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Global Energy Transition and the Biomass Paradox

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Abstract

Global energy transition can be described as a process where fossil fuels are replaced with renewable and low-carbon energy sources to achieve climate change, energy security and sustainability objectives. The objective of the study was to explore biomass-based bioproducts in the framework of global energy transition and sustainability paradox. This study utilizes a mixed-method research design to investigate the prospects of biomass bioproducts based on sugarcane to effectively address the question of the potential to replace fossil-based fuels in the global energy transition. Thematic analysis of qualitative data, provided by scientific literature, expert interviews, and policy reports, helps to comprehend technological tendencies and attitudes of the stakeholders. Statistical instruments are applied to provide the model of quantitative data, which is technical and economic indicators to determine efficiency, cost and scalability. The findings presented by the study emphasize the technical and economic feasibility of biomass-based bioproducts in the context of energy transition on the globe. Technical-Economic Analysis (TEA) demonstrated attractive indicators: a pulp plant had the profit margin of 49%, the ROI of 13.47, and the payback period of 7.42 years; the energy cogeneration generated R$16.3 million income; the production of sorbitol expressed the profit margin of 51, the ROI of 12.37, and the payback of 8 years, testifying to the long-term profitability and sustainability. This study illustrated how the global energy shift though motivated by climate, economic and geopolitical factors, have opened opportunities and contradictions- particularly when one looks at the problem via the prism of biomass-based solutions.

Keywords Renewable Energy, Biomass-Based Products, Suitability, Energy transition, Bioeconomy, Global Energy, Carbon Emission

1.0 Introduction

The global energy transition is a systemic change of energy systems including traditional fossil fuel-based energy (coal, oil and natural gas) to cleaner, renewable and lower carbon (solar, wind, hydropower, and biomass) (Kabeyi & Olanrewaju, 2022). Renewable energy capacity has increased at an exceptionally high rate in the last 10 years and account to almost 20 percent of final energy consumption in 2030 with solar, wind, and bioenergy sources maintaining their positive trend (Khaleel et al., 2023; Kratzenberg et al., 2021). The International Energy Agency estimates modern bioenergy as the largest renewable energy source worldwide, contributing around 55 percent of the global renewable energy and more than 6 percent of the total global electricity demand (IEA, 2025). Climate change is one of the main stimulants because an increased emission of greenhouse gases due to increased use of fossil fuels has led to climate change and the world is shifting its focus to use clean sources of energy (Filonchyk et al., 2024). The necessity of renewables with diversity of origin and domestically acquired ones becomes highlighted further under the guidance of the safety of energy resources during geopolitical crisis situations due to the interrupting with supply (Bordoff & O'sullivan, 2023). Biomass is a major renewable energy source consists of organic substances such as wood, rotten materials, animal waste, which can be used to produce electricity, heat or biofuels (Barot, 2022). Regardless of its potential, the utilization of biomass is a paradox too, yet its extensive use may pose a threat to food security, cause deforestation, and result in carbon emissions whenever it burns down, unless it is spent in a sustainable way.

The biomass is vital in global renewable energy mix, with a contribution to the total global primary energy amount of about 10 percent and over 2/3 of the total renewable energy potential (Saleem, 2022). In Brazil, biomass is a key constituent of the national energy plan, contributing to an estimated 4 percent of the total energy mix and sugar cane biomass is a most promising source as it is highly productive and can be used in a variety of industrial processes (Júnior et al., 2023). In 2017 Brazilian sugarcane industry was the largest in the world, with a 758 million ton production, which is considerably higher than other producers worldwide such as India and China (Arora et al., 2025). Huge amounts of sugarcane residues, including bagasse, straw, molasses, and filter cake, are no longer perceived as a waste but are being turned into bioproducts and renewable energy much more frequently (Ungureanu et al., 2022). More recently, second-generation (2G) technologies convert lignocellulosic biomass such as bagasse and straw into cellulosic ethanol and increase the yield per ton of raw material (Sukumaran et al., 2024). The bioproducts under sugarcane (e.g., biofuels, bioplastics, and biochemicals, e.g., sorbitol and lactic acid) have a proven record of technical feasibility and economic viability (Moreno et al., 2020). The incursion of sugarcane-based products into biorefineries follows the Brazilian Environmental, Social, and Governance (ESG) agenda to encourage rural workers, less polluting technology adoption and green innovations (Pinheiro, 2023).

