Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector

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Abstract

Brazil's sugarcane sector is a significant source of employment, and operates at the intersection of energy, agriculture and land use. Its future development will be affected by the values, decisions and actions of key actors. Accordingly, we report on the results of qualitative semi-structured interviews with 19 participants with expertise in relation to Brazil's sugarcane sector. We used visual aids, and reflections on past events, to structure and contextualise discussions about the future prospects for the sector as a whole, and for four of its potential products – sugar, ethanol, electricity and biogas.

Interviews revealed general expectations of continued growth in the sector, particularly for its energy-related products. However, the possibility of future challenges and tensions is still evident. We suggest three inter-related areas for ongoing reflection. First, there may be value in balancing the desire for minimal intervention, technology neutral styles of policy, with the need for policy that is clear, long-term and impactful. In some cases, more targeted policies for particular actors or emergent technologies, may also be justified. Second, increased clarity on the broader objectives for the sector, including the relative prioritisation of economic, social and environmental objectives, may help industry to make the long term investments consistent with the kind of deep innovation for which there is potential. Third, it is worth reflecting on how the above issues in combination can be leveraged into a global leadership strategy, with consideration of the relative robustness of different leadership strategies within broader emerging global dynamics.

Key words: sugarcane; ethanol; future dynamics; Brazil; sustainable development; biogas

Highlights:

- Perceptions of key actors are pertinent to future prospects for energy sectors
- Experts interviewed on perceptions of past and future of Brazil's sugarcane sector
- Long term clarity of policy and targeted measures may support diverse investors
- Clarity on environmental objectives will support long term innovation
- Opportunities for global leadership, in the context of broader global dynamics

1. Introduction

The Sustainable Development Goals, adopted in 2015 by all United Nations member states, set out a global agenda for addressing economic, social and environmental development [1]. This includes taking urgent action to combat climate change in a manner consistent with equity and justice [2]. There are many positive synergies between addressing climate change and the wider SDG agenda; however, there are also risks of trade-offs, as low carbon technologies can have impacts on natural resources, social structures and human rights [3].

Bioenergy has been explored as a means of promoting environmental, economic and social development simultaneously, as a low carbon fuel that creates jobs and brings income to communities [4-7]. However, in other contexts trade-offs have been identified, and the sustainability of bioenergy has been questioned [8-10].

Brazil has a well-established and extensive modern bioenergy industry, primarily associated with its production of ethanol from sugarcane, and is a signatory to the SDGs and the Paris Agreement. Brazil's Nationally Determined Contribution (NDC), submitted under the terms of the Paris Agreement, highlights the role of the 'sustainable use of bioenergy' in keeping global temperature rise below 2°C [11]. However, the original development of Brazil's sugarcane ethanol industry was rooted in the more social and economic concerns of creating jobs and reducing dependence on imported oil [12].

As in the past, the future of the sugarcane sector will be affected by the balance of these various objectives, and the values attributed to them by key stakeholders and decision makers in the sector. In this paper we therefore consider the future prospects for the Brazilian sugarcane sector and four of its potential co-products – sugar, ethanol, electricity and biogas – by reporting on a series of qualitative semi-structured interviews with relevant industry actors. We aim to explore the factors affecting the policies and strategies of key actors who will drive the future evolution and diversification of the sugarcane sector in Brazil. By reflecting on past dynamics we aim to deepen our understanding of the current perceptions and future expectations of key actors about the sector, thereby enhancing our understanding of its future possibilities.

2. Material and methods

Our research aims to consider the factors affecting the policies and strategies of key actors on the future development of Brazil's sugarcane sector. The theoretical framework for this research arises from the principle that the policies and strategies of actors are influenced by their internal paradigms or mental models. Contributions in a wide range of fields have observed the significance of such internal models in influencing actor behaviour. In the context of corporate scenarios, the role of 'mental models' which affect the 'world views' of managers, has been observed [13, 14]. In political science, terms such as 'ideology' [15-20] and 'doctrine' [21] have been used to describe the narratives [17] and 'mental models we all carry of how the world works' [15], which 'guide our present actions according to our expectations of what will happen in the future' [21]. Hall's concept of policy paradigms is closely related, being 'a framework of ideas and standards that specifies not only the goals of the policy and the kind of instruments that can be used to attain them, but also the very nature of the problems they are meant to be addressing' [22]. A number of other authors have adopted Hall's concept of the policy paradigm as an 'interpretative framework' [22] that affects views

on preferred policy choices and desired outcomes [23-26]. Because of the importance of such interpretive frameworks on policy development, Hall calls for 'a more complete account of the role that ideas play in the policy process'[22].

On the basis of the insights from these independent but related lines of thought, we propose that a valuable contribution to understanding the future prospects for the sugarcane sector can be achieved through understanding the ideas and value frameworks of key actors relevant to the system, whose actions and strategies will be influential on its future evolution.

Accordingly, we adopt a qualitative approach to data collection. Qualitative research is person-centred, contextual and holistic, and interested in subjective meanings [27]. More specifically, we adopt the semi-structured interview method, which 'reflects an ontological position that is concerned with people's knowledge, understandings, interpretations, experiences, and interactions' [28]. As a result of a 'flexible and fluid structure' a semi-structured interview 'can be shaped by the interviewee's own understandings as well as the researcher's interests, and unexpected themes can emerge' [28]. Semi-structured interviews have been used to explore perceptions of key actors in a range of contexts relating to energy, climate change and the SDGs [29-33].

Unlike probabilistic or randomised samples, 'qualitative samples are purposive, that is, selected by virtue of their capacity to provide richly-textured information, relevant to the phenomenon under investigation' [34]. Purposive sampling uses researchers' judgement to identify 'information-rich' cases [35] – participants with expert or in-depth knowledge about the topic under study, and the willingness to communicate and reflect on it [36, 37]. Whilst 'there are no rules for sample size in qualitative inquiry' [35], sample sizes are usually small, relative to quantitative studies, in order to allow in-depth analysis of the material gathered [31, 34, 36]. Such methods are clearly not able to achieve the breadth and generalisability across large populations, available to many quantitative methods; rather their strength lies in in-depth engagement with participants specifically chosen for their knowledge and experience [37].

Our purposive sampling strategy drew on our own knowledge to identify important organisations with involvement in or connection to the sugarcane sector from a range of standpoints. Individuals within these organisations with knowledge of and expertise in sugarcane were then identified and contacted. We aimed for a diversity of opinions amongst those connected to the sector, but as we were interested in 'insider perspectives' [27] we did not aim to sample amongst experts in other fields outside the sector. In accordance with a general guiding principle in qualitative research, sampling was undertaken until data saturation was achieved, that is, the point where the team judged that no new themes or substantive information were arising. [36, 37].

Interest in the research was high as indicated by a response rate of 73%. A total of 17 semi-structured interviews with 19 participants were conducted during August 2019. Interviews took place in São Paulo, Rio de Janeiro and Brasília, according to the locations of the participants, whose occupations spanned industry (n = 5), academia (n = 6), government policy maker (n = 5), government policy advisor (n= 1) NGO (n = 1) and finance (n = 1).

Table 1 lists the categories of interviewee, along with the abbreviation by which we refer to them in the following sections. Individuals within each category are distinguished by a number appended to the category abbreviation (e.g. IND1, IND2, etc.).

Table 1: Interviewees by category

Category	Detail	Number of interviewees	Abbreviation
Industry	Energy companies and industry associations	5	IND
Academia	Energy, agriculture and sugarcane sector expertise	6	AC
Government policy maker	Agriculture and energy departments and divisions	5	GOV
Government policy advisor	Advisor	1	GVA
NGO	Third sector organisation	1	NGO
Finance	Investment institution	1	FIN

The design of the interview built on recommendations to begin semi-structured interviews 'with open questions… which invite the participant to talk freely' [36], to use events that illustrate phenomena of interest as building blocks for the interview [38], and on the usefulness of card-based activities and visual aids in structuring the interview, enhancing engagement and reflection, and reducing interviewer bias [39]. Furthermore, we hypothesised that internal mental models, as well as framing our views on current choices and future outcomes [13-15, 21, 22] also affect our perceptions of the past. If so, a useful way of contextualising interviewees' views on the future could be through exploring their interpretations of past events.

Accordingly, we begun each interview by introducing reflection on the past in an open ended way. We presented a graphic showing the growth in Brazil's sugarcane production since the 1960s, and simply asked the interviewee to explain and interpret it to us. Having discussed the past, the interview then turned to the future. Drawing again on Rowley's insights on card-based activities and visual aids [39], we asked interviewees to play a 'game' and make projections of expected growth or lack of growth in each of the four products, across three time periods, using a grid shown here as

Table 2.

Table 2: Interview template

	Whole sector	Sugar	Ethanol	Electricity	Biogas
Short-term (2025)					
Mid-term (2030)					
Long-term (beyond 2030)					

↑ = increased activity ↓ = decreased activity → = no change 0 = no activity at all

We asked the interviewees to explain their reasons for each of their projections, compared differences in outlooks for the different products and discussed interlinkages between them. The earlier contextualisation in past events encouraged participants to move fluidly and intuitively between future possibility and past experience. Interviewers held a checklist of questions to prompt interviewees during the ensuing discussion if needed, including about the impacts of policies and regulations at the federal and national levels, national and global demand, trends in other parts of the energy system, the role of technological developments, and risks and challenges for the sector. However, interviewees were primarily given the opportunity to explain their perspectives on the future in the way most intuitive to them.

