Bagasse Utilization and Management Strategies in São Paulo Sugarcane Mills

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Summary

This thesis explores the utilization of sugarcane bagasse in São Paulo state, Brazil. Bagasse, a byproduct of sugarcane processing, is a crucial source of bioelectricity in Brazil, with variations in its use across different mills due to differences in cogeneration efficiency. Bagasse also attracts interest from EU companies to be used for BECCS. For the commercialization of this product, it is important for displacement issues to be avoided. This study examines current and potential utilization of sugarcane bagasse in São Paulo state, Brazil to determine the feasibility of freeing up bagasse.

The study begins with a comprehensive overview of the sugar cane sector in Sao Paolo including the variations in cogeneration efficiency of bagasse between mills, other sources of sugarcane bioelectricity in the mills and alternative uses of sugarcane bagasse. São Paulo's sugarcane mills produce approximately 100 million tons of bagasse annually, with the greatest portion (approximately 80%) used for bioelectricity for self-sufficiency of the mills and surplus electricity for the grid, highlighting its importance in Brazil's energy mix. To increase the availability of bagasse for commercialization, the research identifies three main strategies: improving cogeneration efficiency, utilizing sugarcane straw, and producing biogas from vinasse. Among these, efficiency improvements hold the greatest potential to free up bagasse, especially in mills with lower boiler pressures. The study also explores potential future uses of bagasse, such as sustainable aviation fuels and biochemicals, which could compete with current applications but are not expected to be immediate concerns.

The findings suggest that by adopting these strategies, substantial amounts of bagasse could be freed up for other uses without compromising its essential role in energy generation for the self-sufficiency of the mills and the surplus electricity exported to the Brazilian grid.

Preface

This thesis represents the culmination of my studies in the Master's program in Sustainable Development, specializing in Energy and Materials, at Utrecht University.

First, I would like to express my deepest gratitude to my supervisor, Floortje van der Hilst, for her invaluable support, ongoing guidance, and feedback throughout this thesis.

Furthermore, I want to thank my colleagues that worked with me in the field visits in Brazil. Their expertise and encouragement have been crucial in guiding my research and have ensured that I consistently found fulfilment in conducting this study.

Finally, I wish to thank all my friends and family and my partner for their encouragement, understanding, and patience through this journey.

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1. Introduction

Global energy security and climate change mitigation are major guiding factors toward shifting to alternative and renewable energy sources. Sustainable Development Goal 7 includes three main objectives: guaranteeing universal, affordable, and reliable access to modern energy services, significantly increasing the proportion of renewable energy, and doubling the rate at which energy efficiency is improving globally (United Nations, 2017). Global demand for sustainable biomass resources is increasing as countries strive to achieve negative emissions and meet their climate targets. In particular, the European Union has set ambitious goals to reduce carbon footprints

Bioenergy is becoming increasingly important in the world energy mix and has the potential to significantly lower carbon emissions (Reid et al., 2019). Bioenergy with carbon capture and storage (BECCS) is crucial in future energy scenarios, especially for mitigating climate change (Reid et al., 2019). Bioenergy offers baseload power, high-energy density fuels for transport, and carbon-negative potential through BECCS. However, there are sustainability concerns like land use and resource competition, or the constraints of large-scale deployment of BECCS like land scarcity (Reid et al., 2019). Biofuels, made from organic material and specifically referring to liquid or gaseous fuels derived from biomass such as ethanol, are integral to global energy transitions.

Brazil has emerged as one of the world's leading producers of biofuels following the implementation of the Pró-Álcool program in 1975, which encouraged and supported the growth of the sugarcane ethanol industry (Brinkman et al., 2018). Brazil accounted for over 38.6% of global sugarcane production in 2019 (Zheng et al., 2022). From the amount of sugarcane utilized in the mills to produce ethanol and sugar, 25% of this sugarcane processing byproduct is a pulpy fibrous residue called bagasse (Mahmud & Anannya, 2021). Brazilian sugarcane mills have a large supply of bagasse because of milling sugarcane to produce sugar and ethanol. Sugarcane bagasse is mostly used in Brazil for energy generation, making bagasse electricity important in the country, as bioelectricity is one of the four most important sources in the Brazilian energy grid (Kirshner et al., 2022; Herrera & Wilkinson, 2021).

The demand for biomass for power generation in Europe is increasing because of its base load and potential for negative emissions. For example, the Netherlands is an EU country with a goal to achieve the 2050 net-zero emission target, emphasizing negative emissions. According to Strengers et al. (2018/2022), the minimum biomass imports required to realize the maximum realizable potential for negative emissions in the Netherlands would be at least 170 PJ in 2030 and 410 PJ in 2050. However, there are sustainability concerns about dedicated crops and the large volumes of wood needed. Therefore, there is interest in other types of residues. An interesting biomass residue is bagasse due to its high volumes, concentrated availability, and potential for local densification. Brazil's supply of bagasse has already attracted attention from Northern European nations seeking to reduce their carbon footprints by boosting their proportion of renewable energy. As a result, more international multinational corporations are now involved in the ethanol and sugarcane industries (Ogura et al., 2022). Under these circumstances, bagasse seems to be a valuable product to be potentially used for power generation in countries like the Netherlands combined with carbon capture and storage in order to achieve negative emissions.

Notable European companies are actively involved, showing interest in exploring the sustainability of bagasse pellets for co-firing power plants and importing bagasse from São Paulo state. Since the early 2000s, São Paulo has witnessed a substantial increase in sugarcane cultivation, primarily because of the growing ethanol demand, government encouragement, and increased global sugar prices (Ogura et al., 2022). From 2000 to 2015, the sugarcane-planted area in the state expanded by 125%, equating to approximately 3,1 million hectares, and production rose by 128%, amounting to an increase of 243 million tons (Caldarelli & Gilio, 2018).

Although there is promising potential for bagasse to be internationally transported and used as a feedstock in power plants outside of Brazil, bagasse is mainly used domestically for both bioelectricity production and, to a limited extent, as a feedstock for second-generation ethanol (Carpio & Simone de Souza, 2017). Furthermore, as bagasse is currently used in combined heat power systems in the sugar mills of Brazil to provide process energy and, in some cases, to provide surplus electricity to the Brazilian grid, increased demand could create problems if there is a global market for this product. Research by Mai-Moulin et al. (2018) showed that more than 80% of the bagasse is currently utilized locally to heat and power sugarcane mills, as well as to supply excess electricity to the power grid. Mai-Moulin et al. (2018) also argue that based on the anticipated growth in bioelectricity's contribution to Brazil's energy needs, there will likely be a large increase in the demand for local sugarcane residues utilized to produce electricity. Higher demand for bagasse due to exports could affect the energy mix in Brazil, potentially leading to increased use of natural gas or sugarcane straw for process energy in mills. Diverting bagasse from domestic energy production to international markets could potentially reduce its availability for energy generation within Brazil. Bagasse contributes significantly to Brazil's bioenergy sector, and reduced availability for domestic energy production could impact the overall energy mix in the country. With decreased availability of bagasse, alternative energy sources may need to be considered. Finally, there is significant concern about how bagasse can be freed up while mills continue to operate as they do now. Additionally, as the demand for second-generation ethanol and other potential uses increases locally in Brazil, bagasse is becoming more sought after (Carpio & Simone de Souza, 2017).

A significant challenge in covering biomass demands with sugarcane bagasse, is that the Brazilian sugarcane industry lacks precise data on the amount of sugarcane bagasse available in mills and its processing for bioenergy. The variability among mills, ranging from older to more modern mills, smaller to bigger, more efficient and less efficient in terms of cogeneration, complicates understanding how bagasse is utilized. There is no specific categorization of sugarcane mills and different mills need different amounts of bagasse for bioelectricity. Also, the size of the sugarcane mills is different, so the sugarcane that is processed and therefore the sugarcane bagasse amounts are depending on the size of the mill. Additionally, there is limited specific information on the other uses of sugarcane bagasse. This uncertainty hinders effective planning for future scenarios to export bagasse to international markets for bioenergy. Consequently, it is unclear whether sufficient bagasse is available, which mills can supply it, and the exact quantities that can be freed for export without impacting domestic uses.

According to Fabio Vogelaar Carlucci et al. (2021), there is also a lack of data on sugarcane production activities and especially use of bagasse in Brazilian mills, and the available information does not represent all mills. Additionally, there is a lack of comprehensive discussion in scientific literature regarding the displacement effects of mill operations, particularly in scenarios where there is a potential rise in demand for bagasse from the European market. Research has been done to estimate better allocation scenarios of bagasse between 2G ethanol and power generation, depending on the costs of bioelectricity production and ethanol production. However, price sensitivity complicates the determination of specific pathways and the sugarcane industry's risk aversion level is not considered (Carpio & Simone de Souza, 2017). The authors concluded that across the scenarios analyzed, most of the surplus bagasse (excluding what's needed for self-consumption) should be allocated to producing 2G ethanol or generating bioelectricity. However, bagasse has also other uses and the assumptions are general. Furthermore, Kabeyi and Olanrewaju (2023) tried to estimate the bioelectricity potential of sugarcane mills, trying to separate mills regarding their efficiency, but the focus is more into increasing the electricity exports of the mills rather than freeing up bagasse of other uses. There is also a knowledge gap about the potential of freeing up bagasse specifically in Brazil. It is important to note that not all mills in Brazil operate the same way, so future predictions about bagasse usage are challenging, given the lack of a common strategy, and depend on the mill, group, and location scale.

The primary goal of this thesis is to provide a comprehensive overview of sugarcane bagasse utilization in Brazil, focusing specifically on São Paulo state, which accounts for nearly 85% of the country's sugarcane production and can, therefore, serve as a representative model. The research aims to explain the use of sugarcane bagasse for bioelectricity in the state, as well as its other applications and potential future uses. This study will examine the availability of bagasse in São Paulo, detailing how it is utilized across mills with different technical characteristics of cogeneration systems, taking into consideration factors such as bioelectricity exports and bagasse trading. Additionally, the thesis will estimate the amount of bagasse that can be freed up for commercialization through various methods validated from fieldwork, ensuring a thorough understanding of how to manage bagasse resources sustainably.

The goal of this thesis is to comprehensively assess the current and potential utilization of sugarcane bagasse in São Paulo state, Brazil and to determine the feasibility of freeing up bagasse that could possibly be a feedstock for BECCS.

To achieve this goal, one primary research question (RQ) and associated sub-questions are explored:

Main question

How is sugarcane bagasse used in São Paulo state of Brazil and how it can be possible to increase its availability for commercialization without compromising its current role in the sugarcane industry?

Sub-Questions

SQ1**:** How is sugarcane bagasse utilized within the sugarcane mills of São Paulo, Brazil, for bioelectricity generation and other applications?

SQ2**:** What is the availability of bagasse in sugarcane mills of Sao Paulo state?

SQ3: How can bagasse be freed up for other uses without being displaced?

SQ4**:** What other future uses can compete for the utilization of the freed-up bagasse?

The scope of this research is focused on sugarcane mills especially on Sao Paulo state and this is because it is the state of Brazil with the biggest production of sugarcane, according to Ogura et al. 2022, and the largest number of sugarcane mills in the country (more than 170 according to NovaCana, 2024). For this research fieldwork visits are included in sugarcane mills of the state. The study will examine how could bagasse become freed-up from sugarcane mills of Sao Paulo state without being displaced, but not the optimal way to use this bagasse (for example pellet production), however alternative present uses, and possible future uses will be explained. This is because to utilize bagasse for BECCS or another use, primarily is important to assess the feasibility of having available bagasse.

Prior to delving into the calculations of existing bagasse and strategies to increase its availability, the subsequent chapter will offer a comprehensive overview of the sugarcane bagasse sector in Brazil, with a particular focus on São Paulo. This section will give a comprehensive understanding to the nature of bagasse as a byproduct, its current applications, and the historical factors influencing its utilization within the sugarcane industry till today. Additionally, it will explain alternative uses for bagasse outside of the sugarcane mills and present other sugarcane byproducts that could possibly replace part of bagasse in the mills.

2. Overview of sugarcane bagasse sector

This part of the research will provide an overview of the sugarcane bagasse sector in Brazil, with a specific focus on São Paulo state. To achieve this, both literature and fieldwork will be employed. Fieldwork conducted in São Paulo state during March and April 2024, in collaboration with Fundação Solidaridad Brasil, and involved interviews with experts and site visits to sugarcane fields, mills, and relevant organizations. More information about the fieldwork can be found in the appendix. Chapter 2 will start with a presentation of bagasse and its characteristics, then the historical evolution of the bagasse sector, the use of bagasse for bioelectricity in the sugarcane mills and how the cogeneration efficiency can vary, other sources of bioelectricity from sugarcane that can partially replace bagasse and other present applications of bagasse except from bioelectricity.

2.1 Bagasse from sugarcane

Bagasse, the fibrous waste left over from crushing and extracting the juice from sugarcane, is one of the most common agricultural byproducts worldwide (Loh et al., 2013). Brazil has a long history of sugarcane cultivation, which has evolved into a highly advanced industry. The production of sugar and ethanol is central to the economy. Recent years have seen expansion into bioelectricity, and the development of second-generation ethanol from sugarcane bagasse.

In Sao Paulo state the harvest of the 2023/2024 season was 383 million tons of sugarcane (NovaCana, 2024). Moreover, according to Lucena Tavares and Amaral (2014), one ton of sugarcane provides approximately 250-260 kg of bagasse (25-26%) with 50% moisture content. For the last 10 seasons in Sao Paulo state, the average sugarcane harvest per season was 348 million tons per year according to NovaCana (2024), and subsequently, 90 million tons of sugarcane bagasse per year.

Moreover, sugarcane bagasse consists mainly of cellulose, hemicellulose, lignin, ash, and wax (Walford, 2008). More specifically, the dry mass of bagasse is composed (on a dry basis) of approximately 50% cellulose, 28% hemicellulose, 20% lignin, and 2% ash and other compounds (proteins, enzymes, and phenolic compounds) (Lucena Tavares & Amaral, 2014).

Because of its chemical composition and high calorific content, bagasse has the possibility to find utility in various potential applications, including but not limited to biogas, bioethanol, bio-hydrogen, bio-jet fuels, biochemicals, biodegradable items, paper and pulp, soil enhancements, fertilizers, animal feed, construction materials, reinforcement in polymer composites, and additives (Ajala et al., 2021).

2.2 Historical evolution and policy impacts on bagasse utilization in the Brazilian sugarcane industry

Historically, bagasse has been a crucial byproduct of sugarcane processing in Brazil, primarily used as a fuel for combined heat and power (CHP) systems within sugarcane mills (Dantas et al., 2023). Initially, the efficiency of these systems lagged commercial power plants due to regulatory constraints that prevented surplus electricity sales to the grid (Dantas et al., 2023).

This regulatory framework led mills to prioritize maximum bagasse burning for on-site energy needs, resulting in lower efficiency solutions such as low-pressure boilers and backpressure turbines (Dantas et al., 2023).

The landscape, however, began to shift with the implementation of key policies and initiatives aimed at promoting sustainability and reducing greenhouse gas emissions in the Brazilian sugarcane industry (Bordonal et al., 2018). Initiatives like the Brazilian Alcohol Program (Proálcool) launched in 1975 aimed at reducing oil imports through sugarcane-based ethanol production but soon showcased environmental benefits like a substantial reduction in CO_2 emissions as sugarcane bagasse was used for the self-sufficiency of the mills (Bordonal et al., 2018). Falling oil prices and favorable sugar markets in the mid-1980s redirected focus towards sugar production due to increasing attractiveness, leading to ethanol shortages and stagnation in ethanol production despite rising sugarcane yields (Hughes et al., 2020).

The trajectory changed in 2003 with the introduction of flex-fuel vehicles (FFVs), allowing for flexible ethanol-gasoline blends and resolving trust issues in ethanol reliability. This period marked a significant growth phase for ethanol production, supported by government incentives like tax exemptions and a favorable tax system for ethanol fuel. Ethanol production thrived, with increased sales of FFVs and a surge in ethanol output, attracting international investments and promoting sector growth (Hughes et al., 2020).

To meet growth targets and enhance sustainability further, the Brazilian government introduced the "RenovaBio" program to boost renewable fuel shares in the energy mix, with a specific focus on ethanol production growth, aligning with the broader goal of increasing ethanol production capacity by 2030 (Bordonal et al., 2018). RenovaBio, established in 2017, signifies a crucial step towards enhancing the role of biofuels in Brazil's energy landscape. This program enables biofuel facilities, including those producing ethanol and biodiesel, to obtain certification for generating decarbonization credits (CBIOS) by curbing greenhouse gas (GHG) emissions compared to conventional fossil fuels. Fossil fuel distributors are mandated to acquire these credits to fulfill individual GHG reduction targets (Tiburcio et. al., 2023). These policy interventions signal a significant shift towards more sustainable practices in sugarcane production, reinforcing the importance of maximizing the potential of bagasse utilization not only for electricity needs but also for environmental benefits and long-term sustainability goals. The dynamics in the sugarcane sector, influenced by domestic policies, fluctuating global commodity prices, and technological advancements like FFVs, demonstrate the sector's adaptability in responding to market demands and government interventions. The sector's sensitivity to economic factors, such as ethanol and gasoline prices, and global sugar prices, showcases the industry's resilience and challenges in balancing sugar and ethanol production (Hughes et al., 2020).