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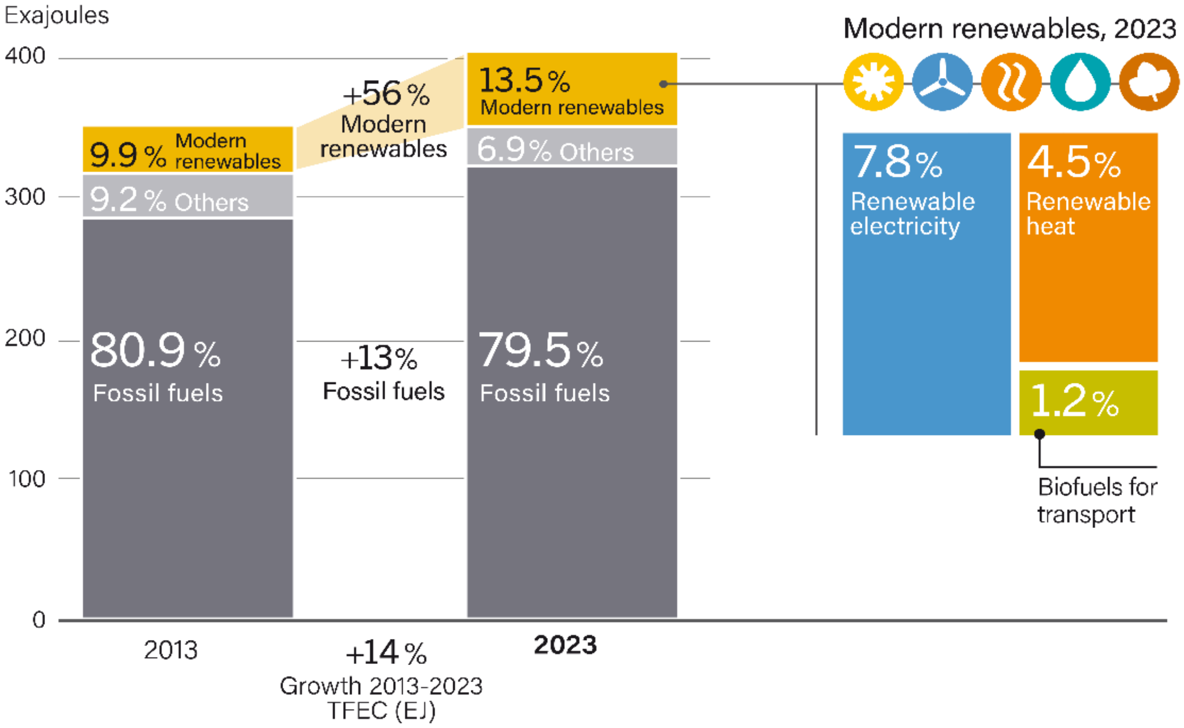

Figure 1: Comparative Analysis of Final Energy Consumption by Source: 2013 vs. 2023 (REN21, 2025)