The interviews were recorded, transcribed and, when carried out in Portuguese, translated into English. In this paper we present our results in a manner that reflects the structure of the interviews and our analysis of them: past dynamics; current and future prospects for each of the products; and cross cutting themes. In addition to presenting and analysing the interview data, we have contextualised it throughout with data from official government and industry sources as well as academic literature. In some cases, this is simply to provide additional factual corroboration on historic events referred to by interviewees. In other cases, we have contextualised interviewees' opinions with other sources, sometimes offering a different perspective. Whilst our primary objective is to present 'insider perspectives' [27] of the sugarcane sector, we do so in the understanding that this may not necessarily be representative of broader views from other sectors. Our intention in providing additional contextualisation is not to undermine or discredit our interviewees' perspectives, but rather to highlight possible differences in outlook between some interviewees and other widely held views, including those outside of the Brazilian sugarcane sector, which is the primary focus of our research. All data is presented as anonymous to respect confidentiality and adhere to ethical standards.

3. Results

In this section we present the results of the interviews integrated with evidence from the literature, which provides context to the opinions given. We first reflect on the past dynamics of the sector, then consider its current status and future prospects, discussing interviewees' specific projections and expectations about each of the four principal products. Following this we draw out some common cross-cutting themes that emerged in different interviews in relation to various aspects of the sector.

3.1. Past dynamics

The past dynamics of Brazil's sugarcane sector have been affected by demands for multiple products. In 1975, in the context of rising global oil prices, the Brazilian government inaugurated the "PROALCOOL" programme to increase the production of ethanol, which could be blended with gasoline, thereby reducing the country's dependency on imported oil [12, 40]. Vehicles capable of running on pure ethanol were later developed, accounting for 80% of all new vehicle registrations by 1983 [41]. All interviewees cited this programme as the key factor behind the rapid increase in Brazil's sugar cane production from the mid-1970s, as shown in Figure 1.

However, by the mid-1980s, falling global oil prices, high sugar prices, and the removal of government export controls on sugar, meant that ethanol became less competitive and sugar the more attractive product for the sugarcane industry, leading to ethanol shortages [12, 42, 43]. Although overall production of sugarcane continued to rise, the production of ethanol stagnated (Figure 1) and sales of ethanol vehicles fell (Figure 2).

As interviewees overwhelmingly agreed, the prospects for ethanol changed again dramatically in 2003 with the introduction by automotive manufacturers of flex-fuel vehicles (FFVs). FFVs are capable of running on any mixture of ethanol and gasoline. This flexibility resolved the problem of trust in the reliability of ethanol which had severely curtailed sales of pure ethanol vehicles [44]. The government supported the new vehicles through tax exemptions (FIN), and the tax system also continued to support ethanol fuel, albeit with some variation between states (GOV4, IND1, IND3, IND5 and [45]). Sales of FFVs increased dramatically (Figure 2), as did the production of ethanol (Figure 1), creating growth in the sector, and attracting international investment [12, 43].

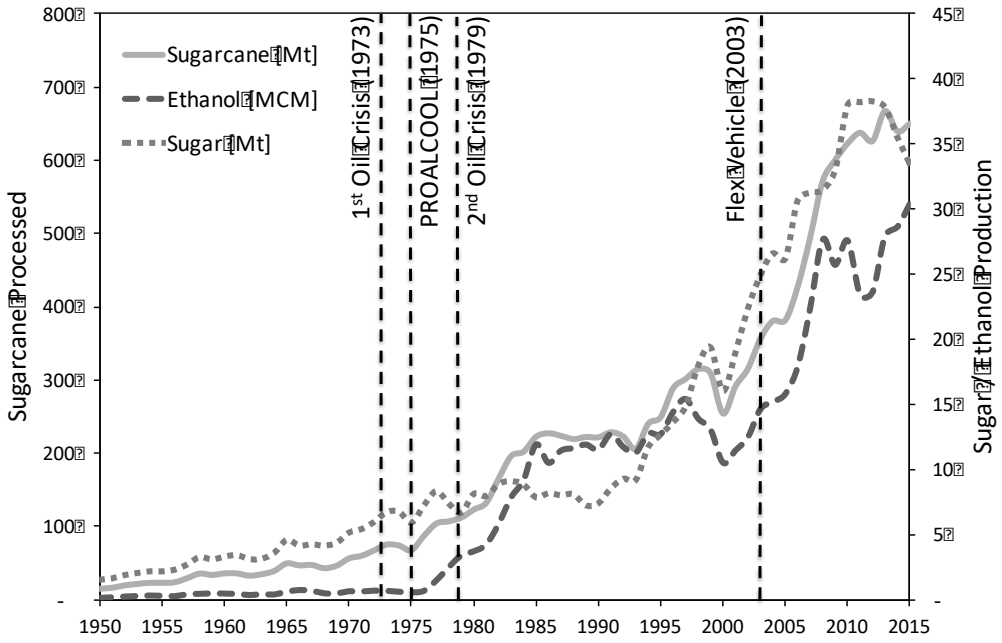


Figure 1: Evolution of Sugar and Ethanol Production in Brazil (1950-2015). Source: Based on data from CONAB [46]

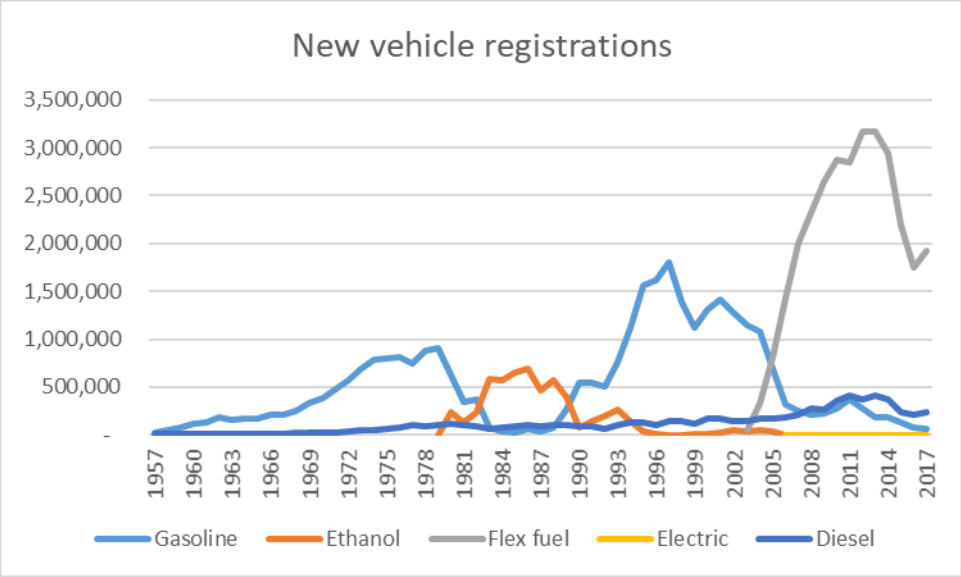


Figure 2: New vehicle registrations in Brazil by year and fuel type, 1957-2017. Source ANFAVEA [41]

Electricity is another potential energy co-product of sugarcane. From every tonne of raw sugarcane crushed there remains around 0.3 tonnes of fibrous residue, known as bagasse [42]. This bagasse can be combusted to generate electricity, which generally enables mills to be self-sufficient in power [45]. In 2004, power sector reforms [47, 48] increased incentives for alternative power sources such as biomass, creating opportunities for sugarcane mills to sell excess power to the grid. There was a strong growth in biomass capacity added to the electricity system during the first decade of the 2000s (Figure 3 and [49]), sugarcane mills being the dominant source of biomass power [49]. In 2018, 54% of sugarcane mills were involved in exporting power to the grid [45]; this represented 7% of total installed capacity [49] and 3.9% of total electricity generated [45].

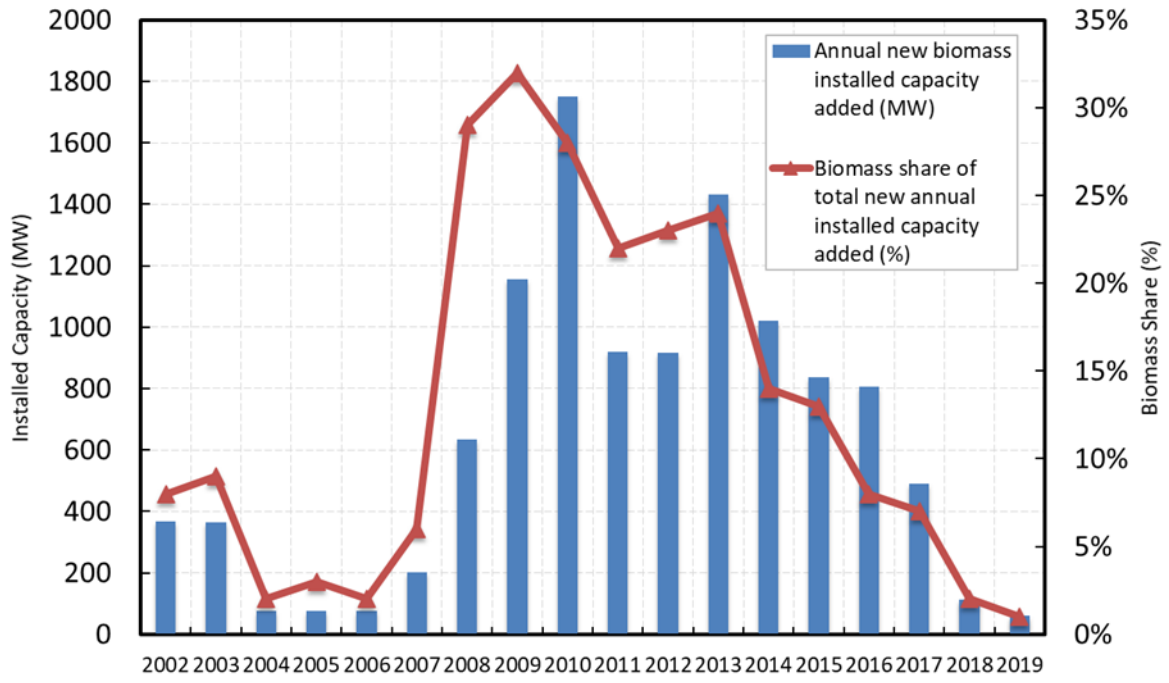


Figure 3: New biomass installed capacity in the Brazilian electricity system. Source: adapted from UNICA [49]

In the context of particularly strong industry growth from the early 2000s (Figure 1 and Figure 3), the ensuing decade has been referred to as a period of 'ethanol diplomacy' [50], as recalled in interview by one government policy maker:

> We can say that we had here in Brazil a presidential diplomacy of ethanol. Lots of MOUs [Memoranda of Understanding] were signed, and we had a strong agenda, the President was really engaged in this process (GOV4)

The ethanol diplomacy period was characterised by energetic and high-level engagement with the EU and the US, with other South American countries and with African countries, with objectives including knowledge transfer, research collaboration, and the potential for Brazilian companies to benefit from exporting technologies at all stages of the supply chain [50, 51]. Institutional changes, [51] and infrastructure investments [12] reflected growing interest in international export markets. The sense of ambition during this period was recalled by one interviewee: "we thought that we could access European Union market and also the US market" (GOV4).