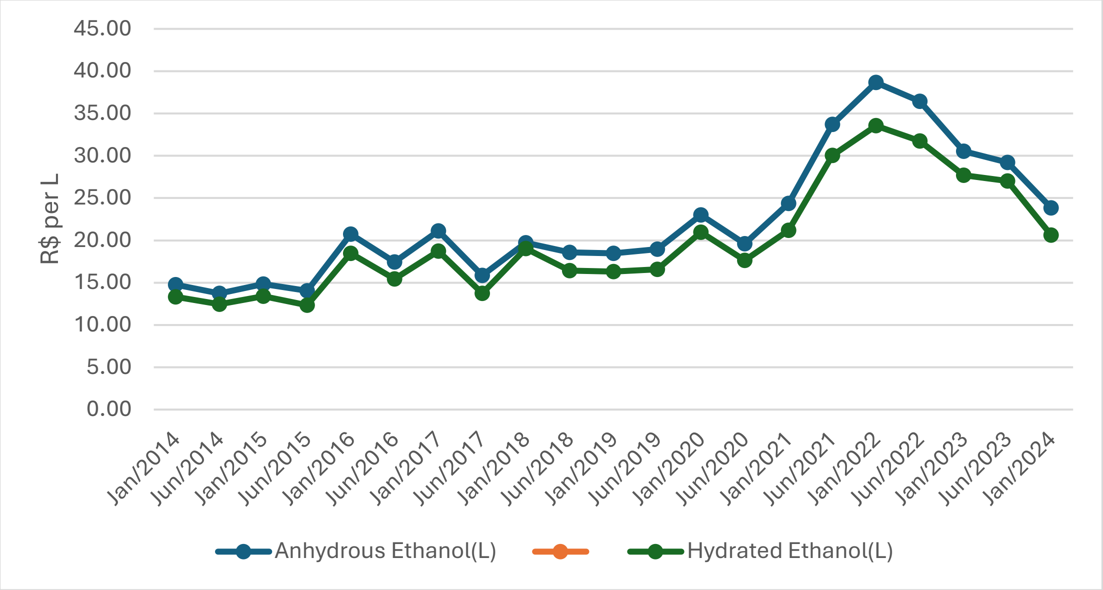

Figure 1. Ethanol prices in Sao Paulo state in Brazilian Reis from January 2014 till 2023 (data derived from NovaCana,2024)

Figure 1. illustrates the fluctuating price trends of anhydrous and hydrated ethanol in São Paulo over the past decade. While prices experienced some ups and downs until 2019, they surged dramatically during the COVID-19 pandemic, more than doubling by the end of 2022. Since then, prices have declined but remain volatile. The fluctuating ethanol prices have had a substantial negative impact on both ethanol-only mills and the overall Brazilian sugarcane industry. This claim is supported by interviews conducted at sugarcane mills in São Paulo, which identified price instability as a major challenge.

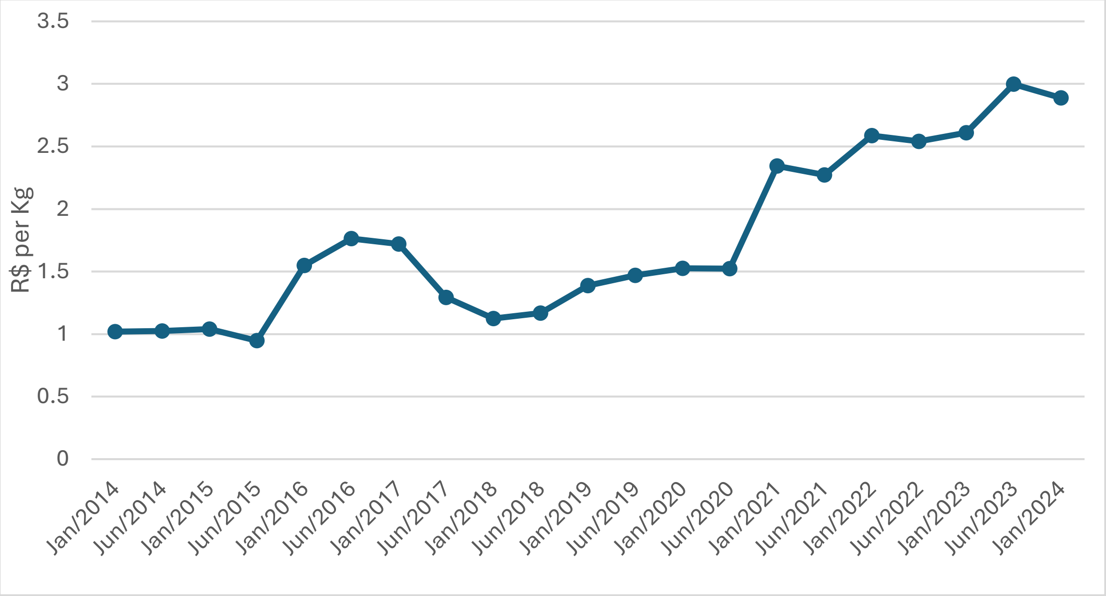

Figure 2. Sugar prices (for one kg) in Sao Paulo state during the last 10 years (data derived from NovaCana,2024)

Figure 2 presents sugar price trends in São Paulo over the past decade. While prices fluctuated between 2015 and 2018, an overall upward trajectory is evident. This has encouraged sugarcane mills to invest in expanded production, potentially leading to increased bagasse availability. Industry experts and mill consultants confirm that rising sugar prices are beneficial for sugar-producing mills and anticipate further production growth in the coming years according to fieldwork information.

2.3 Sugarcane bioelectricity

Sugarcane Bioelectricity in Brazil and Sao Paulo State

In Brazil, bioelectricity is produced from sugarcane in the harvest season, which is during the dry season and the reservoirs are at low level (Carpio & Simone de Souza, 2017). Brazil power system in mostly supplied from electricity generated from hydropower. Large hydropower plants play a significant role in electricity generation, making up roughly 65% of the nation's power supply and contributing to its environmentally friendly energy mix (IEA, 2022). However, expanding hydropower faces obstacles due to the remote locations and environmental concerns of remaining resources (IEA, 2019). Since Brazil's power system relies heavily on hydropower, reduced rainfall during the dry season can lead to lower water levels in reservoirs, impacting hydropower generation capacity. As a result, during periods of low rainfall, the country may need to rely more on other sources of electricity generation to meet energy demands.

In 2023, sugarcane bagasse and straw (in a very small mix with bagasse) emerged as the primary fuels for bioelectricity generation on the country's grid, contributing a total supply of 20,973 GWh. This represented a notable increase of 14% compared to the previous year, showcasing the growing significance of these renewable resources in the energy landscape (UNICA, 2024). To put this into perspective, this amount of bioelectricity equated to approximately 4% of the national electricity consumption for the year, sufficient to meet the needs of 10.8 million residential units (UNICA, 2024). Moreover, the magnitude of this contribution becomes even more apparent when considering international comparisons, as it nearly doubled the annual electricity consumption of a country like Uruguay and accounted for 42% of Portugal's usage or one-third of Switzerland's electricity needs.

In 2023, 86% of bioelectricity for the grid generated between May and November, with 92% including the month of April, which marks the beginning of the sugarcane harvest in the Center-South region. The bioelectricity generation from sugarcane bagasse showed a 14% increase compared to 2022 and accounted for nearly 75% of bioelectricity for the grid in the country. In 2021, considered the driest year since 1931 in the National Interconnected System, bioelectricity supplied 87% of its generation to the grid between May and November of that year, and 95% considering April to November. (UNICA, 2021, UNICA, 2024). In 2023, sugarcane bioelectricity supplied to the national electrical grid was led by the state of São Paulo, experiencing a 15% growth compared to 2022. According to the report of UNICA, 2024, São Paulo accounted for 52,8% of the biomass-generated electricity, offering 11,063 GWh in 2023. This slight increase in São Paulo's share of total sugarcane bioelectricity generation for the grid, up from 52,3% in 2022, underscores its prominent role in the sector.

Bioelectricity in Sugarcane Mills

In Brazilian sugarcane mills, bagasse is traditionally employed as fuel in combined heat and power (CHP) systems to fulfill the energy demands of the mills (Dantas et al., 2013). Bagasse is used to create steam in boilers. The main steam (high pressure) is used to make power for milling, pumping, and producing electricity, except the mills that have milling processes electrified. The secondary steam (low pressure) is used for heating, evaporation, baking, and distillation (Carpio & Simone de Souza, 2017). Burning bagasse as fuel in cogeneration plants, supply about all the energy needed for sugarcane processing mills. These plants produce themselves the necessary thermal, mechanical, and electricity for ethanol and sugar production (Dantas et al., 2013).

Cogeneration involves generating both electricity and usable thermal energy simultaneously. This process follows the Rankine Cycle, where high-temperature gases resulting from biomass combustion are utilized to produce steam, which then drives a turbine to generate electricity (Lopes Silva et al., 2014). Utilizing bagasse for energy production is economically sound, as it fulfills the entire energy needs of ethanol and sugar production processes while generating an electricity surplus that can be sold to the grid (Lopes Silva et al., 2014). Of course, this requires that the mill is connected to the grid.

Finally, according to Alves et al. (2015), typically, about 10% of the bagasse generated by the mills is reserved for emergency situations, such as plant start-ups at the beginning of the season or after unavoidable technical issues causing stops.

Efficiency of Electricity Generation from Bagasse in Sugarcane Mills

In the past, boiler systems in the sugarcane mills utilizing bagasse as a fuel source were not that efficient. However, the sector underwent a transformation with the reforming of the Brazilian Electricity Sector, establishing conditions for the commercialization of surplus electricity on the national grid (Dantas et al., 2013).

Sugar plants were built in the 1970s and 1980s with the intention of using all the bagasse to generate steam and electricity for internal use. Because of the systems' inefficiency, several mills need additional fuel from outside sources (Kabeyi & Olanrewaju, 2023). Development prompted a search for improved cogeneration systems that used higher steam parameters, and in the future, sugar mills may adopt even more advanced technologies like biomass integrated gasification combined cycles. These cogeneration systems could have a 35–40% power generation efficiency (Kabeyi & Olanrewaju, 2023).

Currently, every new mill project or the expansion of existing ones incorporates investments in cogeneration plants to produce additional electricity (Nyko et al., 2011). The widely recognized fact is that the key factors influencing a cogeneration system are the steam pressure and temperature, which have a direct impact on boiler efficiency and the generation of excess electricity (Lopes Silva et al., 2014). The latest high-efficiency boilers being implemented in grid-connected bagasse cogeneration plants have the capability to generate exceptionally high pressures and temperatures (Lopes Silva et al., 2014).

Back pressure steam turbine (BPST) systems, commonly used in many sugar factories, operate with a back pressure turbine that exhausts steam at pressures above atmospheric levels, typically around 2 to 2,5 bar for process use. These systems can still improve electricity generation through process modernization, which reduces steam consumption, alongside improvements in steam and power generation efficiency (Kabeyi & Olanrewaju, 2023). The condensing-extraction steam turbine system (CEST) uses a turbine to provide low-pressure steam for processes, with any excess steam exhausted to a condenser. This system improves performance compared to back pressure steam turbines by aiming to reduce steam consumption from an average of 500 kg per ton of cane (kg/tc) to about 400 kg/tc. Both BPST and CEST systems can operate at various steam generation temperatures and pressures, including 42 bar/400°C, 42 bar/450°C, 67 bar/480°C, 67 bar/515°C, 80 bar/520°C, 100 bar/520°C, and 120 bar/540°C (Kabeyi & Olanrewaju, 2023).

Finally, bagasse cogeneration efficiency is also affected by the moisture content of bagasse and the applied energy generation technology. The less the moisture content the better it is for cogeneration. Modern systems like Rankine cycle steam turbines can produce around 115–120 kWh per ton of cane (kWh/tc), while advanced technologies like biomass integrated gasification combined cycles can achieve 270–275 kWh/tc. Traditional systems show lower electricity and exergetic efficiencies, ranging from 22–25% and 60–70%, respectively (Kabeyi & Olanrewaju, 2023).

The reduction steam consumption in the systems of the mills from 500 kg/tc to about 350 kg/tc can boost power generation by 24%, with additional gains possible through the partial use of sugarcane straw. Efficient conversion systems in modern mills typically produce 115-120 kWh/tc, compared to just 10-20 kWh/tc in conventional mills (Kabeyi & Olanrewaju, 2023).

Fieldwork observations about efficiency improvements in the mills

Hereby, Fieldwork observations from Sao Paulo state of Brazil regarding the improvement of bagasse cogeneration are presented. Something important about the following section is that not all the improvements have adopted from all the mills. This is a general guideline about how the mills changed, however a lot of mills remain in previous stages.

The efficiency of sugarcane mills in Brazil changed drastically through the last decades. Before Pro Alchool, the sugarcane mills were trying to achieve self-sufficiency of their sugar and ethanol production processes with bagasse utilization. However, some mills were also using fossil fuels alongside with bagasse to fulfill their needs. In the early years of sugarcane mills, low pressure boilers (around 21 bar) were used to produce high pressure steam as shown in Figure 3. This steam was used in the milling process of the sugarcane and was also supplied to small electrical capacity (an example from fieldwork: 6MW) counter pressure turbogenerators. The low-pressure steam back after the end of the milling and from the turbo generator, alongside with the electricity produced from the turbogenerator were used for the sugar and ethanol processing. This way of bagasse utilization was marked with a small electrical capacity, low electricity production, only for self-consumption.

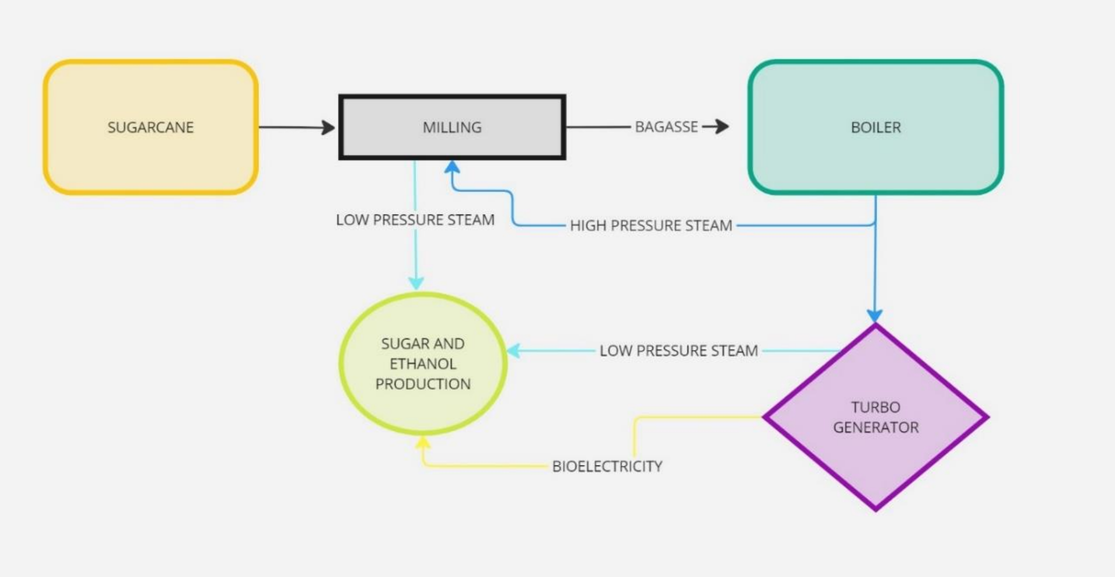

Figure 3. Example of bagasse bioelectricity and steam usage in mills that don't export electricity (mass of bagasse with black, steam flows with blue and electricity with yellow)

The situation changed when the sugarcane mills started producing electricity for exporting to the grid. This was and it is still happening in two ways. The sugarcane mills have fixed contracts to provide electricity to the grid at a standard basis. Those contracts are signed with the electrical agency with a price accumulated to the electricity price at the moment that the contract was signed. Those contracts approximately last for 5 years usually, but they can also last up to 10 years. However, the mills can sell electricity to the grid at any moment at the spot price of electricity. This is convenient when the price is peaks for specific time but there are periods that the price of electricity is very high because of reasons like droughts, that the hydropower is not enough, and more electricity has to be provided from other sources. At those times, mills sign long year contracts that bod them to provide a specific amount of electricity. This scenario of exporting electricity came with great improvements in terms of the equipment of the mills. Some boilers got replaced by higher pressure boilers and some turbogenerators got replaced with counter pressure turbogenerators with bigger electrical capacity (an example from fieldwork: from 6 MW to 26 MW, from 26MW up to 31MW, from 31MW to 45MW). High pressure steam from the boiler goes to milling and turbogenerator, low pressure steam goes to sugar and ethanol processing and the electricity produced from the turbogenerator goes both to the sugar and ethanol processing but also, the surplus electricity that is achieved to be produced gets exported to the grid (Figure 4). The improvements in efficiency don't stop there. In continuation of the previous improvements, the milling process became more modern to process sugarcane easier and maximize the extraction of the juices, while decreasing the milling steam requirements.

