BECCS potential in Brazil: achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues

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Abstract. Stabilization at concentrations consistent with keeping global warming below 2°C above the pre-industrial level will require drastic cuts in Greenhouse Gas (GHG) emissions during the first half of the century; net negative emissions approaching 2100 are required in the vast majority of current emission scenarios. For negative emissions, the focus has been on bioenergy with carbon capture and storage (BECCS), where carbon-neutral bioenergy would be combined with additional carbon capture thus yielding emissions lower than zero. Different BECCS technologies are considered around the world and one option that deserves special attention applies CCS to ethanol production. It is currently possible to eliminate 27.7 million tonnes (Mt) of CO_2 emissions per year through capture and storage of CO_2 released during fermentation, which is part of sugar cane-based ethanol production in Brazil. Thus, BECCS could reduce the country's emissions from energy production by roughly 5%. Such emissions are additional to those due to the substitution of biomass-based electricity for fossil-fueled power plants. This paper assesses the potential and cost effectiveness of negative emissions in the joint production system of ethanol and electricity based on sugar cane, bagasse, and other residues in Brazil. An important benefit is that CO_2 can be captured twice along the proposed BECCS supply chain (once during fermentation and once during electricity generation). This study only considers BECCS from fermentation because capturing such CO_2 is straightforward, thus potentially representing a cost-effective mitigation option for Brazil compared to other alternatives. The assessment shows that fuel prices would increase by less than 3.5% due to the adoption of BECCS from fermentation, while increasing investors' revenues are sufficient to compensate for the investment required. With appropriate government subsidies, or by sharing BECCS costs between all car fuels and all electricity supplied by hydro and bioelectricity, the increment in ethanol and electricity prices could be less than 1% for the final consumer. Meanwhile it would supply 77.3% of all cars' fuel (private cars) and 17.9% of all electricity in Brazil.

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1. **Introduction**

Carbon capture and storage (CCS) projects have been extensively discussed as a relevant strategy for reducing Greenhouse Gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (Edenhofer et al., 2014), this technology will play a vital role in reaching the required level of emission reductions in the future.[1] In December 2010, the United Nations Framework Convention on Climate Change (UNFCCC) recognized, during the 16th Conference of the Parties (COP-16,) that CCS constitutes part of a relevant technology strategy for climate change mitigation and decided to include this option as a project activity under the Clean Development Mechanism (CDM) (UNFCCC, 2010). There are currently 55 CCS projects worldwide in progress, of which only 14 are active, as shown by the Global CCS Institute (GCCSI) at March, 2014 (GCCSI, 2014).

Compared to fossil CCS, combining CCS with bioenergy (BECCS) has the special advantage of yielding negative emissions. For some biomass feedstocks, life cycle emissions are modest and when cogeneration is part of the process, emissions are quite low (EPA 2010). Adding CO_2 capture to such systems might yield negative emissions.

Different technological approaches to BECCS are being considered around the world and one option that deserves special attention is the technology applied to sugar cane-based energy. The benefit of such a technology is that part of the primary energy is converted to ethanol via fermentation, which releases a relatively pure CO_2 stream. Capturing CO_2 at this stage presents a feasible opportunity to achieve negative emissions, making this technology an attractive option for mitigation in Brazil. Section 2 will give an overview of Brazil's national policy on climate change in this context.

The study's objective is to analyze the cost effectiveness of the suggested BECCS scheme in order to assess its attractiveness for Brazil's climate change mitigation portfolio, combining technological knowledge with economic costing of the BECCS chain. Section 2 presents the potential role of BECCS in Brazil and beyond. Section 3 analyzes a case study for Brazil, while policy implications will be discussed in Section 4. Section 5 concludes.

2. **The potential role of BECCS in Brazil and beyond**

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[1] Note, however, that an update of their roadmap is pessimistic about the contribution of CCS to large-scale emissions reductions due to the low number of demonstration projects to date and the limited time left to achieve the necessary diffusion of CCS (IEA, 2012).

In 2009, Brazil passed a law establishing its National Policy on Climate Change (BRAZIL, 2009) setting non-binding pledges to reduce Greenhouse Gas (GHG) emissions. Recently, more precise mitigation goals were established by the Brazilian Intended Nationally Determined Contribution (INDC). Brazil aims to reduce its emissions by 37% below 2005 levels by 2025, and possibly by 43% below 2005 levels by 2030 (UNFCCC 2015), which corresponds to roughly 1 $GtCO_2$.

Brazilian GHG reduction policies envision specific approaches to tackle different sectors, such as energy, forests, transportation, industry and agriculture. The Brazilian Federal Government has been able to accomplish a significant share of emission reductions by decreasing deforestation rates in Amazonia (Observatório do Clima, 2015). As of 2013, the federal government has succeeded in reducing GHG emissions by 76.7% in the Legal Amazon and 60.5% in the Cerrado Savannah. Besides nationwide carbon reduction targets, there are sub-national policies and mitigation goals in several Brazilian States. However, there are very few forests in São Paulo State, and other Southern and Southeastern states, in which most of the Brazilian economic activity takes place, so their potential to contribute to emission reductions through reduced deforestation is limited. Therefore, these regions have to consider other emission sources, and the use of other technologies, especially those related to the energy sector.

With over 80% of the electricity supply being renewable (EPE, 2013b), Brazil has one of the cleanest energy systems in the world; roughly 47% is from renewable sources compared to the world average of 19.5% (EPE, 2013a). Nevertheless, recent investments in Pre-Salt oil resource development might cause significant increases in oil and associated natural gas production[2]. Thus, energy is expected to become the major GHG emissions source beyond 2020. The Brazilian national oil and gas company (Petrobras) is investing in capturing the CO_2 that escapes during the extraction process and injecting it for either enhanced oil recovery (EOR) or storage purposes in man-made reservoirs in the saline layer (Colby et al., 2011). This indicates the relevance of CCS as an important technology to reduce the country's GHG emissions in the mid- and long-term. Nevertheless, such projects are not targeting emissions from fossil fuel combustion, but focus on fugitive emissions from oil and gas extraction.

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[2] This scenario is partially driven by the discovery of the Pre-Salt reservoirs, a major oil field that is estimated to contain at least 8 billion barrels of oil equivalent and associated gas, which will drive the country to triple its oil production (EPE, 2013a). The extraction of oil from the Pre-Salt layer is also expected to result in additional GHG emissions, since CO_2 is present in the fluid in high concentration (10-15%).

Regarding BECCS, its main benefit for the country would be to take advantage of the Brazilian achievements with ethanol, as the fuel would become the first to provide negative emissions over its life cycle carbon balance (Pacca and Moreira, 2009). Brazil has a successful example of innovative energy policy in the Ethanol Fuel Program. BECCS investments could foster socio-economic development and environmental protection concurrently if incorporating sustainable biomass. For instance, rural economic development of sugar cane producing regions, and lower CO_2 emission on the transportation sector results in better air quality in major cities. The demand for investments in the sugar/ethanol sector is significant, considering the high share of Brazilian sugar in the international market and the potential of ethanol demanded by the continuous increase of the flex-fuel car fleet; and yet, it is unclear whether the sector has the financial capacity to meet demand. Even if the sugar and ethanol demand can be met, it is wise to remember the investment needed for additional bioelectricity. . Sugar cane based bioelectricity generation is already responsible for a significant share of electricity supply in the country (see Figure 1) and is expected to grow 6.7 times between 2010 and 2035 in the state of São Paulo (SAO PAULO, 2011). However electricity generation is investment-intensive and might be an exhausting drain on available resources. Financial resources for sugar cane are allocated in the following order: a) sugar; b) ethanol; c) bioelectricity; d) BECCS. Thus, the question arises whether BECCS can generate sufficient returns for the sugar/ethanol industry. Some possibilities include ethanol exports, e.g. of advanced ethanol to other markets such as the USA and certified ethanol to the European Union. Domestic ethanol demand will require an incentive scheme for BECCS-ethanol, blends, or bio-electricity. Therefore, it would be important to determine the economic impact of BECCS to sugar cane products and users.

In addition, the development of demonstration projects for BECCS technologies is still falling behind; a large-scale Brazilian BECCS project has been cancelled due to lack of financial support. This initiative was named "RCCS Project- Capture and Storage of CO_2 deriving from the fermentation process of sugar into ethanol in the State of São Paulo". The choice of São Paulo was based on its high concentration of ethanol production (roughly 2/3 of the national production). The project was designed to capture and store 1 million tonnes (Mt) CO_2 in a saline aquifer within 10 years, at a cost of US$ 30 million. Although the Global Environmental Facility (GEF) would have funded 30% of the project, a lack of supplementary domestic financial support meant it did not become financially viable.

Although no BECCS demonstration project has yet been implemented in Brazil, the technology is available. For instance, some sugar mills in the Northeastern region have installed a system to capture CO_2 from fermentation to use the gas in industrial applications (Furtado, 2014)[3]. Technically, this system could be coupled with the technology implemented by Petrobras, which pumps and stores CO_2 underground[4].