However, towards the end of this decade this rapid growth and general sense of optimism was abruptly attenuated. One factor was the general effect of the financial crisis of 2009 reducing the availability of credit [50, 52], resulting in a "lack of money to invest" (GVA). In addition, the discovery in 2006 of substantial oil and gas reserves off the coast of Brazil [53], may have contributed to a change in policy focus at the Federal level [50]. It was suggested by one policy maker that at this time, biofuel came to be thought of as "an old thing, now we have oil" (GOV5). Poor climatic conditions reduced yields [50], and high global sugar prices in early 2011 [45] encouraged the industry to divert towards sugar production, reducing the supply of ethanol and causing prices to rise substantially, such that "the consumer paid a huge price" (GOV 4). The government took measures to freeze gasoline and diesel prices as a means of controlling rising inflation [52], further eroding the competitiveness of ethanol. These factors caused stagnation in ethanol production, to the extent that "we almost killed the industry" (GOV5). Lack of clarity on the strategic outlook for ethanol was cited in relation to this

period (GOV4, IND3). As a result of these factors the sector entered a period of recession, causing numerous plant closures (IND3 and [54]).

As these events demonstrate, the Brazilian sugarcane sector can be strongly affected by domestic energy policies, as well as by global commodity prices, as most mills are able to vary their relative production of sugar and ethanol in response to the market. Figure *4* depicts the sensitivity of production shares of sugar, anhydrous ethanol (which is blended with gasoline), and hydrous ethanol (which is used directly in FFVs) to the relationship between ethanol and gasoline prices. The global price of sugar is also a major factor (NGO, IND3, AC4, GOV1), and it has been falling since 2011 [45], causing problems for the industry [50]. Some interviewees pointed to recent a shift in the industry away from sugar production and towards ethanol (NGO, IND3), due to relative prices, as shown in Figure *4*. The current low sugar prices were judged to have been caused by a range of factors, including increased production efficiency in other exporting countries, causing an increased surplus (IND3). As a result, "the sector is in a difficult situation now" (AC4).

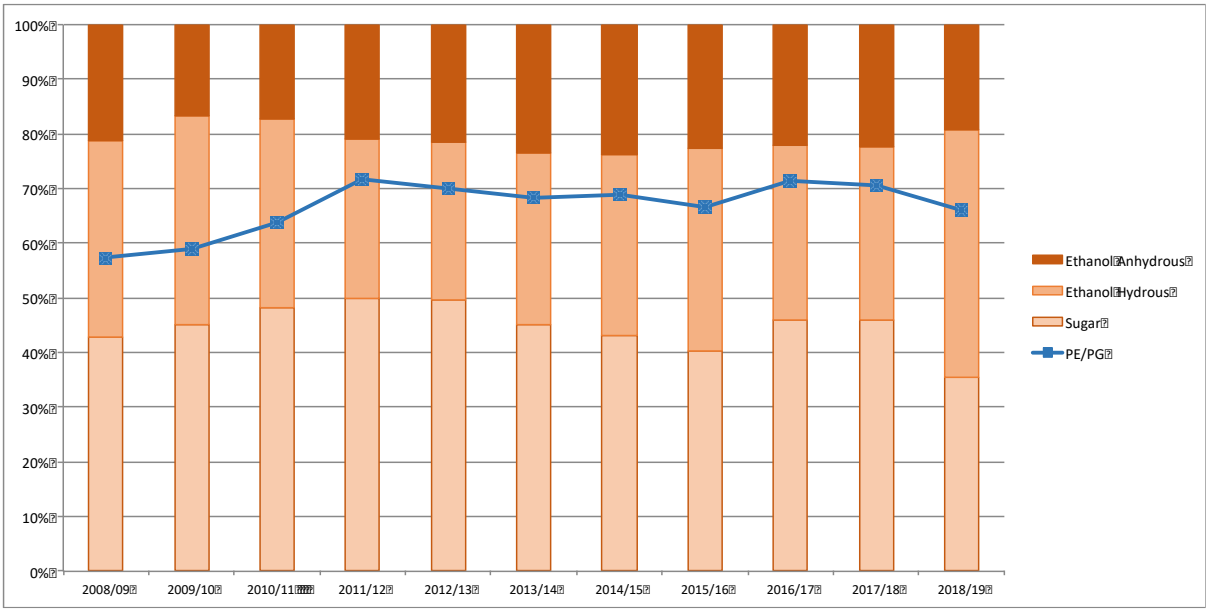


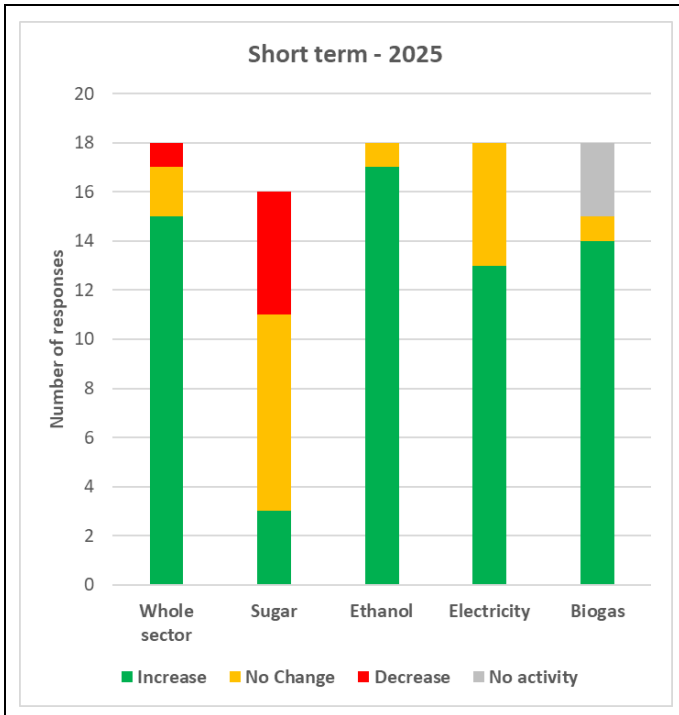
Figure 4: Relative production of sugar, anhydrous and hydrous ethanol in Brazil, based on percentage shares of total recoverable sugar diverted to each product; and ratio of price per litre of hydrous ethanol to gasoline, 2008/09-2018/19. Source: Based on CONAB [46] and EPE [45].

3.2. Current status and future prospects

Despite recent challenges, Brazil remains the world's largest processor of sugarcane [55]. It is the second largest producer of ethanol, behind the US [56], and the second largest producer of sugar, behind India [57]. Activity is concentrated in the central-south region of the country, especially in the state of São Paulo [58-60], although expansion has also been occurring in other states including Paraná, Minas Gerais, Mato Grosso do Sul and Goiás [60].

We asked our interviewees to describe their expectations for the future prospects of the sector. Their responses are summarised in Figure 5. In some contrast, perhaps, to recent conditions, clear majorities of respondents expected overall growth in the sector. More specifically, respondents were most likely to cite the three energy-related products as the key drivers of future growth. Expectations for sugar were notably more mixed, the majority of respondents expecting a levelling off of demand or a decrease, in all three time periods. This suggests the continued importance of diversification, perhaps in particular into energy-related products.

We now highlight some interviewee perspectives on each of the four products, before continuing to discuss cross-cutting themes.



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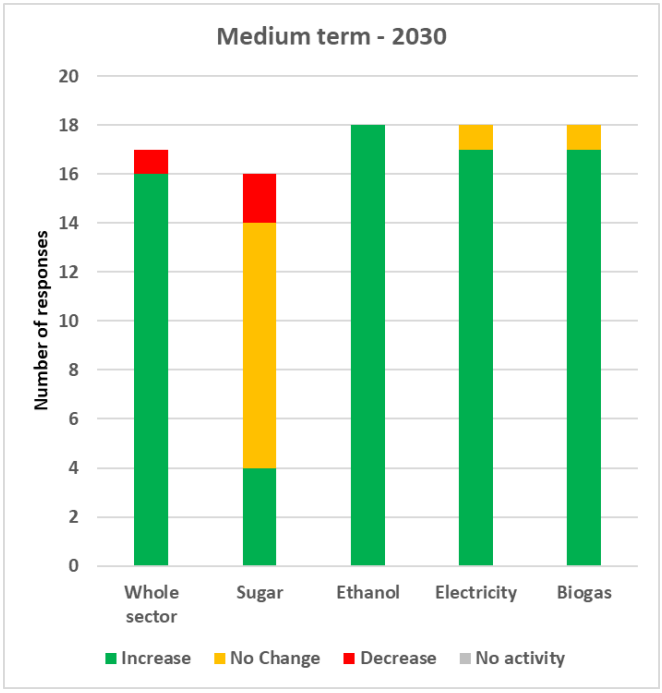

