Second Generation Sugarcane Bioenergy & Biochemicals

Advanced Low-Carbon Fuels for Transport and Industry

Final Version

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Brazilian Contribution to the Implementation of the Paris Agreement

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Brazilian Contribution to the Implementation of the Paris Agreement

Final Version

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Contents

Presentation

The introduction of new advanced low carbon technologies with the addition of sugars converted from cellulosic materials and the development of high-biomass sugarcane (energy cane) has opened a new agroindustrial path. The perspective to improve the potential yield of bioethanol to almost 25,000 liters per hectare is real. As a result, the world will experiment CO_2 emissions reduction. Considering a projected global consumption of gasoline of 1.7 trillion litters in 2025, energy cane based bioethanol would be able to replace 10% of total gasoline consumed in the world using less than 10 million hectares of land.

The tripod second-generation bioethanol (E2G), high-biomass sugarcane (energy cane) and renewable (green) chemistry is under implementation in Brazil through strong public-private partnership. One of the most successful initiative, PAISS – a government plan to support innovation in the sugar/energy and sugar/chemical sectors, led by the National Bank for Economic and Social Development (BNDES) together with the Research and Innovation Agency (FINEP), involved a number of well-established and start-up companies, as well as prominent science and technology institutions. The Center for Strategic Studies and Management (CGEE), together with the parties, is exploring, analyzing and prospecting the impacts related to agroindustrial technology performance and costs, land use gains and GHG emissions reductions of this endeavor to provide a consistent view of the benefits of such an initiative whether it is nationally or globally framed.

Therefore, this study Second Generation Sugarcane Bioenergy & Biochemicals: Advanced Low-Carbon Fuels for Transport and Industry - Brazilian contribution to the implementation of the Paris Agreement, within the framework of the project Positive Agenda of Climate Change: Opportunities of a Low Carbon Economy, intends to give greater visibility to this Brazilian initiative and to its contribution to the development of a sustainable and replicable energy alternative. It also explores the advantages and implications of existing synergies between mitigation, adaptation and sustainable development promoted throughout the life cycle of the second generation bioenergy from sugarcane, identifying challenges and possible solutions to accelerate the development and diffusion of low-carbon technologies based on the model used in PAISS. Furthermore, this final version consolidates the main conclusions of the study and addresses recommendations for the formulation of strategies and measures to foster innovation in order to apply the results of the Twenty-First Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC).

PART I - Second Generation Sugarcane Bioenergy Assessment

Introduction

When properly produced and used, biofuels represent one of the best alternatives to promote the reduction of carbon emissions associated to energy use in modern society, as well as to stimulate sustainable development in its social, environmental and economic dimensions. In this direction, the share of biofuels is increasing in the global energy matrix and nowadays corresponds to about 3% of global energy demand for transportation (IRENA, 2014).

Complementing the conventional processes of sustainable biofuels industry, innovative technologies (second generation, 2G) are maturing fast and becoming available to produce bioethanol from low cost lignocellulosic feedstock, such as agricultural residues, with good efficiency and allowing greater mitigation of GHG emissions. Thus, in the framework of global efforts to reduce climate change, there is interest to consolidate and implement these processes, promoting also innovation in the feedstock production stage and diversification in the downstream processes in this agroindustry, by aggregating biomaterials to the renewable energy output.

The purpose of Part I of this study, is to explore new scenarios for the production of bioethanol and other products adopting the valorization of lignocellulosic residues of the sugarcane culture, featuring the current state of the art and assessing its prospects and, from the Brazilian experience, highlight the importance of public-private initiatives for its effective implementation and forecasting the impact of expanding this experience. This study reviews the current bioenergy development, focusing mainly the advanced processes and the Brazilian perspectives, where the public-private initiatives have been playing a decisive role.

1. Context

Climate change is one of the most relevant issues in the global agenda, since it imposes clear and consistent actions of all countries in order to practically zero global emissions of greenhouse gases (GHG) until the second half of this century and, by doing so, limiting the increase in the average temperature at the Earth's surface around 2ºC. To this end, it is necessary to preserve natural resources and promote an intense decarbonization of the global economy, which in turn depends on greater investments in research, development and innovation (RD&I) in those sectors more likely to generate more significant impacts.

In this sense, the stimulus to the creation of public-private partnerships (PPP's) is an effective way to promote rapid technological transformation in those sectors with the highest potential of mitigation, as well as to strength investments in RD&I projects. In developing countries such as Brazil, where financial resources are scarcer and investments in social and health areas are a priority, stimulus to the formation of PPP's to promote innovation in key sectors is an effective strategy to combine national development promotion with measures to face climate change.

The production, transport and use of energy represents one of the most significant sources of GHGs. Emissions associated with the transport sector accounts for 14% of 2010 global greenhouse gas emission (IPCC, 2014). Though, as 95% of its energy comes from fossil sources, mainly gasoline and diesel, there is a big chance of reducing this numbers through the use of biofuels. According to the DDPP[1], the three basic requirements for a profound and necessary reduction in carbon emissions from energy systems are: a) increased energy efficiency and energy conservation; b) power generation by renewable and low-carbon alternatives; c) transition from fossil fuels to biofuels.

Especially in the case of the latter two requirements, Brazil is a key actor because, in addition to the fact that renewable energies already represent nearly half of its energy matrix, Brazil accumulates undisputed experience in the production and use of bioethanol from sugarcane, using a high-efficiency production chain in the capture and conversion of solar radiation into electricity and liquid fuel. Indeed, the high levels of GHG emissions mitigation by sugarcane bioethanol justified its recognition as an advanced biofuel by the Environmental Protection Agency (EPA) of the United States. And its participation in the supply of energy is relevant: the Brazilian production of bio-bioethanol and electricity from sugar cane currently amounts to more than 16% of the total primary energy production in the country (BEN 2014).

To reach the current state of development in Brazil and open up new possibilities in the future, the expertise and know-how accumulated by the country over several decades in the fields of scientific research and technological development have been crucial. These advances have taken place throughout the whole production chain, consolidating the foundations for the social, economic and environmental sustainability of bioethanol in Brazil. Thus, sugarcane bioenergy provides a concrete reference to be more widely known and adequately promoted in similar contexts, such as tropical countries with suitable climate and availability of land for

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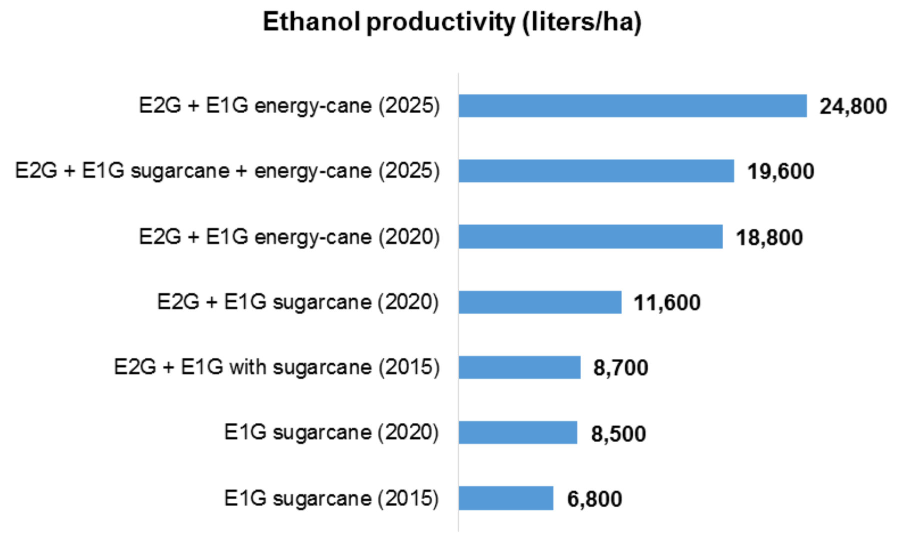
[1] Deep Decarbonization Pathways Project, an initiative that involved research groups from 15 countries which produce 70% of the GHG emissions. The Project assessed several alternatives more likely to promote intense decarbonization of national economies (http://unsdsn.org/what-we-do/deep-decarbonization-pathways/)

this purpose.

Although it already shows good indicators of sustainability, the sugarcane agro industry still has ample room for improvement in order to achieve greater efficiency and productivity gains. In addition to marginal gains associated with the gradual dissemination and adoption of best practices and techniques, the Brazilian agricultural, industrial and management sectors show two technologies that have resulted in striking advances: a) the production of second generation bioethanol (E2G) that employs the lignocellulosic residues from the cultivation (tips and leaves) and processing (bagasse) of the sugarcane as raw materials and b) the breeding and selection of sugarcane varieties with high productivity and high fiber content ("energy cane"), which are likely to result in expressive productivity gains.

It is estimated that the current productivity of bioethanol would increase by up to 45% (CGEE, 2012) with the adoption of advanced technologies such as the second generation, while it is expected that its productivity in terms of sugars produced by acreage could be multiplied by five if genetic improvement techniques are disseminated in the sugar cane culture. Given the best conditions, the ability to mitigate GHG emissions can reach levels greater than 100%, that is, the use of biofuel not only eliminates the emissions from petroleum products that will not be burnt but it also allows, during its production, the generation of renewable electric energy surplus that mitigates emissions from the electricity sector. Figure 1 presents the current and projected levels of productivity of bioethanol for the different technologies.



Source: BNDES, CTBE, MDIC and CGEE

Figure 1 - Bioethanol productivity

On a global scale, liquid biofuels have already replaced 3% of petroleum products used for transporting cargo and passengers (IEA, 2014), and this figure has been expanding at high rates. It is expected that by 2020 it will double its share in the energy matrix. Another point to highlight in favor of biofuels is the clear positioning of FAO, the United Nations Food and Agriculture Organization. After broad consultation and analysis of agricultural markets and their constraints, the Director-General of FAO stated that biofuels, whenever produced efficiently, improve the quality of life and food security, promote rural development and improve the environment. In his words "It is important not to forget that biofuel emerged with strength as an alternative energy source because of the need to mitigate fossil fuel production and greenhouse gases, and that need has not changed. We need to move from the food versus fuel debate to the food and fuel debate. There is no question: food comes first." And he added "But biofuels should not be simply seen as a threat or as a magical solution. Like anything else, they can do good or bad."