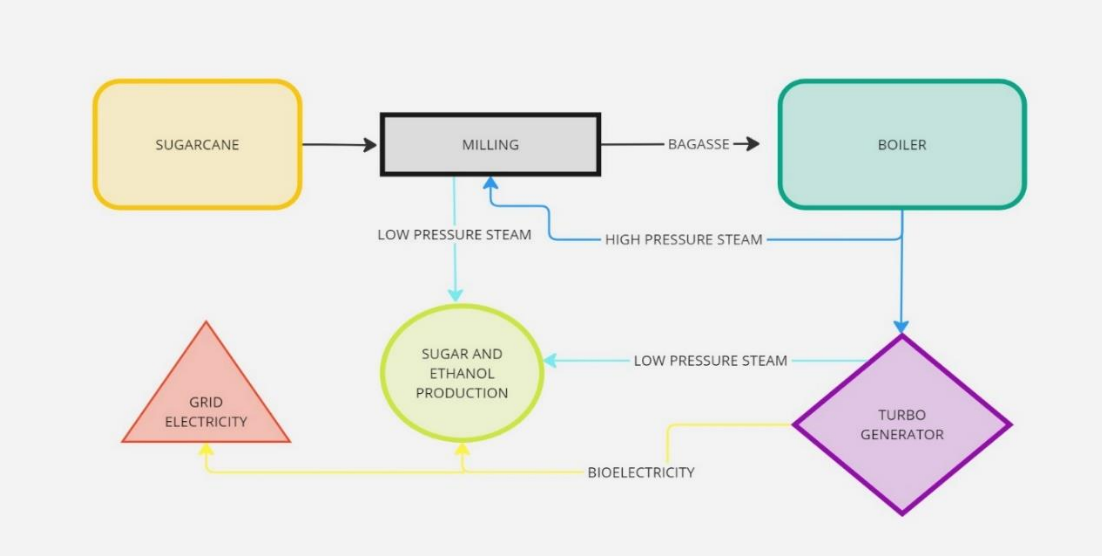

Figure 4. Example of bagasse bioelectricity and steam usage in mills that export electricity (mass of bagasse with black, steam flows with blue and electricity with yellow)

Another breakthrough that changed the operational dynamics of bioelectricity use and production in the sugarcane mills was the electrification of the milling process. In Brazil, juice extraction predominantly utilizes mills with sets of three to five rollers that press the sugarcane, separating the juice from the fibrous bagasse. Typically, four to six mills are arranged in tandem, where the bagasse from each preceding mill is passed on to the next in the sequence. The milling process has become more efficient since it was electrified (Figure 5). Previously, high-pressure steam was used to drive the mills and other equipment, which required more energy. Electric engines, by contrast, are more efficient, consuming less electricity and reducing operational costs. This shift to electrification has significantly improved the overall efficiency of the cane preparation process. That means that all the high-pressure steam goes to the turbogenerator in this scenario. Most of the times, electrification of milling was combined with improving the turbogenerator electrical capacity. That ensures way greater electricity production in comparison to a small increase to the electricity consumption from milling electrification.

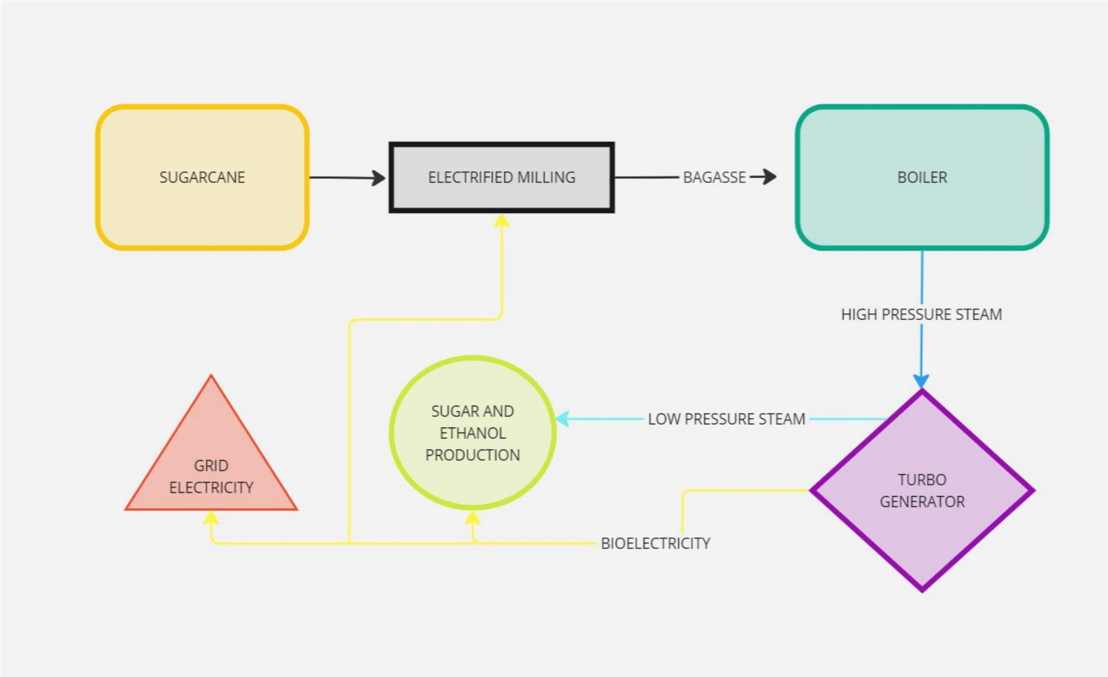

Figure 5 Example of bagasse bioelectricity and steam usage in mills with more processes electrified (mass of bagasse with black, steam flows with blue and electricity with yellow)

Another way to secure greatest electricity generation is the adoption of a condensation turbogenerator system. The most common technology in Brazilian sugar and ethanol mills for generating thermal power and electricity is the direct combustion of bagasse in boilers using the Rankine cycle with back-pressure steam turbines (BST), which discharge steam for the process. However, a lot of mills have adopted the Rankine cycle with extraction condensing steam turbines (ECST) (Figure 6). With the economic attractiveness of selling surplus electricity, mills have considered upgrading to higher pressure and temperature steam generation and using the ECST Rankine cycle for improved efficiency. With the ECST, only electricity is produced from high pressure steam coming from the boilers and this electricity can be provided only to the grid or both to grid and sugar, ethanol processing.

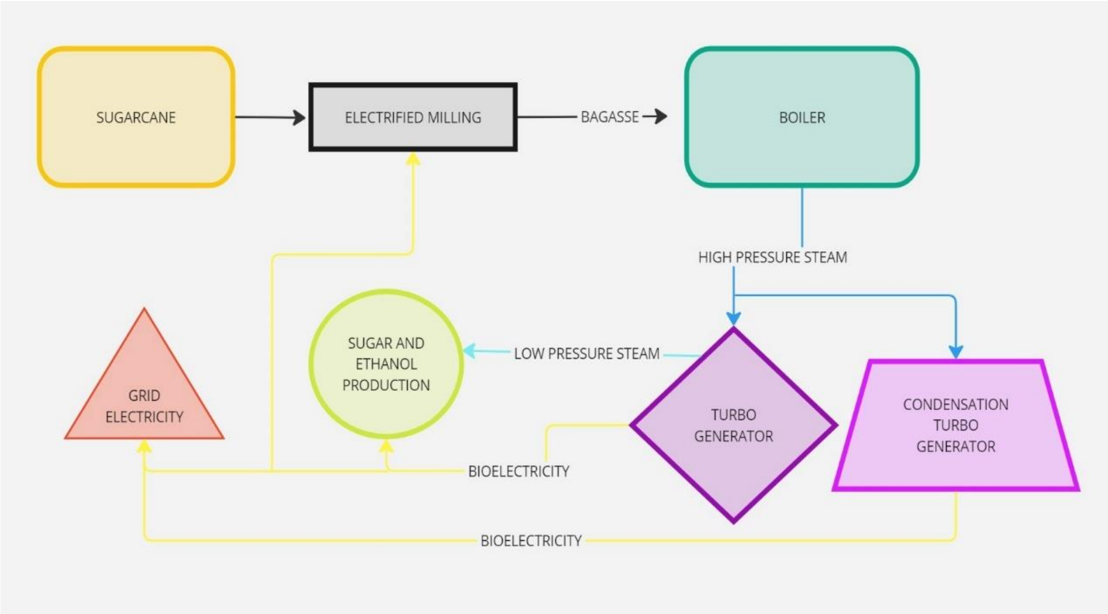

Figure 6. Example of bagasse bioelectricity and steam usage in efficient cogeneration systems with condensation turbo generation (mass of bagasse with black, steam flows with blue and electricity with yellow)

2.4 Other Sources of Sugarcane Bioelectricity in the Sugarcane Mills

Sugarcane Straw Use in the Sugarcane Mills

Sugarcane also generates agricultural waste known as straw or cane trash, including green and dry leaves and sugarcane tops, which is a significant byproduct in the sugarcane-ethanol production process (Fioranelli & Bizzo, 2023). In Brazil, until the 1990s, manual sugarcane harvesting involved burning the straw in the field before cutting to simplify the process and deter harmful animals, a common practice at that time (Fioranelli & Bizzo, 2023). This shift from manual to mechanical harvesting techniques signals a move away from labor-intensive practices, which often included burning fields before harvesting. It is anticipated that the practice of pre-harvest burning will stop by 2021 in São Paulo State's sugarcane-producing areas (Aguiar et al., 2011).

Introduced in the late 1990s, mechanized sugarcane harvesting has grown over time, decreasing the need for burning sugarcane straw. Although straw constitutes a significant energy source from sugarcane, it is mostly left in the field (Bizzo et al., 2014). In Brazil, a federal law aimed to phase out straw burning by 2018 in mechanically harvestable areas (land slope less than 12%) and set an undetermined timeline for total elimination in other regions (Leal et al., 2013). Hassuani et al. (2005) recommend leaving 7,5 Mg of straw per hectare (on a dry basis) in the field for weed and pest control.

The extraction of straw from sugarcane fields can be accomplished using either a baling system or an integrated approach. With the baling system, straw is separated within the harvester and then deposited onto the soil. In contrast, the integrated method gathers both straw and cane together, later separating them at the mill. However, there are concerns about the practicality of the baling system because it requires additional mechanized processes. A significant drawback of straw removal is that it exposes bare soil, which could exacerbate soil compaction and soil erosion caused by heavy machinery during harvesting (Castioni et al., 2021). Balling straw poses challenges in unbaling and milling at the mill. To be used as fuel in bagasse boilers or blended with bagasse, the straw must be crushed to match bagasse's particle size distribution. Additionally, straw differs in composition from bagasse, containing higher levels of Cl and K, along with other elements. This disparity can result in increased hot corrosion, fouling, and slagging on heat transfer surfaces (Fioranelli & Bizzo, 2023).

Sugarcane Vinasse and Biogas Electricity

Vinasse is derived usually from soluble solids of beet, sugarcane, sweet sorghum, grape, and agave. Vinasse's characteristics are largely determined by the raw materials used and the way the ethanol mill is operated (Parsaee et al., 2019). The type of molasses used, the method of fermentation and distillation, and the variety and maturity of the sugarcane all affect the type of the sugarcane-based vinasse. It is a liquid that is created during the rectification and distillation steps of the bioethanol production process (Parsaee et al., 2019).

In a conventional alcohol factory, 8–20 L of vinasse are produced for every liter of ethanol (Parsaee et al., 2019). In Brazilian sugarcane mills, usually 10–15 L of vinasse are produced for every liter of ethanol (Morraes et al., 2014). The application of viniasse on soil as fertilizer for sugarcane cultivation is a common practice due to the high organic matter and nutrient content it contains, particularly potassium, nitrogen, and phosphorous. Economically, this method is considered the least expensive and simplest way to dispose of large volumes of viniasse, in accordance with Brazilian environmental legislation. 150 m^3/ha of vinasse is equivalent to 61 kilograms of nitrogen, 40 kg of phosphorus, 343 kg of potassium, 108 kg of calcium, and 80 kg of sulfur when applied as fertilizer on the field (Parsaee et al., 2019). However, in modern sugarcane mills, managing residues using anaerobic digestion (AD) to recover bioenergy has emerged as particularly appealing waste management strategy due to the possibility of effectively meeting environmental requirements as well as the need for clean energy obtained from biogas (Volpi et al., 2023). When converted to energy, the biogas created by the mono-digestion of 1G vinasse in Brazil has the potential to equal 7.5% of the power provided by hydroelectric facilities. The full combustion of biogas in boilers to produce the necessary steam for the sugarcane industry's operations (7–9%) is an advantage (Parsaee et al., 2019). In this situation, bagasse can have greater value applications.

2.5 Alternative Uses of Sugarcane Bagasse

Sugarcane Bagasse Traded between Mills

From the fieldwork in São Paulo state, it was revealed that several mills do not use all their bagasse to produce electricity for the grid. Sometimes they don’t even use their bagasse to produce electricity except for their self-sufficiency needs. Typically, the lower the cogeneration efficiency of the mill, the more likely it is that excess bagasse is not fully utilized. A common practice in such cases is to transport this surplus bagasse to more efficient mills, especially if they are nearby or part of the same group. The reason that this happens is that: a) a more efficient mill has invested more in selling electricity, so electricity for this mill is also considered a product like sugar and ethanol, and excess bagasse from other mills is used there for those reasons (if they are in close geographical distance). b) there is a mill of the same group in close geographical range with higher efficiency (more modern boilers with highest steam pressure). The distance between the mills that trade bagasse is the distance of transportation with trucks, so there must be a good road connection between the mills to transport and trade bagasse.

A study by Danelon et al. (2016), also revealed that one of the main buyers of surplus bagasse are other sugarcane mills. Consequently, heat production does not compete with cogeneration, particularly when electricity prices are high or when sugar mills have contracts to fulfill with the energy grid.

A lot of mills invested in efficiency improvements when the prices of electricity were very high. While the use of surplus bagasse for bioelectricity generation offers benefits for the mills that produce electricity to sell, it also introduces logistical challenges and costs associated with transportation. Insights from mill interviews suggest that the optimal transportation distance for bagasse is limited to 50 km due to economic considerations.

Sugarcane Bagasse Traded Between Factories for Heat Production

Heat (in the form of steam) from bagasse is highly demanded and relevant in Brazil due to its integral role in the sugarcane and industrial sectors. The utilization of bagasse for non-energy consumption primarily involves steam production, which is crucial for various industrial processes. In Brazil, this demand stems primarily from the ethanol and sugar industries, with occasional usage by the pulp and paper and food industries (Hofsetz & Silva, 2012).

In the context of Brazil's energy balance, data reveals that available bagasse is effectively utilized for electricity or steam generation through cogeneration schemes. From fieldwork, an unexpected finding validated through interviews with mills and experts was that a small amount of bagasse is used in industries outside the sugarcane sector. Specifically, bagasse is used for steam production in other food and beverage industries. Some mills have excess bagasse that they choose not to use for electricity production, possibly due to lower efficiency or because the price they get from selling bagasse to other industries is adequate.

This practice is not easy to monitor or predict as only a small number of mills engage in it, and there is no information about official contracts for selling bagasse. During fieldwork, the orange industry was frequently mentioned since São Paulo is one of the largest orange producers worldwide. According to Hofsetz & Silva (2012), a small quantity of bagasse is occasionally sold to other industries, notably the orange juice sector (around 10%). However, this depends on the proximity of relevant industries. Like trading bagasse for bioelectricity, trading it to other industries for steam production depends on the transportation distance and the presence of nearby industries willing to purchase bagasse for steam production.

Pellets Made from Sugarcane Bagasse

European companies are increasingly interested in importing bagasse pellets from Brazil for several compelling reasons. Bagasse pellets offer a cost-effective alternative to wood pellets, helping to meet the growing demand for biomass and reducing pressure on wood resources.

Bagasse pellets contribute to significant greenhouse gas (GHG) emissions savings, which is crucial for meeting the criteria set by the Renewable Energy Directive II (RED II) for biomass use in electricity and heat generation within the EU. Their favorable GHG emissions performance aligns well with EU sustainability targets and climate goals, particularly under initiatives like Bioenergy with Carbon Capture and Storage (BECCS), which provide renewable energy and enable negative carbon emissions by capturing and storing CO2 during biomass combustion.

Pelletizing bagasse locally near sugarcane mills in Brazil ensures efficient handling and reduces transportation costs. These pellets can be shipped to Europe using established maritime trade routes, leveraging economies of scale to ensure a steady and reliable supply of biomass pellets. Companies like RWE are exploring this sustainable energy transition and researching both the possible environmental benefits and the economic advantages of improved energy efficiency and compliance with stringent EU emissions regulations.