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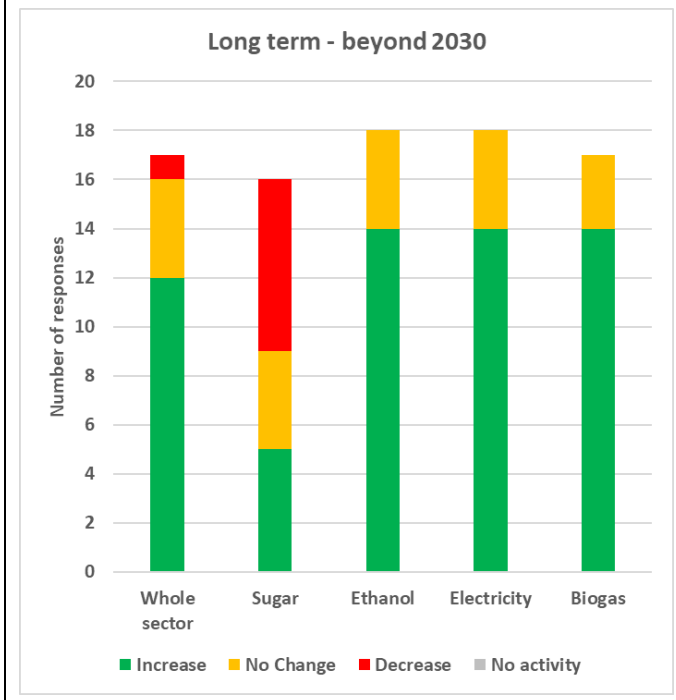

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Figure 5: Interviewees' projections of developments in the whole sugar cane sector and principal products, in the short term (Panel a), medium term (Panel b) and long term (Panel c). N=18. This differs from the total number of interviewees (19) as two were interviewed together and filled in the tables jointly. Where categories do not sum to 18, this indicates that one or more interviewee declined to make a projection in this category.

3.2.1. Sugar

As shown in Figure 5, the future outlook for sugar was subject to the most mixed response.

Some participants considered continued growth in sugar production possible due to continuing increases in global demand (GVA, GOV2, IND1, IND4), not least 'as you have new consumers coming into the market'(GVA).

However, others projected either a stabilisation in sugar demand or a decline (AC1, AC2, AC3, AC5, FIN, NGO) – the latter particularly in the long-term time horizon, due to increasing awareness of the health impacts of sugar consumption. An industry representative argued that for these reasons diversification away from sugar was important for the sector:

> The world is trying to move towards ethanol diversification and production… if you stay alone in sugar the sustainability of the country's sector will not grow and is creating problems for the sector (IND3).

3.2.2. Ethanol

Most interviewees felt that the most significant driver of future ethanol production would be a new national biofuel policy known as 'RenovaBio' which is designed to boost production and use of biofuels, and expected to begin in 2020 [61].

RenovaBio sets annual targets for the carbon intensity (CI) of transport fuel, over a rolling ten-year time frame, with a reduction of the overall CI of fuels of 10% targeted over the next ten years (GOV4 and [62]). Each year the overall annual target is to be translated into mandatory individual targets for each liquid fuel distribution company in Brazil, in proportion to their market share [63]. The policy also sets up a tradable decarbonisation credit, the CBIO, through which distributors can meet their targets. CBIOs are generated by producers of biofuel, in proportion to the quantity of biofuel produced, but also in proportion to their Energy-Environmental Efficiency Grade (NEEA), established by a third-party certified life-cycle analysis of their production process [64]. The policy is intended to offer flexibility to fuel distributors in meeting their targets in the most cost-effective way, whilst also incentivising energy- and environmentally-efficient production processes.

Levels of approval, and indeed enthusiasm, for the policy amongst interviewees, were striking:

> Thinking about a horizon of about 10 years... what will most influence will be RenovaBio… that I think it will be the next key factor there that will make the sector grow a lot in Brazil (NGO).

There are still some uncertainties. It has been suggested there may be a risk of a perverse incentive for larger distributors to buy themselves out of the scheme by paying a fine which is capped at R$ 50m, and that if the scheme's environmental requirements are relaxed, this could undermine its credibility [64]. Further, the currently unknown market price of the CBIO tradable certificate was considered a potential barrier by some interviewees (AC5, GOV1), as "if you don't know the price of the credit, how can the producer invest?" (AC5).

While fermentation of sugars from sugarcane has historically been the dominant means of producing ethanol in Brazil, other production routes are possible. For many years the potential of 'second generation' ethanol produced from lignocellulosic material has been discussed [40, 52, 65, 66]. Second generation ethanol elicited mixed views from interviewees. One government policymaker described the technology as "ready. It's already working" (GOV5). Others were more cautious (AC3 AC4, FIN, GOV3, GVA, IND3, IND4) or sceptical (GOV2, IND1) based on historical experience:

> We've been talking about cellulosic ethanol... for at least 10 years... We're in 2019 and it hasn't changed much (IND1).

Another potential feedstock for ethanol is corn. Extensively used in the US, its use for ethanol in Brazil has been growing rapidly, increasing from 11,000 m^3 in 2013 to 720,000 m^3 in 2018 [45], although 2018 production was still only equivalent to 2% of sugarcane ethanol [59]. Corn ethanol production is concentrated in the states of Mato Grosso and Goiás [45]. Flexible biorefineries, designed for both sugarcane and corn, are able to process corn during the hiatus period between sugarcane harvests, when the plant would otherwise be idle, increasing the annual utilisation factor of the plant [45, 54]. This potential synergy led some interviewees to discuss the production of ethanol from corn enthusiastically (GOV5, GOV1, NGO). Interviewees also drew attention to corn's potential synergies with other crops like soy, and with livestock intensification (GOV2, GOV5).

In discussions of future transport in the context of global decarbonisation, the role of electric vehicles (EVs) is often considered [67, 68]. Some interviewees also considered the possibility that in the long term "ethanol will face big challenge from electric vehicles" (GVA). It was suggested that global automotive manufacturers might be unlikely to "maintain a factory to produce combustion engines just for the Brazilian market", if the rest of the world had transitioned to EVs (IND2). However, greater numbers of interviewees from all backgrounds did not believe that EVs would displace ethanol vehicles in Brazil, in the near or medium term, if at all. This was for a variety of reasons including the costs, infrastructure requirements and technological challenges of EVs (AC2, AC4, FIN, GOV1, GOV2, IND3, IND4, NGO). Some envisaged partial electrification through hybrid electric FFVs (AC2, AC4, FIN, GOV1, IND3, IND5, NGO) and some considered the long term development of fuel-cell vehicles capable of running on ethanol (AC3, GOV1, GOV4, IND3,) – forms of electric transport that would still involve ethanol.

3.2.3. Electricity

Although quantities of electricity exported by sugarcane mills have gradually been increasing since 2010 [49], still only around half of Brazil's mills export excess power to the grid [45]. Dutra and Szklo observe that 'investments in electric power generation are taken with caution by the investors' [48]. One interviewee commented that at the time many mills were making investment decisions, "to sell [electricity] was cheap, to buy was expensive. So the mills didn't bother to invest to sell. They only bothered to invest to be self-sufficient" (IND4).

Interviewees identified various barriers for currently non-exporting mills to upgrade their boilers in order to be able to export, including lack of access to capital, and more broadly a lack of interest or "cultural willingness" (AC1), especially on the part of smaller family firms with limited experience of the power sector (GVA).

Lack of scale was cited as another barrier, as in smaller mills the amount of bagasse produced can be insufficient to generate surplus electricity in the quantities that would justify export; lack of proximity and access to the electricity grid were also seen as disadvantages for many mills (FIN). Furthermore, bioelectricity projects are now struggling to compete against the falling costs of wind and solar, as shown in current and recent power auctions (IND5, GVA, AC1).

However, some envisaged the possibility of RenovaBio creating incentives for bioelectricity, as well as biofuel. The fact that the number of CBIOs a mill can generate for its biofuel is related to its Energy-Environmental Efficiency Grade (NEEA) (as discussed in Section 3.2.2) could indirectly incentivise bioelectricity, as "power plants that export electricity have a better carbon footprint and can earn

more CBIO" (IND5). In addition, if RenovaBio increases ethanol production, this could drive up electricity production simply due to the greater quantities of bagasse produced (GVA).

Some interviewees drew attention to the potential value that bioelectricity can bring to the electricity system, balancing the diurnal variability of wind and solar, and the seasonality of hydro (GOV3, IND3 and [45]), as "biomass is seasonal but not intermittent" (IND5). However, even if these positive externalities were represented in the market price for bioelectricity, the lower prices of solar and wind would still be challenging to compete against (GVA).

3.2.4. Biogas

The final product considered was biogas, which, like electricity, can potentially be produced from residues of sugarcane processes, including 'vinasse', an acidic slurry with high organic content, of which 10-15 litres remain for every litre of ethanol produced [69]. In Brazil, vinasse is mainly disposed of by being spread on the fields to irrigate and fertilise – 'fertirrigation' [70, 71]. However, dosage above recommended values can have adverse effects on water, soils and biota [69, 70, 72-74]. Alternative uses for vinasse have therefore been proposed, one of which is to use it to produce, via anaerobic biodigestion, a methane rich biogas [69, 70, 75, 76]. The vinasse that remains after this process maintains fertilising properties, but has reduced polluting potential due to its lower organic load [69]. Interviewees referred to environmental remediation as an important benefit of the process (AC1, AC2, AC3, AC6, FIN, GOV3). The production of the biogas potentially offers an additional energy product for the industry to valorise.

Biogas is "not a new thing in Brazil" (FIN) – interviewees referred to other potential sources of biogas, including landfill gas, sewage gas, and other agricultural residues (AC2, AC6, GOV1, GOV5, GVA, IND2). However, the technology to produce biogas from vinasse is still incipient, and only a small number of mills are piloting the technology [77]. Accordingly, interviewees tended to view the co-production of biogas in sugarcane mills as a longer term option, although one suggested it was "more ready" than second generation ethanol (FIN).