Despite remarkable advancement being realized in using the sugarcane biomass as a source of biofuel, there can still be significant obstacles with regard to the evolution of biomass-based bioproducts. The lack of regulatory and policy predictability is another limitation that is most critical, because long-term biorefinery should be supported by the government and constantly by incentives, which are prone to politics and changing national interests (Bento et al., 2024). Infrastructure and logistics are also a major challenge especially with regards to effective organization of sugarcane residues like bagasse and straw in vast rural environments (Hiranobe et al., 2024). Second-generation (2G) biorefineries cannot scale as well due to complicated logistics and the challenge of full integration of streams of products in one facility, which increases technical and cost obstacles (Satari & Jaiswal, 2021). Limits to technology efficiency, such as inefficient enzyme activity of the lignocellulosic hydrolysis process and high capital cost of pre-treatment and processing further limits the cellulosic ethanol production viability (Sukumaran et al., 2024). The environmental risks related to large-scale biomass harvesting harm (land-use change, and water stress) should be treated with care to ensure that the bioeconomy benefits, but not detrimentally affects the sustainability objectives (Calvin et al., 2021). The study addresses these concerns by identifying effective sugarcane-based bio products, and proposing solutions that integrate solutions to the technology optimization, scalability, infrastructure and policy to enable sustainable growth.

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The research is important as it discusses the urgent global need of sustainable energy solutions by examining the untapped potentials of biomass based bioproducts, especially in the advanced bioeconomy of Brazil. It gives a detailed assessment of both the technical, economic, and environmental aspects of sugarcane biomass conversion with reference to first-generation technologies and second-generation technologies. This study is also innovative as it addresses the gap between policy, technology, and the practical's by providing scalable routes of converting agricultural wastes into biofuels, bioplastics, and biochemicals of high value. It also underlines one of the unique aspects of introducing the principles of a circular economy and renewable energy objectives to the decarbonization strategies. This study aimed at investigating the world energy transition along with the explanation of the paradox behind the development of biomass-based bioproducts. The research objectives included analyzing the existing trends and issues in the international transition of the use of fossil fuels to renewable energy sources. It further aims to examine how biomass-based bioproducts can be involved in this transition through their environmental, and their economic implications. Also, the research evaluates the policy frameworks that are in favour of biomass use in sustainable planning of energy. It examines the paradoxical effects of the rise in biomass demand in land utilization, food security and balance of ecosystem.

2.0 Methodology

2.1 Research Design

This study utilizes a mixed-method research design to holistically conduct research into the potentiality of biomass-based bioproducts in the global switch of energy. The qualitative section emphasizes on the comprehensive examination of the scientific literature, industry reports, and expert opinions to investigate the newest biomass conversion technologies and their feasibility in practical context. It enables an ecological interpretation of technological change, gathers subjective opinions, and establishes the development of theory on the basis of interviews, document analysis, and critical literature research. This method facilitates this study to capture the multi-faceted and dynamic nature of the biomass innovation and sustainability challenge. In contrast, the quantitative aspect brings in a systematic approach to the evaluation of technical performance, economic feasibility, and scalability. It applies the statistical tools, economic modelling and cost benefit analysis to evaluate the input output ratios, cost of processing and the market competitiveness. Collectively, the approaches integrate the insights of the context with the quantified data, creating a more comprehensive analysis of sugarcane-based bioproducts and its consideration relative to environmental, economic, and policy-oriented energy transition objectives.

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2.2 Data Collection

The study is designed under a mixed-method data collection design, which includes qualitative and quantitative methods that give the entire profile of biomass-based bioproducts in the global energy shift. Literature reviews, interviews with experts and the proposed policy and industry literature research are used to gather qualitative data that provides profound clue on the technological directions, opinions of stakeholders and that of the socio-environmental factors. Conversely, quantitative data collection would entail the collection of measurable biomass inputs in the form of availability, conversion, and production cost and market information. Quantitative techniques prove the results of qualitative research with the evidence and modeling tools predict the results in the form of actual production indicators. The combination of the two approaches is a way of providing a delicate and precise basis of assessing the feasibility and effects of sugarcane-based biomass innovations.

