**CHALLENGES FOR BECCS IMPLEMENTATION THROUGH A SOCIO-TECHNICAL APPROACH[1]**

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ABSTRACT: Some of the great contemporaneous challenges in the world involves dealing with energy, food production and supply, at the same time, reducing greenhouse gas emissions and their impact on climate change. As so, aiming to reduce carbon concentrations in the atmosphere, many studies recommend the inclusion of technologies as Carbon Capture and Storage (CCS) or Carbon Capture Usage and Storage (CCUS) to follow through energy transition to lower carbon concentration. As discussed in this paper and other publications by one of the authors (STC), only fossil fuel replacement is not enough to achieve a temperature increase of up to $2^{o}$ C. Therefore, bioenergy, together with these technologies, named Bioenergy Carbon Capture and Storage (BECCS) or Bioenergy Carbon Capture Usage and Storage (BECCUS), has the potential to reach negative emissions on bioenergy life cycle. Consequently, understanding the challenges for the implementation of such technologies requires a broad perspective that is addressed through a socio-technical approach. In fact, BECCUS can be an option to contribute to these goals, putting together both bioenergy and CCS / CCUS as discussed in previous publication. BECCUS is already becoming a reality in Brazil, since several sugarcane ethanol mills already sell $CO_2$ from their fermentation process to other industries. However, there are still (technical, economic, social and environmental) challenges mainly related to BECCS, not yet implemented in the country. Therefore, this is the main objective of this paper: to analyse the challenges for BECCS in the country in a socio-technical approach.

Keywords: technology, social aspects, sustainability, sugarcane, $CO_2$ emission, $CO_2$ reduction.

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## 1 INTRODUCTION

Some of the great contemporaneous challenges in the world involve dealing with clean energy provision as well as food production and supply, at the same time reducing GHG emissions and their impact on climate change. As so, many studies (e.g. [1] and others) recommend the inclusion of technologies as Carbon Capture and Storage (CCS) or Carbon Capture Usage and Storage (CCUS) to follow through energy transition to clean energy sources. Bioenergy, together with these technologies, named Bioenergy Carbon Capture and Storage (BECCS) or Bioenergy and Carbon Capture Storage and Usage (BECCS/U) (1), has the potential to reach negative emissions.

Biomass energy can be produced from different feedstocks of biological origin, through several different processes to produce heat, electricity, and transport fuels. The advantages of bioenergy are quite well known, considering its environmental, strategic, and social impacts. In addition, bioenergy contributes to reduce GHG emissions, mainly when coupled to BECCS or BECCUS.

Consequently, understanding the challenges for the implementation of such technologies requires a broad perspective that is addressed through a socio-technical approach. As discussed in Bui et al. [1] and Coelho et al. [2], only fossil fuel replacement is not enough to achieve a temperature increase of up to 2º C. Therefore, BECCUS can be an option to contribute to these goals, putting together bioenergy and CCS/CCUS [3]. BECCUS is becoming a reality in Brazil, since some sugarcane ethanol mills already sell carbon dioxide ($CO_2$) from their fermentation process to other industries. However, existing experiences are not so many [2] and there are still several difficulties.

In such context, the aim of this paper is to discuss the main challenges in the implementation of BECCS and BECCUS processes, based on existing uncertainties discussed for CCS by Markusson et al. [4][5], here analysed in the Brazilian environment. These uncertainties cover aspects in the areas of pathway variety; storage safety; development and deployment speed; systems integration; viability considering economic and financial aspects; political, regulatory and policy perspectives; public perception in general and in specific audiences. The assessment of BECCS and BECCUS through such framework will encompass two main objectives in this paper, at first to discuss specific challenges in bioenergy and secondly to support further investigation and decision making.

## 2 THE BRAZILIAN BIOENERGY SECTOR

Brazil has developed a strong bioenergy sector through sugarcane and, more recently, corn ethanol production. Sugarcane biomass products (2) represent 17.4% on the Brazilian internal energy offer (IEO) [6] in 2018, with ethanol production of 35.5 billion litres in 2019/20 from 643 MM tons of cane crushed. Ethanol represented 42% of fuel consumption for light fleet in the country in 2018 [6].