Various potential end use demands for the biogas that could be produced from vinasse have been considered, such as distribution through pipelines to natural gas markets, use in heavy goods vehicles in place of diesel [77, 78], and stationary combustion for power generation or co-generation of heat and power [71, 75, 79].

Interviewees considered pipeline distribution, as for example, "the São Paulo state government are looking to inject biogas in distribution pipelines. This could improve production of biogas" (GVA). The lack of extensive existing infrastructure caused some to argue that biogas could have advantages as a small-scale distributed option, used for internal industrial processes (AC5, AC6, FIN, GOV1, GVA, IND1 NGO).

The possibility of using biogas in trucks as a replacement for diesel has in part been opened up by the development of natural gas-powered vehicles (GOV1), and could be applied to the agricultural vehicles used in the sugarcane production process itself (AC2). This use of biogas could be rewarded by RenovaBio, as the displacement of fossil fuels would reduce the carbon footprint of ethanol production, generating more CBIOs (GOV5, GOV4, IND4). However, a downside of distributed biogas production is the limited potential to supply large-scale and concentrated gas demands, including large vehicle fleets (AC6).

Scale could be a key challenge to vinasse biodigestion. On the one hand, some economies of scale would be expected to be required to make the product cost competitive [77]. On the other hand, one

interviewee emphasised that there were significant technical challenges to large-scale digesters, as a result of which:

> I wouldn't bet on a large scale in Brazil for this industrial application. I think small scale for us, it is enough. Decentralizing the system for us would be more interesting (AC6).

3.3. Cross-cutting themes

As part of the discussions on the four main sugarcane products, a number of cross-cutting themes also emerged, which are discussed in this section.

3.3.1. Policy style: interventionist or liberal?

Most interviewees emphasised the historical importance of policies in supporting the energy-related sugarcane products. “Ethanol is still struggling to sustain itself independently” (IND1), and policies were expected to remain critical to the future evolution of the sector, and its energy products in particular (GVA, AC3). Policies also interact with price dynamics in various globally traded products, including oil, sugar and corn.

Some interviewees expressed pride in Brazil’s history of creating the sector through programmes such as PROALCOOL (GOV5, IND2). However, interviews also revealed caution around the risks of over-interventionist policy styles. It was acknowledged that PROALCOOL “was a success because the government controlled everything” (IND2), but also that by the late 1980s “we weren’t able to sustain that kind of project” (GOV4), leading to the crisis of 1989. In more recent years, government interventions to hold down the price of gasoline came in for criticism, as a result of which “both Petrobras suffered a lot and the sugarcane industry closed more than 100 plants” (IND3).

The interventionist style was at minimum associated with inefficiency and lack of competitiveness; some going further to allege or imply an association with corruption (AC4, IND1, IND4). In this context, RenovaBio was widely welcomed as an innovative policy that did not involve subsidy or over-intervention from the state. The Ministry of Mines and Energy (MME) states that ‘unlike traditional measures, RenovaBio does not propose the creation of a carbon tax, subsidies, presumed credit or volumetric mandates to add biofuels to fuels’ [80]. Interviewees picked up on these themes, observing that whereas “we are used to tax, subsidies, this programme is completely different, it’s very interesting” (AC5), and that “our driver is not subsidies” (GVA). Technology neutrality was also valued, as “the strongest will survive… the most competitive, reliable” (GOV4).

However, if RenovaBio’s targets do succeed in increasing biofuel sales beyond what would otherwise have been competitive in the absence of intervention, this will increase costs for distributors, which will in turn be passed through to consumers at the pump. As such, “Renovabio is a programme that indirectly generates subsidy” (IND1); “in practice, it's a cross-subsidy” (GVA).

This illustrates the delicate balance between the desire for avoidance of intervention, and the necessity of some impacts if any effect is to be generated at all. Non-intervention can conversely risk lack of clarity, particularly for more emerging technologies. One interviewee argued that “public policy has to be clear, so when you get into a project and make a medium and long term investment you know you'll get a return”, and complained that “we never had a medium-long term policy. So you kind of have to guess year after year what you're going to do” (IND3).

3.3.2. Long-term policy objectives: economic, environmental, social?

The clarity and longevity of policies are affected by the long-term persistence of the objectives that motivate them. At the start of PROALCOOL, as one interviewee observed, "the main objective of that policy was economic. Brazil needed to substitute imports" (GOV4). However, in subsequent years "the climate change agenda started, the Kyoto protocol… so we began to discuss biofuels as a path to a greener economy" (GOV4).

MME identifies the objectives of RenovaBio as being concerned both with energy security and reduction of greenhouse gas emissions [80]. Although Brazil remains a signatory to the Paris Agreement, recent political developments have thrown some doubts over whether Brazil wishes to continue to position itself as a global environmental leader [81-84]. It was therefore interesting to find that the environmental objectives of biofuels remained highly prominent for several interviewees. The value of biofuels in contributing to GHG mitigation was widely espoused, in some cases quite passionately:

> I think we can save the world from climate change using plants (GOV5).

Several interviewees (AC1, AC4, GOV2) linked the objectives of RenovaBio to Brazil's NDC, which includes an 'indicative contribution' to 'reduce greenhouse gas emissions by 43% below 2005 levels in 2030' [11]. Renovabio extends over a 10-year time horizon, but the lack of further targets beyond this caused one interviewee to predict lack of growth in the sector beyond 2030 (NGO).

Participants frequently emphasised Brazil's historical role as an environmental leader:

> Brazil has always had a clean energy matrix… it's kind of already in our blood (IND2).

Some also expressed a desire for the country to maintain this leadership role – "to be ahead and show to other countries" (AC5) – and to further increase its ambition beyond that stated in the NDC (AC1). However, others felt that as Brazil's energy system was "the most renewable energy matrix in the world," decarbonisation was "still not an issue for Brazil… it's a nice to have… but it's not mandatory" (AC4), and that:

> Everything is renewable here! We've been using biofuels since 1975... Decarbonize what? In Europe... they're still full of diesel cars in the cities (GOV3).

Some also prioritised the objectives of reducing fossil fuel imports and job creation (AC4, AC5, NGO, GOV1), and emphasised that the sector should "have positive economic and social impacts in possible new regions" (AC3).

However, one interviewee questioned the socioeconomic benefits of sugarcane compared to other sectors (AC1). Another suggested that if security of supply and job creation are the principal objectives, these could arguably be just as well satisfied by the oil and gas sector, particularly given the apparently huge potential of the pre-salt reserves (IND1).

3.3.3. Fossil fuels and biofuels: trade-offs or synergies?

The balance between economic and environmental objectives has direct salience for the balance between fossil fuel and biofuel energy sources, particularly as, since the discovery of the extensive 'pre-salt' oil and gas reserves [53], fossil fuels may also able to meet economic and security of supply objectives (IND1).

Several interviewees emphasised the economic potential of pre-salt oil reserves, one expressing the view that "the country cannot abandon such a wealth" (GOV1). The resulting potential conflict with

biofuels was noted by some (GOV1, IND2). One interviewee expected pre-salt oil and gas to be cost-competitive, and asked “who do these products compete with? With ethanol, with biodiesel... So, the fight isn't easy” (IND1). One participant noted that the scale of investments currently being considered would entail some level of fossil fuel lock-in for several decades (AC4).

On the other hand, the possibility that in a competition between biofuels and fossil fuels, biofuels could have advantages, was also explored. Some stressed the large capital expenditure in pipelines that would be required to bring associated gas from the pre-salt fields to the domestic market (AC2, FIN), and accordingly their uncertainty about whether gas from the pre-salt would be competitive (AC4). If currently limited pipeline infrastructure is a barrier for natural gas, others thought this could present an opportunity for biogas as a decentralised off-grid technology (AC5, AC6, FIN, GOV1, GVA, IND1, NGO). In this context, the kinds of decentralised biogas options discussed in Section 3.2.4 could emerge as more competitive. Another stressed the preference that in an “energy transition… ethanol needs to substitute oil, it can’t just be in addition” (AC1).

However, synergies between biofuels and fossil fuels were also considered. For example, if new gas demands are developed and pipeline infrastructure is constructed, this could also create opportunities for biogas, as consumers may “prefer to consume biogas if there is infrastructure” (GVA).

For some interviewees, the perception of Brazil as an emerging economy with huge growing demands (GOV3, AC3) obviated the need to consider competition between energy sources:

> I think ethanol is very important, soy diesel is very important, fossil diesel and fossil gasoline is very important, and there's room for each of them (IND1).

3.3.4. Land use: abundance or constraints?

Land use impacts have received considerable attention in the context of biofuels, including the potential for environmental impacts arising from land use change (LUC) [85], and competition with food production [86]. Arguments against the relevance of such concerns in the Brazilian context have tended to emphasise the relatively small proportion of agricultural land planted under sugar cane, and the fact that the bulk of sugarcane activity takes place in the centre-south region, far from sensitive biomes such as the Amazon and the Pantanal [65, 87, 88]. However, Smeets et al. identified possible concerns with food-fuel competition, as well as risks of impacts on another biome, the Cerrado, which is located much closer to the central-south production regions [89], and more recent data indicates some north and eastward expansion of sugarcane areas, including into Goiás and Mato Gross do Sul [60]. Further, although evidence suggests that sugarcane expansion has mainly tended to displace directly other agricultural land [90, 91], there is also some evidence of indirect land use change, where the displaced agricultural activity itself is relocated and displaces natural vegetation – although precisely quantifying such effects is uncertain [92]. However, some analyses have suggested that future sugarcane expansion could induce indirect land use change in the Pantanal [93], Cerrado and Amazon [91].

Some interviewees discussed LUC as a potential risk associated with increased sugarcane production, including the LUC emissions from converting new land into sugarcane production (NGO), and drew attention to the saturation of available land area in current dominant producing regions, and the increasing trend of expansion into ‘frontier’ areas, such as Mato Grosso and Mato Grosso do Sul (IND1).