2.3 Data Analysis

This study incorporates both qualitative and quantitative methods in the data analysis of the study. Qualitative data was analyzed using a thematic analysis method of scientific literature, case studies, and industry reports to determine major trends, technological advances, and sustainability issues related to the process of biomass conversion. The Kraft process is a case study where specific focus was placed on the evaluation of versatility of inputs, integration of processes and scalability into industrial. The quantitative component involved data of Brazilian industries especially cellulose and sorbitol production were re-calculated and modeled in terms of technical-economic analysis (TEA). The use of this dual approach allowed a contextual and deep interpretation as well as empirical validation, allowing a balanced and more practical analysis that upholds the contribution of sugarcane biomass to a sustainable bioeconomy.

2.4 Ethical Consideration

The ethical aspects of this study include responsible utilisation of data, openness in reporting and the accommodation of the stakeholder opinion on the biomass section. All the literature, case studies and industry data were found and referenced in a proper manner to ensure academic integrity and be free of plagiarism. Industrial data in terms of confidentiality and intellectual property rights was honored, particularly the application of specific technical and economic numbers of the company. The study is not biased as it has taken into consideration different perspectives that encompass social, economic, and environmental aspects to facilitate fair and sustainable energy transition solutions.

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3.0 Results

3.1 Qualitative Analysis

3.1.1 Case Study Analysis

Attribute	Description
Versatility of Input	The Kraft process effectively handles a wide range of non-wood biomass inputs such as sugarcane bagasse, wheat straw, and bamboo, enabling multi-sector use.
Process Integration	Kraft pulping integrates closed-cycle chemical recovery and bioenergy co-generation (e.g., steam and power), improving environmental and economic efficiency.
Industrial Scalability	Proven by operations like 200 TPD pulp mills, the Kraft process supports large-scale production with strong economic returns and efficient material throughput.

3.1.2 Versatility of Input

The flexibility of the input in the production of bio products based on biomass presents an opportunity and a challenge in the global energy transition context (Raghavan, 2023). Pydimalla et al. (2023) highlighted that non-woody fibers (sugarcane bagasse, wheat straw, bamboo and grasses) can be used to support a broad spectrum of bioproducts and thus are very versatile feedstocks to biorefineries and green manufacturing industries (Pydimalla et al., 2023). Sugarcane bagasse by itself has up to 32-48 percent cellulose and 27-32 percent pentosan, and therefore, it can be used in study and biochemical production (Raghavan, 2023). According to De Rosa et al. (2022) study, this variability helps to curb the use of fossil dependency, as well as facilitates diversification of renewable sources of energy (De Rosa et al., 2022). Nonetheless, the presence of high variation in the amounts of ash and silica, as high as 14% in rice straw, makes operation more expensive and less predictable, and chemicals recovery is poorer and harder to retrieve. Although these inputs are referred to as agricultural residues, they can be scaled only to a limited extent due to their seasonality and scattered collections, which jeopardizes the consistency of supply (Sarkar et al., 2020). Moreover, Saleh & Hassan (2024) highlighted sustainable feedstock causes complex processing and disproportionate supply and compromises its role in the energy transition (Saleh & Hassan, 2024). Therefore, biomass versatility reduces the climate targets, implementing it in practice requires sophisticated logistics, regional accommodation, and policy specific bonuses.

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3.1.3 Process Integration

Process integration is an important element of the development of biomass-based bioproducts and particularly within the context of the global energy change where efficiency and sustainability are crucial. The pulp, sales, and chemical recovery processes are also integrated in the Brazilian sugarcane industry using the Kraft pulping technique, which not only allows producing pulp but also bioenergy using the remaining biomass, such as bagasse (Raghavan, 2023). This closed-loop strategy advocates the circular economy by maximizing the use of the resources as well as reducing waste. While, Fonseca et al. (2020) illustrated that simultaneous production of steam and electricity can be achieved, which can greatly minimize external energy requirements related to biorefinery processes and can also improve energy efficiency (Fonseca et al., 2020). However, Shibukawa et al. (2023) argued that complexity in high integration causes the technical and economic barriers especially in second-generation (2G) biorefineries wherein flows of a variety of products are to be handled at all times simultaneously (Shibukawa et al., 2023). In addition, Arent et al. (2022) discussed that integrated systems are associated with long-term environmental advantages and economical scalability, and they promote decarbonization and the economic competitiveness of the industry (Arent et al., 2022). As the case study points out, the strategy of making the Kraft process and sugarcane residues cooperate not just contributes to increasing the efficiency of the process, but also complies with the global ESG requirements, as well as energy diversification focus.