With this study, we demonstrate the prospects of a new technology – sugar cane-based ethanol production with electricity generation, where CO_2 vented from fermentation is captured[5]. The mitigation potential thus arising for Brazil is important (a) for those regions within Brazil that cannot realize their emission reduction goals through reduced deforestation and (b) for Brazil's future climate change mitigation strategy that needs to take into account the ever rising portion of the country's GHG emission profile from energy generation. Finally, such a technology is also interesting for application in other parts of the world; this presents another important contribution of the paper. It is estimated that BECCS could reduce CO_2 atmospheric concentrations by 0.5 to 1 ppm/yr, sequestering 8 to 16 $GtCO_2$/yr[6] (CI-CDRRS, 2015)

3. **Case study: achieving negative emissions in sugar cane-based ethanol production and electricity generation**

3.1 *Previous studies*

Life-cycle GHG balances from ethanol production using sugar cane as feedstock have been published by different authors (Walter et al 2011, Souza, de Avila, and Pacca 2012). One of the most

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[3] One example is the case of Brazilian bioethanol distilleries equipped with CO_2 recovery systems from the North-American Pentair Haffmans Group, a company that has been selling its technology to breweries (which also generate the gas in the fermentation process and usually reutilize it) and to sugar cane mills in Brazil since 2009. The project relies on the system at the mills that is used for scrubbing ethanol from the vented gas post-fermentation, and adds piping and purification with activated carbon filters. The company has already supplied two systems for facilities in the State of Alagoas (Grupo Usineiro Toledo and Usina Penedo), and in the State of São Paulo (Usina Vale, a mill that produces sugar and alcohol and sells recovered CO_2). The CO_2 recovery system enables the plants to reduce CO_2 emissions and concurrently generates additional income. The first system retrieves an average volume of 70 t/day and the second 35 t/day.

[4] In 2013 Petrobras initiated a CCS project at commercial scale through CO_2 injection for enhanced oil recovery off the Santos coast to test the carbonate reservoir behavior. The capture process is pre-combustion with direct injection, and the processing plant captures roughly 700,000 tCO_2 per year. Petrobras is also leading a pilot project in Miranga Field for CO_2 separation from natural gas. (GCCSI, 2014).

[5] This CO_2 is pure. The small amount of water and ethanol dragged by the CO_2 flux is usually removed due to the ethanol's economic value. Essentially, there is no need for specific CO_2 capture technology.

[6] For the specific BECCS technology described in this paper, essentially CO_2 captured from ethanol fermentation, for each kg of ethanol produced from biological fermentation of sugars, 1 kg of CO_2 is produced and captured. Considering the amount of ethanol commercialized as fuel for transportation by 2014– 93 Mm^3/yr (Licht, 2015), as much as 74 Mt of CO_2 could be captured.

complete evaluations, considering domestic and global, direct and indirect land use change was performed by the US Environmental Protection Agency (EPA, 2010). According to that study, avoided GHG emissions due to gasoline substitution for ethanol in Brazil are 54 gCO_2e/MJ. Using sugar cane bagasse and other sugar cane residues to generate electricity fed into the grid yields even greater values. EPA (2010) finds that the emission of 91 gCO_2/MJ due to the use of liquid fossil fuel can be avoided because ethanol displaces gasoline, and bioelectricity displaces natural gas used in power plants, provided that the sugar mill uses modern efficient steam boilers (100 bar and 535°C).

Nowadays, the total contribution of bioelectricity is modest when considering the average value of electricity delivered to the grid. Data available for 2012 shows that 20 TWh have been exported to the grid, for a sugar cane availability of 600 Mt (BEN, 2013), yielding 33 kWh/t cane. The potential is greater: a survey carried out in 2011 concluded that the most efficient mills were generating around 100 kWh/t cane and exporting 75 kWh/t cane to the grid (CONAB, 2011). In reality, it is possible to generate 110 kWh/t cane using only bagasse and up to 220 kWh/t cane using bagasse and other available sugar cane residues with high pressure and high temperature steam boilers (Olivério, 2010). The full utilization of the bioelectricity potential is crucial to achieve negative emissions when BECCS is adopted.

3.2 *BECCS energy penalty and costs*

The GHG balance from the joint production and consumption of ethanol and bioelectricity is small (9 gCO_2e/MJ) (EPA, 2010) and could be further reduced to zero or below zero if CO_2, which is released during fermentation and residue combustion, is captured and stored underground. Such an approach has been discussed since 2001, and its cost-effectiveness and CO_2 reduction potential has already been evaluated (Möllersten et al, 2003). Nevertheless, a significant amount of energy is required for CCS, mainly for CO_2 separation of the furnace's flue gas but also partly for CO_2 compression.

Möllersten et al. (2003) conclude that the energy penalty due to CCS in the fermentation process is 0.12 $kWh/kgCO_2$, whereas in the flue gas, from bagasse combustion, it is 0.31 $kWh/kgCO_2$. The first alternative is less energy intensive because CO_2 from sugar fermentation exits the reactor at atmospheric pressure and temperature around 37^0C as a pure gas (99%), free of contamination and proper for food and beverage manufacturing (Gollakota and McDonald, 2014). Thus, the only required treatment is the removal of water from the fumes (because the small amount of ethanol dragged by the released CO_2 is usually separated in most sugar mills due its commercial value). The overall cost of capturing and storing CO_2 from the two sources is US$ 53/tCO_2, and yet the study concludes that applying CCS to sugar fermentation is the less expensive option.

Consequently, we believe that it is worthwhile evaluating the costs of BECCS from fermentation in a typical sugar mill unit in Brazil, which, besides ethanol, also produces electricity from crop residues. This is possibly the most cost competitive BECCS alternative. We have combined technical coefficients from a typical sugar mill with data from a large-scale BECCS pilot project.

We assume a sugar mill processing 1,800 tonnes per day (t/d) of sugar cane, but since it operates at 90%, its nameplate capacity will be 2,000 t/d. This corresponds to 4.63 Mt of sugar cane processed per year assuming that the harvesting season comprises 208 days per year, of which only 90% of the days are effective[7]. Although sugar mills with such large capacities are rare in Brazil (see Figure 1), this capacity could easily be met by two facilities in the same vicinity. As shown in Figure 1, electricity cogeneration in sugar mills is always used as self-supply, and many mills also sell surplus electricity to the grid. Usually, electricity consumption in the sugar mills is around 30 kWh/t cane and over 100 units have installed capacity able to meet consumption and sell surplus electricity to the grid.

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[7] Many factors prevent the sugar cane mill and associated facilities from working all days during the harvesting season. Some of them are as follows: intense precipitation that restricts transportation from the field to the mill, processing equipment failure either in the mill or in the cogeneration plant, and labour shortage in severe weather conditions.

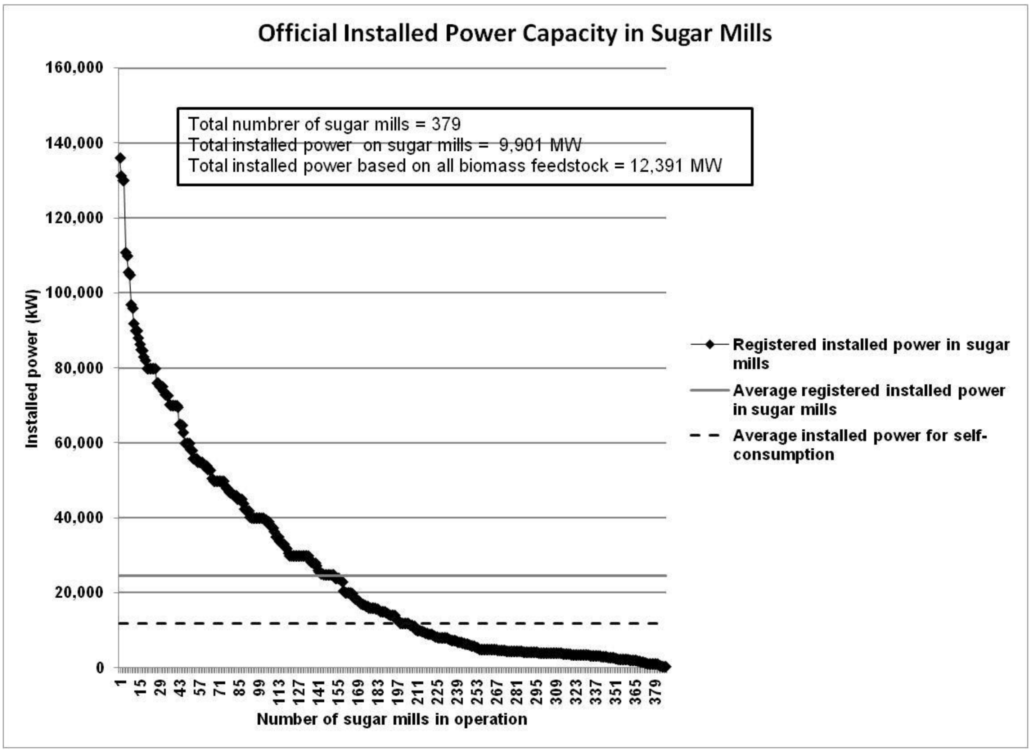


Figure 1. Distribution of cogeneration installed capacity of the 379 registered sugar mills in Brazil by 2014. Prepared by authors based on BIG (2015)

The project produces 1,729 tonnes of CO_2 per day because fermentation yields 1 kg of ethanol and 0.96 kg of CO_2 and the specific gravity of hydrous ethanol is 0.809 kg/liter. At this point, it is useful to note that CO_2 emission from the combustion of sugar cane residues (usually 100% of the bagasse and 50% of tops and leaves) is another possible candidate for CCS in sugar mills. This option is not considered in this paper due its greater cost compared to CO_2 from fermentation (Möllersten et al, 2003). Nevertheless, assuming the carbon content of dry biomass to be 50% of its weight, around 0.37 tonnes CO_2 would be produced from the combustion of 1 tonne of harvested cane. This value can be compared to the CO_2 released from fermentation of 0.070 tCO_2.