Some participants recalled the substantial impact of LUC and deforestation in Brazil's overall GHG emissions, as reflected in the NDC (AC1, IND2). In this context, one emphasised the preference that agricultural land use should not only stabilise, but decrease in real terms (AC1)

However, it was also noticeable that a large proportion of the interviewees expressed strong views that there were no environmental problems with the Brazilian sugarcane ethanol industry. Some emphasised that RenovaBio includes sustainability criteria that would work against deforestation. The Sugarcane Agroecological Zoning (ZAE Cana) was also widely referred to as a mechanism to ensure expansion would be ecologically sustainable (GOV4, GOV5, IND3, IND5). However, in November 2019, after the period in which the interviews took place, the ZAE was revoked by Presidential Decree [94, 95].

Some interviewees emphasised the absence of land use conflict. In common with contributions referenced above, such responses often pointed to the distance between the main sugarcane producing areas, currently largely in São Paulo state and the south, and environmentally sensitive biomes such as the Amazon. They also pointed to the relatively small area of land under sugarcane relative to other agricultural areas, especially pasture, and to the size of the country as a whole (AC2, AC3, AC4, GOV5). They emphasised that even small improvements in the productivity of pasture could free up large areas capable of absorbing any expansion from sugar cane or other crops (FIN, GOV2).

Productivity improvements were also envisaged as possible within the sugarcane sector itself, including through replanting of crops, development of new crop varieties, learning by doing following the relatively recent changes in mechanisation in the sector, the development of second generation ethanol, as well as the introduction of 'internet of things' technologies to enable precision irrigation and optimisation of equipment maintenance (AC2, AC3, FIN, GOV4, GOV5, IND2, IND4, NGO). Through such means, it was felt that output could increase, but "with an area of sugarcane that already exists" (NGO).

However, in recent years sugarcane productivity and yields in Brazil have not substantially increased [45, 90, 96, 97]. Noting this, one interviewee was not clear that productivity would necessarily increase in the future (IND1).

3.3.5. Industry structure

The industry structure has undergone several changes during different phases. There was considerable entry of large foreign companies into the sector during the boom period leading up to 2008 (AC1, GOV2, IND3, IND4). Following the more recent contraction in the industry "consolidation will still exist, because you still have many plants in difficulty" (GOV2). Indeed, one interviewee suggested that internationally it is now considered a "good time to buy plant in Brazil" (NGO).

Several interviewees commented that the size and access to capital of the larger actors means they have better potential to invest in more diverse and technologically advanced options, such as biogas, bioelectricity and potentially second generation ethanol, than smaller family firms (NGO, AC1, AC4, AC5).

This discussion was given important context by reflections on the importance from a commercial perspective of flexibility (AC2, IND2), given the numerous interactions of national and global demands, and commodity prices, that can affect profitability – "being flexible is the key point for making money in this industry" (AC2). This suggests that targeted support, for example dedicated credit lines (AC4),

to help smaller players access co-product technologies and thereby diversify their strategies, could be crucial to their survival.

3.3.6. Global drivers

PROALCOOL began as a national policy to improve Brazil's self-sufficiency and resilience to the vicissitudes of global energy markets [12]. In contrast, the period of 'ethanol diplomacy' hoped to build international engagement in biofuels [50]. A government policy maker recalled that "we thought that we could access European Union market and also the US market", but "the market didn't come as they thought it would come. The US kept its barriers… and of course the EU market was much more difficult to access" (GOV4). The US supported its domestic corn ethanol industry (GOV4, GOV5) and overtook Brazil as the global leader in ethanol production in 2006 [98].

As reported by Afionis et al, attempts to develop ethanol coalitions with the EU also foundered [50]. Several of the interviewees were critical, even frustrated with the EU position. One complained that Europe "didn't like ethanol... they build all the barriers… they started the discussion of food versus fuel…" which the interviewee argued was "a political agenda" (GOV5). Others also critically characterised Europe as being too focussed on environmental impacts and trade-offs with food supply, which they argued was not an issue at least for Brazilian biofuels (AC2, FIN).

Nonetheless, several interviewees remained optimistic about future ethanol export markets, raising the prospect that biofuel blending mandates in India and China could create substantial new global demands for ethanol (AC1, AC2, FIN, GOV2, IND3, IND5, NGO).

Furthermore, global low carbon future trajectories could have critical roles for bioenergy, including in hard to decarbonise sectors and in achieving negative emissions [99-101]. Interviewees considered the potential longer term economic benefits from pursuing a low carbon agenda in a global context of decarbonisation. In a world with high demand for carbon credits, "we could finance some projects here using international money" (AC5). Brazil's potential to achieve negative emissions, for example by attaching carbon capture and storage to ethanol production (IND2, AC2), or through reforestation (IND2), could also be a critical source of emissions credits in a world attempting to reach net-zero emissions, making Brazil a key player "in world economy and environmental terms" (AC2). Several participants also raised the possibility of producing biokerosene, as a possible way of achieving low carbon air travel (AC5, GOV1, GOV3,). Additional products, within the broader scope of a 'bioeconomy', were also considered, including chemicals, fertilizers and renewable plastics (AC3, GOV3, IND2, IND3).

However, some interviewees were more sanguine about global markets (AC5, GOV2), one commenting "we have still issues producing to meet the demand here" (AC5).

4. Discussion

Our discussions with sector experts revealed broad expectations of continued growth in Brazil's sugarcane sector, with product diversification expected to be a key strategy. However, history has shown that growth in the sector has not been constant and inevitable, but dependent on policies, on the broader context and motivations for those policies, and on global dynamics. Each of these factors will continue to influence profoundly the future evolution of the sector.

Past policies such as PROALCOOL famously had a dramatic impact on the sector, and interviewees were still conscious of the importance of policy signals in the sector today. At the same time, there

was considerable awareness of history's lessons on the perils of top-down government intervention, in contrast to which the new policy RenovaBio was praised for its less interventionist, more technology-neutral style. However, history suggests that transformative change does require strong and consistent forms of intervention, and that such programmes can have long term and beneficial impacts for the economy and for technological innovation [65]. Learning from PROALCOOL suggests that long-term internal policy stability should be combined with some degree of agility to respond to external factors, such as the prices of related global commodities. Looking forward, there are opportunities for further diversification in energy conversion technologies and products; however, several of these are at nascent stages of development. In addition, in spite of consolidation trends [54], the sector remains somewhat heterogeneous, and includes smaller actors whose access to capital and appetite for risk may be limited. In such conditions, it may be that some more granular and technology- or actor-targeted policy support, may also be justified, as well as more purely technology-neutral frameworks.

Whereas in the 1970s domestic biofuels were the answer to the question of security of supply, since the discoveries of major domestic fossil fuel reserves, they are no longer exclusively so. In such context the balance between economic and environmental motivations for bioenergy policies becomes salient to their stability and longevity. Some interviewees felt that environmental motivations were central to bioenergy policies, and hoped that Brazil would maintain a global environmental leadership role; others felt that the pre-salt reserves were too valuable a resource not to exploit, and that Brazil's already relatively low carbon energy system meant that it should feel no obligation to forgo such wealth. Although several interviewees expressed the view that there was no competition between fossil fuels and biofuels, others felt – and history, perhaps, suggests – that they do tend to compete for the same energy services.

History also emphasises that the commodities involved in the story of Brazil's sugar cane sector – fossil fuels, biofuels and sugar – are global commodities and thus subject to global market vicissitudes. But they will also be driven in the coming decades by deep global concerns – climate change and health. The uncertainties inherent in these dynamics are worth reflecting upon. Being a major player in each of these three commodities could enable Brazil to influence global innovation trends in a way conducive to its own development strategies, as was the ambition during the ethanol diplomacy period. Writing in 2016, Afionis et al observed 'a lack of domestic strategy and vision', commenting that 'Brazil's ethanol diplomacy has been impacted by this domestic standstill' [50]. Returning to an internationally influential position on biofuels would require a clear strategy, and particularly in view of doubts in many places outside of Brazil as to the sustainability of biofuels, the ability to demonstrate clearly their compatibility with environmental and social protection [95]. Furthermore, although Brazil is a highly influential world actor, there are also elements beyond its control. It may be worth considering high sunk-cost investments in energy infrastructure in the context of alternative global energy scenarios. As one example, in a low carbon future, advanced and sustainable biofuels may be extremely high value commodities [99-101], whereas fossil fuel production would be subject to declining demands [102].

5. Conclusions

We have explored the future prospects for Brazil's sugarcane sector, using semi-structured interviews with expert stakeholders. Through considering past dynamics, we uncovered key actors' perceptions of the sector which may be critical in forming its future direction. In conclusion, we offer three areas of reflection, the consideration of which may be conducive to effective strategizing for policy makers, industrialists and academics.

First, alongside the clear preference, as expressed by the majority of interviewees, for minimal intervention, technology neutral styles of policy, there may also be value in ensuring that this is balanced with the need for policy that is clear, long-term and impactful. It is possible for long-term frameworks to incorporate flexibility to respond to global external conditions, increasing resilience. There may also still be a role for technology- and sector-specific targeted action, including for nascent technologies and small as well as larger actors, in addition to technology neutral frameworks.

Second, increased clarity on the broader objectives for the sector, including the relative prioritisation of economic, social and environmental objectives, may help industry to make the long term investments consistent with the kind of deep innovation for which there is potential. A clear and long-term (post-2030) strategy on the role of biofuels in Brazil's energy system, their relation to social, economic and environmental objectives, and how this affects synergies or trade-offs between bioenergy and fossil fuels in Brazil's future energy mix, would assist in this.

Third, it is worth reflecting on how the above issues in combination can be leveraged into a global leadership strategy. In which area does Brazil wish to show leadership, and how can leadership best be demonstrated? How resilient are the different possible strategies to alternative global scenarios, that could affect the relative value of each commodity? Though Brazil is a major and influential global actor and the world's largest sugarcane producer, a strategy that is also sensitive to broader global dynamics will render successful outcomes more likely.