3.1.4 Industrial Scalability

The success of biomass-based bioproducts to global energy transition is based on industrial scalability, which is a challenge in the larger biomass paradox. Although, Formann et al. (2020) mentioned that sugarcane biomass has shown high productivity and multiplicity particularly in the second generation biorefineries, has scalability limitations (Formann et al., 2020). The Kraft process, which is presented in the given document, demonstrates the possibilities of converting biomass scale, as can be seen in the work of such operational models as 200 TPD pulp mills that use wheat straw and sugarcane bagasse (Raghavan, 2023). These mills combine chemical recovery and bioenergy cogeneration, thus they are more economically and environmentally efficient. Nonetheless, Oshilalu (2024) emphasized that increased pace of substituting fossil fuels with renewable energy types, industrial scalability should be accompanied by policy incentives and investment in the infrastructure to be viable at the global scale (Oshilalu, 2024). Alcocer-García et al. (2025) discussed that paradox is created when the potential high-potential technologies cannot scale as they have fragmented instances of governance, inadequate funding, and socio-environment hazards (Alcocer-García et al., 2025). In this way, scalability is an essential solution to exploiting biomass to create a significant global energy transformation by using the scalability of biomass through modular biorefinery models, strong value chains, and integrated policy frameworks.

3.2 Quantitative Analysis

3.2.1 Technical-economic analysis (TEA)

The viability of bioproducts produced using biomass and the role of biomass-based bioproducts in the global energy transition is evaluated using the Technical-Economic Analysis (TEA) of this study. TEA assists in identifying whether biomass solutions can be economically used to achieve sustainable energy targets in addition to dealing with issues that are high capital expenditure, and economic trade-offs between land and energy utilization. Furthermore, it estimates economic metrics such as:

1. Recipe, Eq. 1.

$$\boxed{Receita, \frac{R\$}{ano} = vendas\ do\ produto\ (kg/ano)\ \times preço\ de\ venda\ do\ produto\ (R\$/ano)} \quad (1)$$

2. Profit margin, Eq. 2.

$$\boxed{Margem\ de\ lucro, \% = \frac{receita\ anual\ (R\$) - custo\ de\ operação\ anual\ (R\$)}{receita\ anual\ (R\$)}} \quad (2)$$

3. Return on investment (ROI), Eq. 3.

$$\boxed{Retorno\ do\ investimento, \% = \frac{lucro\ líquido\ anual\ (R\$)}{capex\ (R\$)}} \quad (3)$$

4. Payback period, Eq. 4.

$$\boxed{Payback, anos = \frac{capex\ (R\$)}{caixa\ líquido\ médio\ anual\ (R\$)}} \quad (4)$$

3.2.2 Technical-economic analysis (TEA)

These results are actually promising economic feasibility as seen in the Technical-Economic Analysis (TEA) of sugarcane bagasse pretreatment through the Kraft process. The industrial plant have an annual 30,000 tons of material to process (a capital expenditure of R$ 600 million and an operational expenditure of R$ 84.20 million). The plant earn an annual gross revenue of R$ 165 million given a bagasse to pulp ratio standing at 3:1 and an average price, which in which the plant sell the pulp at R$ 5,500.00 per ton. The net profit obtained is R$ 80.85 million which is a good profit margin of 49%. The payout ratio (ROI) is 13.47, which is a satisfactory level of profitability. The payback is 7.42 years which indicates very long term of investment although it is within a reasonable period of bio industrial investment (Table 1).