Most industries produce both sugar and ethanol from sugarcane, and due to market, the production can be defined by the best fit according to their needs. In 2020, due to COVID-19 pandemic that resulted in strong decrease in fuel consumption in the country, most mills decided to produce more sugar instead of ethanol [7].

Besides the production of first-generation ethanol, there are two pilot plants for 2G ethanol in the country, using sugarcane residues, at Costa Pinto mill (Raizen group), Sao Paulo state, and Granbio, in Alagoas state [8].

Due to ethanol consumption and the large use of flex vehicles (3), positive environmental impacts were noted in large cities such as Sao Paulo capital, with strong reduction on particulate, as measured by several studies e.g. [9]. Recently, following the trend for more sustainable vehicles, new ones are being manufactured, such as hybrid-flex vehicles as Toyota Corolla [10], or tested, such as the one with ethanol-on-board-reformer/fuel cell [11] by Nissan [11] as illustrated in figure 1.


Figure 1: Ethanol on board reformer-fuel cell by Nissan being tested in Brazil. Source [12].

In 2017 the so-called National Biofuels Policy (RenovaBio) [13], was established in the country, aiming to increase the share of biofuels in the Brazilian energy mix, besides contributing to achieve the targets committed, under the 2015 Paris Agreement. RenovaBio defines the basis for biofuels certification, in the form of a Decarbonization Credit (CBIO), to be traded on the stock exchange, under free market conditions [14][15].

## 3 METHODOLOGY

The methodology applied in this work was a literature review on bioenergy, sugarcane and ethanol production, BECCS, BECCUS in Brazil, presenting also a brief summary of the Brazilian bioenergy sector. Although, technologies related to BECCS and BECCUS are still in their early stages of development in Brazil, with no project implemented up to the date of the publication of this paper. As so, the challenges to move forward rise many uncertainties that must be considered in the analysis and decision-making process. In that sense, a broad perspective that considers technical, environmental, legal, regulatory, economic, financial and social issues is relevant [16]. Therefore, BECCS and BECCUS were analysed through a socio-technical framework proposed by Markusson *et al.* [4][5] which appoints seven uncertainties related to the development and implementation of CCS that will be presented in this paper. After this broad CCS perspective, through an analytical methodology based on such framework, the paper will then appropriately focus the discussion specifically on the CCS related to the bioenergy process.

## 4 CCS UNCERTAINTIES FRAMEWORK

## 4.1 CCS Challenges Framework

Markusson et al. [4][5] have discussed the challenges involved in Carbon Capture and Storage (CCS) through a social technical perspective. They point out the complexity within energy transition to a low carbon economy, in which carbon abatement technologies are often considered part of the solution. CCS can be described as the process of capturing the carbon dioxide ($CO_2$) from industrial or power plants, transporting it to an appropriate storage facility and keeping it underground. This process prevents the carbon release into atmosphere although it can be controversial due to many uncertainties related to technological aspects as the variety of technologies being developed, the maturity of each of them, the feasibility of its implementation and capacity to be integrated into systems, to mention a few. On the other hand, the authors also stress the contribution of social science in this matter, presenting other elements as cost, financial viability, security, risk, legislation, and moreover, public acceptance.

In order to address a vast range of uncertainties and interrelate them, as one affects the other in a complex system, Markusson *et al.* [4][5] propose a framework that encompasses seven uncertainties, aiming to build a structure to support decision making on CCS matters as well as to be applicable for the analysis of a more extensive range of low carbon technologies. In this paper, such framework of uncertainties will be used to analyse the bioenergy with carbon capture and storage or usage, seeking to apply the methodology to support the analysis and decision making in this area.

The framework consists of an interdisciplinary approach that encompasses technical and social issues as economic, financial, political and societal perspectives through qualitative and quantitative assessment indicators of uncertainty. It was structured by a literature review of concepts as Technology Assessment (TA) which is originally from the 1960's and emerged as a reaction to the effects of the rising technologies on society. The framework takes a socio-technical systems perspective understood as "clusters of aligned elements, such as technical artefacts, knowledge, markets, regulation, policies, cultural meaning, rules, infrastructure, etc." [17].

The authors [4][5] recognise a relation of co-evolution of technology and society, with cross impact as they are intertwined. The model assesses uncertainties, here understood as the lacking knowledge on any relevant feature, as there are many possible paths into the future for the seven key dimensions they have identified.