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References

1. UN. *Sustainable Development Goals*. 2020 [cited 2020 26th May]; Available from: https://sustainabledevelopment.un.org/?menu=1300.
2. Robinson, M. and T. Shine, *Achieving a climate justice pathway to 1.5 °C.* Nature Climate Change, 2018. **8**(7): p. 564-569.
3. Fuso Nerini, F., et al., *Connecting climate action with other Sustainable Development Goals.* Nature Sustainability, 2019. **2**(8): p. 674-680.
4. Singh, R., A. Bhatia, and M. Srivastava, *Biofuels as Alternate Fuel from Biomass-The Indian Scenario*, in *Energy Sustainability through Green Energy*, A. Sharma and S.K. Kar, Editors. 2015, Springer: New York. p. 287-313.
5. Zhu, L.D., et al., *Microalgal biofuels: Flexible bioenergies for sustainable development.* Renewable and Sustainable Energy Reviews, 2014. **30**: p. 1035-1046.
6. Milder, J.C., et al., *Biofuels and ecoagriculture: can bioenergy production enhance landscape-scale ecosystem conservation and rural livelihoods?* International Journal of Agricultural Sustainability, 2008. **6**(2): p. 105-121.
7. Kgathi, D.L., et al., *Potential impacts of biofuel development on food security in Botswana: A contribution to energy policy.* Energy Policy, 2012. **43**: p. 70-79.
8. Renzaho, A.M.N., J.K. Kamara, and M. Toole, *Biofuel production and its impact on food security in low and middle income countries: Implications for the post-2015 sustainable development goals.* Renewable and Sustainable Energy Reviews, 2017. **78**: p. 503-516.
9. Acheampong, M., et al., *In pursuit of Sustainable Development Goal (SDG) number 7: Will biofuels be reliable?* Renewable and Sustainable Energy Reviews, 2017. **75**: p. 927-937.
10. Pimentel, D., et al., *Food Versus Biofuels: Environmental and Economic Costs.* Human Ecology, 2009. **37**(1): p. 1.
11. Federative Republic of Brazil. *Intended Nationally Determined Contribution Towards Achieving the Objective of the United Nations Framework Convention On Climate Change* 2016 [cited 2020 19th May]; Available from: https://www4.unfccc.int/sites/NDCStaging/pages/Party.aspx?party=BRA.
12. Hira, A. and L.G. de Oliveira, *No substitute for oil? How Brazil developed its ethanol industry.* Energy Policy, 2009. **37**(6): p. 2450-2456.
13. Wack, P., *Scenarios: unchartered waters ahead.* Harvard Business Review, 1985. **September-October**: p. 73-89.
14. Wack, P., *Scenarios: shooting the rapids.* Harvard Business Review, 1985. **November-December**: p. 139-150.

15. Sunderlin, W.D., *Ideology, social theory, and the environment*. 2003, Lanham, USA: Rowman and Littlefield Publishers. 261p.

16. Clapp, J. and P. Dauvergne, *Paths to a green world: the political economy of the global environment*. 2005, Cambridge, Massachussetts: MIT Press.

17. Leach, M., I. Scoones, and A. Stirling, *Dynamic sustainabilities - technology, environment, social justice*. 2010, London: Earthscan.

18. Naes, L.O., E. Polak, and B. Chinsinga, *Bridging research and policy processes for climate change adaptation.* IDS Bulletin, 2011. **42**(3): p. 97-103.

19. Chinsinga, B., R. Mangani, and P. Mvula, *The political economy of adaptation through crop diversification in Malawi.* IDS Bulletin, 2011. **42**(3): p. 110-117.

20. Alam, K., et al., *The political economy of climate resilient development planning in Bangladesh.* IDS Bulletin, 2011. **42**(3): p. 52-61.

21. Crick, B., *In defence of politics*. 1964, Harmondsworth: Penguin.

22. Hall, P., *Policy paradigms, social learning, and the State: the case of economic policymaking in Britain.* Comparative Politics, 1993. **25**(3): p. 275-296.

23. Wilson, C., *Policy regimes and policy change.* Journal of Public Policy, 2001. **20**(3): p. 247-274.

24. Hay, C., *The 'crisis' of Keynesianism and the rise of neoliberalism in Britain: an ideational institutionalist approach*, in *The rise of neoliberalism and institutional analysis*, J.L. Campbell and O.K. Pedersen, Editors. 2001, Princeton University Press: Princeton.

25. Mitchell, C., *The political economy of sustainable energy*. Energy, Climate and Environment Series, ed. D. Elliot. 2008, Basingstoke: Palgrave Macmillan.

26. Campbell, J.L., *Institutional analysis and the role of ideas in political economy*, in *The rise of neoliberalism and institutional analysis*, J.L. Campbell and O.K. Pedersen, Editors. 2001, Princeton University Press: Princeton.

27. Padgett, D., *Qualitative methods in social work research. Third edition.* 2017, Thousand Oaks, California,: Sage.

28. Mason, J., *Semistructured interview*, in *The SAGE encyclopaedia of social science research methods*, M.S. Lewis Beck, A. Bryman, and T. Futing Liao, Editors. 2004, SAGE: Thousand Oaks, California.

29. Hameso, S., *Farmers and policy-makers' perceptions of climate change in Ethiopia.* Climate and Development, 2018. **10**(4): p. 347-359.

30. Horn, P. and J. Grugel, *The SDGs in middle-income countries: Setting or serving domestic development agendas? Evidence from Ecuador.* World Development, 2018. **109**: p. 73-84.

31. Salehi, S., et al., *Conceptual definition and framework of climate change and dust storm adaptation: a qualitative study.* Journal of Environmental Health Science and Engineering, 2019. **17**(2): p. 797-810.

32. Edwards, M.L., *"Just report the science": How scientists frame their engagement in contested debates over fracking in the Barnett Shale.* Energy Research & Social Science, 2018. **45**: p. 67-74.

33. Lindoso, D.P., et al., *Harvesting Water for Living with Drought: Insights from the Brazilian Human Coexistence with Semi-Aridity Approach towards Achieving the Sustainable Development Goals.* Sustainability, 2018. **10**(3): p. 16.

34. Vasileiou, K., et al., *Characterising and justifying sample size sufficiency in interview-based studies: systematic analysis of qualitative health research over a 15-year period.* BMC Medical Research Methodology, 2018. **18**(1): p. 148.

35. Patton, M., *Qualitative Research and Evaluation Methods. Fourth Edition*. 2015, Thousand Oaks, California: Sage.

36. Moser, A. and I. Korstjens, *Series: Practical guidance to qualitative research. Part 3: Sampling, data collection and analysis.* The European journal of general practice, 2018. **24**(1): p. 9-18.

37. Palinkas, L.A., et al., *Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research.* Administration and policy in mental health, 2015. **42**(5): p. 533-544.

38. Bearman, M., *Focus on Methodology: Eliciting rich data: A practical approach to writing semi-structured interview schedules.* Focus on Health Professional Education-a Multidisciplinary Journal, 2019. **20**(3): p. 1-11.

39. Rowley, J., et al., *Using Card-Based Games to Enhance the Value of Semi-Structured Interviews.* International Journal of Market Research, 2012. **54**(1): p. 93-110.

40. Stolf, R. and A.P.R. de Oliveira, *THE SUCCESS OF THE BRAZILIAN ALCOHOL PROGRAM (PROALCOOL) - A DECADE BY-DECADE BRIEF HISTORY OF ETHANOL IN BRAZIL.* Engenharia Agricola, 2020. **40**(2): p. 243-248.

41. ANFAVEA, *Anuário da Indústria Automobilística Brasileira*. 2018, São Paulo: Associação Nacional dos Fabricantes de Veículos Automotores.

42. Hofsetz, K. and M.A. Silva, *Brazilian sugarcane bagasse: Energy and non-energy consumption.* Biomass and Bioenergy, 2012. **46**: p. 564-573.

43. Gilio, L. and N.R. Castro, *Avaliação de Aspectos Limitantes ao Crescimento do Etanol e o Setor Sucroenergético no Brasil.* Revista Eletrônica de Energia, 2016. **6**: p. 58-74.

44. Moraes, M.L. and M.R.P. Bacchi, *Etanol: Do início às fases atuais da produção.* Revista de Política Agrícola, 2014. **4**: p. 5-22.

45. EPE, *Análise de Conjuntura dos Biocombustíveis, Ano 2018.* . 2019, Empresa de Pesquisa Energética.

46. CONAB, *Boletim de Cana-de-Açúcar*. 2019, Companhia Nacional de Abastecimento.

47. Rego, E.E. and V. Parente, *Brazilian experience in electricity auctions: Comparing outcomes from new and old energy auctions as well as the application of the hybrid Anglo-Dutch design.* Energy Policy, 2013. **55**: p. 511-520.

48. Dutra, R.M. and A.S. Szklo, *Incentive policies for promoting wind power production in Brazil: Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation.* Renewable Energy, 2008. **33**(1): p. 65-76.

49. UNICA, *Bioeletricidade em Números 2018*. 2018, União da Indústria de Cana de Açúcar

50. Afionis, S., et al., *Unpacking Brazil's Leadership in the Global Biofuels Arena: Brazilian Ethanol Diplomacy in Africa.* Global Environmental Politics, 2016. **16**(3): p. 127-150.

51. Dalgaard, K.G., *The Energy Statecraft of Brazil: Promoting biofuels as an instrument of Brazilian foreign policy, 2003-2010*. 2012, Department of International Relations, London School of Economics.: London.

52. Angelo, C., *Growth of ethanol fuel stalls in Brazil.* Nature, 2012. **491** p. 646–647.

53. Husseini, T. *Tracing the history of exploration in the Brazilian pre-salt oil region*. 2018 [cited 2020 22nd May]; Available from: https://www.offshore-technology.com/features/pre-salt-oil-region-brazil/.