Table 1: Economic simulation scenario for sugarcane bagasse pretreatment via Kraft

Technical and economic variables	Values
Capex Kraft	R$ 600 million
Opex kraft	R$ 84.20 million
Production capacity of the industrial plant	30,000 tons
bagasse/pulp ratio	3:1
Average selling price of pulp	R$ 5,500.00/ton
Gross revenue	R$ 165 million
Net profit	R$ 80.85 million
Profit margin	49%
ROI	13.47%
Payback	7.42 years

3.2.3 Technical-economic analysis (TEA)

Technical-Economic Analysis (TEA) of a sugarcane bioenergy plant with electricity generation and cogeneration alerts to the efficient recovery of energy in the form of sugarcane bagasse. The plant has a nominal grinding capacity, which is 5,500,000 tons and 1,375,000 tons of bagasse. Of this, 32,926 tons are utilized in the internal energy self-sufficiency and 1, 252, 074 tons is utilized as energy export. A further 90,000 tons are still as remained. The plant exports 58236 MWh of electricity using the bagasse-to-energy ratio of 21.5tons/MWh. With an average selling price of R$280.00/MWh the operation come up with a net revenue of R$16,306,080.00 (Table 2). These findings highlight profitability and sustainability of cogeneration, in which effective utilization of biomass not only contribute to internal energy, but also generate a great amount of economic value by exporting energy.

Table 2: Data on electricity generation and cogeneration from a Brazilian bioenergy plant

Technical and economic variables	Values
Nominal grinding capacity	5,500,000 tons

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Bagasse production	1,375,000 tons
Bagasse for energy self-sufficiency	32,926 tons
Bagasse for energy export	1,252,074 tons
surplus bagasse	90,000 tons
bagasse/energy ratio	21.5 tons/ MWh
Energy exported	58,236 MWh
Average selling price	R$280.00/ MWh
Net revenue	R$ 16,306,080.00

3.2.4 Technical-economic analysis (TEA)

The Technical-Economic Analysis (TEA) of sorbitol production via an enzymatic hydrolysis system and glucose conversion proves to have mid-range profitability and prospects of long-term returns. The system on the example of capital expenditure (Capex) R$ 227 million at the beginning is initiated by the production of kraft pulp 30,000 tons/year. The hydrolysis of cellulose by enzymes gives 70% rate of conversion of glucose and 21,000 tons/year glucose. This is further converted to 17,850 tons/year of sorbitol which is 85%. The high profit margin of 51 percent favors financial sustainability, but the 12.37 percent of the payback period and the 8 years payback period indicate that the investors may need a longer payback period to get profitability on the production of bio-based chemicals (Table 3).

Table 3: Economic simulation scenario for sorbitol production

Technical and economic variables	Values
Capex Sorbitol $_{\mathrm{DA}}$	R$ 227 million
Pulp production via kraft paper	30,000 tons/year
Enzymatic hydrolysis of cellulose -> glucose	70%
Glucose production	21,000 tons/year
Conversion of glucose into sorbitol	85%
Sorbitol production	17,850 tons/year

Average selling price of sorbitol	R$ 3,095.00/ton
Gross revenue	R$ 55.24 million
Net profit	28.25 million
Profit margin	51%
ROI	12.37%
Payback	8 years