In fieldwork interviews, employees of sugarcane mills were asked about the feasibility of pelletizing bagasse. They generally considered the process straightforward and were not opposed to the idea, provided that the revenue generated would be sufficient. However, due to various economic factors, they could not specify a fixed price for the pellets that would incentivize them to undertake pelletizing and allocate bagasse for this purpose. The sugarcane mill in Jau, named Diamante and owned by Raizen, already produces pellets from bagasse and transports them via riverboats, although in the Fieldwork it was unable to visit this mill. Experts from Campinas University also supported the idea of shipping pellets to Europe for bioelectricity production, recognizing its potential benefits. However, there are two main challenges associated with pelletizing. Firstly, a single sugarcane mill cannot produce a significant number of pellets because the bagasse is already being utilized for other purposes. Secondly, even within São Paulo state, some mills are located far from ports, complicating transportation logistics due to the state's vast area.

The process of making pellets from sugarcane bagasse involves several key steps to ensure the quality of the end product. The process of making sugarcane bagasse pellets is relatively similar to the processing of wood pellets. Initially, bagasse is collected and after the milling of sugarcane to extract the juice in the sugarcane mills. Due to its high moisture content of around 50%, the first step involves drying the bagasse using either sun drying or mechanical drying methods, reducing the moisture to approximately 10-15% to improve pellet quality and combustion efficiency (Loh et al., 2013). Usually, in sugarcane mills in Sao Paulo, bagasse is transferred to an outdoor storage place to be ready to get fed into the boiler. For bioelectricity production, bagasse cam be burned with 50% moisture but for pelletizing it needs to be dried.

Once dried, the bagasse undergoes size reduction through grinding or milling machines to achieve uniform particle size (Raj & Jeewan Vachan Tirkey, 2023). This is also a process that happens in the sugarcane mill before bagasse is used for cogeneration in the boiler. To enhance the binding properties and durability of the pellets, additives such as molasses, starch, or lignin may be mixed with the ground bagasse (Raj & Jeewan Vachan Tirkey, 2023). The bagasse is then fed into a pellet mill, where it is compressed through a die and rollers into cylindrical pellets (Anukam et al., 2016). The heat generated during this process, typically around 90°C, causes the lignin in the bagasse to act as a natural binder (Anukam et al., 2016). After pelletizing, the hot pellets are cooled using a pellet cooler to ambient temperature, solidifying them and enhancing their durability (Anukam et al., 2016). The final pellets are then screened to remove fines and dust before being packaged for storage and transportation. Overall, producing high-quality sugarcane bagasse pellets involves drying, grinding, mixing, pelletizing, cooling, and screening steps to ensure the pellets are suitable for industrial uses.

Second Generation Ethanol from Sugarcane Bagasse

Sugarcane bagasse cellulosic ethanol is also called "second generation" (2G) ethanol (Carpio & Simone de Souza, 2017). Producing ethanol from bagasse is a smart substitute for boosting ethanol production, offering both financial and environmental benefits (Carpio & Simone de Souza, 2017).

Four steps are involved in the 2G ethanol production process: pretreatment, enzymatic hydrolysis, fermentation, and distillation (Daniel et al., 2023). Pretreatment exposes cellulose and hemicellulose molecules in lignocellulosic biomass, initially protected by lignin layer. Enzymatic hydrolysis then selectively converts these components into simple, fermentable sugars (C5 and C6), leading to ethanol and carbon dioxide production through yeast fermentation. The final step involves distillation to separate bioethanol from water (Daniel et al., 2023). Cellulosic ethanol, like first-gen ethanol, emits fewer pollutants than fossil fuels, serving as a renewable, sustainable energy source. Its abundant raw material doesn't compete with food production. Promising options include cellulosic feedstocks, enhanced efficiency, and carbon dioxide capture, dependent on development factors (Daniel et al., 2023). In 2014, GranBio launched a plant in São Miguel dos Campos, Alagoas, Brazil, designed to annually produce 82 million liters of ethanol from sugarcane straw (Daniel et al., 2023). In 2015, the Costa Pinto plant Raízen, a joint venture between Cosan and Shell, was inaugurated in São Paulo, Brazil. This facility is designed to annually produce 40 million liters of ethanol, utilizing sugarcane bagasse and straw as raw materials (Daniel et al., 2023).

Finally, the research of Carpio & Simone de Souza, (2017), showed that for the economic parameters for second generation ethanol, the productivity is between 158 and 335 liters of ethanol for a ton of dry bagasse and the cost is between 0,33-0,39 US$ per L of ethanol. However, those numbers are based on research scenarios and productivity and cost differs in each plant.

During fieldwork, it was observed that the sugarcane sector, including experts and chemical engineers from local mills, is actively engaged in research and development of second-generation (2G) ethanol. As the sole producer of 2G ethanol in São Paulo, Raízen is expanding its operations with plans to acquire a plant in Alagoas and establish a new facility in Guariba, São Paulo. Further growth within the 2G ethanol industry is anticipated.

In fieldwork, it was observed that economists consider predicting electricity prices in Brazil challenging yet anticipate potential decreases in the coming years. They also highlighted the likelihood of increased incentives to support 2G ethanol production. Chemical engineers emphasized the critical role of 2G ethanol in future energy scenarios, despite its higher production costs.

The approximate production cost for 2G ethanol is 10 Brazilian reais per liter, compared to 2,2 Brazilian reais per liter for first-generation ethanol. Due to these higher costs, 2G ethanol is mainly aimed at export markets, especially Europe and the United States, where there is a higher demand for sustainable fuels made from agricultural residues like bagasse. By focusing on 2G ethanol, Brazilian companies can avoid some of the complexities of local market negotiations and benefit from international demand.

2G ethanol is also expected to play a significant role in producing aviation fuels and other future sustainable fuels. Raízen plans to open around eight new 2G ethanol plants in São Paulo. Discussions about 2G ethanol in Brazil have also become political, with limited local demand compared to the larger international market.

Specialists we interviewed agreed that the production and demand for 2G ethanol will grow in Brazil but not significantly. They mentioned that starting contracts and logistics for 2G ethanol will help avoid negotiations with the Brazilian government and take advantage of increased sustainability incentives abroad. The approximate cost comparison between 1G and 2G ethanol underscores the necessity of targeting export markets and leveraging sustainability incentives.

Bagasse for Animal Feed

The demand for animal feed in Brazil drives the relevance of utilizing bagasse in this capacity. Bagasse serves as a crucial component in producing high-quality animal feed, meeting the nutritional needs of livestock across the country.

Mills play a role in this process by incorporating bagasse with molasses and dry yeast to create a nutrient-rich feed product. For instance, three mills within the Biosev Group collectively produce approximately 85000 tons of animal feed annually using this approach.

This feed composition offers a cost-effective alternative to conventional feed products available in the market, enabling mills to enhance the value of their businesses, particularly those engaged in integrated agriculture-livestock systems.

3. Methods

This section will outline the methodology part of the thesis.

Chapter 3.1 will detail the methods employed to estimate the total amount of sugarcane bagasse generated by all mills in São Paulo. The estimated bagasse quantity will be allocated to different mill categories based on their cogeneration characteristics, such as boiler steam pressure.

In Chapter 3.2, the bioelectricity production from bagasse in each mill category will be estimated. This will provide a baseline for exploring ways to increase bagasse availability while maintaining the current levels of bioelectricity exported and used for self-sufficiency.

Chapter 3.3 will outline the methodology for estimating how bagasse availability can be increased while maintaining the same level of bioelectricity production. The selected methods for freeing up bagasse include straw incorporation in boilers, selected efficiency improvements, and the use of biogas vinasse for bioelectricity production.

Finally, Chapter 3.4, includes the methodology for finding out which future uses are possible to utilize this freed up bagasse that was calculated in the previous stages and can compete with the present alternative ways of using bagasse that are presented in Chapter 2.5.

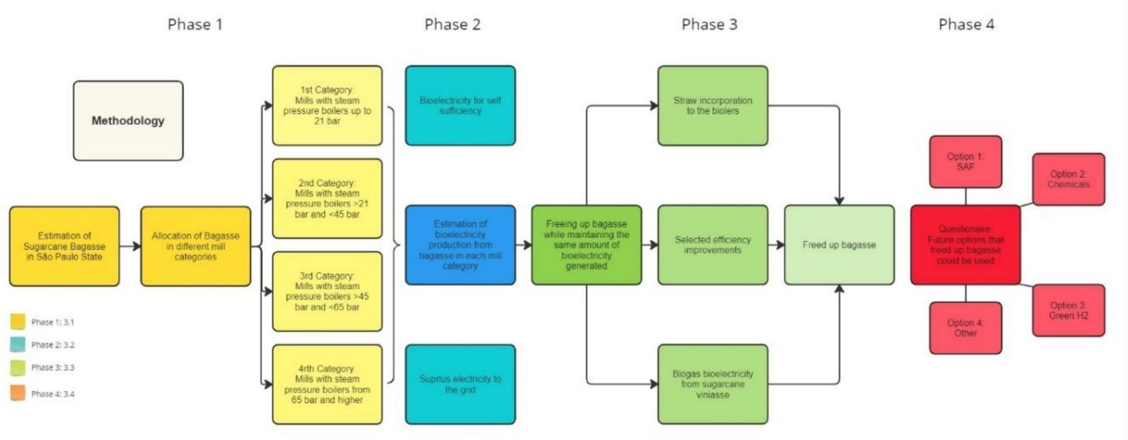

Figure 7. Methodology framework separated in different phases according to the methodology chapters

3.1 Estimating the availability of sugarcane bagasse in Sao Paulo state sugarcane mills

The initial phase is focused on estimating the total annual production of sugarcane bagasse within the state of São Paulo. This quantification serves as a foundation for subsequent calculations related to electricity generation from bagasse and potential strategies to free up bagasse as well. A precise estimation of bagasse mass and its distribution across various mill types is important to proceed to further calculations. Sugarcane mills within São Paulo exhibit heterogeneity in terms of processing capacity and cogeneration efficiency. To account for this variability and to estimate the bagasse availability more accurate, a categorization approach will be implemented. This approach will involve grouping mills based on specific characteristics that will be explained later on this Chapter. Subsequently, the total estimated bagasse production will be apportioned amongst these categories. Finally, assumptions based on fieldwork interviews will be made to decide the quantities of bagasse that is used for electricity (self-sufficiency of the mill and exporting to the grid) and traded bagasse.

There are various ways to estimate the mass of bagasse that is produced in the mills of Sao Paulo on a yearly basis. The amount of sugarcane harvested in the season differs every year, so the mass of sugarcane and the mass of bagasse subsequently fluctuate depending on the characteristics of the harvest season. Hereby, in this research, the way to estimate the bagasse that is produced on a yearly basis is based on the total milling capacity of the sugarcane mills in Sao Paulo. Novacana, the largest database on the Brazilian sugarcane-energy sector, provides information on the crushing capacity of Brazilian plants, market prices of products such as energy, and exports (Novacana, 2024). Data for milling capacity of sugarcane was filtered to include only mills from Sao Paulo state. The processing capacity per mill was aggregated, and the amount of bagasse was estimated, assuming bagasse constitutes 26,4% of the sugarcane processed (Seabra et al., 2011). Equation 1 shows how the sugarcane bagasse availability is estimated.

Equation 1. Mass of sugarcane bagasse produced per year

$$Sugarcane\ bagasse = sugarcane \times 26.4\%$$

Where: sugarcane bagasse (million t) = bagasse produced per year in sugarcane mills and, sugarcane (million t) = sugarcane total processing capacity of Sao Paulo state.

Cogeneration efficiency per mill varies significantly due to differences in boiler and turbogenerator technology and pressure steam pressure generation, which range from 21 bar to 90 bar (Fieldwork, personal communication with engineers of 5 different mills). Figure 1 presents the correlation between the milling capacity and the electricity generated in the whole 2023 for 92 mills from Sao Paulo with known data. Figure 8 shows the correlation between milling capacity and electricity generation of Sao Paulo mills, and it is presented to show that between the sugarcane processing capacity of mills and their yearly electricity generation, there is considerable variation from the trendline. This is very important because more bagasse production does not mean more electricity generation, and the mills that they have more bagasse are not always the most efficient. This variability further raises questions about the quantity of bagasse used for electricity production in each mill. In conclusion, the milling capacity of the mill does not determine the electricity that the mill produces (both for self-consumption and export).

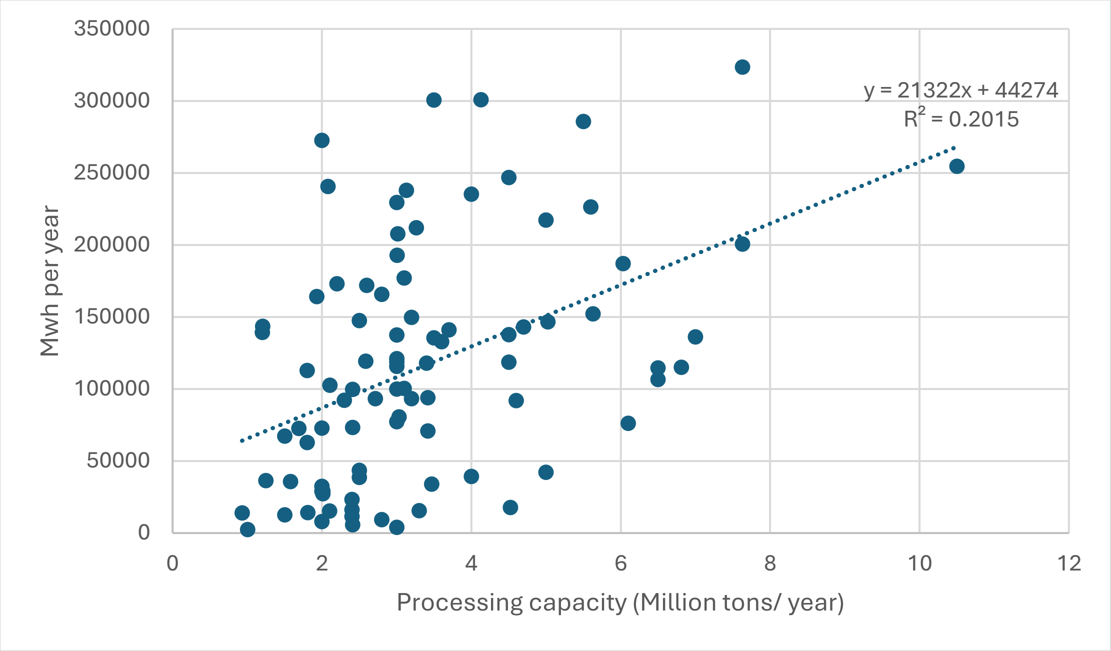

Figure 8. Electricity generation of sugarcane mills per milling capacity (Data derived from NovaCana, 2024).

According to Campos Trombeta and Caixeta Filho (2017), in southcentral Brazilian sugarcane mills, 39% operate at a maximum boiler steam pressure of 21 bar, 22% operate at a boiler pressure higher than 21 bar till 45 bar, 5% operate at a steam boiler pressure higher than 45 bar till 65 bar, and 34% operate above 65 bar. Most of the mills included in this research are mills of Sao Paulo (more characteristics of those mill categorization will be provided in the next Chapter). This is relevant to this research because bagasse is utilized differently in different types of mills and to progress to more calculations regarding electricity generation is better to allocate bagasse to different mill categories with different cogeneration characteristics. Furthermore, those percentages are matching with information from fieldwork from interviews with sugarcane mill consultants about boiler pressures in mills (Fieldwork, personal communication with mill consultants and mill engineers, 2024). As shown in Figure 8, for the mills of Sao Paulo, milling capacity is not proportional to annual electricity generation, but boiler pressure is (as presented in Chapter 2). Hereby the mass of the sugarcane bagasse found in Equation 1 will be allocated to the mills with different boiler pressures according to the percentages the research of Campos Trombeta and Caixeta Filho (2017). So, the mass of bagasse is allocated as shown in Table 2 in different types of mills.

Table 1. Bagasse mass allocation in different types of mills

Mill categories (boiler pressure)	Sugarcane Bagasse (million tons)
≤21 bar	39%* Sugarcane Bagasse
>21 bar and ≤45 bar	22% *Sugarcane Bagasse
>45 bar and ≤65 bar	5%* Sugarcane Bagasse
>65 bar	34%* Sugarcane Bagasse

In continuation, the percentages of bagasse that is destined for electricity generation (for the self-sufficiency of the sugarcane mill and for surplus electricity exports) and for trading are estimated. Based on fieldwork data (Fieldwork, personal communication with Operational Engineer of sugarcane mill, 2024), it was observed that mills with lower pressure steam have more surplus bagasse since they typically use around 80% for self-sufficiency. Mills with higher efficiency tend to use most of their bagasse for electricity production, particularly if they have large contracts to export determined amounts of electricity to the grid (Fieldwork, personal communication with mill consultant, 2024). To account for this, it is assumed that mills with very low steam pressure boilers (up to21 bar) trade 15% of their bagasse, mills with >21-≤65 bar boiler pressure trade 10%, and mills with higher steam pressure boilers (above 65 bar) trade only 5%. Those assumptions were made after Fieldwork (personal communication with engineers in mills and two consulting companies, 2024) and although a separation like this is not made in other bibliographies it is very important to separate the bagasse that is used for bioelectricity and the bagasse used for other reasons in order to proceed to the calculations for the freed up bagasse that can be replaced with another way in order for the bioelectricity production to be the same.