Given this favorable diagnosis, the BNDES and FINEP launched in 2011 the PAISS – a government plan to support innovation in the sugar/energy and sugar/chemical sectors. This plan has invested about US$ 3 billion in public-private partnership projects with focus on research, development and innovation (RD&I) of advanced low-carbon technologies, especially in the areas of second generation bioenergy and biochemicals and development of energy cane. The plan is in its second phase and positive results are already observed, as the implementation of two plants on a commercial scale and a demonstrative plant of E2G in Brazil; their installed capacity can produce about 140 million liters of bioethanol per year.

Thus, Brazil has managed to stay in the technological frontier of bioenergy, making efforts comparable to those observed in the United States, Europe and China, whose installed capacity are respectively 305, 80 and 65 million liters of bioethanol per year. The first figures about the production and marketing of E2G by Brazilian companies have been stimulating enough to encourage significant investments: a Brazilian company (Raizen) presented its plans to invest approximately US$ 1.5 billion to deploy eight 2G bioethanol plants until 2024, with total capacity of 1 billion liters of bioethanol per year.

Expectations about the competitiveness of E2G, shown in Figure 2, reinforce the soundness of these investments and indicate that it may cost the same as a US$ 40 oil barrel, with reduced impact in terms of occupation of agricultural areas. As shown in Figure 3, the production of E2G in association with the cultivation of high-yielding varieties may notably increase the production of biofuels per unit area, reasonably reducing land area required to substitute 10% of global gasoline consumption in 2025.

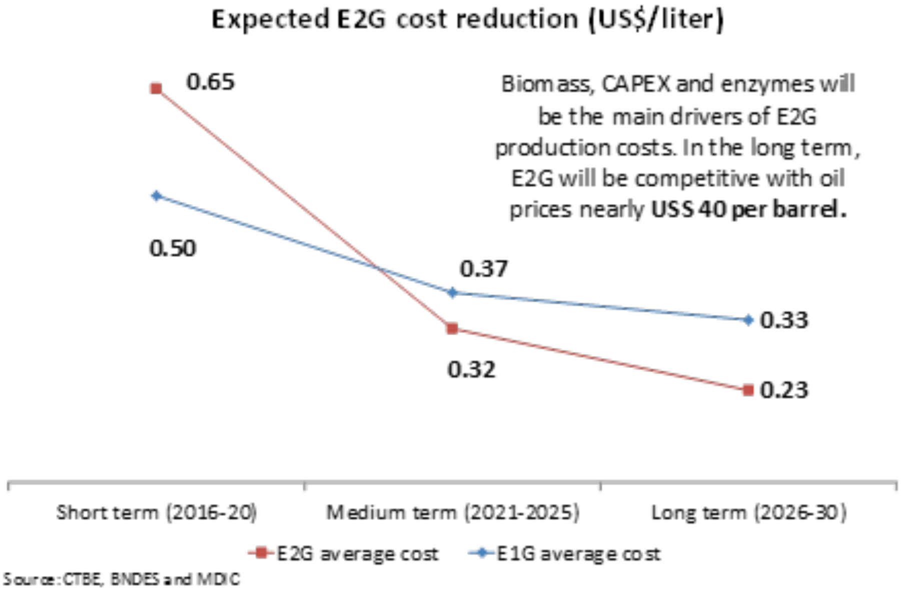


Figure 2 - Cost estimates for bioethanol 2G

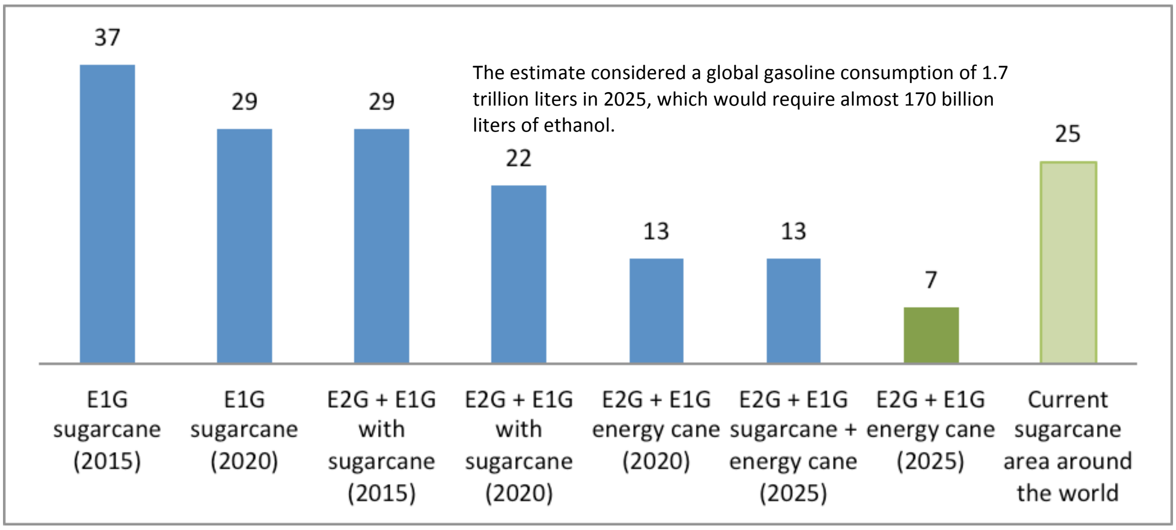


Figure 3- Agricultural area of sugarcane required for global E10 in 2025 (million hectares)

By facilitating the development and implementation of innovative energy technologies with great impact on sustainable development and significant reduction of GHG emissions in the transport sector, where the energy alternatives are limited, the Brazilian PAISS has also great relevance for the global context and is fully aligned with the objectives of the Climate Convention (COP21) Solutions Agenda in the framework of the Lima-Paris Action Plan of the French Presidency and with those of international dialogues about climate issues, such as the Low Carbon Technology Partnerships Initiative (LCTPi) of the World Business Council for Sustainable Development (WBCSD) (see Annex 2).

2. Modern bioenergy: current status and perspectives

More than a hundred centuries ago mankind progressively substituted collecting and hunting by planting crops and breeding animals; today we are moving from fossil fuels, stored in the subsoil for millions of years and currently voraciously consumed, towards cultivating and harnessing renewable sources of energy. Like in those distant times, when nomadic tribes started to live in stable communities and villages, currently we are starting a profound revolution in the way we obtain energy from nature and use it, as an essential resource for our welfare and production. In this context, modern biomass and bioenergy are increasingly important.

"I foresee the time when industry shall no longer denude the forests which require generations to mature, nor use up the mines which were ages in the making, but shall draw its raw material largely from the annual products of the fields"

[Henry Ford, Modern Mechanics (1934)]

Figure 4 - Ford Model A (1896) fuelled by pure bioethanol [Fuel Testers (2008)]

Biomass is essentially made with carbon captured from the atmosphere by plants during their growth, through photosynthesis, converting solar radiation in chemical energy stored as sugars (such as starch and sucrose) and lignocellulose. Bioenergy is generated when the chemical energy contained in biomass is released through combustion or other processes, using from simple wood stoves up to complex and integrated biorefineries to supply useful forms of final energy and materials, such as heat, power, plastics and fibers.

Currently, biomass as a source of energy contributes to around 10% of global primary energy used, about 55 EJ in 2013 (IEA, 2014). A large share of this corresponds to traditional use of fuel wood, predatorily produced and collected, and used in low efficient stoves; however the modern bioenergy is expanding and replacing these old bioenergy systems by sustainable production routes. Around 4.4 EJ were produced as liquid biofuels in 2014 (REN21, 2014); ethanol and biodiesel currently supply about 3% (IRENA, 2014) of world energy demand in road transport, with forecasts to contribute up to 30% in 2050, when it is expected that 1.7 to 2.1 billion cars will be running in our planet, about 2.6 times the global fleet in 2010 (IEA, 2014). The expansion of motorization in developing countries is the main driver for the increasing consumption of liquid fuels, and the renewable alternatives are essentially liquid biofuels.

In fact, modern bioenergy production, encompassing liquid biofuels for transport vehicles as well as bioelectricity produced sustainably, is evolving at growth rates greater than conventional fossil energy supply. Today about 50 countries have implemented or are implementing biofuels mandates aiming to reduce carbon emissions and local air pollution, to improve energy security and the need to overcome oil dependence, rural development, job creation, as well as increasing energy access to developing regions and consequently increasing food security.

Bioenergy is also opening innovation opportunities and new business models, contributing to a new economy based on biomass, and supplying diversified biomaterials. Based on 2013 data, Figure 5 - **Feedstocks and liquid biofuels production in 2013 (SCOPE, 2015)**[2] depicts the current liquid biofuels production and the main feedstock used, also introducing two basic parameters for biofuel sustainability: the liquid biofuel yield (in liters per hectare) and the GHG emission mitigation, compared with fossil fuels[3], representing respectively the agro-industrial productivity and the overall energy efficiency. Figure 6 presents the evolution of the global biofuels production during the last decade, when the United States and Brazil were the top producers, followed by Germany, China, Argentina, Indonesia and France far behind (Figure 7).

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[2] There are relevant differences among the feedstock used for biodiesel production. The crop yield for oil palm is up to 5,700 l/ha, for soybean up to 700 l/ha and for rapeseed up to 1,500 l/ha. Directly related to GHG emission mitigation, the energy yield ranges from 16-21 GJ/ha/yr for soybean and 60-70 GJ/ha/yr for rapeseed to 135-200 GJ/ha/yr for palm oil (SRREN IPCC, 2011).