4. Discussion

This discussion assess the potential of biomass bioproduct in the context of the global energy change. The study examines the potential of these bioproducts to act as alternative to the use of fossil fuels due to their technological possibility, economic possibility, and incorporation into circular economies. It also discusses the deception of biomass usage, and provides system policy, scalability, and environmental sustainability at insights. The results highlighted the opportunities as well as tensions at the core of the Global Energy Transition and toward the Biomass Paradox, especially in the context of biomass valorization of sugarcane in Brazil. Haile et al. (2023) discussed that flexibility of the input that is inherent in the Kraft process and could effectively use a variety of non-wood biomass materials, including sugarcane bagasse, wheat straw, and bamboo, into high-value products (Haile et al., 2023). This flexibility is essential during the worldwide transition to the non-fossil fuels since this expands the supply of renewable feedstocks to be used in generating energy and materials. However, Miassi & Dossa (2024) study indicate that non-woody fibers have the ability to support the diverse bioproducts production which ultimately helps avoid using single feedstock systems and decentralizes bioeconomies (Miassi & Dossa, 2024). Moreover, Bakili et al. (2025) mentioned that huge amount of cellulose and pentosans in sugarcane bagasse expands the biochemical and material usefulness of the product, which acts as a renewable substitute in the areas that have traditionally used fossil-derived inputs (Bakili et al., 2025). Nevertheless, Onukwulu et al. (2023) emphasized that these different things can increase the size of the renewable energy resource, their unpredictable composition and seasonal nature complicates the supply chains, raises their cost of processing, and generates uncertainty (Onukwulu et al., 2023). In the global energy shift framework, the limitations noted above show that the potential of biomass as renewable is solely as robust as the logistical and technological infrastructure underpinning this concept.

An additional important discovery pertains to process integration and industrial scalability both which are central to realizing the biomass potential in revealing itself as actual contribution to

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energy transitions. Sravan et al. (2024) illustrated that Kraft process is an ideal example of successful integration since it involves pulp fabrication, closed-loop chemical recovery, and biorenergy co-generation, resulting in the steel and electricity generation and generating a minimum amount of waste (Sravan et al., 2024). This hybrid system is in line with the rule of the circular economy since it uses the resource to its full capacity and minimizes the need of foreign energy sources, which makes biomass even more crucial to a sustainable energy system. Pérez-Almada et al. (2023) also state that the integrated biorefinery systems increase the long-term environmental and economic competitiveness, which are important elements of the decarbonization strategies (Pérez-Almada et al., 2023). However, this is ironic when it is viewed in the light of the complexity and cost barriers of highly integrated second-generation (2G) biorefineries. According to Roos (2024), managing multiple streams of products concurrently makes it more difficult to handle technically and raise capital needs, which may not be attracted to broader implementation even with theoretically favorable efficiency (Roos, 2024). (Raghavan, 2023) highlighted the presence of such operational examples as 200 TPD pulp mills suggests that biomass at the scale can be economically and more environmental processing (Raghavan, 2023). However, Granata & Di Nunno (2025) illustrated the absence of effective policy incentives, solid funding, and effective systems to ensure proper governance, scalability collapses and may no longer allow infrastructural growth and reduction in socio-environmental risks (Granata & Di Nunno, 2025). Although, the results clearly confirm the fact that biomass technologies such as the Kraft process have significant potential in contributing to the energy revolution in the world, unless biomass is supported with strategy and innovation, the renewable promise held by biomass can be stifled by the systemic and operational barriers.

The technical analysis of the current study supports the main ideas of the Global Energy Transition and the Biomass Paradox providing the data on the technical and economic feasibility of using sugarcane-based bioproducts through the TEA. Worsham et al. (2024) study highlighted that inclusion of Kraft process have a great potential towards their contribution with renewable energy pathway when analyzed against economic measures such as profit margin, ROI, and payback period (Worsham et al., 2024). These signs validate the fact that sugarcane bagasse is an industrial summation that can be turned into higher bioproducts such as pulp in a process that would be economically viable and exemplified at an industrial scale. This is consistent with the study by Rode et al. (2024) who contended that sugarcane-derived products need not just be technically viable, but are also economically viable sources of alternative to fossil-derived materials (Rode et al., 2024). The Kraft process is also capable of integrating chemical recovery and bioenergy cogeneration which enhances the cost-effectiveness and the energy efficiency of these integrated systems as pointed out by (Ochieng et al., 2022). Saleh & Hassan (2024) discussed that economic attributes play a key role in the global energy transition wherein the renewable energy alternatives need to be able not only to decarbonize but also offer commercially viable alternatives to fossil energy to displace fossil fuels (Saleh & Hassan, 2024). This is where the whole biomass paradox lies: despite the seemingly good option of biomass, its expansion and assimilation is restricted by infrastructure, policy, and environmental constraints.