Furthermore, approximately 10% of bagasse is stored in the sugarcane mills and is kept for emergency back up and for the starting and testing of the boilers before the beginning of each harvest season (Fieldwork, personal communication with operational engineer of mill, 2024).

From fieldwork interviews (Fieldwork, personal communication with operational engineer, 2024), was known that different mills require varying amounts of bagasse for self-sufficiency, ranging from 30% to less than 80% depending on their efficiency. Based on this, the following assumptions for different types of mills will be made:

Bagasse processed ≤21 bar pressure boilers: In these mills, it is assumed that 70% of the bagasse is used for self-sufficiency. Based on previous assumptions, 15% is traded, and 5% is used to produce surplus electricity for the grid.

Bagasse processed at >21-≤45 bar pressure boilers: It is assumed that these mills use 55% of the bagasse for self-sufficiency. Based on the previous assumptions, 10% is traded, and 25% is used to provide electricity to the grid.

Bagasse processed at >45-≤64 bar pressure boilers: It is assumed that 35% of the bagasse is used for self-sufficiency. Based on the previous assumptions, 10% is traded, and 45% is used for surplus electricity.

Bagasse processed at above 65 bar pressure boilers: It is assumed that 30% of the bagasse is used for self-sufficiency. Based on the previous assumptions, 5% is traded, and 55% is used for surplus electricity.

All the mills keep 10% of bagasse stored, according to Fieldwork information and Alves et al. (2015).

Table 2 presents information about bagasse use in the mills.

Table 2. Bagasse use in the sugarcane mill types

Mill categories (boiler pressure)	**Sugarcane Bagasse Total (million tons)**	**Percentage of bagasse for self sufficiency**	**Percentage of bagasse for export bioelectricity**	**Percentage traded**	**Percentage stored**
≤21 bar	39%* Sugarcane Bagasse	70%	5%	15%	10%
>21 bar and ≤45 bar	22% *Sugarcane Bagasse	55%	25%	10%	10%
>45 bar and ≤65 bar	5%* Sugarcane Bagasse	35%	45%	10%	10%
>65 bar	34%* Sugarcane Bagasse	30%	55%	5%	10%

While the bagasse distribution is based on Fieldwork data, including interviews with consultants, experts, and mill engineers, it acknowledges inherent limitations. Categorizing over 170 sugarcane mills in São Paulo presents a challenge, as trading fractions can fluctuate based on external factors. Fluctuations in electricity prices can impact both electricity exports and the market price of bagasse itself. To address these limitations, a sensitivity analysis will be conducted. This analysis will explore scenarios with different trading percentages (both higher and lower) and variations in the estimated percentages of bagasse destined to produce electricity supplied to the grid.

3.2 Estimation of electricity produced from different types of mills

This part of the research is estimating the electricity that can be yearly produced from the mills of Sao Paulo state. This includes both the electricity to be exported to the grid and the electricity needed for self-sufficiency, in continuation of the previous steps. This will be used as a comparison point for the free up scenarios and the electricity that will be estimated to be sold to the grid in a year will be compared with the electricity that was sold last year in the state according to the report of Unica (2024). The electricity is generated in every mill category will be useful to later stages of this research that different ways to provide the same amounts of electricity can help free up bagasse from the mills while avoiding displacement issues.

First, from the previous stages it is defined how much bagasse is used for electricity for the mills and for surplus electricity for the grid in the different mill categories regarding their boiler pressure. Kabeyi and Olanrewaju (2023), provide estimates of electricity produced per ton of sugarcane based on different boiler steam pressure configurations. They acknowledge that these values are averages due to multiple factors affecting the conversion efficiency of sugarcane to electricity. The estimated values are shown in Table 3.

Table 3. Electricity produced per mill category with different boiler steam pressure (derived from Kabeyi and Olanrewaju (2023))

Steam Pressure of Boiler (Bar)	21	45	60	82
Generation potential (GWH/MILLION TON SC)	25	84	110	164

Those four different values for electricity generation associated with boiler steam pressure fall in the four categories of the mills with different ranges of steam pressure as described in Table 2. Hereby the values of Table 3 will be used for the calculation of electricity generation from bagasse in the different mill categories. Here is important to note that the sugarcane mill with a boiler pressure of 21 bar is using a low back pressure turbogenerator, the milling of the sugarcane is happening with the use of low-pressure steam (Kabeyi and Olanrewaju, 2023).

The rest of the mills are using condensing extraction turbines, which can operate in a variety of steam pressures and temperatures (Kabeyi and Olanrewaju, 2023). The mills with 45 bar boiler pressure have a turbine capacity of 25MW the ones of 60 bar, 30MW and the ones of 82 bar 50MW (Kabeyi and Olanrewaju, 2023). The mills of 21 bar they have a very small turbine capacity around 8MW (Kabeyi and Olanrewaju, 2023). Table 4 presents the mill characteristics including the assumptions from Chapter 3.1 and Chapter 3.2.

Table 4. Mill category characteristics. (Data derived from fieldwork (personal communication with boiler engineers, (2024)), (Kabeyi and Olanrewaju, 2023), (Campos Trombeta and Caixeta Filho, 2017), NovaCana(2024)).

Mill categories (based on steam pressure)	**Generation potential (GWh/ million ton of bagasse)**	**Sugarcane Bagasse Total (million tons)**	**Approximate number of mills in Sao Paulo**	**Turbine capacity (MW)**	**Type of turbine**
≤21 bar	96	40	68	8	Back pressure
>21 bar and ≤45 bar	323	23	39	25	Condensing extraction (mostly)
>45 bar and ≤65 bar	423	5	9	30	Condensing extraction
>65 bar	631	35	60	50	Condensing extraction

For the calculation of electricity that the mills generate per year, first the GWh/million tons of sugarcane were converted to GWh/ million tons of sugarcane bagasse as shown in Table 4. In continuation, the mass of bagasse calculated before that is used for the total yearly electricity production for the mill, the mass of bagasse that is used for electricity for self-sufficiency and for exporting to the grid are multiplied with the GWh/ million ton of sugarcane produced in every different mill category (Percentages of Table 2), as shown in Equation 2. The result is the GWh per year that every mill category with different steam pressure is producing for total electricity production, electricity for self-sufficiency and electricity to the grid.

Equation 2

$$E = sugarcane\ bagase * generation\ potential$$

Where: E= electricity produced per mill category/ year in GWh per year, sugarcane bagasse (million tons per year) = bagasse produced per year in sugarcane mills of each category and, generation potential in GWh per million tons of sugarcane bagasse= electricity production from bagasse in each mill.

3.3 Scenarios to free up bagasse

Currently, all bagasse is used for self-sufficiency, surplus electricity production, or other alternatives like trading among mills, the food industry, and animal feed. Given this utilization, this part of the research explores different scenarios where bagasse could be freed from the sugarcane mills. This will be done because as explained in the Introduction, bagasse is one material that is more and more sought after, from European companies that want to use pelletized bagasse for BECCS, and other future potential uses of bagasse that will be explained in Chapter 3.4. One scenario involves substituting up to 15% of the bagasse with straw in the boilers, freeing up bagasse for other uses while maintaining similar electricity output. Additionally, using biogas vinasse for electricity production could free up bagasse otherwise used for this purpose. Finally, improving efficiency in mills, particularly in low efficiency mills could also free up sugarcane bagasse. Maintaining the same electrical output for self-sufficiency and electricity exports is important to avoid displacement of bagasse. Hereby in the free up scenarios this research is looking for replacements for electricity generation in the mills. One non-free-up scenario that will be included for comparison purposes which involves using the traded fraction of bagasse, which would primarily affect electricity and heat production in other industries.

3.3.1 Use of sugarcane straw for electricity generation

Fieldwork revealed that the maximum recommended incorporation of straw into boilers is 15% of the total biomass weight (Fieldwork, personal communication with boiler engineers in 4 different mills, 2024). This limitation stems from several factors. Straw possesses a different calorific value and moisture content compared to bagasse. Additionally, its different composition, particularly high levels of chlorine (Cl) and potassium (K), can induce corrosion and fouling on boiler surfaces (Fioranelli & Bizzo, 2023). That means that a maximum of 15% is recommended for preserving the boiler in a good condition. In this research a percentage of 10% and one of 15% of straw in the boiler will be used and compared. Those percentages will be applied to all the mill types together as those percentages of straw can be incorporated to all the boiler types.

The lower heating value of bagasse with 50% moisture content is 7.2 MJ/kg and the lower heating value of straw with 25 % moisture content is 12 MJ/kg. These numbers relate to the moment after sugarcane harvest, and extraction of juice from sugarcane processing. For the case of straw collection, usually the fans of the harvesting machines that they dispose the straw to the land after the collection, are turned off to collect the needed straw together with the sugarcane. This method has two main problems: it is difficult to estimate the amount of straw collected, and some straw must remain in the field. With this method the straw is mixed with the sugarcane so is difficult to be separated later in the mill and keep a needed straw percentage on the field.

To address these issues, the chosen method is baling the straw. After the sugarcane harvest, the straw will be left in the field for approximately 10 days, then collected, compressed into bales, and transported to the mill. In this form, the straw will have an increased lower heating value of 13.3 MJ/kg because is dryer and a moisture level of 15% (Cervi et al., 2019). The bales can be cylindrical or prismatic, making them easier to transport. At the mill, the straw will be unbaled and chopped in the particle size of bagasse to be fed together to the boiler. Table 5 presents the different characteristics of straw and bagasse moisture content and LHV.

Table 5. Selected LHV and moisture content of bagasse and straw (derived from personal communication with sugarcane farmers and Cervi et al., (2019))

	Bagasse	**Straw**
LHV (MJ/kg)	7.2	13.3
Moisture content (%)	50	15

In continuation the amounts of straw for 10% and 15% replacement were calculated from the available bagasse for bioelectricity in the sugarcane mills (equal to the amount of replaced bagasse). This numbers when multiplied with the LHV ratio provide the mass of bagasse freed up in both replacement cases. Equation 3 shows the calculation of freed up bagasse from straw replacement.

Equation 3

$$Freed\ up\ bagasse = (10 or 15\%) * bagassebioel * LHVratio$$

Where Freed up bagasse= bagasse freed up in selected mill category (million tons per year), bagassebioel= bagasse used for bioelectricity in the selected category (million tons per year) and LHV ratio= LHVstraw (MJ/kg)/LHVbagasse (MJ/kg) from Table 5.

3.3.2 Use of biogas from sugarcane vinasse

The second case of replacing bagasse for electricity production is proposing the use of biogas derived from sugarcane vinasse. This is another method to free up sugarcane bagasse. Vinasse is a byproduct of ethanol production so first the ethanol produced annually in the state of Sao Paulo must be estimated and then the proportion of vinasse that comes as a byproduct. In continuation the biogas that can be annually produced from this amount of vinasse will be estimated. The power potential of this biogas will be calculated and finally the electricity that can be produced annually in Sao Paulo state if all the vinasse is used for bioelectricity.

First, the hydrated and anhydrous ethanol produced in Sao Paulo in m^3 were found in the data of NovaCana for the harvest season of 2023/2024. Then, the total ethanol that was produced in the state was calculated in m^3. Table 6 presents the total ethanol produced annually (last year) in Sao Paulo state.

Table 6. Ethanol production 2023/2024 season in Sao Paulo state (data derived from NovaCana,2024)

Ethanol 2023/2024 Sao Paulo	**Amount**	**Unit**
Anhydrous ethanol produced	6182038	m^3
Hydrated ethanol produced	7751623	m^3
Total ethanol produced	13933661	m^3

For the vinasse production as an ethanol byproduct and the biogas that could be produced from vinasse, the average values were derived from Parsaee et al., (2019) and are presented in the following Table 7. The assumption for this scenario is that all biogas produced from vinasse in Sao Paulo state will be used for bioelectricity production within the mills. The biogas production process is assumed to occur through anaerobic digestion within the mills.

Table 7. Vinasse and Biogas Production in m^3 (derived from Parsaee, 2019)

	Amount	**Unit**
Average vinasse production	12	m^3 / m^3 bioethanol
Biogas Production from Vinasse (60% methane)	18.2	m^3 / m^3 viniasse

Equation 4 presents the estimated annual vinasse production potential in São Paulo State (data from Table 7):

Equation 4

$$Vinasse\ = 12 * Total\ ethanol$$

Where: vinasse is the vinasse that is possible to be produced in a year (m^3/year), Total ethanol is the ethanol produced in the state in one season (here data from Table 6 are used) in (m^3/year).

Equation 5 presents the biogas that can annually be potentially produced from vinasse (data from Table 7):

Equation 5

$$Biogas\ flow = 18.2 * Vinasse)$$

Where: Biogas flow= biogas that can annually be potentially produced from vinasse (m^3/year) and Vinasse calculated in Equation 5(m^3/year).

Furthermore, Anaerobic digestion occurs in digesters, which can operate in batches or continuously. For high-volume waste streams like vinasse in sugar and alcohol production, continuous flow is the preferred choice due to the large amount of material being processed. Up flow Anaerobic Sludge Blanket reactors (UASB) are a good example of a continuous flow digester and the selected for this bagasse- freeing up case.

For the electrical power generated from the biogas, the lower calorific value of CH_4, the percentage of CH_4 in biogas, the efficiency of the internal combustion engine, and the constant for unit adjustment were derived from Isabela Zanon Pereira et al., (2020), and are presented in the following table.

Table 8. Values for calculating the electrical power generated from biogas derived from Isabela Zanon Pereira et al., (2020)

$LHV_{(CH4)}$	**Lower calorific value of CH_4 (J/m^3)**	$35.5 * 10^6$
C_{CH4}	**Percentage of methane in biogas**	60%
ηICE	**Internal combustion engine efficiency**	33%
k	**constant for unit adjustment**	$31.536 * 10^9$

Equation 6 presents the electrical power potential from biogas in the sugarcane mills of Sao Paulo:

Equation 6

$$P = Biogas\ flow * \mathrm{LHV_{CH4}} * \mathrm{CCH4} * \mathrm{\eta ICE} / \mathrm{k}$$

Where: P in KW is the power potential, biogas flow in (m^3/year) calculated in Equation 6 and the rest of the symbols presented in Table 8.

Finally, Equation 7 presents the electricity that can be annually generated from biogas in the mills of Sao Paulo state.

Equation 7

$$E = P * t * CF$$

Where: E= electrical energy (GWh/year), P power potential form Equation 7 (GW), t= 8760 annual hours (hours/year) and a capacity factor (CF) of 80%. Same values were adopted by Isabela Zanon Pereira et al., (2020).

To assess the potential substitution of sugarcane bagasse with biogas derived from vinasse in terms of electricity generation, it is necessary to convert the biogas-generated electricity into an equivalent bagasse mass. However, accurately determining the specific mill origin of this bagasse presents a challenge. To address this, an average steam pressure of 40 bar is assumed as a reference point for the subsequent calculations.

3.3.3 Efficiency improvements in the sugarcane mills

During the fieldwork in Sao Paulo state, specialists in sugarcane mills were interviewed in the form of unstructured interviews regarding the willingness of the smaller and lower efficiency sugarcane mills to progress to efficiency improvements like changing the boilers or the turbogenerators to be more efficient in their electricity production (needed for their self-sufficiency and the electricity exports to the grid). In the essence of this research, this is about the possibility of mills to be converted to another category of mills.

Fieldwork indicates that most sugarcane mills in São Paulo have downplayed efficiency improvements due to prevailing low energy prices. To incentivize investments in efficiency upgrades, a significant increase in energy prices — approximately five times more — would be necessary to offset the substantial upfront costs associated with such projects.

In this proposed scenario, a transformation is envisioned, where the low-efficiency mills operating at a boiler with steam pressure of 21 bar or less, which are using back pressure turbo generators according to Kabeyi and Olanrewaju (2023), will invest only in replacing their turbo generators with condensing- extraction ones. From the same study (Kabeyi and Olanrewaju (2023)), that also the parameters of electricity generation for the different boiler steam pressures were derived, (Table 3), the new value of 45 KWh of electricity per ton of sugarcane will be used instead of 25 KWh of electricity per ton of sugarcane. The next assumption is that all the other sugarcane mills will now operate with a steam pressure of >64 bar. The turbo generators will remain condensing extraction-type. Table 9 presents the new mill characteristics in terms of cogeneration, electricity production.

Table 7. Mill cogeneration characteristics before and after efficiency improvements (data derived from Kabeyi and Olanrewaju (2023))

Mill characteristics before efficiency improvements			**Mill characteristics after efficiency improvements**		
Mill categories (based on steam pressure)	**Generation potential (GWh/ million ton of bagasse)**	**Type of turbine**	**Mill categories (based on steam pressure)**	**Generation potential (GWh/ million ton of bagasse)**	**Type of turbine**
≤21 bar	96	Back pressure	≤21 bar	173	Condensing extraction
>21 bar and ≤45 bar	323	Condensing extraction (mostly)	>65 bar	423	Condensing extraction
>45 bar and ≤65 bar	423	Condensing extraction			
>65 bar	631	Condensing extraction			

Then the excess bioelectricity from the efficiency improvements of mills with steam pressure of boilers of 21 bar and those of 22 to 64 bar will be calculated (Equation 8). Excess bioelectricity means the bioelectricity that the mills can now generate additional to the amount that they generated before the efficiency improvements.