[3] Specifically for ethanol from sugarcane, the average GHG emissions for a large number of mills, in 2008 (excluding LUC) were 21.3 gCO_{2eq}/MJ, corresponding to 75% mitigation (Brazilian gasoline: 86 gCO_{2eq}/MJ). Many mills already had mitigation greater than 80%. Currently, improvements such as higher electricity surplus (in 2010: 10 kWh/ton cane, in 2014; 30 kWh/ton cane) and the rapid adoption of harvesting of unburnt cane, probably led the average mitigation to levels above 80% (Seabra and Macedo, 2011; UNICA, 2015).

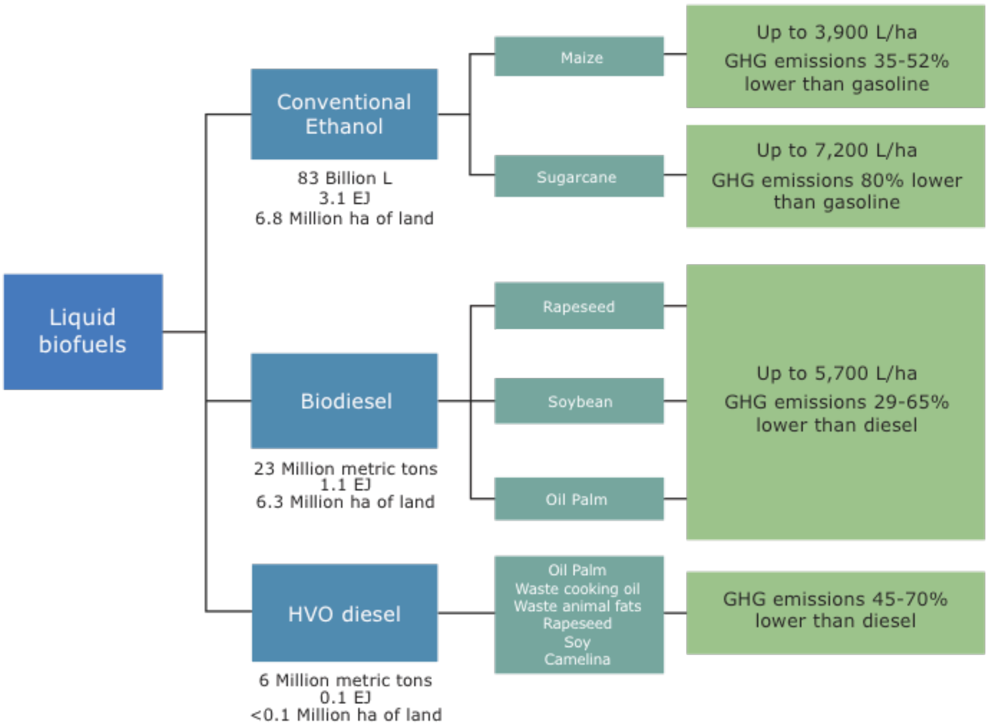


Figure 5 - Feedstocks and liquid biofuels production in 2013 (SCOPE, 2015)

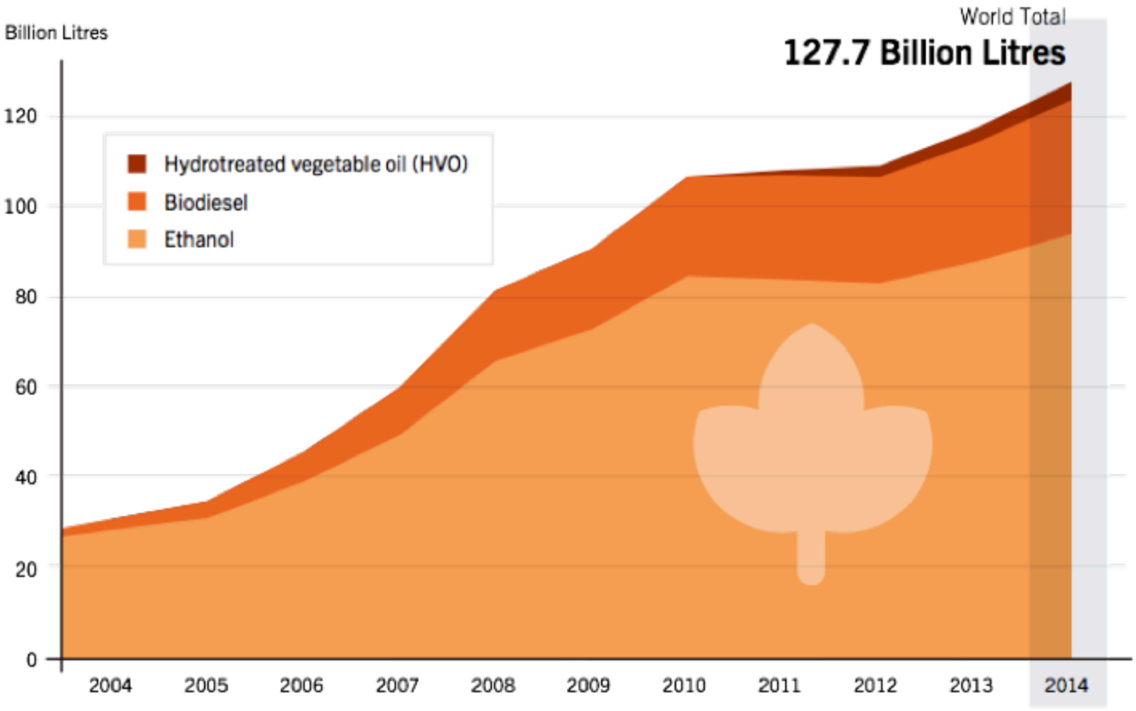
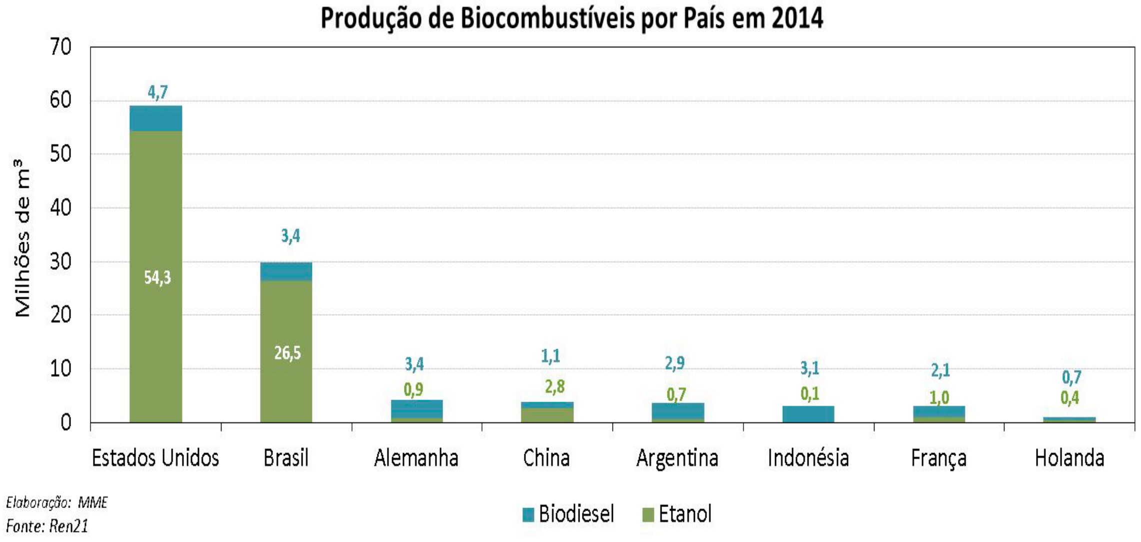


Figure 6. World production of ethanol, biodiesel and HVO (REN21, 2015)



Elaboração: MME
Fonte: Ren21

Figure 7. Bioethanol and biodiesel production in selected countries (REN21, 2015)

According to IRENA, biomass currently makes up 75% of the total renewable energy consumption, with traditional biomass use accounting for more than 50%, frequently not sustainable. As the use of traditional biomass decreases, the shares of modern renewables will more than triple. As energy demand continues to grow, this requires a quadrupling of modern renewables in absolute terms. Costs have fallen significantly and will continue to decline through technology innovation, competition, growing markets and regulatory streamlining.

In this way, bioethanol, biodiesel, renewable diesel, and wood pellets trade created an international market, stimulated by policy efforts and growing demand in industrialized and developing countries. At the same time, several voluntary schemes for certification of biomass, biofuels, and bioenergy production according to criteria and principles set by the strict sustainability schemes are available, assuring that the production and logistics of supply of biomass to conversion processes making fuels, energy, and products are based on economic, environmental, and social considerations. A good example of certification framework is the Global Bioenergy Partnership (GBEP)[4]. GBEP is a Task Force on Sustainability supported by several relevant countries and international organizations and institutions, and provides a methodology and a set of indicators to assess properly the sustainability of bioenergy projects.

Detailed and independent assessments have demonstrated, based on sound scientific methods, that there are good conditions for expanding the modern and sustainable bioenergy production. The last SCOPE (Scientific Committee on

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[4] For more details on GBEP Task Force, purposes and functions, partners and membership, please visit: http://www.globalbioenergy.org/

Problems of the Environment) report (2015), *Bioenergy and Sustainability: bridging the gaps*, prepared by 137 experts from 82 institutions and 24 countries to analyse a range of issues related to the sustainability of bioenergy production and use, concluded that bioenergy developed knowledgeably and implemented considering local and regional needs, can help to:

- increase resilience in food supply;
- both locally and globally decrease pollution;
- preserve biodiversity;
- improve human health;
- rehabilitate degraded land;
- mitigate climate change; and
- provide economic and business opportunities.

One of the main motivations for increasing the use of biomass to generate energy is that under correct conditions GHG emissions are reduced. Decreasing emissions is critical and urgent to avoid serious interference with the climate system as reported by the IPCC 5th Assessment Report. At the same time, more than 2 billion people lack access to modern energy services, which are a fundamental prerequisite for poverty reduction and human development. To transition into a sustainable energy matrix the United Nations has launched the SE4ALL initiative to achieve three global interlinked energy policy objectives by 2030: 1) ensuring universal access to modern energy services; 2) doubling the global rate of improvement in energy efficiency; and 3) doubling the share of renewable energy in the global energy mix by 2030.