The parameters of the pumping system required to inject the daily production underground are based on the Illinois Basin Decatur Project (IBDP) and the Illinois ICCS Project (Jones and McKaskle, 2014; Gollakota and McDonald 2014).

The total installed power of the system for handling 2,000 t/day of CO_2 is 12,232 kW. Therefore, the energy penalty for pumping high pressure (14 Mpa) CO_2 underground is 0.119 kWh/liter of ethanol, or 0.147 kWh/kg of ethanol.

Such electricity can be provided by the sugar mill when processing ethanol, since it is commercially feasible to generate up to 208 kWh/t cane using all available bagasse plus a 50% share of residues (Olivério, 2010). Typical modern sugar mills in the South/Southeast of Brazil are designed to handle between 2 and 3 Mt of cane per year, while a few manage around 6 Mt of cane per year. Whatever their capacity, most of them convert roughly half of the cane to sugar and the other half to ethanol.

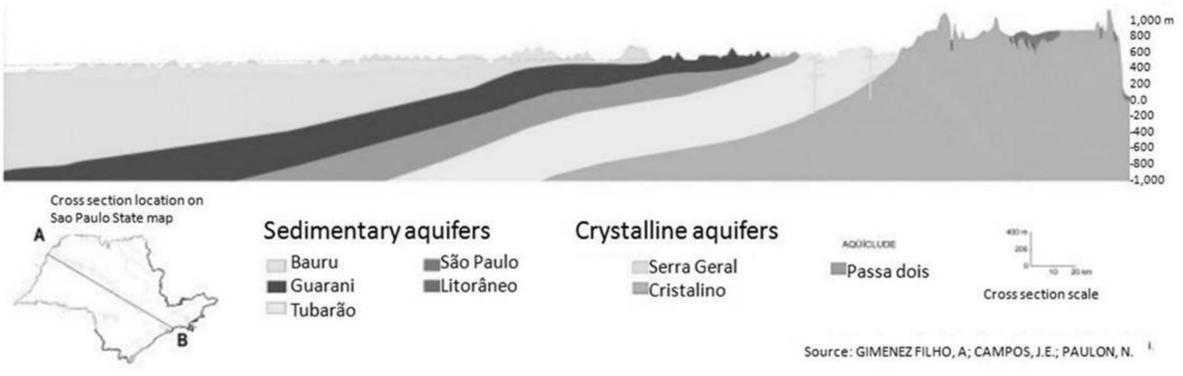
Assuming a conversion rate of 208 kWh/t cane, the total daily average generated electricity is 4,623 MWh, equivalent to an installed power capacity of 238 MW (assuming a 0.9 load factor).

With total power generation of 4,623 MWh/day, the compression requirement of 264 MWh/day represents a modest demand of 5.7%. Electricity could be sold to the grid at US$ 60/MWh, so this amounts to US$ 3.3 million per year of foregone revenues. Another way to evaluate this cost is to quote it as an abatement cost of US$ 9.16/tCO_2.

3.3 Compression and storage cost

Typically, compressor acquisition and its field installation are responsible for more than 50% of the total capital cost. At the Sleipner project (Torp and Brown, 2004), the total investment is quoted as US$$_{1996}$ 96 million, from which US$ 79 million is for the compressors and US$ 15 million for the off-shore injection well. For the Weyburn project total investment was US$$_{2000}$ 10 million (Torp and Brown, 2004), but a split for each component is not provided. For the IBDP, total investment was US$ 208 million (Gollakota and McDonald 2014), but, again, the split is not available. A presentation at the 2012 NETL CO_2 Capture Technology Meeting (Koopman 2013) quotes installed cost of high capacity and high pressure compressors as: 10-stage 6000 hp, $8.0 million at $1350/hp, pressure ratio 200:1 at 1.70 per stage; 8-stage 20,000 hp –$15.0 million at $750/hp and $23.0 million when installed at $1150/hp, pressure ratio 143:1 at 1.86 per stage, for commercial units. We estimate that the total investment in compressors is US$ 59.24 million, and the underlying assumptions are provided in the supplementary material.

The injection well cost depends on the existence of a proper geological reservoir at least 1,200 m below surface (USDoE, 2010). This requirement matches with information available for a geological formation below the Guarani aquifer. This freshwater reservoir extends continuously from the middle of the state of São Paulo (SP) to the state of Mato Grosso do Sul (MS), Parana and Santa Catarina, reaching parts of Paraguay and Argentina. Its depth is around a few hundred meters in the middle of the state of SP and goes deeper than 1,200 m at the border of SP with MS (see Figure 2). Its water is exploited by many cities in both states, and due to the number of wells already installed, the geology of the region is well-known. Furthermore, we must use saline aquifers, which are known to exist below the Guarani reservoir, such as the Tubarão saline aquifer (see Figure 2). However, its rock porosity is not yet well studied. The cost of drilling a 1,200 m deep well is approximately US $500,000. However, it might be necessary to drill at least 3 wells in order to find a reservoir with appropriate conditions, such as good rock porosity. Thus, the total cost of finding a well is $1,500,000. In addition, in order to avoid contamination of shallower aquifers that are important drinking water sources (Piramboia and Botucatu) and in order to allow for the injection of pressurized CO_2, the well must be insulated by a steel casing. This adds 40% to the cost of the successful well. Consequently, the total well cost is US $2,100,000 (Hashiro, 2015).



Source: GIMENEZ FILHO, A; CAMPOS, J.E.; PAULON, N.

Figure 2: Hydrogeological profile of the state of São Paulo

Source: Altimetria: cartas do IBGE, escala 1:250.000; Limites geológicos: carta geológica do Brasil ao milionésimo, folhas Paranapanema (LOPES et al. 2004) e Rio de Janeiro (LEITE et al. 2004)

Transportation cost is evaluated based on the assumption that existing saline aquifers are also continuously distributed over the same region of the Guarani aquifer. In addition there are around one hundred sugar mills distributed over an area of 200 X 200 km in the Western part of SP state, which yields an average density of one per 400 km^2. Given these two assumptions, a typical length of 10 km for a CCS pipeline is a reasonable figure. The total cost of a twenty cm diameter pipeline with 10 km length is US$ 5 million (Knoope et al, 2013). Table S2 displays all investment costs considered in our analysis.

In our model, taking into account the significant proportion of hydroelectricity in the Brazilian electricity matrix (90% of the consumption, on average), we assumed that electricity used to power the CCS system will be supplied by the grid, instead of providing it through the sugar mill. This can be justified by: a) the need to avoid double-counting of the CCS cost, since the electricity generated at the mill will be more expensive than the power generated in sugar mills without CCS; b) providing a procedure to reduce the overall CCS cost, given that there is often excess hydroelectricity to guarantee the grid supply security and the CCS project does not need to operate continuously throughout the year or even every year; c) the fact that ethanol and bioelectricity production from sugar cane are not feasible during part of the year, since the sugar cane harvesting season is limited to 208 days per year. Thus, from the total investment cost quoted in Table S2, the value of US$ 21.35 million, which is the cost for power generation used in CCS operation, is removed and replaced by an annual operational cost covering the expenses from hydroelectricity acquisition from the grid. Furthermore, it is important to add a value that represents maintenance costs of the complete system in particular compressors, to the operational cost of CCS. This cost is assumed to constitute 5% of the investment cost in compressors, i.e. US$ 2.96 million/yr. Considering both of these operational costs, and assuming a lifetime of 18 years for the facility, the overnight construction of CCS comprises US$ 6.65 million/yr and its operational cost is US$ 3.31 million for annual electricity acquisition, at a unit cost of US$ 60/MWh[8]. Thus, the total annual cost adds up to US$ 9.99 million. The electricity acquisition value is discussed in the following subsection. Given all these cost assumptions, and considering that the total amount of CO_2 handled by the CCS system is 360,236 tonne/yr, the full overnight CCS cost for the producer is US$ 27.20/tCO2. In comparison, a study done in Europe has found equivalent values of between US$ 44-66/tCO2 for CCS projects applied to power plants (ZEP, 2015).