Based in that socio-technical framework proposed for CCS, the aim of this work is to identify the uncertainties related to BECCS and BECCUS analysing their impacts, to serve two purposes, first to validate the uncertainties for BECCS and BECCUS as well as to support future decision making.

The seven CCS innovation uncertainties pointed out by Markusson et al. [4][5] are:

1. Variety of pathways for technology development and support
2. Storage safety
3. Scaling up and speed of development and deployment
4. Integration of CCS systems
5. Economic and financial viability
6. Policy, political and regulation
7. Public acceptance

These uncertainties will be discussed in the next session of the paper.

## 4.2 CCS Uncertainties

Considering CCS many have been the technologies developed for capture, for transport and for storage. Which of these technologies will become the best solutions? When? Will they succeed? This requires the evaluation of competing solutions and the analysis of systems integration, as to how the technologies fulfil an integrated system in a process that demands dealing with multiple technological, regulatory and legal pathways, as well as dialoguing with society seeking to build trust and respond to safety and risk concerns [4][5].

Technologies require experimentation through demonstration plants, that imply in significative financial investments and that can receive social resistances through 'Not In My Back Yard' (NIMBY) reactions. As implementation requires support from governments for funding and legislation, their representatives are challenged to understand the diverse alternatives presented by experts. Although, scientists are not always aligned and favourable to the same solutions, the majority agrees that CCS is important [1] but lacks consensus on the purpose of its use and the pathways to be adopted. Market competition, economics and integrated assessment modelling (IAM) also appoint to different directions depending on the assumptions, sometimes with only slight differences, others with antagonist views. This panorama arises in new technologies breakouts up to when some level of stability is reached and the focus becomes on improvements, in a cycle of novelty followed by refining and again to creation [5].

The energy technology to which the CCS is integrated to can be provided by coal, fossil fuel, biofuel, solar, wind, hydrogen and may serve different reaches of $CO_2$ mitigation. Also depends on stimulus and subsidies that are in place or taken down of old and new technology alternatives reinforced or not by governments at country or local level [5].

One line of though argues that CCS is a way through to lock-in to fossil fuels in the energy grid. Others justify the relevance of CCS within fossil fuel system as part of the solution while cleaner sources of energy suffer from intermittence and require further investments [1]. CCS also can be considered by some as a bridging technology to be in place during only a few years [1]. The debate follows further with a myriad of perspectives at stance.

On the safety standpoint the major concerns are related to if it is possible to safely storage $CO_2$ for long periods of time. Storage could be offshore, where risk and safety are seen as less impacting then in geological onshore formations, close to a community. The main risks are leakages that may affect other resources as water or land, or even a more extensive one with a global reach as $CO_2$ being released back into atmosphere. In any of the cases, population's health could be threatened [5]. Lessons learned by previous catastrophes in other kind of energy systems as the nuclear one have shown that although rare, they can be devastating. With such background it can be hard to settle the best set of legislations, and whom to hold accountable over time.

Another uncertainty mentioned by Markusson et al. [5] refers to the possibility to scale up technologies and the speed in which they develop and are deployed. The problems that can rise may be unknown beforehand, as technology limitations, public resistance, lack of government support, among others. Assessment of such variety of elements can be tricky, considering that countries or agents within a same country may perceive CCS differently [5].

Learnings from other previous technological large scale deployment processes show that even when supply and demand evolve alongside, many decades can go passed between stages, in a cycle of growths in unit numbers to scaling up and looping back to growth setting for more units deployed, leading to the maturation of such technology [5]. For Bui et al. [1], many technologies associated to CCS, mainly the transport through pipelines, are in the high end of development, with advanced technical readiness level (TRL) in which such technology is viewed as commercially feasible.

Another perspective from previous learnings has to do with if top down scientific approaches would be more favourable for CCS platforms as opposed to a bottom up low-tech incremental approach that seems more suitable to renewable energy sources [5]. The challenge with CCS is that each project can be very specific due to the local characteristics of the site in which it is implemented. For instance, onshore and offshore, how integrated is the system of capture, transportation and storage, what are the bottlenecks, how knowledgeable, informed and involved is the community with the project, and so forth.