As a fundamental aspect regarding the perspectives for modern bioenergy expansion in the near future, in the last years the relevant potential for expanding bioenergy production in several regions became evident, and the concerns on bioenergy contribution to increase food prices and cause serious environmental effects were better evaluated, indicating that the solar energy harvesting by photosynthesis and its posterior conversion to modern energy vectors makes sense and is able to promote sustainable development. Sustainable conventional and innovative bioenergy production routes are in place; data on land availability, as well as on required infrastructure and costs for a reliable supply of biomass in many countries and scenarios became available.

Today there is a sound base of data assessing the current and future requirements of arable land to sustainably produce food, feed and biomass for energy and materials, to assure that, from a global perspective, land is not a real concern. Besides the large amount of land available as low productivity pastures and the potential of increasing cropping productivity and pasture intensification, nearly half the gross biofuel land area is associated with commercial co-products (such as food and animal feed). A gross land demand for modern bioenergy was estimated at between 50 Mha and 200 Mha by 2050, delivering between 100 and 200 EJ/year of modern bioenergy in 2050, as shown in figure 8 (SCOPE, 2015). According to FAO (2012), the land available for rain fed agriculture is estimated to be 1,400 Mha of 'prime and good' land and a further 1,500 Mha of marginal land that is 'spare and usable'. Around 960 Mha of this land is in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha) with much, if not all of it, currently under pasture/rangeland (SCOPE, 2015).

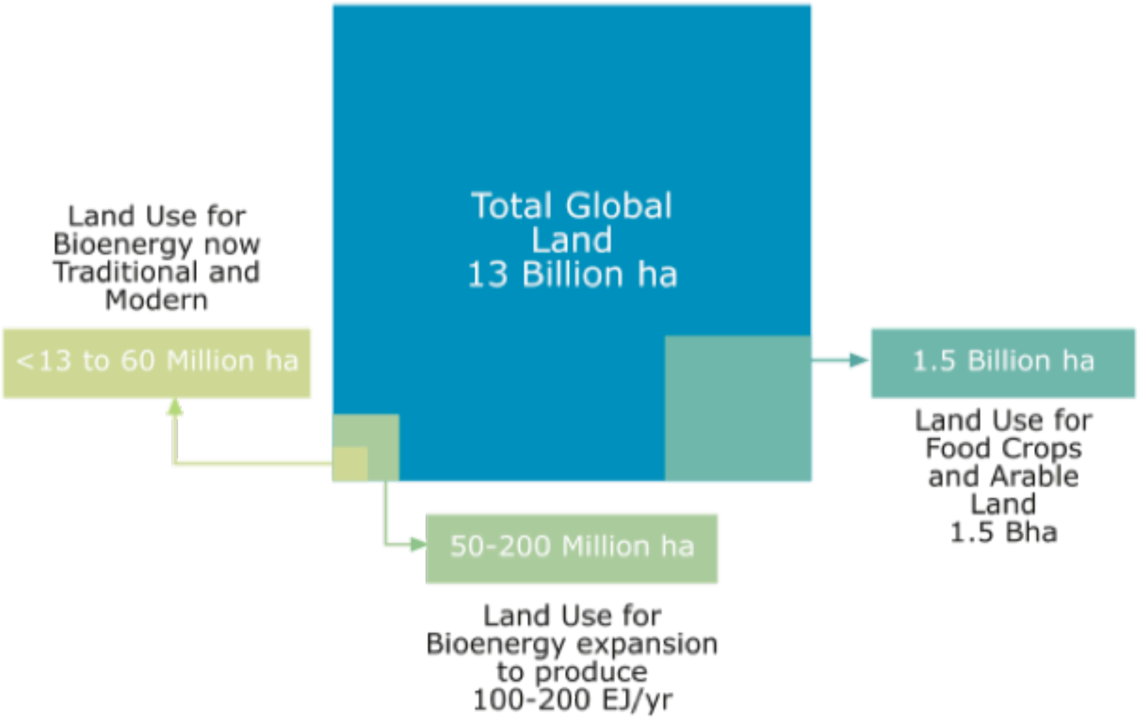

Figure 8. Global land availability (SCOPE, 2015)

Regarding GHG mitigation, as appointed in the IPCC Special Report Renewable Energy (IPCC, 2012), to achieve climate mitigation scenarios, bioenergy and specially liquid biofuels, have a crucial role relative to other potential renewable energy sources, as summarized in Figure 9. It presents the estimated global renewable primary energy supply by source in the groups of Annex I (AI) and Non-Annex I (NAI) countries in the framework of United Nations Framework Convention on Climate Change, evaluating 164 long-term scenarios by 2030 and 2050 and highlighting the expected contribution of Non-Annex I countries.

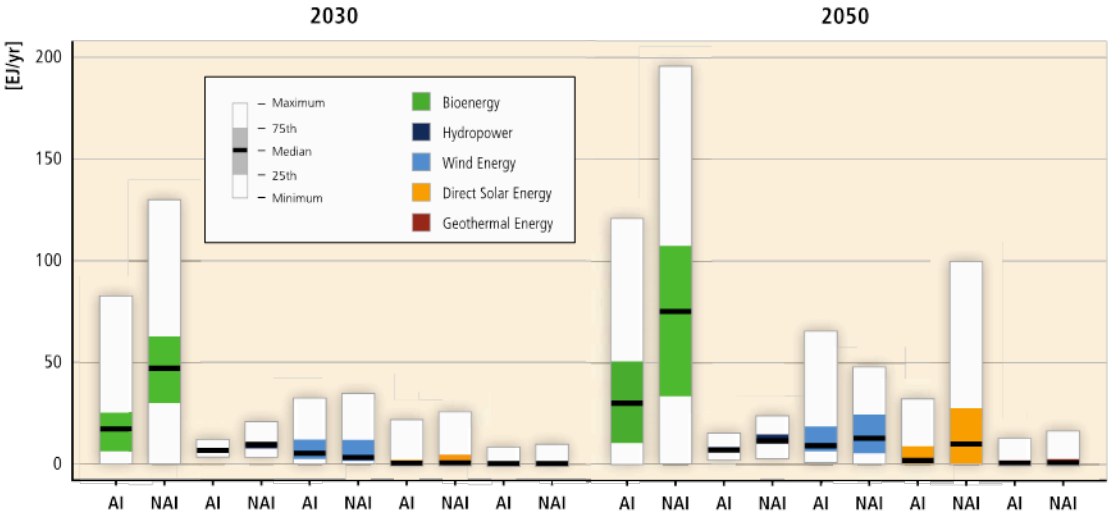

Figure 9. Estimated global renewable primary energy supply by source by 2030 and 2050 (IPCC, 2012)

As a main remark from this introductory appraisal of modern bioenergy context and perspectives, it should be stressed that, based on several independent studies (SCOPE, 2015), when properly implemented and managed, the production and use of liquid biofuels is not a threat to food security, biodiversity and ecosystem services. Indeed, the evolution of this agroindustry has been done mostly achieving environmental, economic and social benefits, such as improving soils, integrating production chains, delivering co-products, generating income and jobs. Introducing innovative feedstock and processes, such as lignocellulosic material and ethanol 2G, can reinforce this positive record, allowing climate mitigation much more effectively while improving economic performance to accomplish broader societal needs.

3. Bioethanol from sugarcane industry: evolution and diversification

Sugarcane, a perennial grass with tall stalks rich in sugars, which grows in the tropical and subtropical regions is one of the most efficient solar energy converter to biomass and consequently a feedstock of choice for bioenergy production. The harvested stalks are roughly 70% moisture and the dry matter is composed basically by sucrose and lignocellulose, which typical contents are indicated in Figure 10.

Sugarcane is planted once and harvested repeatedly after 12 to 18 months of growth for 5 to 6 years. Approximately one-third of the total energy in the above-ground biomass of today's sugarcane cultivars, is captured as the sugars (mostly sucrose) fraction present in the stalk while another third is present in the fibrous sugarcane bagasse and the last third is the straw (or trash) left in the field after mechanical harvesting. Both last fractions are essentially lignocellulosic materials. In the Brazilian conditions, the average energy content of the total above ground biomass harvested annually is 7,400 MJ/ton of cane for an average crop of around 70 ton/ha.year, about 510 GJ/ha.year (Leal, 2010). Thus, as a whole, one ton of sugarcane is equivalent to around 1.2 barrel of petroleum.

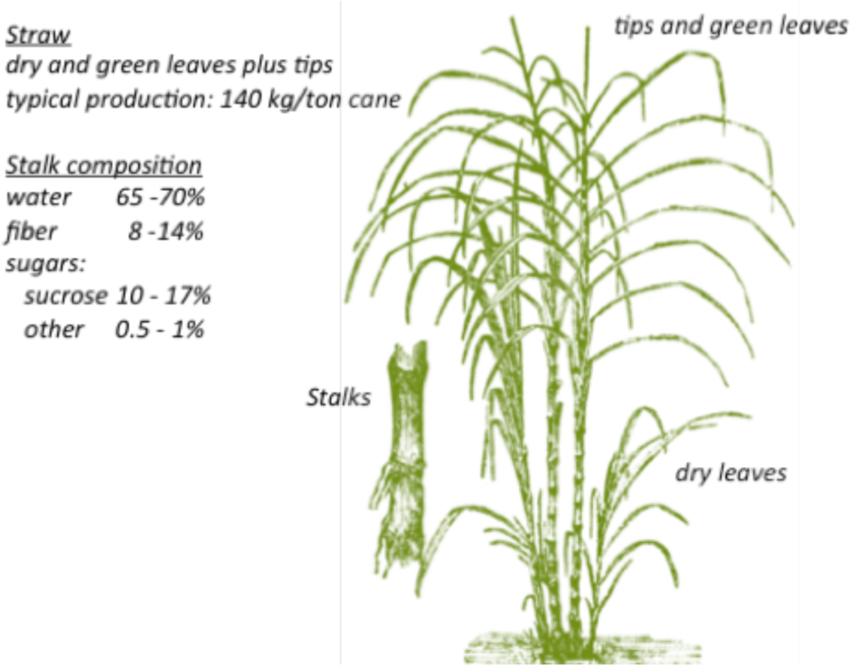

Figure 10. Typical sugarcane biomass composition (BNDES/CGEE, 2008)

FAO (2015) estimates that in 2013 about 26 million hectares were cultivated with sugarcane in more than 90 countries, with a worldwide harvest of 1.83 billion tons, which in energy terms corresponds approximately to more than 6 million barrels of oil per day. Brazil was the largest producer of sugarcane in the world, followed by India, China, Thailand, Pakistan and Mexico. The primary driver of sugarcane agriculture is the sugar production; cane accounts for 80% of sugar produced; the rest is made from sugar beet.