Equation 8

$$Eexcess = E' - E$$

Where: E excess= excess bioelectricity (GWh/year), E’ is bioelectricity after efficiency improvements (GWh/year) and E is the bioelectricity before the improvements (GWh/year).

Then, Equation 2 will be used as previously to calculate the sugarcane bagasse that will be available from the excess bioelectricity, for each new category using the new generation potential.

3.3.4 Comparison with the trading fraction of bagasse

Finally, according to the interviews from fieldwork, bagasse is mostly traded for animal feed or for steam production for operational purposes in other factories (mostly orange juice production). Given the big potential of bagasse as described previously in this research, this amount of bagasse that is traded can be used in other like second generation ethanol or pelletizing that must be proven if they are more sustainable first. The amount of bagasse that is traded and the bagasse that is freed up with different methods, will be compared and projected together with a visual. Here is important to note that the use of the traded bagasse for other reasons is considered displacement of bagasse and is a free up scenario of bagasse like the previous. However, is interesting to look at those different amounts together, as in the future maybe the traded bagasse will be used differently.

3.4 Future scenarios for the freed-up bagasse

The initial sector overview highlighted various alternative present uses for bagasse beyond bioelectricity generation. From personal communication with EU companies (RWE, 2024), it is known that sugarcane bagasse is an attractive option as a feedstock for BECCS in Europe. However other possible uses of bagasse can compete in the future for the freed-up bagasse. To gain deeper insights into industry perspectives on bagasse utilization, a questionnaire was developed and distributed to sugarcane mills in São Paulo with the assistance of the NGO Solidaridad Brasil.

The questionnaire was translated in Portuguese and included this question: "Future uses of bagasse: Considering future markets for bagasse from 2030 onwards, assess the probability of these bagasse uses becoming a reality."

The possible uses were:

1. *Use of bagasse for the production of sustainable aviation fuel.*
2. *Use of bagasse for the production of chemicals.*
3. *Use of bagasse for the production of green hydrogen.*
4. *Other future uses of bagasse.*

4. Results

This section of this research will present the results that were derived from the data described in the method section alongside with information from Fieldwork.

Chapter 4.1 will delve into the availability of sugarcane bagasse in São Paulo state and its utilization within mills with varying cogeneration capabilities. The chapter will present quantitative results regarding bagasse usage for cogeneration, including the amounts used for electricity exports to the grid and self-sufficiency. This analysis will provide a quantification of the bagasse available within the mills.

Additionally, the chapter will explore the bioelectricity generated from sugarcane bagasse in São Paulo's mills, offering insights into the quantities exported to Brazil's grid and retained for internal use. This quantification will shed light on the electricity requirements for these purposes and the generation capacity of each mill category with different cogeneration characteristics.

Furthermore, Chapter 4.2 will examine various scenarios for freeing up bagasse, such as replacing bagasse-derived bioelectricity with sugarcane straw bioelectricity, biogas from vinasse bioelectricity, or efficiency improvements. The trading fraction of bagasse will also be compared to these alternatives.

Given the growing demand for bagasse from Europe (BECCS), Chapter 4.3 will present different future options for bagasse utilization that could compete with BECCS. Based on expert opinions, the chapter will evaluate the feasibility of these options for the future.

4.1 Use of sugarcane bagasse in different types of mills

In this research bagasse is allocated in different types of mills regarding the steam boiler pressure. Bagasse is mostly used for cogeneration but also the bagasse that is traded and stored is considered. Figure 9 shows the mass of bagasse that exists in different types of mills as a byproduct of sugarcane, according to the Fieldwork information and literature assumptions (Novacana, 2024), (Campos Trombeta and Caixeta Filho, 2017).

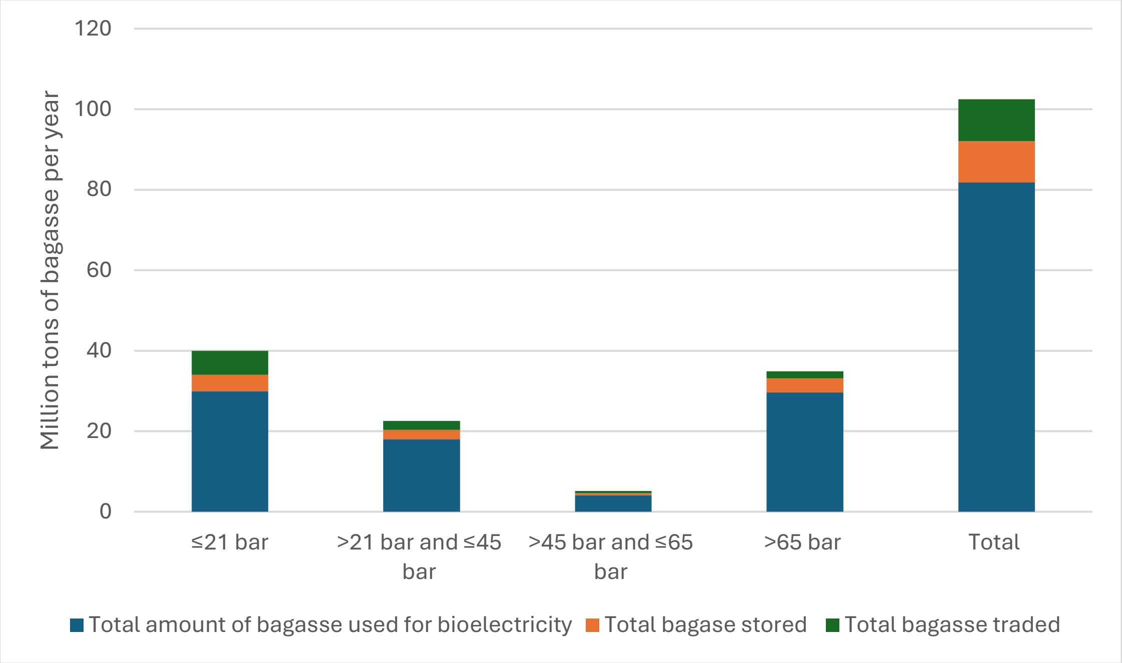

Figure 9. Million tons of bagasse in each category of sugarcane mill per year including bagasse for bioelectricity, stored and traded.

In Figure 9, the amount of bagasse shared in different types of sugarcane mills and the bagasse that stays in the sugarcane mill for electricity production, the bagasse stored for emergency start of the boiler (for example in the beginning of the season) and the bagasse traded to different industries. From the left to the right of the horizontal axis the first category includes 68 mills, the second category includes 39 mills, the third category includes 9 mills, and the final category includes 60 mills.

The total sugarcane bagasse production in Sao Paulo state of Brazil amounts to 102.5 million tons (derived from NovaCana as the byproduct of summed milling capacity of sugarcane). Mills equipped with 21 bar (or less) of steam pressure boilers represent the largest share, producing 40 million tons of bagasse out of the milled sugarcane. Following this, mills with >64 bar steam boilers produce 35 million tons. The >21 to ≤45 bar category contributes with 23 million tons, while the >45 to ≤65 bar category produces a significantly lower 5 million tons of sugarcane bagasse from crushed sugarcane, indicative of fewer mills and lower processing capacity in this group. Notably, the highest bagasse production is concentrated in mills operating at the lowest and highest boiler steam pressure levels.

10% of annual bagasse production, or 10 million tons, is typically stored across all mill types. The mills with the lowest and the highest-pressure boilers account for the largest share of stored bagasse. This stockpile is crucial for boiler ignition and testing prior to each milling season. However, prolonged exposure to rain and varying climatic conditions can degrade bagasse quality, affecting its lower heating value (LHV) and moisture content. As a result, mills gradually replace stored bagasse throughout the season (Fieldwork).

The biggest share of traded bagasse belongs to the mills with the lower steam pressure and is equal to 6 million tons of bagasse. In total 10 million tons of sugarcane bagasse are being traded yearly to other industries which is approximately 10% of the total amount of bagasse. Mills operating at lower steam pressures, specifically those with up to 21 bar boilers, exhibit higher trading volumes. Conversely, as steam pressure increases, the amount of bagasse traded decreases significantly. Mills with higher pressure boilers tend to utilize a larger proportion of their bagasse internally for energy generation and other processes.

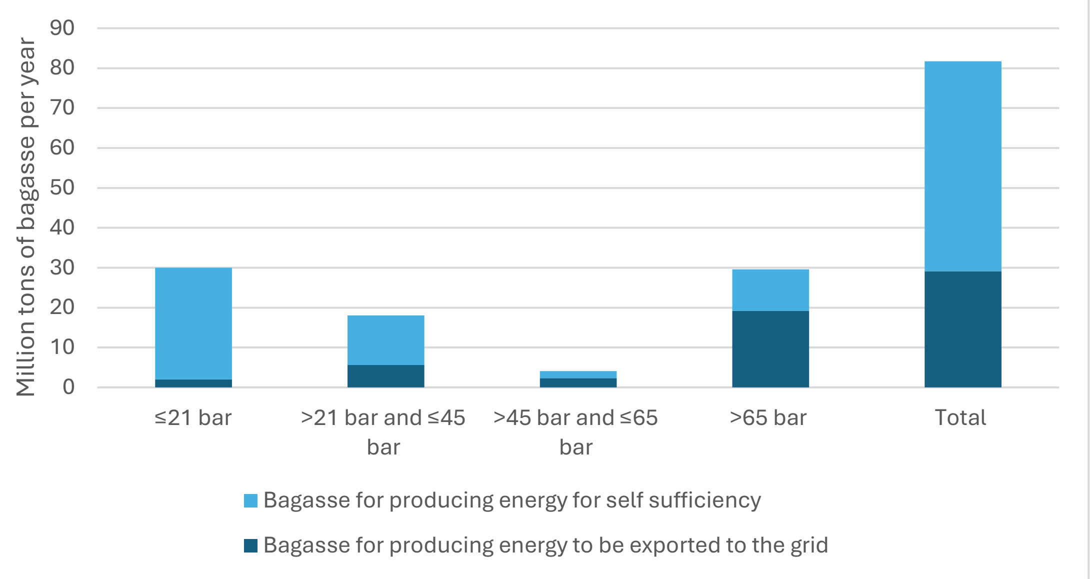

Figure 10. Use of bagasse that is processed in sugarcane mills of Sao Paulo for bioelectricity

Figure 10 presents the use of sugarcane bagasse that is processed in the sugarcane mills of Sao Paulo state for bioelectricity production. As boiler steam pressure gets higher more bagasse is used for producing surplus electricity to be sold to the grid. Indeed, during fieldwork this information was verified from experts and from data of NovaCana (2024), can be observed that most of the mills that have contracts to export electricity they are higher efficiency mills. The amount of bagasse existing in each type of mill is a result of the number of mills that exist in each category, that explains big differences between categories, however the amount of bagasse used for cogeneration or self-sufficiency of mills is based on the cogeneration efficiency of each category. Mills with higher generation capacity can produce more electricity so they export a bigger percentage.

In total 82 million tons of sugarcane bagasse are yearly processed in the sugarcane mills of Sao Paulo. From them, 29 million tons are used for surplus electricity exports and 53 million tons for self- sufficiency for the processes of the mills (sugar and ethanol production).

Regarding bagasse used for surplus electricity, the biggest proportion belongs to the mills with the higher steam pressure boilers, accounting for 19 million tons per year where the rest of sugarcane mills use 10 million tons per year for exporting electricity. In the other hand, the mills with ≤21 bar steam boiler pressure use 28 million tons per year for self-sufficiency (and only 2 million tons for electricity exports). The mills with >21 bar and ≤45 bar of steam pressure in their boilers come second with 12 million tons used for self-sufficiency while mills with a steam pressure more than 65 bar use 10 million tons per year for self-sufficiency. What is more important to keep out of those numbers is that most of the bagasse that is destined to become electricity for the grid of Brazil is bagasse from the most efficient mills with the best cogeneration systems.

The significance of bagasse for electricity exports is visible as more than one third of the bagasse that stays in the sugarcane mill and is fed in the boilers is destined to provide surplus electricity. That shows the importance of bagasse electricity as a product of the mill alongside sugar and ethanol.

About the availability of sugarcane bagasse and SQ1 from the results of this research it can be observed that approximately 102 million tons of sugarcane bagasse exist in Sao Paulo state, where approximately 82 million tons of sugarcane are burned in the boilers of the mills for producing electricity and approximately 10 million tons are traded to other industries while other 10 million tons are stored for emergency situations. For bagasse that is used for cogeneration the biggest proportion is going to the self-sufficiency of the mills however more than one third of this bagasse goes to exports of electricity according to the calculations of this research.

Figure 11 shows the electricity produced from the different mill categories for their self-sufficiency, projecting also the electricity that is provided to the grid as surplus electricity in the state of Sao Paulo for a year.

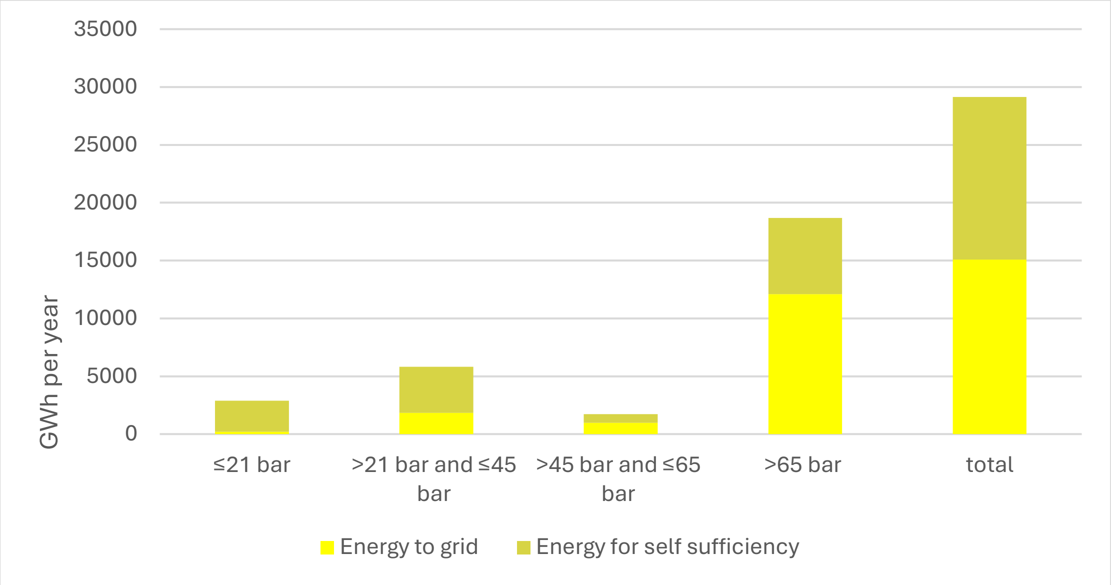

Figure 11. Electricity produced from sugarcane bagasse in different mill categories

Bioelectricity generation from sugarcane bagasse reveals a surplus: annual electricity exports to the grid marginally exceed the total electricity consumed by the mills for their annual ethanol and sugar production.

This mostly accounts for the sugarcane mills with the higher boiler pressure as a big proportion of the sugarcane bagasse is used in the boilers in those mills. The mills with boiler steam pressure greater than 65 bar generate approximately 12094 GWh's per year for the electricity exports and 6598 GWh's per year for their operations according to this research calculations. This category represents the largest bioelectricity producer among all mill types, significantly impacting São Paulo state's overall sugarcane-based power generation both for mill operations and surplus.

Conversely, mills equipped with lower steam pressure boilers exhibit a significantly lower proportion of surplus electricity. For instance, mills operating at 21 bars generate only 191 GWh annually for export, while consuming 2686 GWh for internal operations. This trend is evident when comparing the total annual bioelectricity exported by mills operating below 65 bar (2988 GWh) to the output of those operating above 65 bar (12094 GWh).

4.2 Sugarcane Bagasse that can be freed up

This part of the research will discuss the results of the calculations regarding different ways to free up bagasse for other purposes.

4.2.1 Replacement of bagasse with sugarcane straw in the boilers

In Figure 12, the bagasse that can annually free up when 10% of sugarcane straw and 15% of sugarcane straw are incorporated in the boiler is presented in million tons.