4. **Implications for policy support**

The sugar mill revenue from product sales is estimated to be $60/MWh (LEILÃO, 2013) and $0.6/liter[9]. CCS installation generates an additional producer cost of US$ 30.29/tCO_2, which is a realistic value when the financial costs of the sugar mill with CCS plus the economic return on the

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[8] The average consumers' price of electricity in Brazil by 2012 was US$ 169.58/ (FIRJAN, 2012). Considering the transmission and distribution prices, and taxes the average electricity sales price at the power plants were US$ 43.81/MWh (EPE, 2013b: Instituto Acende Brasil, 2011). Considering hydroelectricity supply in 2012 was 415,000 GWh and thermoelectricity 112,000 GWh, the respective producer sales price were US$ 38.37 and 63.95/MWh. Since the BECCS unit is expected to import mainly hydroelectricity the value assumed in this study is justified.

[9] The average sales prices of hydrous ethanol and anhydrous ethanol in 2012 at sugar mills without taxes were US$ 0.567 and US$ 0.644/liter, respectively (ANP, 2013). This yields an average ethanol sales price of US$ 0.6015. Since in this study we are anticipating a greater increase in the use of ethanol than in gasoline, and a consequent increase in demand for hydrous, rather than anhydrous ethanol, the assumed value looks reasonable.

investment is taken into account. Details on the calculation of the additional CCS cost are presented in the supplementary material.

Based on these conditions we have evaluated four policy scenarios.

4.1. Sharing the cost between ethanol fuel and bioelectricity

Given that this cost is shared between both products, one possibility is to increase the bioelectricity production price by US$ 1.49/MWh and the price of ethanol by US$ 0.021/liter. These are both sold at the sugar mill gate without taxes[10]. Comparing this to the price of ethanol at the pump in producing regions in Brazil (US$ 0.953 and 1.123/liter for hydrous and anhydrous, respectively (ANP, 2013; PETROBRAS, 2015)) we can identify the value of other trading costs (distribution and retail), and taxes. The average generation sales price of electricity to final consumers represents 25.83% of the final price and the average taxes represent 45% of the final price (Institute Acende Brasil, 2011). Considering these costs and taxes occurring between the farm gate and end-users, the additional cost of CCS will be fully paid by ethanol consumers at US$ 0.0334/liter, increasing its price to US$ 0.987, or 3.50%. Since a share of the CO_2 cost is also included in the price of bioelectricity, this bioelectricity will be sold at US$ 138.58/MWh, which means an increase of US$2.716/MWh to final consumers (see Table 1).

4.2. Sharing the cost between all light vehicles fuel consumers and all electricity consumers

Actually, considering the important contribution of such a project for climate change mitigation, the cost increase might be paid not only by final hydrous ethanol consumers, but by all car users, regardless of fuel. In the country, the amount of gasohol sold represented 80.12% of total fuel used by Otto engines in 2012 (ANP, 2013), while the hydrous ethanol (92% pure) takes the remaining share of 19.88%; no neat gasoline is sold to final consumers. The gasohol is a blend of 20% anhydrous ethanol and 80% gasoline by volume[11], at an average consumer price of US$ 1.366/liter (ANP, 2013). Thus the 49.6 million cubic meters of liquid fuels used for cars are primarily composed of 64.10% gasoline, 19.88% hydrous ethanol (92% pure), and 16.02% anhydrous ethanol (99.3% pure). Sharing the extra cost of US$ 0.0334/liter of ethanol across all these fuels, we conclude that

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[10] The cost added by CCS can be shared between ethanol and bioelectricity sold by the mill. Several combinations of figures are possible, including charging all cost to either one of them. In this discussion, we choose one particular set of extra costs for electricity and ethanol.

[11] For many years gasohol has been a blend of 75% gasoline and 25% anhydrous ethanol. In particular, for 2012 the composition was 80% gasoline and 20% anhydrous ethanol.

their final consumer prices would rise by US$ 0.0066, which implies a hydrous ethanol relative price increase of 0.70%. The price increase would be slightly higher for anhydrous ethanol and gasoline, which are sold at a higher price than hydrous ethanol (see car fuel price at Table 1). Our model assumes that BECCS might be adopted by two thirds of Brazilian sugar mills (400 Mt of sugar cane per year), so the share of hydrous ethanol could reach 77.3% of the total fuel used for passenger cars.

The increase in bioelectricity price to consumers could also be shared by all electricity consumers supplied by hydro and bioelectricity. Since the hydroelectricity supply is 415,000 GWh and bioelectricity could provide 74,312 GWh per year if 400 Mt cane (two thirds of the total sugar cane harvested in 2012) were processed in BECCS modern sugar mills, the US$ 2.716/MWh bioelectricity price increase would be distributed equally, in a percent basis, across all final electricity consumers at an average price of US$ 0.474/MWh (see electricity price at Table 1).

4.3. Government subsidy to bioenergy producers

Another possibility is for a government subsidy or tax reduction to cover the estimated CO_2 emission cost to society. By 2014, about 40 countries and over 20 sub-national jurisdictions have put a price on carbon. Assuming Brazil would accept a CO_2 cost of US$ 10/tCO_2[12], the net CO_2 producer cost for BECCS would then be US$ 19.93 /tCO_2. Under such a scenario, the additional cost of ethanol and bioelectricity at the sugar mill gate would be US$ 0.0141/liter of hydrous ethanol (or US$0.0224 for the final consumer and US$ 0.0044 when the extra cost is also shared with gasohol) and US$1.819/MWh for bioelectricity consumers (or US$0.276/MWh when the extra cost is also shared with hydroelectricity consumers), respectively. These last figures correspond to a relative increase in hydrous ethanol and bioelectricity consumer's price of 0.47% and of 0.20% for BECCS (see Table 1).

4.4. Tax moratorium on prices increasing due to BECCS

Another, more plausible, approach would be to negotiate a moratorium with governments on the taxing of price increases in liquid fuels used in passenger cars and bioelectricity sales to the grid due to CCS projects given their relevant and unique contribution to climate change mitigation. Since taxes charged on fuels and electricity are quite significant in Brazil, such an action would impact the

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[12] Brazilian government has not shown willingness to provide direct environmental subsidy; therefore, we have adopted a modest value.

final price of these energy carriers. To properly evaluate the extra cost of these energy carriers under this scenario, we have evaluated the market price of liquid car fuels in 2012 taking into account trading costs, taxes, and their values under the proposed government policy (Table S4).

Based on the assessed market values, we conclude that hydrous and anhydrous ethanol, as well as gasoline excess charges to cover CCS activities must increase on average by US\$ 0.0065/liter relative to the current cost. This means a price increase for the final consumer of 0.50% for hydrous ethanol and also for anhydrous and gasoline to cover the CCS deployment cost. It is important to remember that in our model this cost would be shared with electricity consumers; on top of these fuel price increases, bioelectricity and hydroelectricity prices for the final consumer must be increased, on average, by US\$ 0.261/MWh or 0.17% for bio- and slightly more for hydroelectricity, as shown on Table 1 and Table S5. This implies a cost, for the consumer, of US\$ 31.63/$\mathrm{tCO_2}$ for liquid fuels and US\$ 2.73/$\mathrm{tCO_2}$ for electricity, which totals US\$ 34.36/$\mathrm{tCO_2}$ (see real BECCS price at Table 1).

Table 1- Impacts on the cost and prices of BECCS and in fuel and electricity due different government policies*

	No Carbon Tax			With Carbon Tax @ US$ 10/tCO2			With Tax Moratorium	
	Producer cost increase	Consumer price increase	Shared Consumer price increase[a)]	Producer cost increase	Consumer price increase	Shared Consumer price increase[a)]	Consumer price increase	Shared Consumer price increase
Overnight BECCS cost (US$/tCO2)	27.200			17.200				
Real BECCS price (US$/tCO2)	30.293	47.908	47.908	19.930	32.094	32.094	34.364	34.364
Bioelectricity (US$/MWh)	1.494	2.716	0.412	1.001	1.819	0.276	1.494	0.227
Ethanol (US$/liter)	0.0210	0.0334	0.0066	0.0141	0.0224	0.0044	0.0246	0.0048
Bioelectricity (%)	5.91%	2.00%	0.30%	3.96%	1.07%	0.20%	1.10%	0.17%
Ethanol (%)	3.50%	3.50%	0.70%	1.48%	2.35%	0.47%	2.58%	0.50%
Electricity (US$/MWh)			0.474			0.317		0.261
Car fuel (US$/liter)			0.0088			0.0059		0.0065
Electricity (%)			0.30%			0.20%		0.17%
Car fuel (%)			0.70%			0.47%		0.50%

[a)] CO2 cost for electricity shared between bio and hydroelectricity supply; CO2 cost for ethanol shared between all cars'fuels

* Figures calculated by authors considering: ethanol w/ BECCS consumer price = US$ 0.621/liter, financing interest rate = 2%, equity share = 20%, IRR on equity = 6%

4.5. Consequences for society

Another way to put BECCS into perspective is by comparing its cost to other mitigation alternatives in the country. In a recent assessment, the cost of emission reductions due to the production of ethanol through cellulose hydrolysis was 37.64 US\$/$\mathrm{tCO_2}$, whereas the cost of emission reductions due to new cogeneration projects that yield surplus electricity was 27.9 US$/t CO_2 (Schaeffer, Szklo, de Gouvello, 2010). These values are comparable to the ones presented in our assessment.