3.1. Ethanol from sugarcane in Brazil

It is interesting to focus the Brazilian context, where sugarcane has been used to make vehicular fuel for a long time and today answers for more than 19% of total primary energy supply, as biofuel and bioelectricity (MME, 2015). Actually, it was a long history; as shown in Figure 11, ethanol is mandatorily blended with all gasoline sold in Brazilian gas stations since 1931 and today sugarcane is used to produce sugar, ethanol, bioelectricity in Brazilian mills.

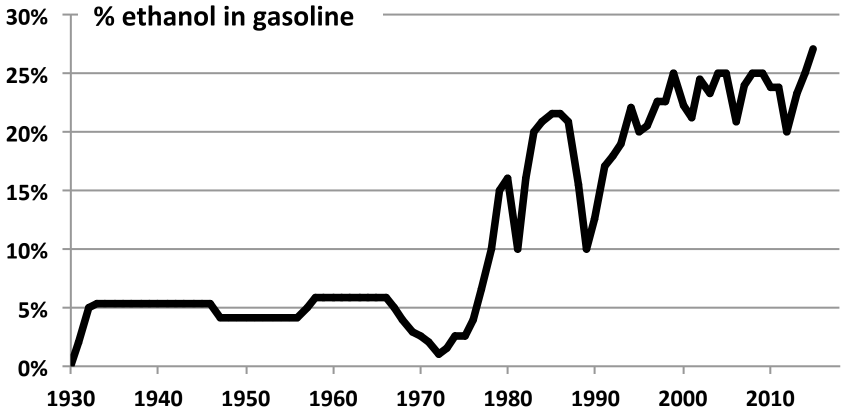

Figure 11. Mandatory ethanol content in Brazilian gasohol (BNDES/CGEE, 2008, updated)

Sugarcane is cultivated in Brazil since the 16th century, during the colonial times, when sugar production was the main economic activity. Currently it is the third most important crop in terms of area, after soybeans and corn. The sugarcane agroindustry contributes with about 2% of the Brazilian Gross National Product (Neves, 2009). The largest sugarcane-producing area is the Center-South region, which accounts for more than 90% of Brazilian sugarcane production. In the 2014/2015 harvest season, the cultivated area was approximately 10.9 million ha, 1.2% of national area, for a total sugarcane production of 632 million ton (UNICA, 2015). Of this total, about 50% of sugar content in sugarcane was used to produce ethanol, in about 400 mills.

Considering the state of art agroindustrial units, adopting conventional processes, sugarcane is produced, transported and processed in well-established systems, allowing to its efficient use. Sugarcane harvest periods vary according to rainfall to allow cutting and transportation operations while reaching the best maturation point and maximizing sugar accumulation. After the introduction of environmental regulation progressively prohibiting pre-harvest burning of sugarcane (a traditional procedure to increase manual cutting productivity), today harvesters of green (unburned) chopped sugarcane are largely adopted.

With the adoption of mechanized harvesting, the use of sugarcane trash (about 140 kg of dry straw per ton of stalks) began in some mills and is expanding, envisaging agronomic and energy gains. Today, it is accepted that leaving 40% to 60% of trash as soil coverture after harvesting is possible in most cases. Depending on several variable such as logistics system, distances and unitary transport cost, terrain slope, soil characteristics and agronomic conditions, two schemes for trash harvesting have been considered: a) integral harvesting, when the straw would be harvested, chopped and transported together with the sugarcane stalks, and b) baling system, when the trash is left in the field for about 15 days after sugarcane harvesting in order to reduce its water content. After that period, straw is windrowed, collected and compacted in bales, as indicated in Figure 12, which are then loaded and transported to the mill.

Figure 12. Trash bales ready to be transported to the mill, Usina da Pedra, 2013

Each system presents advantages and problems that make site specific the best option. Straw recovery along with sugarcane stalks leads to lower load density in the transport trucks, and recovery costs are strongly dependent on distances. On the other side, baling system involves more agricultural operations, and straw recovery can become very expensive (Cardoso et al., 2015). Nowadays, the additional biomass represented by sugarcane trash is used as fuel and improved the mill's energy balance, but potentially could be considered also for other aims, such as feedstock in advanced biofuel processes. However, although the technology currently available for trash collection, transport and use have been improved significantly and is somewhat already available, it still demand efforts to reach better levels of reliability, performance and cost, to allow for large scale adoption.

The harvested sugarcane is promptly transported to the mill to avoid sucrose losses. Except for a few companies that use some sort of waterway transport, the transportation system is based on trucks with cargo capacity between 15 and 60 tons. In recent years sugarcane logistics has undergone significant development, involving integrated operations of cutting, shipment and transport, to cut costs and diminish soil compaction.

In Brazilian mills bioethanol and sugar are usually produced jointly, in proportions defined depending on the relative prices of these products and set relatively easy in a limited range. The initial processing stages are basically the same as for sugar production, as shown in Figure 13. After sugarcane stalks chopping and shredding, they are sent to crushing mills (more adopted) or diffusers, to separate the sugarcane juice containing sugars and bagasse; bagasse is sent to the mill's power plant to be used as fuel. For sugar production this juice is screened, chemically treated and clarified. Recovering sugar from the slurry produced in the clarification by vacuum rotary filter generates the filter cake, used as fertilizer. The clarified juice is then concentrated in multiple-effect evaporators and crystallized. In such process only part of the sucrose available in the sugarcane is crystallized and the residual streams with high sugar content (molasses) can reprocessed again to recover more sugar or diverted as input for ethanol production, due its high content of fermentable sugars.

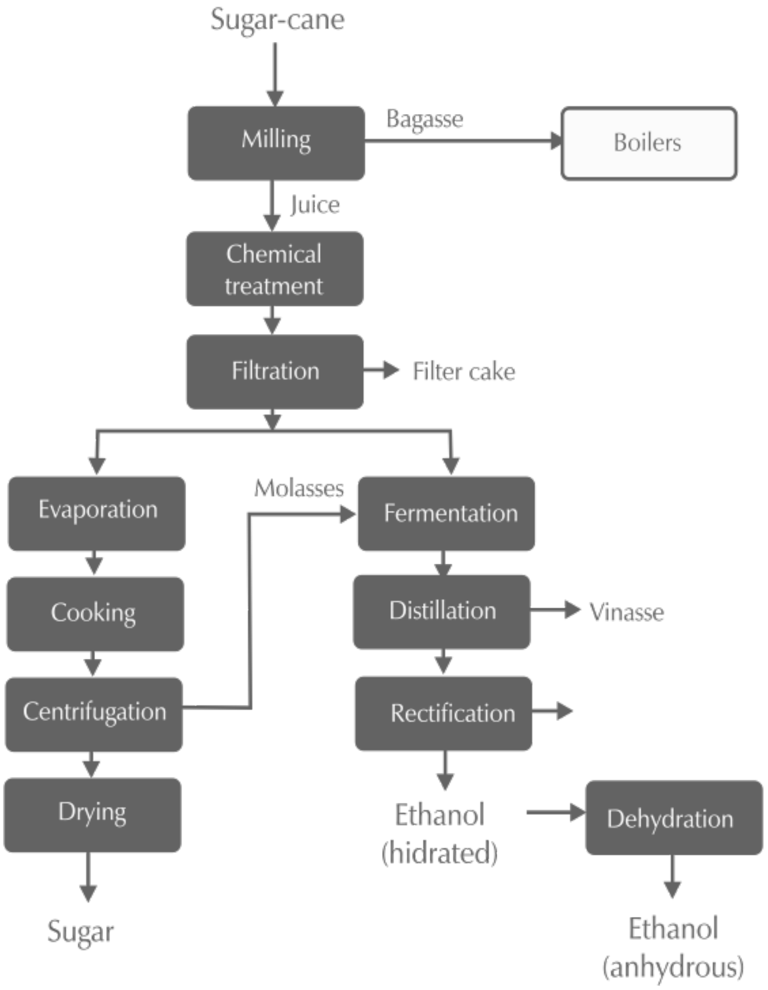

Figure 13. Typical Brazilian sugarcane process (Seabra, 2008)

Therefore, the solution to be fermented for sugarcane bioethanol production (or mash) may be sugarcane juice alone or a mix of juice and molasses, the latter being more frequently practiced in Brazil. This mash is sent to fermentation reactors, where yeasts (*Saccharomyces cerevisae* species) are added to it and fermented for a period ranging from 8 to 12 hours, resulting wine with ethanol concentration from 7% to 10%. In Brazilian distilleries is generally adopted the Melle-Boinot fermentation process, characterized by the recovery of wine yeasts by means of centrifugation. Then, after fermentation yeasts are recovered and treated for new use, while the wine is sent to distillation columns. In distillation ethanol is initially recovered in hydrated form, with nearly to around 6% of water in weight, producing vinasse or stillage as residue, generally at a ratio of 10 to 13 liters per liter of hydrated ethanol produced. Hydrated ethanol can be stored as final product or sold to be dehydrated. As hydrated ethanol is an azeotropic mixture, the dehydration process requires a distillation with addition a ternary component (usually cyclohexane) or by adsorption process with molecular sieves. The anhydrous ethanol presents less than 0.4% of water in weight.

