 6 - CAPEX Estimate

Classification	**Quati STP (Scenario 1)**	**Padilha Sul STP (Scenario 2)**	**WWTP Belém Hytron NEA (Scenario 3)**	**WWTP Belém *Metacon* (Scenario 4)**
	Cost (€)			
Land	88.577	106.507	155.665	155.665
Transport of biogas (pipelines and valves)	18.727	18.727	18.727	18.727
Biomethane production (removal of CO_2 and other impurities and chromatography)	271.439	393.162	623.499	623.499
Hydrogen production (reformer, steam generator, PSA, WGS and inert gas[41])	787.022	1.386.517	9.551.311[42]	12.750.000[43]
Hydrogen supply (compressor, storage and cargo column)	2.191.011	2.790.262	4.588.015	4.588.015
Monitoring and safety (Sensors, exhaust system, CPEs, PPEs)	81.705	114.717	369.539	369.539
Civil infrastructure (field interventions and civil works)	226.592	294.569	430.524[44]	430.524
Integration engineering (specialized service, management, and project)	120.089	211.574	480.850[45]	480.850
Total (€)	**3.785.162**	**5.316.035**	**16.218.130**	**19.416.819**

Source: Prepared by the authors, 2023.

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[41] Used in maintenance and/or emergency downtime.

[42] The cost includes three national modules for 200 Nm^3/h of renewable hydrogen each.

[43] The cost of the equipment in EUR is 2.5 million. Exchange rate of the euro to the real (EUR/R$) of R$ 5.34 (price quotation of November 22, 2033); import tax rate of 70%. In total, three imported modules are being considered for 250 Nm^3/h of renewable hydrogen, each.

[44] Same prices due to similar scale.

[45] Same prices due to similar scale.

6.2 Operating costs (OPEX)

Table 7 shows the costs related to the operation and maintenance of the arrangements.

Table 7 - Estimated OPEX

Classification	**Quati (Scenario 1)**	**Padilha Sul (Scenario 2)**	**WWTP Belém Hytron NEA (Scenario 3)**	**WWTP Belém Metacon Scenario 4**[46]
	Cost (€/year)			
Human Resources (operators)	94.382	94.382	141.573	141.573
Administrative costs	1.124	2.247	4.494	4.494
Consumable elements (activated carbon)	1.837	4.158	21.757	21.757
Purifier Operation and Maintenance	549	1.242	6.499	6.499
Reformer Operation and Maintenance	7.863	13.858	95.506	12.7500
Distribution Operation and Maintenance	43.820	44.944	46.816	46.816
Cost with the electricity demand of the plant	5.991	9.033	16.346	12.528
Total	**155.566**	**169.864**	**332.991**	**361.167**

Source: Prepared by the authors, 2023.

6.3 Operating revenues

As for revenues, the possibility of commercialization of renewable hydrogen by the SPE was considered, identified by the mass produced annually and the cost per kilogram of hydrogen (€/kg), currently marketed. For this feasibility analysis, the value of renewable hydrogen considered was €2.81/kgH_2[47] . This is the price of fossil hydrogen sold in Paraná state.

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[46] As there is no input of data and technical details of Metacon's technology, some of the points evaluated were analogous to the costs with Hytron NEA's technology.

[47] As there is no input of data and technical details of Metacon's technology, some of the points evaluated were analogous to the costs with Hytron NEA's technology.

7. FINANCIAL MODELING

To analyze the economic attractiveness of investments, the Free Cash Flow to Firm (FCFF) method was used. This method is supplied with the estimates of CAPEX, OPEX and revenues, and has as outputs the indicators of economic feasibility, such as Internal Rate of Return (IRR), Net Present Value (NPV) and Payback (time of return on an investment). For the financial modeling, the following economic premises were adopted:

- Analysis time of 20 years, according to the useful life of the reformers and purifiers;
- Average cost of biogas molecule: 0.07 €/Nm³;
- Total CAPEX investment without financing;
- The effect of inflation was not considered, as the budgets have a base date of November 2023;
- Tax Regime: Taxable Income (income tax of 15% p.a., 10% p.a. of the amount that exceeds 240 thousand reais per year, 9% p.a. of social contribution);
- Discount rate: 8.5%, considering the long-term Selic[48];

The economic results according to the premises are detailed in Table 8.

Table 8 - Summary of the financial analysis

Indicators	**Sul Quati I (Scenario 1)**	**Padilha Sul Scenario 2**	**WWTP Belém Hytron NEA (Scenario 3)**	**WWTP Belém *Metacon* (Scenario 4)**
Net operating revenue * (€)	79.341	191.184	1.147.106	1.433.882
EBITDA* (€)	-(96.847)	-(62.202)	333.205	612.487
Net income* (€)	-(287.052)	-(329.333)	-(477.702)	-(367.265)
NPV				
NPV 10 years (€)	-(4.420.612)	-(5.724.164)	-(14.031.859)	-(15.478.816)
NPV 20 years (€)	-(4.701.662)	-(5.904.673)	-(13.064.903)	-(13.701.386)
Payback				
DISCOUNTED PAYBACK	Longer than the analysis period			

* Considering financial data for 2024.