We must realize that the construction of the first BECCS installations will probably involve extra costs, firstly because our assessment has not included some project items such as CO_2 dewatering[13], environmental licensing, project monitoring, geological site feasibility studies, etc. and secondly because the first-of-a kind project always carries some learning costs. Regarding the first point, it is reasonable to add some contingency reserves of about 20% of the evaluated cost shown in Table S2. As this is essentially an R&D process, a case can be made for these costs to be borne by society.

Once successful, the BECCS project could be enlarged to take advantage of the existing ethanol producing logistics in Brazil. As discussed above, a significant share of investment expenditures are due to CO_2 compression; the larger the volume of CO_2 produced within the proximity of the storage site, the lower the investment costs. Indeed, compressor cost is strongly dependent on capacity.

Finally, a typical car using hydrous ethanol has an annual consumption of 1,650 liters of ethanol. Assuming a long term optimistic consumer cost of only US$ 20/tCO_2, either by policies and/or technological improvement, instead of our calculated value (US$ 47.91/tCO_2 – see Table 1) consumers, when using a BECCS facility similar to the one modelled in our case study (producing 2,225 m^3 of ethanol/day, sequestering 1.729 tCO_2/day), bear an annual expense of US$ 6.24/car, if BECCS cost is shared between all cars fuels. Regarding the bioelectricity price impact on consumers, it is necessary to note that average monthly electricity consumption by household is around 160 kWh. Due this CCS cost increase, consumers pay an electricity premium of US$ 0.152/MWh, with annual impact of US$ 0.297. Since residential consumption represents roughly a third of total consumption in the country, final direct and indirect annual cost of electricity to consumers total US$ 0.963 per household. Looking at both the cost of liquid fuels and electricity, total annual expenses for carrying out this CCS program in Brazil would amount to US$ 7.21 per household.

It is worthwhile noting that with this extra expense, 27.7 MtCO_2 would be removed from the atmosphere every year compared to the current baseline scenario. Assuming that a long-term cost

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[13] Pipeline construction and operation costs are assumed to be small. According to Möllersten et al (2003), for a flow of 125 t/hr and a 50 km pipeline, the cost is US$ 7-10/tCO_2. For this project, the flow is 100 t/hr, but the pipeline is assumed to measure less than 10 km (see Jones and McKaskle, 2014). Furthermore, the energy required for CO_2 transportation and equipment (low pressure compressor) has already been included in our cost calculation as shown in Table S2. Thus, even considering US dollar inflation in the period 2003/2013, the transportation cost is similar to the value estimated by Möllersten et al. (2003).

of US$ 20/tCO_2 is achievable, this represents US$ 554 million/yr. According to the IPCC's Fifth Assessment Report (Edenhofer et al., 2014) the achievement of CO_2 atmospheric concentration stabilization at 550 ppm requires emission reductions between 50 and 15 GtCO_2/yr from 2010 to 2100. The cost of achieving this is 0.04% of World GDP (US$ 70 trillion). Put differently, the reduction must be 1.3%/yr or 650 MtCO_2/yr in the initial years, at a cost of US$ 28 billion/yr or US$ 43.1/tCO_2. Putting the results of this study roughly into context, if all mitigation was based on ethanol CO_2 fermentation CCS, the cost would be US$ 13.0 billion/yr or less than 50% of the IPCC estimates.

5. **Conclusion**

This paper has presented a case study on a BECCS scheme, where CCS is applied to CO_2 vented from a Brazilian ethanol fermentation installation using ethanol by-products (bagasse and other sugar cane residues). The by-products are used for the production of heat and bioelectricity self-consumption, as well as for third parties users through the electric grid. Ethanol produced from such a BECCS plant must be sold to final consumers at US$ 0.0334/liter above the regular ethanol price, which translates into a price increase of 3.50%. Bioelectricity price also increases by US$ 2.716/MWh, which corresponds to a 2.00% increase in the current market price.

Alternatively, the extra cost of the ethanol could be charged to the gasoline blend rather than the ethanol alone. Blended gasoline is one part ethanol and five parts gasoline, and consumers would pay an extra charge of US$ 0.066/liter to compensate the BECCS ethanol producer. This is found to be sufficient for the BECCS investor to be attracted to the BECCS system investment. An increase of US$ 0.066/liter represents a 0.70% increase in the price of hydrous ethanol and a little more in the blended gasoline price. Similarly, the bioelectricity incremental cost due to BECCS could be distributed across electricity supplied through hydropower, which is the cheapest electricity source in the country. This would generate an average increase in bio- and hydroelectricity prices of US$ 0.412/MWh (see Table 1) representing a relative increase of 0.30% for bioelectricity and slightly more price increase for hydroelectricity.

In addition, we discussed the possibility of government subsidies. One option is for a US$ 10/tCO_2 premium to be paid to the mill owner and the other is a government moratorium on taxing additional costs of ethanol and bioelectricity from a BECCS sugar mill. Both options imply a small final price increase to the consumer, with the latter option being the most favorable one. Ethanol prices would be increased by US$0.048/liter or 0.50%, while the electricity price would show an increase of US$0.261/MWh (0.17 %). This translates into an additional annual cost of US$12.38 per household in Brazil. In conclusion, the proposed technology, where CO_2 is captured from fermentation alone, is not far from being economical, and further research into this area is warranted. Capturing the CO_2 released from the sugar mill furnaces should also be examined as, with a CCS efficiency of 100%, this could capture 628% more CO_2 than the amount calculated in this study. In this way negative emissions could be pushed even further.

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Supplementary material

Technical details of the CO_2 compression system:

The CO_2 compression at the Illinois Basin Decatur Project (IBDP) consists of a centrifugal booster blower, four parallel 4-stage reciprocating compressors, a dehydration unit, and a centrifugal pump (Jones and McKaskle 2014). Table S1 shows the technical characteristics of the CO_2 compression system.

TABLE S1: Technical characteristics of IBDP CO_2 compression system

	Initial pressure	Initial temperature	Enthalpy	Final pressure	Final temperature	Enthalpy	Power	Capacity
	MPa	^{0}C	kJ/kg	Mpa	^{0}C	kJ/kg	kW	tCO2
Gas blower - 4 stages	0.1	37.8	516.81	0.24	93.3	565.32	2238	2,000
Compressor 2, 1st stage	0.24	35	513.17	0.52	145	612.64	2424	500
Compressor 2, 2nd stage	0.52	35	510.72	1.71	156	617.99		
Compressor 2, 3rd stage	1.71	35	499.38	4.10	123	572.04		
Compressor 2, 4th stage	4.1	35	472.16	9.80	133	550.05		
Centrif. Booster	9.8	35	295.84	15.80			298	2000

Source: Prepared by authors based on Gollakota, S and McDonald, S ,2014; Jones and McKaskle, 2014

Cost assumptions for the compression system:

1) A scale factor of 0.55 was adopted for the compression system;

2) Installation cost adds US$ 400/hp to the 20,000 hp compressor, which is 53% of the compressor cost, and might be higher for smaller units.

Considering this project's CO_2 injection rate (1,729 tCO_2/day) and the compressor configuration used in the IBDP project, it makes sense to use 4 four-stage 3,250 hp high pressure compressors, 1 gas blower of 3,000 hp for the low pressure compressor and 1 centrifugal booster for final compression, with 400 hp.

3) For the high pressure compressor (3250 hp) cost is US$ 11.06 million, including installation work, whereas only the compressor costs US$ 6.15 million and installation costs US$ 4.91 million.

4) For the low pressure compressor, with a capacity of 3,000 hp, the cost is obtained in the same way as the previous one, yielding a total compressor cost of US$ 5.93 million plus 4.74 millions for installation – totaling US$ 10.67 million.

5) For the centrifugal booster with a capacity of 400 hp, the same approach is used, yielding total costs of US$ 4.31 (2.39 and 1.92) million.

Total compression system cost is US$ 59.24 million (4X11.06+1X10.67+1X4.31).

Table S2 shows a complete cost of the CCS system considered in our analysis, including data already presented on the main text.

TABLE S2 –BECCS system costs in sugar mills in Brazil

Equipment	Investment (Million US$_{2012}$$)	Cost share
Compressors	59.24	67.56%
Power generation for CCS	21.35	24.35%
Injection well preparation	2.10	2.39%
Pipelines	5.00	5.70%
Total	87.69	100.00%

Source: Prepared by authors

Real CCS cost to society

In the main text, we have calculated overnight mitigation cost of CO_2 due to a BECCS system implemented in an efficient sugar cane mill, which collects and stores CO_2 from sugar fermentation. Nevertheless, society has to pay for the project cost and its revenue, because no investor would be interested in the installation and operation of the proposed BECCS system. In order to consider these aspects, plus the fact that the installation of modern sugar mills entails the construction of an efficient electric plant that is able to produce and sell high amounts of electricity to the grid while mitigating CO_2 emissions from sugar fermentation, a financial model was used.