The expansion of ethanol production occurred alongside significant productivity gains in agricultural and industrial activities, with benefits for sugar production as well, as indicated in Figure 14. Today, for representative Brazilian mills, the yield of sugarcane is 80 ton/ha and the average yield of the process is around 90 litres of ethanol per ton of cane, meaning an average sugarcane ethanol production of 7,200 liters per hectare (Leal et al., 2012). In recent decades, up to 2010, performance grew at a cumulative average annual rate of 1.4% in agriculture (yields, in ton/ha) and 1.6% in agro-industry (conversion efficiency, in litre of ethanol/ton), resulting in a cumulative average annual growth rate of 3.1% in ethanol production per hectare. As a result of these remarkable gains, the overall production cost has been reduced circa 70% during the last three decades (Goldemberg, 2012). This remarkable gain in productivity, 2.6 times the volume of ethanol for a given area, was achieved through the steady incorporation of new technologies, mainly, but not only, in the agricultural aspects of production. However, in the last five years, agro-industrial productivity has declined due to the recent crises in the sector, which has essentially been caused by a lack of clear public policies for bioenergy, as explained in other sections.

Bioelectricity production using sugarcane bagasse in cogeneration schemes has expanded intensely during the last years: nowadays there are more than 10 GW of installed capacity in sugarcane mills, which were responsible for generating 32.3 TWh in 2014, 5.1% of the total electricity produced in Brazil (MME, 2015), with a potential to reach 18% by 2020 (EPE, 2015). The implementation and evolution in sugarcane straw recovery will eventually lead to higher levels of surplus electricity. On average, the current levels of electricity surplus to the grid are around 30 kWh/t sugarcane but the more modern units, adopting state of art cogeneration steam cycles produce more than 60 kWh/t, even using only bagasse (not including trash).

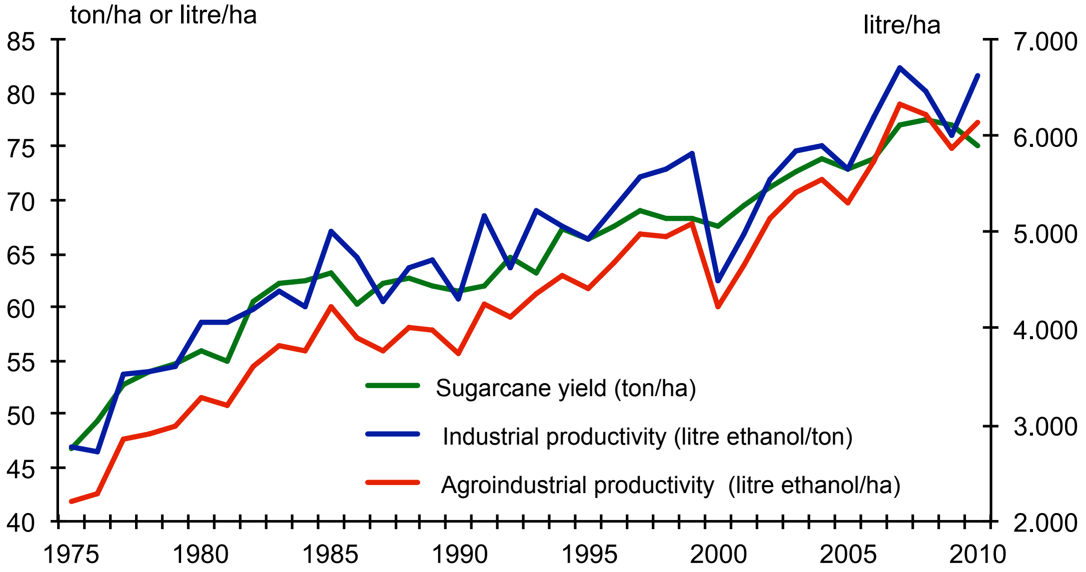

Figure 14. Evolution of the sugarcane agroindustry productivity in Brazil (UNICA, 2015)

3.2. Evolution of ethanol use as vehicular fuel in Brazil

The long experience with ethanol use in Brazil is illustrative of the relevant role of public policies to promote sustainable bioenergy. Table 1 summarizes the development of ethanol use in the Brazilian fleet of light vehicles during the last eight decades, with periods of intense expansion followed by times of stagnation.

Introduced to reduce the impact of dependence on imported fuels and absorbing the excess production of the sugar industry, ethanol participation in Brazilian energy matrix has varied over successive decades, as presented in Table 1. During the period 1931–1975, an average of 7.5% of the gasoline demand was substituted by this biofuel.

Table 1. Development of ethanol use as vehicular fuel in Brazil

Year	Event
1931	Introduction of mandatory blending, minimum 5% ethanol in gasoline
1975	Launched the National Alcohol Program, adopting 10% ethanol content in gasoline, further elevated to 20%, and promoting ethanol production and use
1979	Dedicated cars able to use pure hydrated ethanol were introduced, expansion of ethanol production
1985	End of government support to dedicated cars, retraction of interest in hydrated ethanol use
2003	Flex-fuel cars, able to use any blend of gasoline and ethanol, were introduced with good acceptance by consumers

1925 1975 2003

Figure 15. Highpoints of bioethanol as fuel in Brazil

In 1975, the effects of the first oil crisis motivated the expansion of ethanol use in Brazilian cars and the government launched the National Alcohol Program with a combination of incentives for production and use of ethanol in blends and pure in limited fleets. Given this favorable legal framework, between 1975 and 1979 the production of ethanol expanded significantly, from 0.58 Mm^3 to 3.68 Mm^3. In 1979, with oil prices reaching new heights, the ethanol program gained new force, stimulating the use of hydrated ethanol in engines adapted or specially made to use it. Under this scenario, ethanol production reached 11.7 Mm^3 in 1985, exceeding the intended goal by 8% (BNDES/CGEE, 2008). Around 1985, the situation began to change because of the decline in oil prices and strengthening of sugar prices. In 1986, the government reviewed the incentive policies for ethanol and stimulated the sugar production for export. These events brought difficulties to the ethanol market, with demand overcoming supply. The mechanisms for creating ethanol safety reserves failed, and emergency measures, such as reducing the level of ethanol in gasoline, importing ethanol and using gasoline-methanol blends as substitutes for ethanol, became necessary.

During the 90s, the Brazilian government implemented administrative reforms, adopting free-market pricing in the sugar-ethanol sector, removing progressively subsidies and reducing of the government's role in fixing fuel prices. A new regulation was implemented to organize the relationships between sugarcane producers, ethanol producers, and fuel distributors. The only feature kept from the original legal framework was the differential tax on hydrated ethanol and gasoline, which was intended to maintain approximate parity of consumer choice between hydrated ethanol and gasoline. In this context, ethanol is traded freely between producers and distributors. Within the sphere of agro-industry, the sugarcane is also traded freely, but its price is mainly determined according to a contractual voluntary model jointly coordinated by the sugarcane planters and ethanol and sugar producers (BNDES/CGEE, 2008).

In 2003, adding environmental benefits to the previous drivers for promoting ethanol, flex-fuel cars were launched and were well accepted by consumers. Flex-fuel cars offer owners the options of using gasoline (blended with ethanol), hydrated ethanol, or any blend of the two, depending on price, autonomy, performance or availability conditions. Thus, the consumption of hydrated ethanol in the domestic market made a comeback, creating new opportunities for the expansion of the sugarcane industry in Brazil, as well as the possibility of opening the international market for ethanol as fuel. During the period 2003–2008, the Brazilian sugarcane industry expanded rapidly, new and more efficient mills were commissioned, and a consolidation process was initiated, at the same time that positive indicators for the industry's environmental sustainability were demonstrated (Macedo, 2005; Goldemberg et al., 2008). Currently flex-fuel cars represent approximately 90% of sales of new cars, as indicated in Figure 16, and pure ethanol can be used by 36 million Brazilian vehicles (mostly cars with flex-fuel engines), representing approximately 66% of the national fleet of light road vehicles (ANFAVEA, 2015).

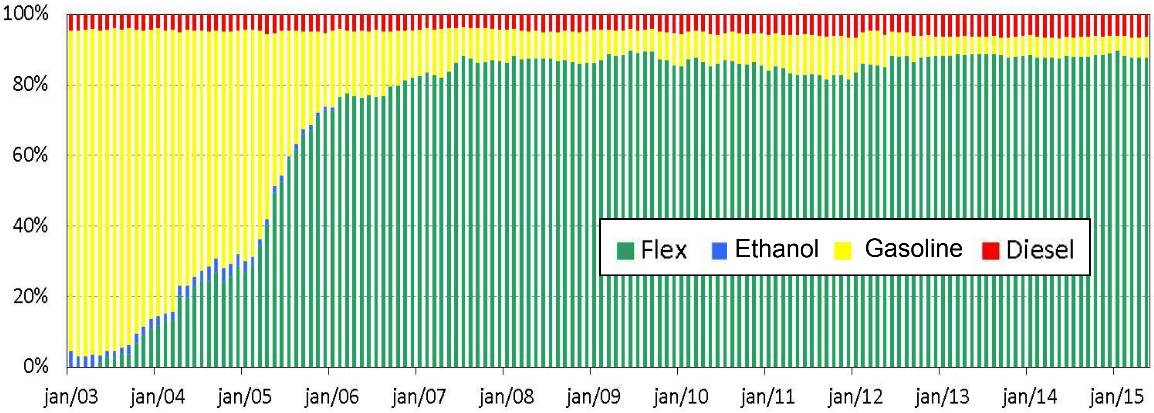

Figure 16. Sales of light vehicles in Brazil by fuel (ANFAVEA, 2015)

However, since 2008, the Brazilian ethanol agroindustry has stagnated, and the expansion process was interrupted. Although some other causes can be mentioned, such as adverse weather, cost increases and yield reduction due to the learning process of the adoption of mechanical harvesting, it is clear that the main reason is the increasing lack of ethanol competitiveness due to government intervention in gasoline prices (either imposing lower prices at Petrobras refineries (ex-taxes), as well as reducing the Federal taxes on this fuel), officially motivated by inflation control. Thus, as the Brazilian fleet is predominantly flex-fuel, ethanol consumption was displaced by gasoline; ethanol production felt and gasoline had to be imported. In 2015 some measures have been taken to recovery the ethanol market, re-establishing partially taxes on gasoline and increasing the ethanol blend to 27%, arisen positive expectations of ethanol recovery. This stop-and-go process highlights the relevance of public policies, setting clear perspectives to the market and fair playing field for producers in order to effectively promote sustainable bioenergy.