Integrated systems require a complex interconnection of components, some of which require customization. Such integration and scaling-up dimensions also affect cost and financial viability, which are important to attract investments and support from regulation. Assessment models may not have the complete picture of all factors to be analysed and if they have, the assumptions or the data may not be sufficiently accurate. The market for an effective carbon price has not yet taken off. The decision to invest in CCS may not be only economic, but part of a broader national orientation or global international pact to reduce greenhouse gas emissions. Incentives from a political standpoint and policy that supports early stages of development and deployment tend to be critical for CCS investments. To emphasise the argument of CCS as part of the energy grid and a solution towards climate change mitigation, apart from political and regulatory measures, it also results from the perception of all agents by the trust on players, the perceived risk and safety of the process, and the level of information, resistance or social acceptance [5].

These seven uncertainties also apply to BECCS and BECCUS as a CCS process, although it has specificities worldwide and in Brazil that will be discussed in the next section of this paper.

## 5 BECCS WORLDWIDE AND IN BRAZIL: UNCERTAINTIES AND SOLUTIONS

In Brazil, BECCS is not so evolved in the local market, as it is still in a research and developing phase. There is no legislation yet and local studies are just a few, as discussed ahead, despite the existing experiences with BECCUS. However, BECCS is seen as an additional perspective to achieve the commitments approved in the Paris Agreement.

As it is well-known, the Paris Agreement was signed by countries during the COP21, in 2015, committed to reducing greenhouse gas (GHG) emissions, in order to maintain the global average temperature increase at 2°C, compared to pre-industrial levels and to pursue efforts to limit the increase to 1.5°C [18]. Then, the signatory countries sent their proposals indicating how they would reduce their GHG emissions – the Intended Nationally Determined Contribution (INDC). Later on, after local approval, they are called NDC (National Determined Contribution) [18]. More recently, the Intergovernmental Panel on Climate Change (IPCC) [19] highlights the importance of bioenergy and the actions of BECCS and BECCUS as a way to mitigate global warming.

On another hand, as discussed in Section 2, there is an important experience of biofuels in the Brazilian market. Besides the recent biodiesel program, there is the second largest ethanol program worldwide [20].

Initiated in the 70's, the ethanol production has increased continuously, allowing the Brazilian energy matrix in 2019 to reach 45.3% provided by renewable energy sources, with sugarcane products responsible for 14.7% [6]. The introduction of BECCS and BECCUS into the sugarcane sector, would enable the ethanol carbon footprint to be much lower than the current range (10-46 gCO2/MJ), conceivable achieving negative emissions [1][15].

In the state of Sao Paulo, the most industrialized in the country and the largest ethanol producer, there is also a trend for GHG emissions mitigation. Renewables correspond to about 59.5% of the state energy mix [21], and approximately 60% of Brazilian ethanol production comes from this state. In the 2019/2020 season, 344 MM (metric) tons of sugarcane were crushed in the state, producing 16.5 billion litres of ethanol [22].

For this state, biogenic (4) $CO_2$ estimate from the authors is approximately 12 million tons produced only from the sugarcane juice fermentation process, during sugarcane season. In addition, there are the biogenic emissions from bagasse boilers and from biogas (5) upgrade, potentially possible to be captured as well, corresponding to a significant potential for BECCS/U.

In brief, the BECCS technology is being discussed in the country and still needs to evolve, in order to achieve a commercial scale. Geological formations close to ethanol plants in Parana's basin with the potential for large storage have been recently mapped, [30]. One in particular (Rio Bonito formation) has the capability of being employed for storage with subsequently mineralization of $CO_2$.

In light of the difficulties for implementing the traditional BECCS, BECCU arises as an alternative for the destination of $CO_2$ in bioenergy plants, mainly for the energy sector of the sugarcane industry and for the production of high added value products.

As mentioned above, Brazilian experience is mainly related to BECCU, with the biogenic $CO_2$ from ethanol mills being captured, transported and sold to greenhouses, as well as to beverage and chemical industries [15]. The production of other products from $CO_2$ is currently being investigated, and new technologies employing electrochemical reactors are under development, [31].

As presented in further details by Coelho et al [15], with RenovaBio, if a negative biofuel carbon intensity is demonstrated, a bonus of up to 20% will be applied [23] to the decarbonisation credits (CBIO) awarded to the biofuel. So far (by 2020), sales of CBIO have just been launched. However, it is important to develop studies to measure the impact of adopting BECCS in the program.