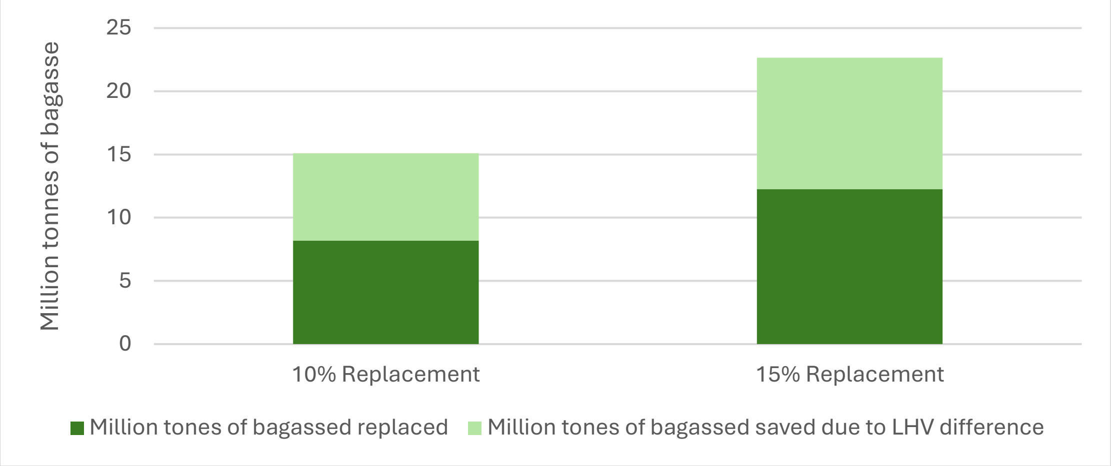

Figure 12. Million tons of sugarcane bagasse freed up due to 10% & 15% straw replacement in the boilers

If 10% of the mass of biomass that is fed into the boilers of all the mill types gets replaces with sugarcane straw instead of sugarcane bagasse, 8 million tons of bagasse per year are replaced as input to the boilers replaced by straw and 6 million tons per year can also be saved because of the difference of the LHV of straw and bagasse. This equals to a total of 15 million tons of bagasse that can be freed up in this case. An important note here is that the maximum replacement that mills and farmers consider possible (Fieldwork, personal communication with engineers and agronomists, 2024) is 15% it is very interesting to see the freed up bagasse of a 10% replacement as it could be more economical viable to the mills with less truck transportations of straw from the field to the mills.

In a case of 15% replacement of bagasse with straw in the boiler, which is the maximum of straw that can be safely incorporated in the boilers according to Fieldwork, 12 million tons of bagasse can be replaced with straw as biomass fed in the boilers and 10 million tons of bagasse can be freed up because of the higher LHV of sugarcane straw. This equals to 23 million tons of bagasse that can totally free up in this case.

4.2.2 Replacement of bagasse with biogas derived from vinasse

Figure 13 shows the electricity that could be generated from biogas compared to the electricity that is annually generated from sugarcane bagasse.

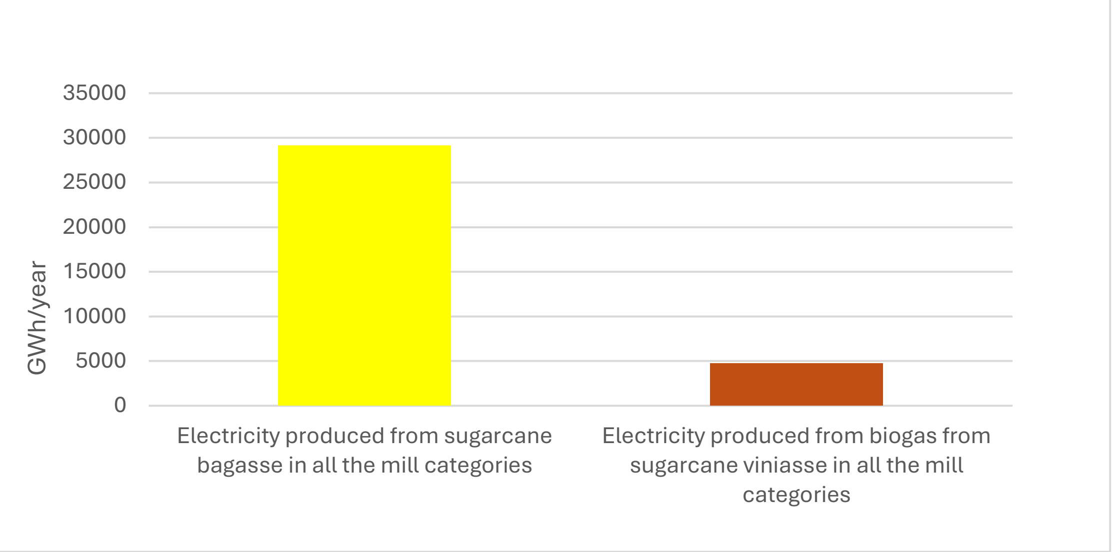

Figure 13. Electricity that can be generated from biogas compared to the electricity generated by sugarcane bagasse

According to the calculations of this research, the electricity that could be generated from biogas derived from vinasse, is 4753 GWh per year while the electricity derived from bagasse in all types of mills accounts for 29136 GWh per year. The electricity that is generated from biogas is estimated to be equal to 16% of all the electricity generated by bagasse in the state of Sao Paulo.

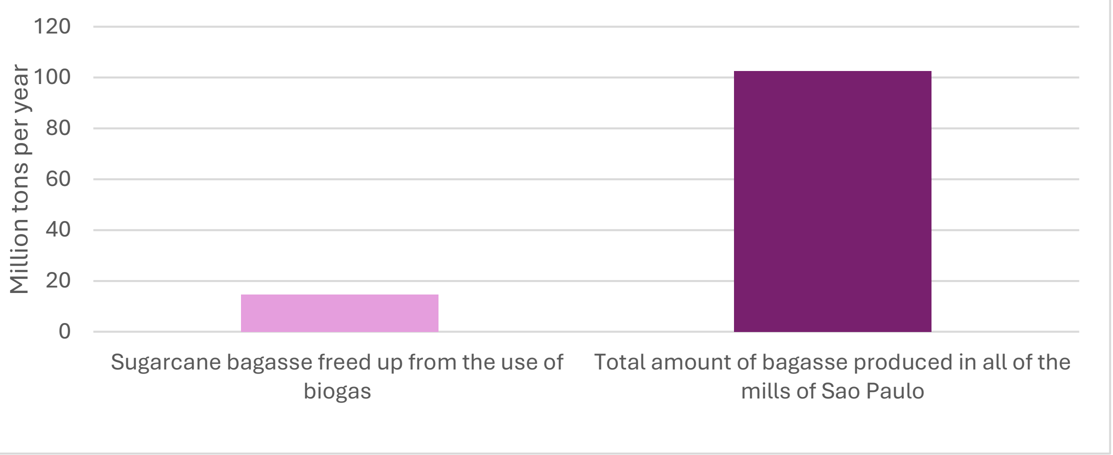

Figure 14. Comparison of bagasse that could be freed up from biogas use with the total amount of bagasse in the mills of Sao Paulo in millions of tons per year

An average amount of bagasse that could be freed up from the use of biogas in the sugar cane mills of Sao Paulo is 15 million tons per year as shown in Figure 14, however this amount can vary (estimated maximum of 49 million ton per year) (although this is not a realistic scenario) and a minimum of 7.5 million tons per year depending on the efficiency and type of boilers that will be used. The result of this research is based on the fact that the mills will not do further major efficiency improvements in their boilers. However, if the mills decided to progress to further investments with more suitable boilers for biogas, the maximum beforementioned could possibly be generated. The selected value of 15 million tons per year is approximately 14 % of the bagasse produced in the sugarcane mills of the state and 18% of the bagasse that is used for cogeneration. Given that vinasse, a byproduct of ethanol production, can be further utilized as a fertilizer post-digestion (Fieldwork, personal communication with farmers and agronomists, 2024), the integration of biogas offers a promising opportunity for diversifying bioelectricity generation sources in São Paulo's mills. Fieldwork also indicates strong industry interest in pursuing this approach. Given the need for sustainable industry fuels, vinasse biogas looks an appealing option based on the results of this research.

4.2.3 Efficiency improvements in the mills

First, the electricity generated annually from the sugarcane mills of Sao Paulo state before and after the suggested efficiency improvements are presented in Figure 15.

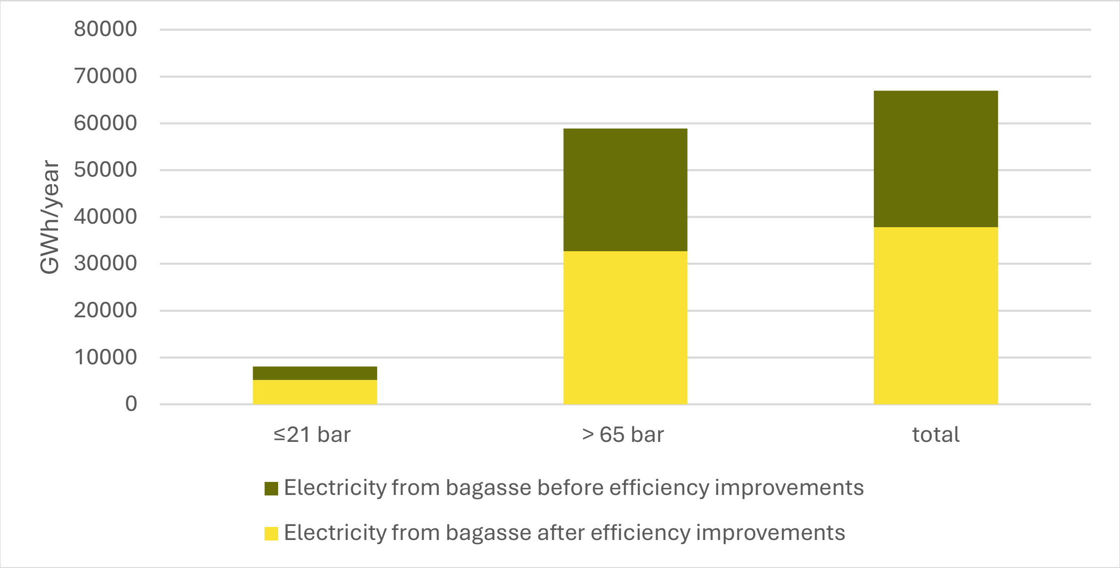

Figure 15. Electricity generated annually from sugarcane mills before and after efficiency improvements

In the ≤21 pressure mills the suggested improvement was the transition from the back pressure turbo generators to the condensing extraction turbogenerators which led to 2309 extra GWh that could be generated per year. This is a great improvement considering that the sugarcane mills produced almost doubled, but a small amount of bioelectricity comparing with mills with other cogeneration characteristics such as bigger pressure of the boiler.

The mills that had a boiler with steam pressure ≥22 to <64 bar increased the pressure to ≥65 bar which led to a significant increase of bioelectricity generation of 6411 GWh per year. Those mills were supposed to run with condensing extraction turbo generators, so the only change was the boiler pressure. The biggest and most significant is observed from the mills operating with a pressure of 22-45 bar that from around 323 GWh per million ton of sugarcane bagasse fed in the boiler they now generate 631 GWh per million ton of sugarcane bagasse. The 46-64 bar mills were few to make a considerable difference as they are not enough in number.

In Figure 16 the million tons of sugarcane bagasse that could be annually freed up with the suggested efficiency improvements of the sugarcane mills are presented

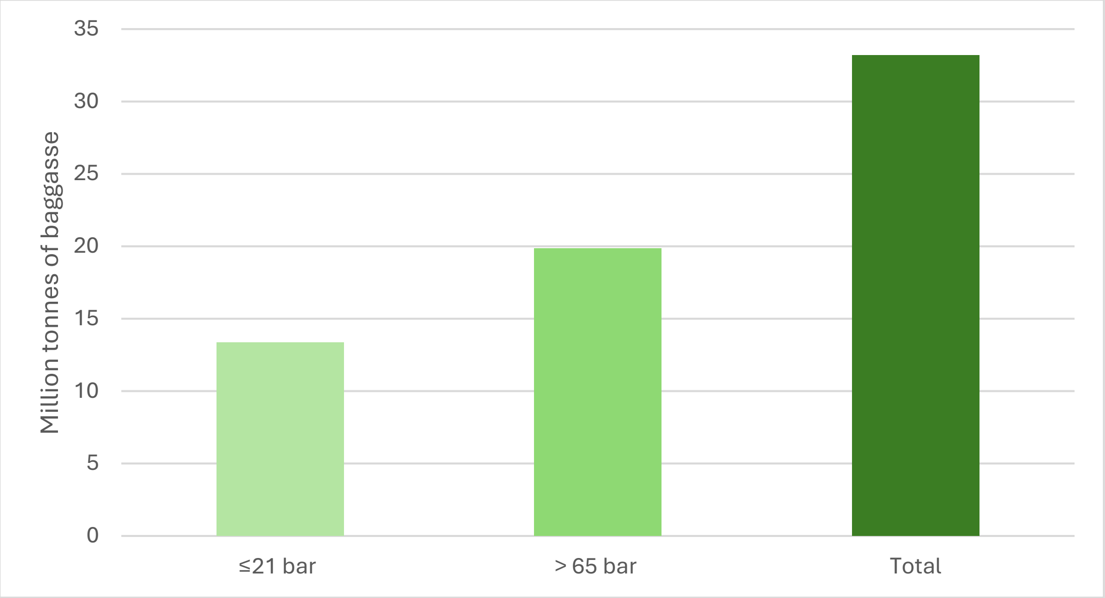

Figure 16. Million tons of sugarcane bagasse freed up from efficiency improvements in different mill categories

The bagasse that was freed up from all the proposed improvements accounts for approximately 33 million tons yearly, 13 from them coming from the lowest boiler pressure mills and 20 million tons to be freed up from the rest of the sugarcane mills. Considering that the total estimated sugarcane bagasse available in Sao Paulo state is 102,5 million tons, the freed-up bagasse from efficiency improvements is 32% of this. Here is important to highlight that efficiency improvements can be a lot in different types of mills, including adding new boilers and turbogenerators together or other changes. This research provided just an example to show that a significant amount of bagasse could be freed up in the state.

4.2.4 Comparison with trading fraction of bagasse

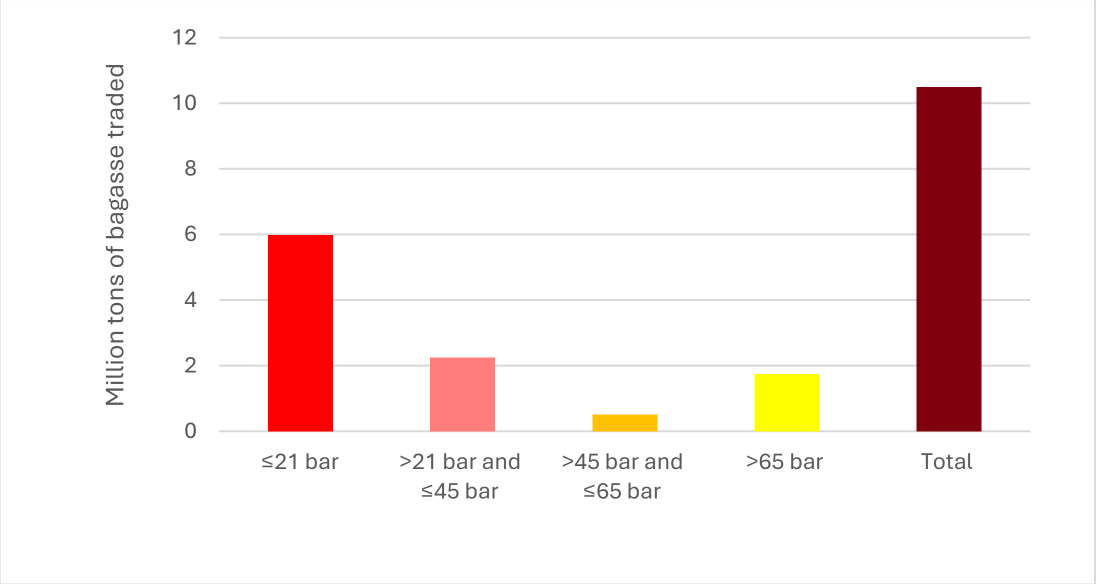

Figure 17. Million tons of sugarcane bagasse traded annually from different mill types in Sao Paulo state

Figure 17 illustrates that mills operating at the lowest boiler pressures contribute the most to bagasse trading, accounting for 6 million tons annually. This represents the largest portion of the total traded bagasse, which amounts to 10 million tons per year. Although mills with boiler pressures exceeding 65 bar trade the smallest percentage of total bagasse in comparison to the mills of different cogeneration characteristics, the amount of sugarcane bagasse traded is still substantial at almost 2 million tons annually.