4. Second generation ethanol processes

The production of ethanol using lignocellulose as feedstock can happen trough biochemical or thermochemical conversion. In the biochemical route, the more developed one, a pre-treatment of biomass should be performed to separate the polymeric matrix of sugar-derived cellulose and hemicelluloses, and lignin, an alkyl-aromatic polymer, thus more difficult to process than grains or sugar crops. There are several competing pre-treatment options. Pre-treatment and hydrolysis lead to sugars that can be fermented to ethanol and other products. Today the most common application considered for the lignin is to supply process heat and electricity but additional products are being developed.

Ethanol concentrations (at the end of fermentation) and rates vary depending on catalysts, temperature, and time, as well as reactor selection and process integration conditions. Additionally, pre-treatment optimization conditions vary from one feedstock to another, thus generating many technology options and need for optimization. Various competing routes are under development. Considerable technical progress has been made and scaling up to commercial scales is underway but no industrial plant has operated yet at full capacity. Energy balance and overall costs need to be improved. Integration of second generation (2G) with 1G ethanol production provides an option for fully renewable production of energy without the use of fossil fuels for thermal processes and electricity in the conversion process.

While cellulose hydrolysis produces hexose, a molecule with six carbons (C6 sugar), hemicellulose hydrolysis produces pentose (C5 sugar). The hemicellulose hydrolysis is easier when compared with cellulose, but fermenting C5 sugar is more complicated than C6 sugars. Taking this onto account, the bio-chemical processes in development show different degrees of process integration: SHF (separated hydrolysis from fermentation); SSF (simultaneous hydrolysis/C5 fermentation); SSCF (simultaneous hydrolysis and co-fermentation of C5 and C6 sugars), indicated in Figure 17; and CBP (totally integrated processes). All these processes must be preceded by pre-treatment of lignocellulosic feedstock, which can be chemical/mechanical (as steam explosion), chemical (organic solvents) and other combinations.

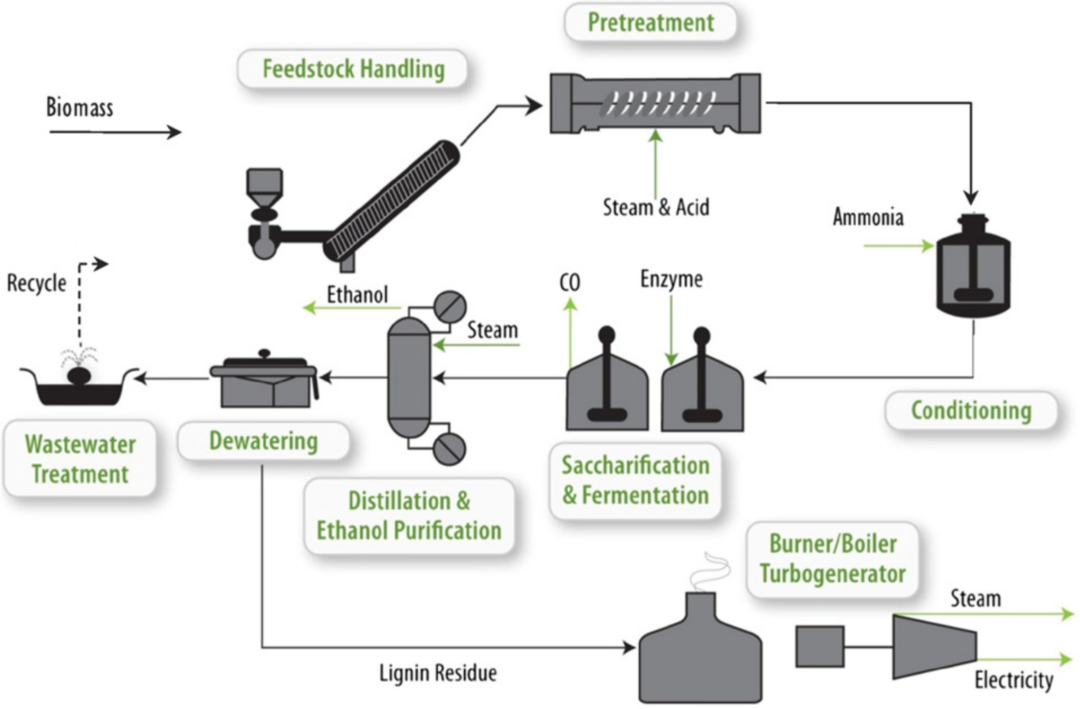

Figure 17. Process flow diagram for one route for biochemical conversion (SSCF) of bagasse to ethanol (apud Seabra and Macedo, 2011, modified from Aden et al., 2002).

Other biofuels that are also undergoing parallel technology development include other alcohols; syngas derived compounds obtained through gasification, microbial products using tools of synthetic biology, or fatty alcohols via heterotrophic algae in dark fermentation.

4.1. Current status of technology for ethanol 2G

Biofuels 2G, including the biochemical and the thermo-chemical (biomass gasification followed by biofuel synthesis, such as Fisher-Tropsch process) are taken longer time to reach mature technologies than expected 15 years ago. In the first half of the last decade large (public and private) investments in the US and Europe motivated the implementation of many projects, today still in R&D (or closed), starting demo plants and a few “first of the kind” commercial scale plants. Still today activities are mostly motivated by government policies (mandates and incentives).

A comprehensive analysis presented by the NREL in 2013 (NREL, 2013) on the goals and achievements of the E2G developments in the US looked to a “standard” conceptual project based on corn stove, SSCF, 2,000 ton ethanol/day; following the advances (projected mostly from lab and pilot scale) from 2000 to 2012, very interesting results are shown:

- Production cost (projected): 2.42 US$/liter (2001) to 0.57 US$/liter (2012);
- Technology improvements achieved in all five process steps: Biomass Supply, Feedstock logistics, Pre-treatment, Enzymatic Hydrolysis, and Fermentation;
- All the biomass-processing steps were validated at *pilot scale* (1 ton/day continuous; and 8 m^3 for batch fermentation).

At this time, many plants (demonstration, and some actually commercial scale) were being built. It seems that in some cases by-passing steps in the development led to problems. Many projects were cancelled, at risk, or incomplete (BCG, 2014); still some commercial scale plants are starting in the US (Abengoa, DuPont, Poet-DSM); in Europe (M&G); in China (Shandong), and in Brazil (Granbio, Raizen, Abengoa) (BNDES, 2015a). Recent public-private partnership (PPP) conducted by BNDES and FINEP, further commented, have enhanced the development of E2G technologies in Brazil; two commercial plants and one demonstration plant are starting to produce the biofuel. Anyway, great progress has been made (costs and performance) and it is expected that, given the proper development time, E2G processes will succeed in bringing large ethanol volumes to the market.

4.2. Comparison of power generation and ethanol production from sugarcane residual biomass in Brazil

Biomass costs (and reliable supply) are an essential consideration, in all cases. In Brazil the integration of 1G ethanol plants (with large biomass surplus) with 2G processes presents challenges, but also very promising routes. Some studies have been looking into different integrated systems, and all recent initiatives in Brazil consider those possibilities.

Increasing energy efficiency in the use of cane biomass (beyond the conventional steps of producing ethanol from sugars and improving power generation from bagasse and, starting now, from cane residues) may lead to important changes in the sugarcane agroindustry. Figure 18 shows an overview of the possibilities, including advances in conventional electricity production and ethanol 2G processes, based on the expected performances.