A recent study, by Bossle [24], indicates that the price of the CBIO could range between BRL 17 and BRL 149 per CBIO (6), showing good prospects for the program. New projects to be developed at the Research Centre for Gas Innovation (RCGI), founded by FAPESP (the funding agency of the state of Sao Paulo) and Shell, hosted at the University of Sao Paulo, are expected to contribute to this discussion, mainly in the case of BECCS/BECCUS and the sugarcane sector.

In the analysis of CCS three steps deserve attention: $CO_2$ capture, transportation and storage. In the case of carbon usage from the sugarcane sector, challenges to end-uses are related to seasonality, production costs and economic competitiveness (7).

According to IEA [25], ethanol production facilities are “a particularly low-hanging fruit because of the high concentrations of $CO_2$ available for capture”. In addition, IEA [25] analyses that the mitigation potential of BECCS/BECCUS in itself may vary a lot because it includes a wide range of applications, from enhanced oil recovery (EOR) to production of synthetic fuels via the so-called power-to-X (PtX). It also mentions carbonation of beverages (8), $CO_2$ fertilization in greenhouses (8), crop cultivation and algae [1], or its use as raw material in industrial processes for production of fuels, chemicals and plastics (8), as shown in Figure 2.

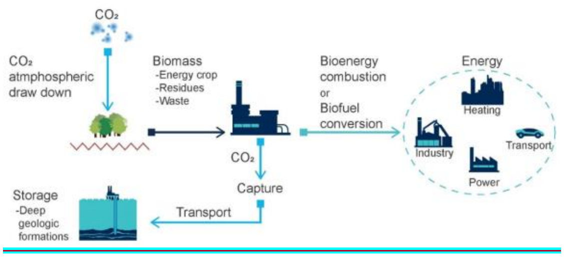


Figure 2. Bioenergy and carbon capture and storage (BECCS) schematic. Source: [26].

According to Global CCS Institute [26], there were, in 2019, five plants worldwide using BECCS technologies, capturing 1.5 million tonnes per year (Mtpa) of $CO_2$. It mentions the one large-scale BECCS facility, the Illinois Industrial CCS, capturing up to 1 Mtpa of $CO_2$. This facility produces ethanol from corn at its Decatur plant, producing $CO_2$ from the fermentation process that is stored in a dedicated geological storage site. Outside North America, Laude et al. [27] analyses a BECCS facility in Orleans, France, capturing $CO_2$ from fermentation in a sugar-beet mill, producing sugar and high-quality ethanol for perfume and chemical industries.

Other bioenergy facilities utilize the $CO_2$ for crop cultivation in greenhouses [26], similar to the one existing in Parana State, Brazil [2]. In this case, part of the $CO_2$ from fermentation in ethanol plant, from COPCANA mill, is used for greenhouses. The rest of the $CO_2$ is transported in a pipeline and sold to Raudi Industries, to produce sodium bicarbonate ($Na_2CO_3$) (9). This is maybe the only example of BECCUS in Brazil, besides the use for soft drinks, as implemented by most local sugarcane mills [2].

In fact, despite the small number of plants in operation with BECCUS, there is also a significant potential for it, mainly applied for ethanol plants, where the technology for $CO_2$ capture is already mature (10). For Brazil, Moreira et al. [28] developed a preliminary evaluation, analysing the capture of $CO_2$ from fermentation in a sugarcane ethanol plant to be injected in Guarani Aquifer and estimated a GHG emissions reduction for Brazil equal to 5% in 2016. Another study for Brazil, related to economic aspects, Merschmann et al. [29] evaluated the $CO_2$ capture from ethanol fermentation in the South-Central region of Brazil, transported and performed an enhanced oil recovery in oil fields of the Campos basin.

Future projects expected to be developed at RCGI/FAPESP/SHELL forecast more detailed analysed for technical, economic, environmental and social aspects, including issues related to social perception of BECCS in sugarcane sector (7).

## 6 FINAL REMARKS

As discussed in this paper, BECCS/U plays a major role in reducing GHG emissions towards meeting the Paris Agreement and NDC targets. Through the CCS seven uncertainties framework proposed by Markusson et al. [4][5], the objective of analysing the bioenergy sector with carbon capture and storage or usage in Brazil was enabled.