54. FGV Energia, *Biofuels. FGV Energia Booklets, August 2017, Year 4, Number 8. ISSN 2358-5277*. 2017.

55. FAO. *FAO Statistics Division-FAOSTAT*. 2019 [cited 2019 10th October]; Available from: http://www.fao.org/faostat/.

56. DOE. *Alternative Fuels Data Center - Maps and Data - Global Ethanol Production*. 2020 [cited 2020 5th June]; Available from: https://afdc.energy.gov/data/.

57. ISO. *About Sugar - The Sugar Market*. 2020 [cited 2020 21st May]; Available from: https://www.isosugar.org/sugarsector/sugar.

58. NovaCana. *NovaCana – As Usinas de Açúcar e Álcool do Brasil* 2020 [cited 2020 19th May]; Available from: https://www.novacana.com/usinas_brasil.

59. UNICA. *UNICADATA / Production data / Sugarcane production and processing / Per specific product*. 2020 [cited 2020 19th May]; Available from: http://www.unicadata.com.br/historico-de-producao-e-moagem.php?idMn=31&tipoHistorico=2.

60. UNICA. *UNICADATA / Production data / Planted area / Total area per state*. 2020 [cited 2020 19th May]; Available from: http://www.unicadata.com.br/historico-de-area-ibge.php?idMn=33&tipoHistorico=5.

61. Presidência da República Secretaria-Geral Subchefia para Assuntos Jurídicos, *LEI Nº 13.576, DE 26 DE DEZEMBRO DE 2017. Dispõe sobre a Política Nacional de Biocombustíveis (RenovaBio) e dá outras providências.* 2017.

62. CNPE, *RESOLUÇÃO No 5, DE 5 DE JUNHO DE 2018. Estabelece as metas compulsórias anuais de redução de emissões de gases causadores do efeito estufa para a comercialização de combustíveis. Conselho Nacional De Política Energética.* 2018.

63. ANP, *Resolução ANP 791. Agência Nacional de Petróleo Gás Natural e Biocombustíveis*. 2019.

64. Carvalho, L. and G. Barra, *RenovaBio: challenges between idea and execution*. 2019, UBS Global Research.

65. Goldemberg, J., *Ethanol for a Sustainable Energy Future.* Science, 2007. **315**(5813): p. 808.

66. Jolly, L. and L.B. Rocha, *A fast-changing landscape for fuel ethanol?* International Sugar Journal, 2009. **111**(1323): p. 150-155.

67. Strauch, Y., *Beyond the low-carbon niche: Global tipping points in the rise of wind, solar, and electric vehicles to regime scale systems.* Energy Research & Social Science, 2020. **62**: p. 101364.

68. Zhang, R.S. and S. Fujimori, *The role of transport electrification in global climate change mitigation scenarios.* Environmental Research Letters, 2020. **15**(3): p. 12.

69. Christofoletti, C.A., et al., *Sugarcane vinasse: Environmental implications of its use.* Waste Management, 2013. **33**(12): p. 2752-2761.

70. Rabelo, S.C., A.C. da Costa, and C.E. Vaz Rossel, *Chapter 17 - Industrial Waste Recovery*, in *Sugarcane*, F. Santos, A. Borém, and C. Caldas, Editors. 2015, Academic Press: San Diego. p. 365-381.

71. Bernal, A.P., et al., *Vinasse biogas for energy generation in Brazil: An assessment of economic feasibility, energy potential and avoided CO2 emissions.* Journal of Cleaner Production, 2017. **151**: p. 260-271.

72. Kumar, S. and L. Viswanathan, *Production of biomass, carbon dioxide, volatile acids, and their interrelationship with decrease in chemical oxygen demand, during distillery waste treatment by bacterial strains.* Enzyme and Microbial Technology, 1991. **13**(2): p. 179-187.

73. Navarro, A.R., M. del C. Sepúlveda, and M.C. Rubio, *Bio-concentration of vinasse from the alcoholic fermentation of sugar cane molasses.* Waste Management, 2000. **20**(7): p. 581-585.

74. Santana, V.S. and N.R.C. Fernandes Machado, *Photocatalytic degradation of the vinasse under solar radiation.* Catalysis Today, 2008. **133-135**: p. 606-610.

75. Moraes, B.S., et al., *Anaerobic digestion of vinasse from sugarcane biorefineries in Brazil from energy, environmental, and economic perspectives: Profit or expense?* Applied Energy, 2014. **113**: p. 825-835.

76. Moraes, B.S., M. Zaiat, and A. Bonomi, *Anaerobic digestion of vinasse from sugarcane ethanol production in Brazil: Challenges and perspectives.* Renewable and Sustainable Energy Reviews, 2015. **44**: p. 888-903.

77. Leme, R.M. and J.E.A. Seabra, *Technical-economic assessment of different biogas upgrading routes from vinasse anaerobic digestion in the Brazilian bioethanol industry.* Energy, 2017. **119**: p. 754-766.

78. de Souza, S.N.M., et al., *Production potential of biogas in sugar and ethanol plants for use in urban buses in Brazil.* Journal of Food, Agriculture and Environment, 2012. **10**(1): p. 908-910.

79. Pazuch, F.A., et al., *Economic evaluation of the replacement of sugar cane bagasse by vinasse, as a source of energy in a power plant in the state of Paraná, Brazil.* Renewable and Sustainable Energy Reviews, 2017. **76**: p. 34-42.

80. MME. *RenovaBio*. 2020 [cited 2020 25th May 2020]; Available from: http://www.mme.gov.br/web/guest/secretarias/petroleo-gas-natural-e-biocombustiveis/acoes-e-programas/programas/renovabio.

81. Diele-Viegas, L.M. and C.F.D. Rocha, *Why releasing mining on Amazonian indigenous lands and the advance of agrobusiness is extremely harmful for the mitigation of world's climate change? Comment on Pereira et al. (Environmental Science & Policy 100 (2019) 8–12).* Environmental Science & Policy, 2020. **103**: p. 30-31.

82. Ferrante, L. and P.M. Fearnside, *Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate.* Environmental Conservation, 2019. **46**(4): p. 261-263.

83. Abessa, D., A. Famá, and L. Buruaem, *The systematic dismantling of Brazilian environmental laws risks losses on all fronts.* Nature Ecology & Evolution, 2019. **3**(4): p. 510-511.

84. de Area Leão Pereira, E.J., et al., *Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest.* Environmental Science & Policy, 2019. **100**: p. 8-12.

85. Martucci do Couto, G., et al., *Response of soil microbial biomass and activity in early restored lands in the northeastern Brazilian Atlantic Forest.* Restoration Ecology, 2016. **24**(5): p. 609-616.

86. Tomei, J. and R. Helliwell, *Food versus fuel? Going beyond biofuels.* Land Use Policy, 2016. **56**: p. 320-326.

87. Coelho, S.T., et al., *Brazilian sugarcane ethanol: lessons learned.* Energy for Sustainable Development, 2006. **10**(2): p. 26-39.

88. Pereira, M.G., et al., *The renewable energy market in Brazil: Current status and potential.* Renewable and Sustainable Energy Reviews, 2012. **16**(6): p. 3786-3802.

89. Smeets, E., et al., *The sustainability of Brazilian ethanol—An assessment of the possibilities of certified production.* Biomass and Bioenergy, 2008. **32**(8): p. 781-813.

90. Lourenzani, W.L. and M.M. Caldas, *Land use change from the sugar cane expansion in the western region of Sao Paulo state, Brazil.* Ciencia Rural, 2014. **44**(11): p. 1980-1987.

91. van der Hilst, F., et al., *Mapping land use changes resulting from biofuel production and the effect of mitigation measures.* Global Change Biology Bioenergy, 2018. **10**(11): p. 804-824.

92. Verstegen, J.A., et al., *What can and can't we say about indirect land-use change in Brazil using an integrated economic – land-use change model?* GCB Bioenergy, 2016. **8**(3): p. 561-578.

93. Duden, A.S., et al., *Biodiversity Impacts of Increased Ethanol Production in Brazil.* Land, 2020. **9**(1): p. 17.

94. Presidência da República Secretaria-Geral Subchefia para Assuntos Jurídicos, *DECRETO Nº 10.084, DE 5 DE NOVEMBRO DE 2019*. 2019.

95. Hofmeister, N. *In surprise move, Brazil has removed restrictions on Amazon sugarcane production*. 2019 [cited 2020 5th June]; Available from: https://news.mongabay.com/2019/11/in-a-surprise-move-even-to-the-sugarcane-industry-president-bolsonaro-has-removed-restrictions-on-sugarcane-production-in-the-brazilian-amazon-experts-expect-land-speculators-to-benefit/.

96. Caldarelli, C.E. and L. Gilio, *Expansion of the sugarcane industry and its effects on land use in São Paulo: Analysis from 2000 through 2015.* Land Use Policy, 2018. **76**: p. 264-274.

97. Camara, M.R.G.d. and C.E. Caldarelli, *Expansão canavieira e o uso da terra no estado de São Paulo.* Estudos Avançados, 2016. **30**: p. 93-116.

98. Lamers, P., et al., *International bioenergy trade—A review of past developments in the liquid biofuel market.* Renewable and Sustainable Energy Reviews, 2011. **15**(6): p. 2655-2676.

99. Butnar, I., et al., *The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy?* GCB Bioenergy, 2020. **12**(3): p. 198-212.

100. Daioglou, V., et al., *Integrated assessment of biomass supply and demand in climate change mitigation scenarios.* Global Environmental Change, 2019. **54**: p. 88-101.

101. Wise, M., M. Muratori, and P. Kyle, *Biojet fuels and emissions mitigation in aviation: An integrated assessment modeling analysis.* Transportation Research Part D-Transport and Environment, 2017. **52**: p. 244-253.

102. Lefèvre, J., W. Wills, and J.-C. Hourcade, *Combining low-carbon economic development and oil exploration in Brazil? An energy–economy assessment.* Climate Policy, 2018. **18**(10): p. 1286-1295.