The model considers the facility composed by: 1) a sugar mill without energy (heat and power) supply; 2) an electric power plant producing heat and power through cogeneration, which is the standard in all mills in Brazil; 3) the CCS system.

For the sugar mill, the investment cost is evaluated considering a value of US$ 80 per tonne of cane processed per year (Marques, 2008)[14], and 80% of the value is financed at 2% interest rate, over 16 years, with constant amortization values throughout the period.

For the modern electric power plant the investment cost is US$ 1,756 per kW installed for a 60 MW plant[15], and 80% is financed at the same conditions of the sugar mill. For the CCS system, total cost is quantified on Table S2 (except the US$ 21.35 million that, as discussed in the main text, is unnecessary since electricity supply for CCS is acquired from the grid), and financed under the same conditions already discussed for the sugar mill and electric power plant.

Inflation is neglected and due to lack of regulation, installation depreciation cost is not accounted for. Revenues are accounted separately from ethanol sales, electricity sales, and, eventually, from the value attributable to CCS's CO_2. Ethanol sales price at the sugar gate is assumed as US$ 0.60/liter (ANP, 2013) without taxes; electricity sales price is assumed as US$ 60.00/MWh, without taxes, for the facility operating without the CCS installation.; CO_2 might be remunerated through carbon credit (typically, US$ 10 to 20/tCO2, or another kind of subsidy discussed on the main text).

The model calculates Project's Internal Rate of Return (IRR) and Equity's IRR, assuming no inflation on values. Thus, real IRRs must be evaluated considering the calculated IRRs plus inflation. Therefore, interest rates for financing are low, while equity's IRR around 6% is considered attractive to investors.

The main parameters considered in the model are summarized on Table S3.

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[14] This source concludes that the average investment cost for sugar cane mills ranges from 57 to 86 US$/tcane in 2008. Considering all economic figures are quoted in US$ 2012, we select values near the top of the range. Sensitivity evaluations were carried out for values of US$ 75 t0 85/tcane, without any significant impact on our main conclusions.

[15] For other power capacity, an economic scaling factor of 0.75 is used to account for the cost per kW.

Table S3: Economic - financial model assumptions (All monetary values in 2012 US$)

Sugar mill investment cost (US$/tcane processed)	80
Sugar mill financed investment (%)	80.00
Sugar mill financed interest (%)	2.00
Sugar mill financed grace period (year)	2
Sugar cane financed period (years)	16
Sugar mill construction time (years)	2
Ethanol sales price at sugar mill gate (US$/litre)	0.60
Sugar cane cost (% of ethanol sales price)	50
Sugar cane processing cost (% of ethanol sales price)	32
Sugar cane to hydrous ethanol (92%) yield (litres)	90
Sugar cane yield (tonnes/ha)	100
Electricity plant investment (US$/MW)	1756
Electricity plant financed interest (%)	2.00
Electricity plant financed cost share (%)	80
Electricity plant financed grace period (years)	4
Electricity plant financed period (year)	16
Electricity plant construction time (years)	2
Acquired electricity cost for the CCS system (US$/MWh)	60

Table S4: Price profile due commercialization without BECCS and with BECCS cost shared with all liquid fuels used in cars -moratorium taxation scenario

	Values for year 2012[a] (US$/liter)			**BECCS cost shared with all car fuels[a](US$/liter)**		
Car fuel type	Hydrated eth.	Anhydrous eth.	Gasoline A	Hydrated eth.	Anhydrous eth.	Gasoline A
Consumption share[b]	19.880%	16.024%	64.096%			
Fuel price at mill/refinery	0.6000	0.6443	0.8183	0.6044	0.6488	0.8239
Distribution margin[c]	4.54%	8.00%	17.00%	4.54%	8.00%	17.00%
Service station margin[c]	5.00%	7.00%		5.00%	7.00%	
Disrt&Service stat. price	0.0910	0.1685	0.2425	0.0916	0.1697	0.2442
Taxes share[c]	27.54%	27.64%	25.64%	27.54%	27.64%	25.64%
Taxes value	0.2626	0.3105	0.3658	0.2644	0.3126	0.3683
Fuel for consumers[c]	0.9536	1.1233	1.4266	0.9602	1.1311	1.4362
increase[d]				0.0066	0.0078	0.0096
BECCS fuels overtaxes				0.0018	0.0022	0.0025
BECCS fuels taxes return				0.0018	0.0022	0.0025
BECCS fuel real price increase				0.0048	0.0057	0.0072
BECCS fuels relative price increase				0.50%	0.50%	0.50%
Average BECCS price increase				0.0065		
Average BECCS relative price increase				0.50%		
Average BECCS price (US$/tCO2)[d]				31.11		

	Values for year 2012[a] (US$/liter)			Values with BECCS applied to all car fuels[a](US$/liter)		
Car fuel type	Hydrated eth.	Anhydrous eth.	Gasoline A	Hydrated eth.	Anhydrous eth.	Gasoline A
Consumption share[b]	19.880%	16.024%	64.096%			
Fuel price at mill/refinery	0.5670	0.6443	0.8183	0.5729	0.6500	0.8240
Distribution margin[C]	7.00%	8.00%	17.00%	7.00%	8.00%	17.00%
Service station margin[C]	6.00%	7.00%		6.00%	7.00%	
Disrt&Service stat. price	0.1240	0.2041	0.2420	0.1253	0.1700	0.2442
Taxes share[C]	27.54%	27.64%	25.64%	27.54%	27.64%	25.64%
Taxes value	0.2626	0.3105	0.3658	0.2654	0.3133	0.3684
Fuel for consumers[C]	0.9536	1.1233	1.4266	0.9636	1.1333	1.4366
increase[d]				0.0100	0.0100	0.0100
BECCS fuels overtaxes				0.0028	0.0028	0.0026
BECCS fuels taxes return				0.0028	0.0028	0.0026
BECCS fuel real price increase				0.0073	0.0073	0.0075
BECCS fuels relative price increase				0.76%	0.65%	0.52%
Average BECCS price increase				0.0074		

[a] Values in US$/liter when no unit shown; [b] ANP, 2013; [c] PETROBRAS, 2015;

[d] Calculated with model described in text for BECCS hydrous ethanol producer price @ US$ 0.621/liter, interest on financing share of 2%/yr, 20% equity share, and 6% internal rate of return on equity.

Source: Prepared by authors based in ANP, 2013 and PETROBRAS, 2015 data

Table S5 displays typical average prices for commercial electricity sales, including transmission, distribution costs, and taxes.

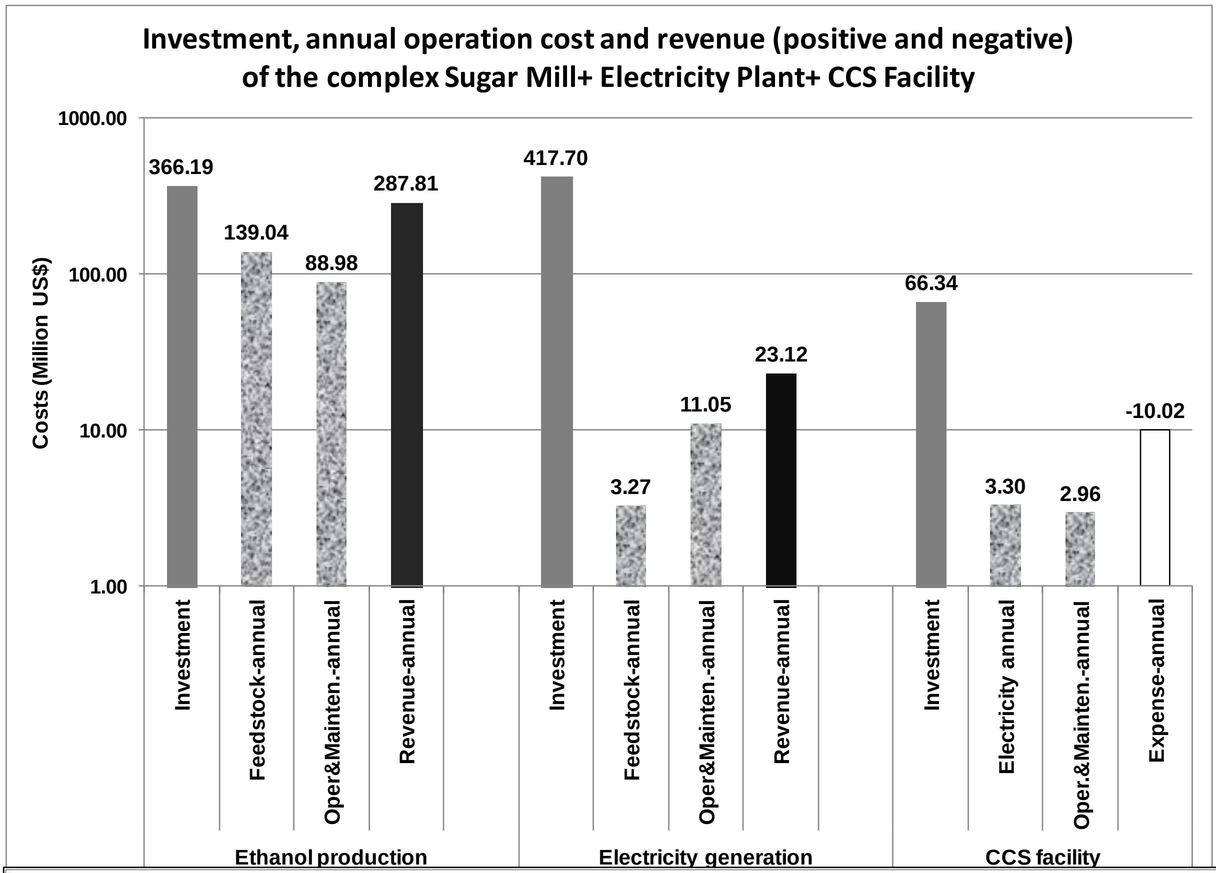
Table S5: Average cost composition of electricity to final consumers.