Source: Prepared by the authors, 2023.

The result in cash flow in the four scenarios reflects the situation in which investments and operating expenses exceeded revenues. This situation highlights the need to improve the conditions for the implementation of

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[48] According to Focus Bulletin of November 2023.

projects of this nature. In order to clarify the main aspects of improving the context of implementation of renewable hydrogen projects and their impact on project indicators, a sensitivity analysis of this project was carried out.

8. SENSITIVITY ANALYSIS

Sensitivity analysis is an important resource for companies and investors. The method seeks to understand how much the result will be impacted if one of its variables is changed. In this sense, some elements and conditions were considered in the sensitivity analysis that affect the context of the project, directly impacting the sale price of hydrogen, in CAPEX and OPEX, bringing strategic guidelines for hydrogen projects.

For the four scenarios, the sensitivity of the selling price of the hydrogen produced, previously considered to be €2.81/kg, and the investment cost (CAPEX) were evaluated. In the sensitivity analysis, three curves are presented: one related to the premises of the base scenario and the other two applied to the Net Present Value (NPV), one with a 10-year analysis and another with a 20-year analysis. This is done to assess the accumulated discounted cash flow when NPV reaches zero in these periods.

The analyses provide the following conclusions for biogas production units:

- Quati I: For this scenario, it was observed that the feasibility of the plant occurs when the sale price of hydrogen is €24, considered the minimum value to make the plant viable in the 20-year analysis period.
- Padilha Sul: For this scenario, it was observed that the feasibility of the plant occurs when the sale price of hydrogen is €16.42, considered the minimum value to make the plant viable in the 20-year analysis period.
- WWTP Belém - Hytron NEA: For this scenario, it was observed that the feasibility of the plant occurs when the sale price of hydrogen is €8.23, considered the minimum value to make the plant viable in the 20-year analysis period.
- WWTP Belém - *Metacon*: For this scenario, it was observed that the feasibility of the plant occurs when the sale price of hydrogen is €7.5, considered the minimum value to make the plant viable in the 20-year analysis period.

The sensitivity analysis compares between the parameters, which one presents the lowest effort factor for feasibility to occur. Therefore, as this factor decreases, it becomes more likely that the required values will be achieved. In this case, the results show that it is more tangible to increase revenue from the sale of hydrogen than the CAPEX investment reduction strategy.

As for the sale price of hydrogen, it is understood that it is necessary to seek alternatives for the purpose of increasing profitability, such as other renewable energy sources (carbon credit and other incentives), not restricted to only increasing the price of the molecule, which can make it less competitive in the market.

9. LEVELIZED COST OF HYDROGEN PRODUCTION (LCOH)

Based on the values of CAPEX, OPEX, Capital Charge Factor (CCF) and volume of hydrogen produced per year, the levelized cost of hydrogen production (LCOH) was determined for the four scenarios, by Equation 1.

$$LCOH = \frac{(CAPEX * CCF) + OPEX}{OUTPUT} \qquad \text{(Eq. 1)}$$

The CCF considers the interest rate and the reference output in the analysis, which in this case is the volume of hydrogen marketed. The LCOH value for each scenario is presented in Table 9.

Table 9 - Levelized cost of renewable hydrogen for each of the scenarios

Scenario	**LCOH (R$/kg)**	**LCOH (USD/kg)[49]**	**LCOH (€/kg)**
Quati I	90	18	17
Padilha Sul	61	12	11
WWTP Belém Hytron NEA	30	6	6
WWTP Belém *Metacon*	29	6	5

Source: Prepared by the authors, 2023.

The effect of scale on the reduction of the levelized cost of hydrogen, observed in Table 9 partially stems from the increase in revenue in operations on larger scales. In the case of the LCOH of renewable hydrogen produced by the electrolysis route in Brazil, the cost can vary from 0.32 to 0.67 €/kg[50], indicating greater competitiveness in relation to the hydrogen produced by the biomethane steam reforming. Electrolysis is the most widespread and technologically mature technology on the market for the production of renewable hydrogen.

Comparing the levelized costs of renewable hydrogen with fossil hydrogen, according to the LCOH Brazil Index published by CELA, the LCOH of grey hydrogen is in the range of 1 to 2.69 €/kg[51]. It is important to note that, according to the Energy Research Company (EPE), Brazilian refineries have a grey H_2 production capacity ranging from 35,000 to 3,570,000 Nm^3/day[52], which contributes to a positive effect of the scale on the levelized cost of grey hydrogen. Therefore, one of the strategies to increase the competitiveness of renewable hydrogen over grey hydrogen is to invest in large-scale projects, giving preference to large biogas production biodigestion systems (above 5,000.001 Nm^3/year)[53].