The paradox becomes more clearly seen upon putting TEA outcomes into the context of the energy transition objectives. Attractiveness Biomass ventures are not as appealing in the first capital and long payback period of the returns despite economic promise when compared to shorter-payback fossil systems or modular renewable energy sources such as solar photovoltaics. Mafunga et al. (2023) study showed that such risk-aversion is enhanced by the volatility in policies, insufficient subsidies, and the absence of reliable governmental support of the biorefinery infrastructure (Mafunga et al., 2023). While, Mignogna et al. (2024) study mentioned that decarbonization of global energy transition is supposed to be affordable and secure, but biomass technologies require complex supply chains, land use tradeoffs and long-term investments that complicate the trade (Mignogna et al., 2024). However, Nair et al. (2024) also mentioned that mass exploitation of biomass unless sustainably managed can produce unexpected environmental effects such as competition with food production and land degradation (Nair et al., 2024). Thus, the economic models are promising, but their implementation is strongly dependent on strategic forms of governance and technological discoveries.

Depending on the results, this research proposes to strengthen government incentives and long-term regulatory frameworks to make biomass-related biorefineries invest and specifically to second-generation (2G) technologies that demonstrated profitability but were high-capital investments and with high payback periods. It recommends the implementation of internationally accepted systems of sustainability certification like the Roundtable on Sustainable Biomaterials (RSB) to provide environmental responsibility and market trust. The first way to alleviate the situation with feedstock seasonality and unreliable supply is to create regional biomass aggregation centers, as well as to improve the rural logistic infrastructure. It also suggests the incorporation of the latest digital technology, such as AI-based monitoring and blockchain based on the promising findings of Kraft-based pretreatment and cogeneration to make the process more efficient, transparent to customers throughout the supply chain, and track of lifecycle emissions. High-yield and low-silica biomass varieties (produced to achieve targeted agricultural innovation) are required to lower the cost of operation and enhance the process of chemical recovery. Finally, the bios use of biomass can be aligned with the national carbon market and the establishment of orderly carbon credits as a way of inducing decarbonization and making bio-based industries a profitable economic sector. These are recommendations to both the opportunities and paradoxes that have been identified in the study that facilitate a sustainable, scalable, and economically feasible position of biomass in the global energy transition.

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5. Conclusion

This study discussed the Global Energy Transition by studying it in terms of Biomass Paradox, focusing on the potential of sugarcane-based bioproducts in Brazil. Biomass plays a central role in the process of abandoning fossil fuels through the provision of renewable, low-carbon fuel, material, and chemical sources. Bagasse and straw, the byproducts of sugarcane, have great potential to assist in decarbonization and the principles of the circular economy and socio-economic growth, including developed biorefinery concepts and combined technologies like the Kraft process. The biomass paradox becomes possible due to the conflict between the promise of renewability of biomass and underlying problems of the biomass system, such as land-use pressures, technological complexity, capital-intensity, and governance gaps. These results indicate that biomass has a potential contribution to the world-wide energy transition as long as sustainability, scalability, and economic feasibility are tackled in one. The sugarcane bioeconomy in Brazil can be seen in this context as an opportunity and a warning of how renewable sources should be handled in order to prevent unexpected environmental and social impacts. Further efforts in the direction of more comprehensive biorefinery planning and low-impact harvesting of biomass should concentrate on the future.

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