	Average electricity cost[a]	Hydro elec.[b]	Hydro elect.	Bio elect[d]	Bio elect w/o BECCS	Bioelect w/ BECCS	Bioelect w/ BECCS w/ tax return	Bioelect w/ BECCS sharing cost[f]	Bioelect w/ BECCS sharing cost and taxes return[f]	Hydroelec w/ BECCS sharing cost and taxes return[f]
	(US$/MWh)	(GWh/yr)	(US$/MWh)	(GWh/yr)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)
Generation	43.809	415,000	38.372[c]	74,312	25.265[e]	26.759[e]	26.759[e]	25.492[e]	25.492[e]	38.638[e]
Transmission	8.479		8.479		8.479	8.479	8.479	8.479	8.479	8.479
Distribution	40.983		40.983		40.983	40.983	40.983	40.983	40.983	40.983
Sub-total	93.271		87.834		74.727	76.221	76.221	74.954	74.954	88.100
Taxes	76.312		71.864		61.141	62.363	62.363	61.326	61.326	72.082
Consumer cost	169.583		159.698		135.868	138.584	138.584	136.280	136.280	160.182
Price increase due BECCS						2.716	2.716	0.412	0.412	0.485
Overtaxes						1.222	1.222		0.186	0.218
Overtaxes return						0.000	1.222	0.000	0.186	0.218
Consumer price w/ tax return						138.584	137.362	136.280	136.095	159.964
Price increase due BECCS						2.716	1.494	0.412	0.227	0.267
Relative final price increase						2.00%	1.10%	0.30%	0.17%	0.17%

	Average electricity		Hydro elec.[c]	Hydro elec.[d]	Bio elect[e]	Bio elect[a][f]	Bioelect w/ BECCS[f]	Bioelect w/ BECCS w/ tax return[f]	Bioelect w/ BECCS sharing cost[f]	Hydroelec w/ BECCS sharing	Bioelect w/ BECCS and taxes return[f]	Hydroelec w/ BECCS taxes return[f]
Item	Cost share[a]	Cost[b] (US$/MWh)	(GWh/yr)	(US$/MWh)	(GWh/yr)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)	(US$/MWh)
Generation	25.83%	43.809	415,000	38.372	74,312	37.708	45.703	45.703	38.922	39.586	38.376	39.040
Transmission	5.00%	8.479		8.479		8.479	8.479	8.479	8.479	8.479	8.479	8.479
Distribution	24.17%	40.983		40.983		40.983	40.983	40.983	40.983	40.983	40.983	40.983
Sub-total	55.00%	93.271		87.834		87.170	95.165	95.165	88.384	89.048	87.837	88.502
Taxes	45.00%	76.312		71.864		71.321	77.862	77.862	72.314	72.857	71.867	72.410
Consumer cost	100.00%	169.583		159.698		158.490	173.028	173.028	160.698	161.905	159.704	160.912
Price increase due BECCS							14.537	14.537	2.208	2.208	1.214	1.214
Overtaxes							6.542	6.542				
Overtaxes return							0.000	6.542				
Consumer price w/ tax return							173.028	166.486	160.698	161.905	159.704	160.912
Price increase due BECCS							14.537	7.996	2.208	2.208	1.214	1.214
Sharing price increase w/ hydro[g]							2.208	1.214				
Relative final price increase							9.17%	5.04%	1.39%	1.38%	0.77%	0.76%

[a] Calculated based in average electricity price (FIRJAN, 2012; Instituto Acende Brasil, 2011) and average bidding hydroelectricity price (MME, 2012), as well as the share of hydro (415 TWh) and thermal power (132 TWh) in Brazil (EPE, 2013); [b] EPE, 2013; [c] Price from 2012 bidding (MME, 2012); [d] Authors assumption based in the installation of 86 BECCS mills processing 400 Mt of sugar cane/yr; [e] Generation cost evaluated from authors' model discussed in the paper; when the BECCS is shared with ethanol priced at US$ 0621/l for the consumer; [f] Part of the BECCS cost paid by hydrous, anhydrous, and gasohol fuel users, and the other part shared by all users of bio (74.3 TWh) and hydroelectricity (415 TWh). Source: Compiled by authors.

Figure S1 synthesize some results from our model.


Investment, annual operation cost and revenue (positive and negative) of the complex Sugar Mill+ Electricity Plant+ CCS Facility
Costs (Million US$)
1000.00
100.00
10.00
1.00
366.19
139.04
88.98
287.81
417.70
3.27
11.05
23.12
66.34
3.30
2.96
-10.02
Investment
Feedstock-annual
Oper&Mainten.-annual
Revenue-annual
Investment
Feedstock-annual
Oper&Mainten.-annual
Revenue-annual
Investment
Electricity annual
Oper.&Mainten.-annual
Expense-annual
Ethanol production
Electricity generation
CCS facility

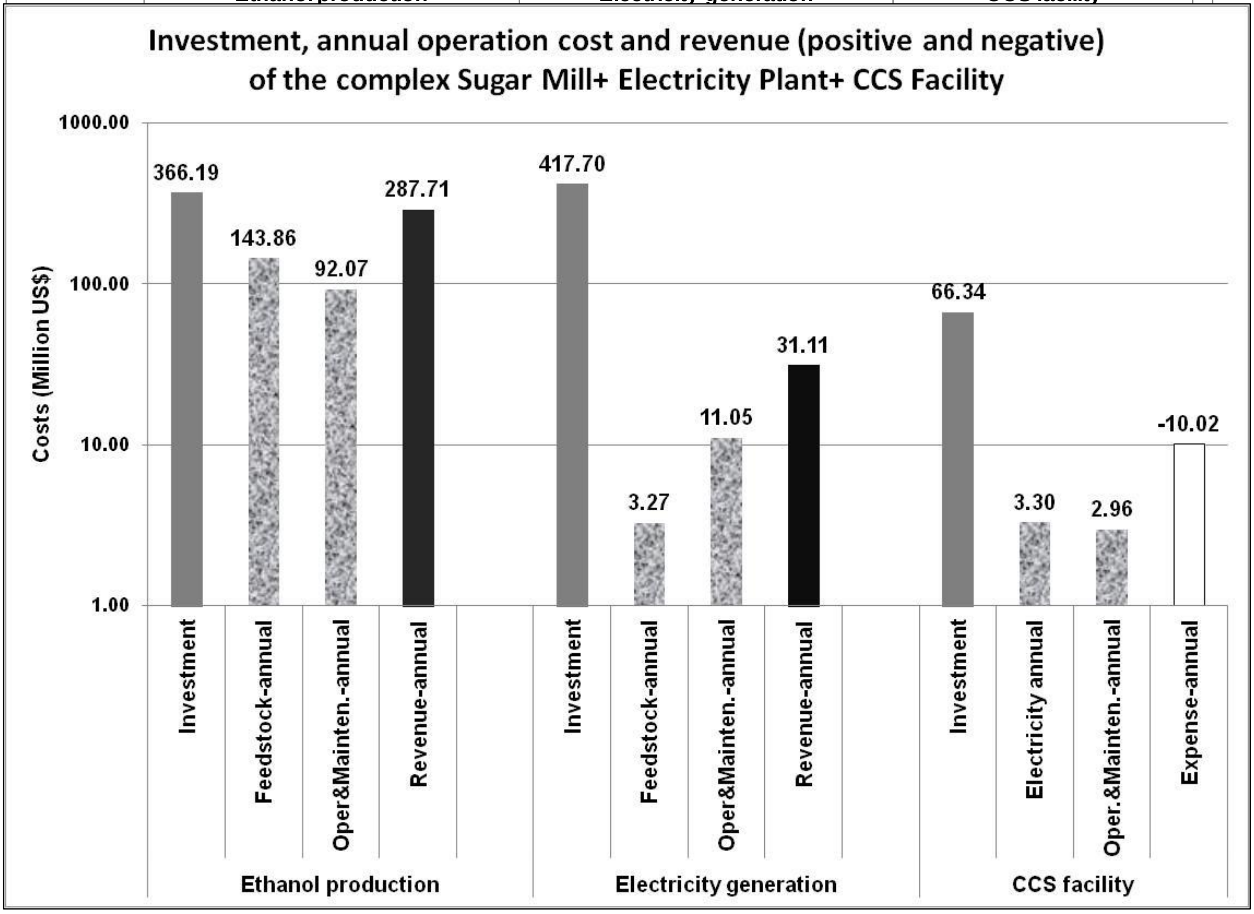

Investment, annual operation cost and revenue (positive and negative) of the complex Sugar Mill+ Electricity Plant+ CCS Facility
Costs (Million US$)
1000.00
100.00
10.00
1.00
366.19
143.86
92.07
287.71
417.70
3.27
11.05
31.11
66.34
3.30
2.96
-10.02
Investment
Feedstock-annual
Oper&Mainten.-annual
Revenue-annual
Investment
Feedstock-annual
Oper&Mainten.-annual
Revenue-annual
Investment
Electricity annual
Oper.&Mainten.-annual
Expense-annual
Ethanol production
Electricity generation
CCS facility