Analyzing the production scales in the context of Sanepar, the UASB reactors deliver a very small amount of biogas, which makes the feasibility of the project even more difficult. However, the use of sludge from aerobic

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[49] Considering the dollar price of 4.90 on November 22, 2023.

[50] Clean Energy Latin America (CELA), LCOH – Levelized Cost of Green Hydrogen in Brazil, 2023.

[51] Clean Energy Latin America (CELA), LCOH – Levelized Cost of Green Hydrogen in Brazil, 2023.

[52] EPE: Production and consumption of gray hydrogen in refineries in Brazil, 2022.

[53] According to the classification of biogas plants defined in BiogasMap, 2023.

stations for the production of biogas, in addition to being an opportunity to treat an environmental liability, also offers a greater potential for biogas production and, consequently, hydrogen.

Therefore, the current scenario indicates that investments in larger plants will present greater feasibility. On the other hand, investment in smaller plants should strengthen R&D actions aimed at supporting and accelerating the development of the reform technology, reducing costs and, thus, contributing to the increased attractiveness of the business model.

10. FINAL CONSIDERATIONS

The evaluation of the economic indicators obtained from the economic feasibility analyzes for the business models and the selected production scales offers relevant information that should contribute to decision making of hydrogen projects in WWTPs.

The results from the economical perspective of the analyzes of the three renewable hydrogen production scales (considering all inputs and outputs, such as CAPEX, OPEX and revenues) show that the current scenarios did not present feasibility *due to the high impact of plant implementation costs*. Based on the information observed, certain challenges and solutions were considered as a guidance (Table 10).

Table 10 - Challenges and solutions for the implementation of hydrogen plants

Challenges	Solutions
Reform and distribution stages are the items with the greatest impact on the costs of implementing the arrangements[54].	Development of the supply chain and tropicalization[55] of technologies and search for solutions with lower operating and maintenance costs.
High levelized cost of renewable hydrogen.	Increase in the production scale of plants.
The scales evaluated are small compared to the current production of grey hydrogen (up to 250 times larger).	The increase in scale is an opportunity to be exploited to increase the competitiveness of renewable hydrogen with grey, thus improving financial indicators.
Few suppliers in the domestic market (reform technologies and hydrogen storage and supply).	**Opportunity in this niche for German suppliers, aiming to establish a dynamic of competitiveness, increase the production chain and reduce prices.**
High investment cost of the plants and low financial return.	Strategies focused on increasing revenues or seeking ancillary revenues.

Source: Prepared by the authors, 2023.

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[54] About 70-80% of the total cost of CAPEX and 30-50% of the cost of OPEX. As deliverable of working package 03, there are estimates that transportation and distribution costs may be three times the costs of hydrogen production.

[55] The tropicalization of technologies refers to the process of adapting or customizing technologies, products, or solutions to meet the specific needs, conditions, and characteristics in foreign regions. This may involve adjustments to cope with the business operations, climate, culture, socio-economic conditions, and other factors that are distinctive in tropical environments.

Based on the challenges and solutions presented for the production of renewable hydrogen in WWTPs, strategies can be strengthened in the sector to enable different production scales and technological routes, as presented in Table 11.

Table 11 - Strategies for the implementation of hydrogen plants

Strategies
1) Tropicalization of hydrogen reform and disposal technologies to engage national and international stakeholders to implement actions to encourage economic development and technological innovation at the production of renewable hydrogen.
2) Development of technological routes that can generate ancillary revenues (or avoided cost) for the project, such as: - capture and purification of carbon dioxide; - by-products produced that may have commercial value; - thermal reuse of exhaust heats; - reuse water from water treatment modules for the processes.
3) Creation of financing lines and tax incentives dedicated to this type of enterprise to reduce taxes for sustainable appeal technologies.
4) Consolidation of certification, regulation and public policies that encourage the use and production of renewable hydrogen.
5) Establishment of a global carbon market, as renewable hydrogen produced in WWTPs must be an integrative mechanism of sustainable practices that demonstrates environmental responsibility.

Source: Prepared by the authors, 2023.

Despite the challenges pointed out and the considerable investments required, the implementation of pilot projects for the production of renewable hydrogen provides an opportunity for the development of this sector in Brazil. The strategic vision and the potential environmental and economic benefits can overcome the challenges, highlighting the importance of this initiative in the current landscape of transition to more sustainable and innovative energy sources.

Besides the hydrogen, there are other ancillary revenues that can be commercialized together with the hydrogen from steam reforming, such as: the carbon dioxide and exhaust heats. However, there is still a lack of practice and regulations on the CO2 market in Brazil, and the subject is under development at R&D level between CIBiogás and Sanepar. Regarding the sale of process heat, which is quite common in Europe, the residual heat and gases from catalytic steam reforming are recirculated and used as inputs for the surplus itself. With the pre-study on the feasibility of the plants, there is no concrete information on the consumption of these waste gases and heats, and whether there is a portion left over for a market.

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