Results of such analysis point out that even though technologies are still being developed, there are some plants in operation, being five in the United States and one in France, through which it is possible to learn and speed-up the deployment. In Brazil, there are no BECCS plants in operation identified up to the present moment, although the Brazilian experience relates to biogenic $CO_2$ capture from ethanol mills, then transported and sold to greenhouses, beverages and chemical industries, denoting the usage aspect (BECCU).

Other dimension that requires attention is the need to integrate production systems in the mills with capture, transport and usage or/and storage processes. As not many storage sites have been deployed, safety assessment demands further investigation while mapping geological sites close to ethanol plants that enable to store large quantities of $CO_2$ with low energy demands. If such geological formations turnout to be capable of future $CO_2$ mineralisation alongside, as previous studies have indicated, BECCS could be positively perceived by government, legislators, industry and most importantly by local population.

The sugarcane sector in Brazil is formed mainly by few large industrial groups concentrating most ethanol production and a majority of medium or small mills, these ones being heterogeneous, conservative and resistant to major changes. The locations in which they are established have significant large populations that have not yet been specifically exposed to information about BECCUS/U, climate change and low carbon solutions. As so, another challenge refers to understanding and communicating with each public efficiently, including some of the entrepreneurs.

Conversely, the CBIO market may help to push forward the efforts to appropriate BECCS/U into to the possible solutions that collaborate towards a more sustainable and circular economy.

Evidences from this analysis lead to argue that new investigations are required. In this sense, the Research Centre for Gas Innovation (RCGI), with its five years of experience in leading projects focused on cleaner energies, which also incorporate CCS studies, will be able to contribute. Funded by FAPESP, the funding agency of the state of São Paulo and Shell Brasil, and hosted by the University of São Paulo, it is directing further research to support the Brazilian Sustainable Development Goals (SDGs) and its NDCs, to deal with challenges as:

- Increasing the Brazilian ethanol carbon footprint
- Providing bioenergy carbon capture and storage solutions (BECCS).
- Developing innovative technologies to utilise the $CO_2$ to produce high added value products (BECCU).
- Developing innovative technologies to support the mitigation of GHG and improve safety in capture, transport and storage processes.
- Incorporating natural based carbon sinks into CO2 abatement value chains.
- Evolving economic and market mechanisms.
- Developing standardisation and regulations.
- Designing scenarios and supporting decisions through integrated assessment models (IAM).
- Understanding the social perception of all agents related to the process of transitioning towards a low carbon society.

These are some examples of further studies to support the appropriate alignment of socio-technical investigations covering a broad approach to tackle complex challenges as GHG mitigation and climate change. Many others will be necessary to build deep knowledge and experience in the bioenergy with carbon capture storage and usage.

## 7 NOTES

(1) In this paper the term BECCS/U - Bioenergy and Carbon Capture Storage and Use will be used following IEA Bioenergy spelling - http://task40.ieabioenergy.com/wp-content/uploads/2020/06/IEA-Bioenergy-Task-40-Deployment-of-BECCS/U-Value-Chains.pdf

(2) Hydrated ethanol used in flex vehicles, anhydrous ethanol added to gasoline (27% in vol) and sugarcane bagasse for electricity. Available at: <http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-377/topico-470/Relat%C3%B3rio%20S%C3%ADntese%20BEN%202019%20Ano%20Base%202018.pdf> Accessed 01.07.2020.

(3) 98% of existing vehicles fleet are flex, running with any combination of gasoline and ethanol up to 100% pure (E-100).

(4) Biogenic carbon relates to the $CO_2$ emissions from biomass, corresponding to those absorbed during photosynthesis process in sugarcane growth.

(5) Biogas can be produced in sugarcane mills from vinasse (or together with filter cake, bagasse and straw), the by-product from ethanol distillation.

(6) Worst case scenario: BRL 17 $CBIO^{-1}$; Realistic scenario: BRL 34 $CBIO^{-1}$; Optimistic scenario: BRL 146 $CBIO^{-1}$

(7) In 2021, a new set of projects on BECCS/BECCUS for sugarcane mills in Brazil is expected to start at Research Centre for Gas Innovation (RCGI) founded by FAPESP and Shell.

(8) Already being used in Brazil.

(9) Personal visit. S. Coelho.

(10) Despite the fact that this production is seasonal, active only during the harvesting season.

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## 10 LOGOS

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