Figure S1 - Results from the financial model used in the calculation. Note: the value “Expense-annual” for CCS refers to a negative figure. Since the chart is displayed in logarithmic scale the value is presented as positive figure, but in blank color.

A calculation based on Table S3 parameters, in which a benchmark rate of return on equity of 6% above inflation is assumed for the investor, shows that the cost of CO_2 CCS is US$ 30.29/tCO_2.

In order to compensate the investor for this CO_2 cost, ethanol has to be sold at the sugar mill gate at US$ 0.621, and bioelectricity sold to the grid[16] at a price US$ 26.76/MWh without accounting for taxes. As noted, comparing to the cost calculated at section 3.3, the CO2 value is 11.3% higher, even considering the modest interest rate on the loan, which is available for infrastructure projects, in Brazil, through the National Development Bank (BNDES).

This calculated CO_2 cost is significant when compared to CO_2 market price. In US, prices around US$ 40/tCO_2 are being considered by the government, but presently around US$ 12.00 are accounted for in some projects (EIA, 2015). During part of the Kyoto Protocol agreement, projects were supported with CO_2 shadow prices near US$ 40/tCO_2, but most of the time the price was around or even below US$ 20. Thus, it is very clear that even this BECCS technology, in which the CO_2 capture cost is almost zero, requires regulation or support, as already discussed in the main text, thus affecting the ethanol and/or bioelectricity final sales price.

Sensitivity Analysis

Figures S2 and S3 provide information regarding the sensitivity of our results with respect to 3 parameters of our model: a) financing interest rate; b) equity share on the investment; and c) expected rate of return on equity, essentially the project’s degree of attractiveness for the investor. Figure S2 shows the value that has to be paid to the investor in order to install and operate the CCS facility while receiving the same revenue when the CCS facility doesn’t exist.

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[16] In reality, from the 208 kWh/tcane generated in the complex sugar mill/bioelectricity plant, 40 kWh is used on site. Thus, only 168 kWh/tcane is commercialized through the grid. In our model electricity self generated is not overpriced to pay for CCS costs.

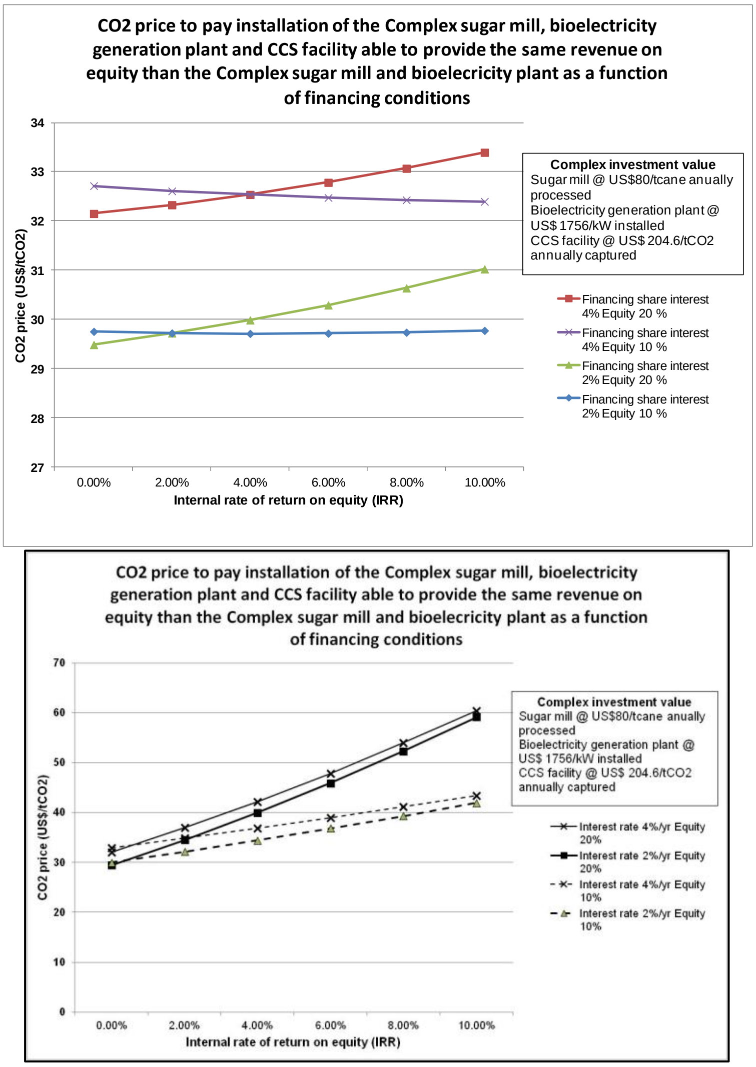

Figure S2 – CO_2 breakeven price to match the BECCS scheme given finance variable interest rates and equity shares. Source: Prepared by authors

Figure S3 shows bioelectricity sales price, at the electricity plant gate, without any taxes, for the investor recovering the CCS costs through sales of electricity and ethanol. This last product is sold at US$ 0.621, instead of the regular market price of US$ 0.60.

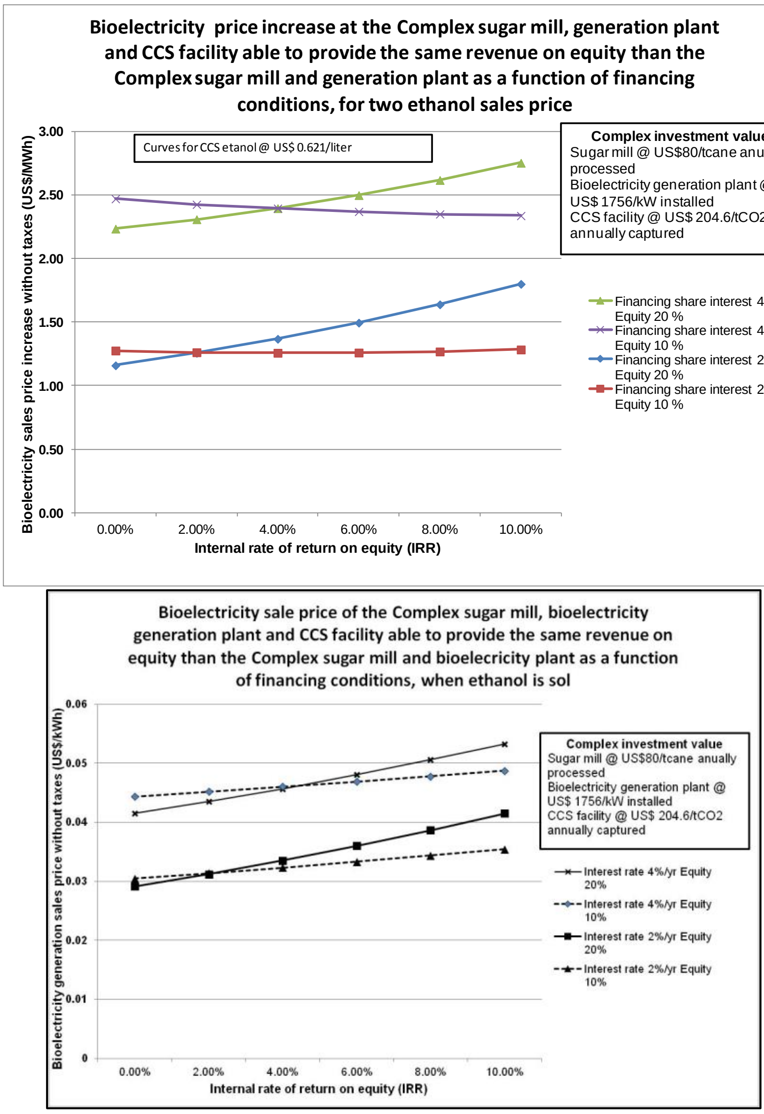

Figure S3 – Biolectricity sales price given variable interest rates and equity shares
Source: Prepared by authors

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