4.2.5 Comparison of free up scenarios

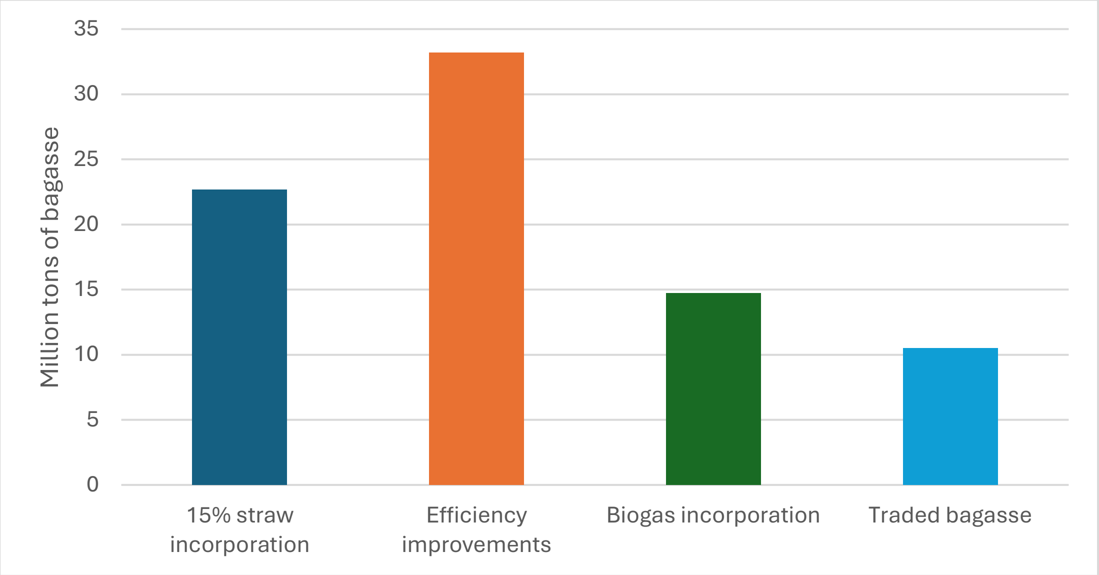

Figure 18. Comparison of different bagasse free up scenarios

Figure 18 illustrates the potential for freeing up additional bagasse through various scenarios that include the cover of bioelectricity production with other alternatives. The most promising approach, offering the potential to free up 33 million tons, involves implementing all suggested efficiency improvements across all mills. Incorporating 15% sugarcane straw into the boiler biomass presents a second viable option, with the potential to free up almost 23 million tons annually. This is supported by field observations with increased straw utilization during periods of higher electricity prices. While a maximum of 30% straw incorporation is feasible, maintenance concerns limit its widespread adoption. Biogas from sugarcane vinasse offers a third avenue for freeing up bagasse, with a potential of almost 15 million tons. This figure could rise with complementary efficiency improvements. Lastly, while bagasse trading (10 million tons annually) offers the smallest potential for freeing up additional bagasse, it can contribute to overall bagasse availability when considered alongside other strategies, but it is important to consider displacement issues.

4.3 Future uses of bagasse

In this part of the results the answers of the questionnaire that was submitted to sugarcane mills and experts in Sao Paulo will be presented. Considering that the mills will continue to generate the same amount of bioelectricity and offer also the surplus to the grid, in this part possible futures of the freed-up bagasse are presented.

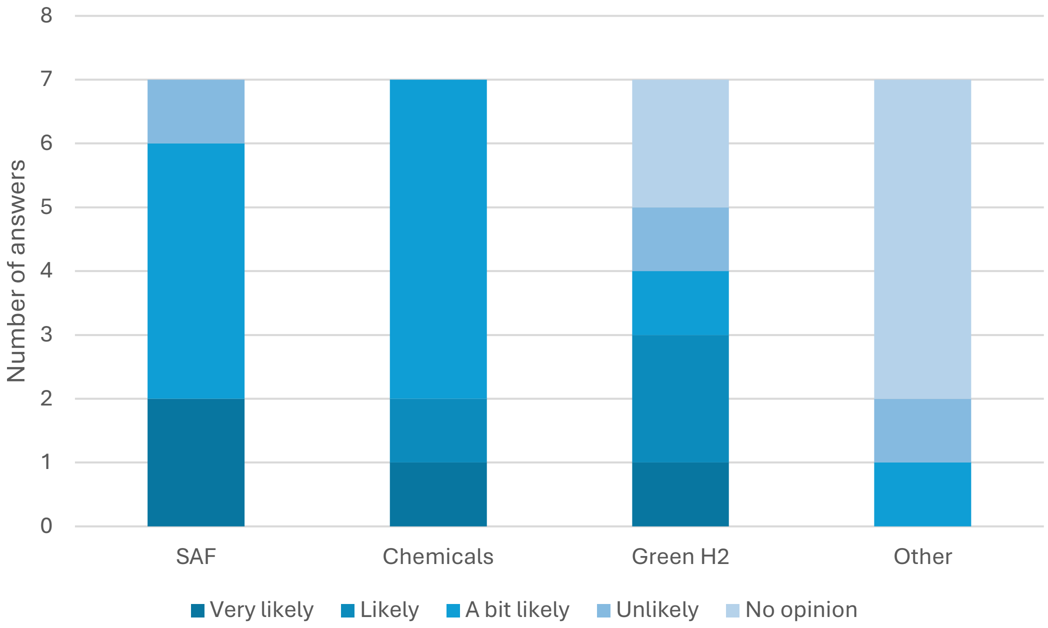

Figure 19. Future uses of bagasse after 2030, according to fieldwork questionnaires in Sao Paulo state (y axis includes the number of answers from experts)

Sustainable aviation fuels and chemicals from bagasse were the most favorable options according to experts (Figure 19).

Deuber et al., (2023) research highlights the potential of sugarcane residues (bagasse and straw) as a feedstock for producing Sustainable Aviation Fuel (SAF) through Hydrothermal Liquefaction (HTL). The study demonstrates that this approach not only significantly reduces greenhouse gas emissions compared to traditional jet fuel but is also economically viable. By meeting stringent international standards like RED II and the RFS, HTL SAF from sugarcane bagasse and straw emerges as a promising and sustainable alternative for the aviation industry.

Furthermore, sugarcane bagasse presents a promising feedstock for the biochemical industry**.** Its abundant availability and lignocellulosic composition make it an attractive substrate for microbial fermentation processes (Singh et al., 2022). A wide range of valuable biochemicals can be derived from bagasse, including xylitol, a sugar alcohol with applications in the food, pharmaceutical, and dental industries; biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), offering sustainable alternatives to traditional plastics; and various organic acids like gluconic, succinic, lactic, citric, and butyric acids, which find utility in diverse sectors (Singh et al., 2022). Additionally, sugarcane bagasse can serve as a precursor for furfural production, a platform chemical with applications in the chemical industry (Singh et al., 2022).

According to experts' green hydrogen production could also be a destination for sugarcane bagasse in the future. Cellulose and hemicellulose, the primary components of sugarcane bagasse, are complex sugars that can be converted into hydrogen gas through a process called dark fermentation (Lai et al., 2014). Unlike photosynthesis, dark fermentation occurs in the absence of light and relies on microorganisms to break down organic matter into hydrogen and other byproducts. Sugarcane bagasse is a particularly promising feedstock for this process due to its relatively low ash content compared to other agricultural residues, making it more suitable for green hydrogen production (Lai et al., 2014).

According to the experts however there is a doubt about the timeline that those technologies will be commercially available in Sao Paulo on a big scale. They argue that till 2030 those technologies are far from being available and till then sugarcane bagasse can have only specific uses like bioelectricity and the alternative uses analyzed in the sector overview section.

5. Discussion

Limitations

The information of other studies regarding bagasse exact quantification Brazil is limited since bagasse is a byproduct of sugarcane with value for the mills, however in this sector a lot of information are kept private as the sugarcane industry is a competitive sector in Brazil as understood from fieldwork. The sector however in a state like Sao Paulo is quite big including more than 170 mills with special characteristics (in electricity production from bagasse) as learned from the fieldwork. For example, there is not a standard in the used amounts of bagasse and the cogeneration characteristics.

Another important limitation of this research was the percentages of traded bagasse. Those percentages were estimated from Fieldwork interview however the bagasse market from mills to other industries is not official. What is suggested is an extended survey to mills and industries that buy bagasse (animal feed producers) to estimate a more accurate percentage of traded bagasse.

Visiting all the mills was not realistic, so the categorization provided was the best solution as quantifying amounts of bagasse to be freed up, taking into consideration that mills have different cogeneration characteristics and different amounts of electricity generation. The last part about electricity generation of the different mill types (as categorized in this research) was a challenge as no other research has tried to estimate potential freed up bagasse taking into consideration that the mills have different boiler pressures and temperatures, turbogenerators etc. Categorizing the mills in a realistic way was a challenge for this research as the methods included some generalizations to make it possible. The methods had some biases that although were necessary and there is awareness about them, it is important to consider their impact on the results. The assumption that the generation potentials adopted from Kabeyi and Olanrewaju, (2023) can be applied to the 4 mill categories of different boiler pressures was a generalization that could affect the free up results.

The assumptions about bagasse used for self sufficiency and exports although they are based on communication of fieldwork, the limited amount of mills visited its not sufficient to provide exact numbers in order to progress to completely accurate calculations. The only data available about electricity generation of mills were in NovaCava database (2024), however they don’t inlude information about the elecricity exports and there are not informaton about all the mills. Furthermore, the categorization of the mills affects the results of freed up bagasse for efficiency improvements as a different categorization would provide different results as the improvements require mills from one category to move to another. The questionnaire distributed to the mills received a limited number of 7 responses, potentially impacting the accuracy and representativeness of the results.

Fieldwork in São Paulo state proved challenging to coordinate, particularly in securing the cooperation of sugarcane mills and experts for on-site visits during the beginning of a hectic harvest season. As a result, the number of field visits was limited, hindering the collection of comprehensive data on bagasse trading and electricity exports.

Atlthough there are limitations in the study, there was not a chalenge to find and provide information about the historical evolution of cogeneration efficiency of Sao Paulo sugarcane mills and there were sufficient information in literature about the overview of the sugarcane sector. Also, literature about bagasse replacement with straw and biogas from viniasse was suficient enough to provide a good fundation for this research, so there is a good basis online for building freeing up scenarios (Isabela Zanon Pereira et al., 2020), (Cervi et al., 2019).

Suggestions for future research

To address the limitations of this study, future research could explore alternative data collection methods, such as more extensive surveys or detailed case studies of individual mills with different cogeneration characteristics. It is suggested for future studies to provide extensive data about bagasse trading derived from the surveys abovementioned. An extensive categorization of all the sugarcane mills taking into consideration milling capacity, number of boilers, boiler steam temperature, boiler steam pressure, turbogeneration capacity and type is suggested for detailed mill categorization in more than 4 categories as this thesis provided for all of the mills in the state of Sao Paulo state for more accurate results.

Implementing free-up scenarios involving biogas, straw, and efficiency improvements requires a comprehensive cost-benefit analysis to assess their economic viability. A detailed cost benefit analysis should consider factors such as capital expenditures, operational costs, maintenance expenses, and potential revenue streams from sales of the extra bagasse or its use in the mill. The scenarios then can be compared to see what is more economically viable and advantageous for the mills to invest. Furthermore, it will be interesting to see a future analysis that will present the price of bagasse and how can it be affected by different variables such as the demand of it or the prices of electricity.

Furthermore, a CO2 analysis has to be done to each of the scenarios involving the different free-up scenarios, including biogas, straw, and efficiency improvements. This analysis should quantify the greenhouse gas emissions associated with each scenario, taking into account both direct and indirect emissions. Some scenarios could be more CO2 intensive than others. This allongside this the cost benefit analysis will provide a a guide for the sugarcane mills to see in which scenarios they can invest.

Further studies should explore how second-generation ethanol production, pelletizing and exporting bagasse, and bioelectricity generation might compete for the freed-up bagasse in the future. As the market dynamics evolve, particularly during periods of low hydropower availability that drive up the price of bioelectricity, sugarcane mills might be incentivized to allocate more bagasse toward electricity generation. Additionally, advancements in second-generation ethanol technology could reduce production costs, making it a more attractive investment for mills. The potential for pelletizing and exporting bagasse could also expand significantly if international contracts are secured, opening new revenue streams. Therefore, it is recommended that future research includes different scenarios of demand for bagasse. In conclusion, by examining various demand scenarios for bagasse, future research can ensure that mills are well-prepared to capitalize on evolving market opportunities.

6. Conclusion

This research targeted to investigate the current and potential utilization of sugarcane bagasse in Sao Paulo state, Brazil. Specifically, the research sought to understand how bagasse is currently used within the sugarcane industry and sugarcane mills mainly for bioelectricity production and to explore strategies for increasing its availability for potential commercialization without compromising its essential role in the Brazilian sugarcane industry.

The study began by investigating the role of sugarcane bagasse in the sugarcane industry by providing a spherical analysis of the role of bagasse in the industry showing how has become a crucial source of bioelectricity. It showed that bagasse bioelectricity is considered a product of the mill comparable to ethanol and sugar production. The research revealed that cogeneration of bagasse is not a standardized process across all sugarcane mills in Sao Paulo. There are significant variations in how mills utilize bagasse for cogeneration, with different types of boilers and turbogenerators affecting electricity production. The sugarcane industry has seen advancements in cogeneration efficiency, but there are still variations among mills. Some mills use outdated methods, while others have adopted modern technologies to improve bioelectricity production. The biggest variables that affect electricity generation are boiler steam pressure and temperature and type of turbogenerator used. Straw can be used in cogeneration systems to generate electricity and heat, further optimizing energy efficiency with restrictions in its availability, transportation costs, and the specific characteristics of the mill's equipment. Vinasse, additional to its use as a fertilizer can also can be valorized through anaerobic digestion to produce biogas, which can be subsequently converted into electricity. This research explored alternative uses for sugarcane bagasse beyond cogeneration. These include trading bagasse between mills, using it for heat production, and producing second-generation ethanol. For pelletizing bagasse for export to the EU, which is a potential application, industry insights shows that its considered as a possible option, depending on the logistics.

In continuation, annual bagasse production of sugarcane mills was estimated using fieldwork and literature assumptions. Mills were categorized with selected cogeneration characteristics to make the allocation of bagasse in different mills possible. Bagasse was estimated considering the amount that is used for bioelectricity for self-sufficiency, surplus electricity, traded and stored. Sao Paulo state produces a significant amount of sugarcane bagasse, totaling approximately one hundred million tons annually. Both mills with lower and higher steam boiler pressures produce the biggest shares of bagasse in Sao Paulo. Mills with higher steam pressure boilers tend to use a larger proportion of bagasse for producing surplus electricity, which is then exported to the grid. More than one-third of the bagasse retained by mills (including all categories) for cogeneration, is destined for electricity exports, highlighting the significant role of bagasse in Brazil's energy mix. This highlights the important role in Brazil's energy landscape.

The results about the free up scenarios of bagasse showed that all the different pathways to free up bagasse can make a considerable amount of it available. Sugarcane straw use for bioelectricity, biogas from vinasse and efficiency improvements were considered as the most possible options. Efficiency improvements have the biggest potential to free up bagasse however this depends on the adoptions of the sugarcane mills. By implementing efficiency improvements across various mill categories, particularly in mills with lower boiler pressures, a substantial amount of bagasse can be freed up for commercialization or other applications. Sugarcane straw and biogas from vinasse adoption to the boilers for electricity production also showed a great potential to free up bagasse, with the straw incorporation being more effective to some extend in freeing up bagasse. What comes next is for the mills to see which option can be more economically and environmentally viable to have a complete perspective.

About future possible scenarios of bagasse utilization that could possibly compete for the available bagasse, sugarcane is possible to have new applications in the future. According to the experts the future holds promise for the development of sustainable aviation fuels, biochemicals, primarily and green hydrogen following, from this valuable byproduct. Those uses could contest for the use of bagasse but according to professionals this will not possibly happen very soon.

The main research question, "How is sugarcane bagasse used in São Paulo state of Brazil, and how can it be possible to increase its availability for commercialization without compromising its current role in the sugarcane industry?" has been addressed through this study. The findings demonstrate that sugarcane bagasse is mostly used for bioelectricity production within the mills however the amount of bagasse used for surplus electricity is significant, with big variations in mills with different cogeneration efficiency. The research identified pathways, which are firstly efficiency improvements, secondly the use of sugarcane straw, and finally biogas from vinasse, that in this order they could free up substantial amounts of bagasse without undermining its critical role in energy generation. These insights could provide an initial guideline for future investments of bagasse from the side of the mill, or the investor interested on using the bagasse in a practice (for example BECCS) that could envision a sustainable future.

7. Appendix: Fieldwork interviews

During the fieldwork conducted in the state of São Paulo, various experts in the field of sugarcane and sugarcane bagasse were interviewed. These included sugarcane farmers, representatives from sugarcane mills, and industry experts.

The interviews with sugarcane farmers focused on the potential use of sugarcane straw for cogeneration and whether the removal of specific percentages of straw from the fields could impact soil quality. Representatives from sugarcane mills provided detailed information about the cogeneration technologies they employ and how bagasse is utilized for bioelectricity production. These discussions also explored the mills' willingness and capacity to invest in the proposed methods for freeing up bagasse, as well as the feasibility of implementing these methods.

Industry experts offered an overarching view of the sugarcane sector. They were asked to share their perspectives on the role of bagasse in the industry, its potential for alternative uses, and the viability of the proposed free-up methods.

These interviews provided valuable insights into the current practices, challenges, and opportunities within the sugarcane industry in São Paulo, particularly concerning the utilization and potential commercialization of bagasse.

Table 8 presents the stakeholders approached in Brazil:

Table 8. Stakeholders interviewed in Brazil

Sugarcane farmers	Farmers around the regions of Riberao Preto, Piracicaba, Jau and other locations in Sao Paulo state
Sugarcane mills	Colorado, Batatais, Coletta, Sao Manuel, da Pedra, Alta Mogiana
Sugarcane experts	Professor Pedro Ramos (UNICAMP), Gabriel Casarotti (PECEGE), Peterson Arias (PECEGE), Control Union Consultants, Solidaridad experts, Dr. Rafaela Rossetto
Sugarcane associations	AFOCAPI, Socicana, CanaOeste, UNICA, IAC, Assosicana

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