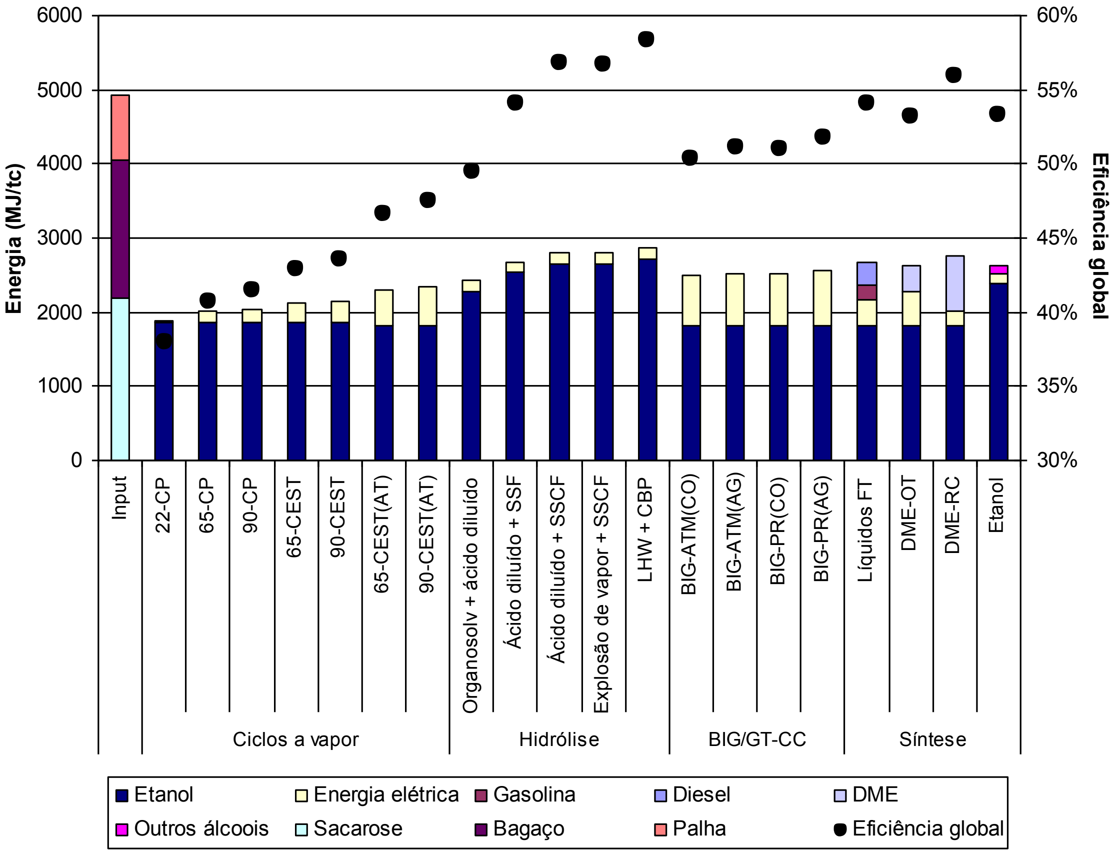

Figure 18. Sugarcane energy input, mill production breakdown and energy output (in columns, left axis), and global energy efficiency (in dots, right axis) for several routes for lignocellulosic processing in sugar mills (Seabra and Macedo, 2011)

In the context of the sugarcane agroindustry, energy efficiency can be assumed as the ratio between the total commercial energy output (including ethanol, electricity, and other Fischer-Tropsh fuels) and the energy input (energy in cane: sucrose and other reducing sugars, bagasse and 40% of the trash). Considering a reference mill in Brazil and the results presented in Figure 18, the range of energy efficiency for some alternatives under consideration for using lignocellulosic material is shown in Table 2 (Seabra and Macedo, 2011).

Table 2. Energy efficiency in using surplus bagasse and straw in sugarcane mills (Seabra and Macedo, 2011)

Process	Energy Efficiency
Conventional steam cycles	38-47%
Ethanol 2G (by hydrolysis)	49-58%
Gasification + combined cycle electricity	51-52%
Gasification + Fuel Synthesis	54-56%

To select the most interesting processing route for a given context, besides energy efficiency, additional considerations should be made, taken into account aspects such as the commercial energy cost and value (local), local policies, the resulting emissions, and of course the technology availability. Financing mechanisms are an important issue, and they may be different in each case, as in Brazil, today. In Brazil the value of electricity and ethanol are strongly dependent on public policies, with large uncertainties. In the last years, almost all greenfield sugar mills have opted for high pressure boilers and turbo-generators with some condensing capacity, to allow for more electricity production; because the ethanol demand was stagnated. Indeed, the ethanol 2G alternatives depend directly on how the domestic and international ethanol markets develop.

5. Modern biomaterials in the sugarcane agroindustry

Plastic materials play an important role in our modern life, with a wide range of applications, whether replacing traditional materials or creating new products. The main inputs to produce plastics in the petrochemical industry are natural gas and petroleum- naphtha. Production processes are usually grouped into three categories: a) first generation industries, which supply basic petrochemical products or building blocks, such as ethene (or ethylene), propene (or propylene) and butadiene; b) second generation industries, which transform the petrochemical building blocks into so-called final petrochemical products, such as polyethylene, polyesters and many other; and c) third generation industries, in which the final products are converted in final consumer products, such as films, containers, and objects.

Ethanol is a homogeneous and reactive substance that can be used as an input in various traditional petrochemical processes, as shown in Table 3, which in this case could be called alcohol-chemical processes. The most important process among them is ethane, produced by the dehydration of bioethanol and precursor of a wide range of second-generation products, such as polyethylene, polypropylene, and polyvinyl chloride (PVC). Assuming a conversion efficiency of 95%, 1.73 kg or 2.18 liters of bioethanol are consumed for each kilogram of ethane produced (BNDES/CGEE, 2008).

Based on the dehydrogenation of ethanol into acetaldehyde, it is possible to generate another important class of intermediate butadiene and polybutadiene, basic components of synthetic rubber used for various applications, including tires. Almost all products listed in Table 3 have widespread use in the industry, agriculture and final use, with important markets at a global scale. Considering the world ethylene demand forecasted for 2020, about 200 million tons (Technip, 2013), the use of bioethanol to replace 10% of other inputs would result in a demand of 44 billion liters, which is more than 1.5 times the current Brazilian bioethanol production.

Table 3. Basic processes of the alcohol-chemical industry (Schuchardt, 2001, adapted)

Processes	Main products	Typical application
Dehydration	Ethylene Propylene Ethylene-glycol	Plastic Resins Solvents Ethyl Ether Textile Fibers
Dehydrogenation Oxygenation	Acetaldehyde	Acetic Acid Acetates Dyes
Esterification	Acetates Acrylates	Solvents Textile Fibers Adhesives
Halogenation	Ethyl chloride	Cooling Fluids Medical Products Plastic Resins
Amonolysis	Diethylamin Monoethylamine	Insecticide Herbicide
Dehydrogenation Dehydration	Butadiene	Synthetic Rubbers

During the 80s, projects to promote the use of ethanol to substitute fossil inputs in the Brazilian petrochemical industry were successfully implemented by Oxiteno and Coperbo, and discontinued in 1985 because low oil prices. Oxiteno used sugarcane bioethanol regularly as an input at its unit in Camaçari, Bahia, with an annual production of ethylene estimated at 230,000 tons. Oxiteno is still interest in developing own technology in green chemistry, targeting to reach 20% of raw materials from renewable sources and 35% of products with renewable components (Oxiteno, 2012). Coperbo, the Pernambuco Rubber Company, has a long history tying ethanol to the production of chemical inputs. In 1965, this company started the production of its butadiene unit in Cabo, Pernambuco, to manufacture 27,500 tons per year of synthetic rubber based on ethanol, aiming to meet the growing demand for this elastomer, mainly used for tires production.

However, the approval by the Government in the following years of exports of molasses, reducing ethanol production, and imports of natural rubber, hampered the company’s operations. In 1971 Coperbo was transferred to Petroquisa, the former petrochemical subsidiary of Petrobras, which gave it a new impulse to increase the ethanol use. The inclusion of acetic acid and vinyl acetate in its product line led to the creation of the National Alcohol-Chemical Company, which was later controlled by Union Carbide, a company that is currently managed by Dow Chemical (BNDES/CGEE, 2008).

On the frontier of biomaterials based on sugarcane are the biodegradable plastics, which can be a solution for the increasing problem of land and water pollution with conventional plastics. Biodegradable plastics are polymers that, under appropriate environmental conditions, decompose completely in a short period of time due to microbial action. Biodegradable bioplastics add an important advantage: to be produced from renewable sources, like starches, sugars or fatty acids. One example of a bioplastic is polylactic acid (PLA), which is composed of lactic acid monomers obtained from microbial fermentation.

Another possibility is to obtain the biopolymers directly from micro-organisms as in the case of polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA) and their derivatives; in these cases the biopolymer is biosynthesized as energy reserve material of micro-organisms (BNDES/CGEE, 2008). Although currently the basic bioprocess is well understood, scaling-up production units and economic feasibility remain as barriers to overcome for large production. Nevertheless, as an example of innovation implementation in this context, Usina da Pedra mill started-up in 1995 a pilot plant to produce 0.5 ton/year of biodegradable bioplastics, using batch fermentation processes and sugarcane by-products as feedstock. Based on tests and results from this pioneer venture, that plant was remodeled to produce 50 ton/year, improving the process and a spin-off company was created, Biocycle, aiming to operate a 3,000 ton/year unit. To produce 2.2 kg of plastic, 6.6 kg of sugar are consumed, meaning that 1 ha of sugarcane can produce approximately 3.6 ton of bioplastics (Biocycle, 2015).

Recently the sugar cane industry in Brazil has advanced in the use of sucrose (not ethanol) to produce biomaterials, besides the established production of many others (lysine, citric acid, butanol, etc). With the use of genetically modified microorganisms (respectively, yeasts and algae) Amyris and Solazyme have started production of farnesene and many oils (for food, feed and industrial applications, besides fuel). One of the industries aims at large scale production (up to 100 thousand ton oil/year) pushing the integration with the sugar mill to a quite different level.

6. Energy cane development

During a long time, the selection of sugarcane varieties has oriented the high photosynthetic efficiency of this plant to augment sucrose content and reduce fibre in cane stalks, in order to increase sugar production and facilitate milling operation. Such usual paradigm of sugarcane breeding has imposed to backcross commercial *Saccharum officinarum* hybrid varieties with sugary and low fibre ancestral species, reducing its vigour and limiting its productivity. The potential field productivity of sugarcane is estimated to be about 400 ton of fresh biomass per hectare per year in optimum conditions (Souza et al., 2013), while the world commercial average productivity is less than 25% of that value. In fact, despite the significant increase in productivity and diversification of varieties observed in recent decades, the genetic potential of sugarcane still allows additional significant gains, with clear implications to overall agroindustry performance and prospects for lignocellulosic feedstock processing.

A revision of the usual paradigm focused on sugar was pioneering recommended by A. G. Alexander during the 1980's in Puerto Rico, indicating that the fiber content should be re-evaluated, with global gains in productivity and performance. In his proposal, aimed to recovery the economically depressed Puerto Rican sugarcane industry in that time, Alexander's group always stressed the possibility of using the whole plant: the juice, the fiber and also the top and the leaves, from the more productive cultivars (Matsuoka et al., 2014).

Under this concept, currently more understood and feasible after the advances in sugarcane genetics, energy cane is essentially a cane with a lower sucrose content and higher fiber content than usual sugarcane varieties, and most importantly, presenting higher yields in ton of plant material per hectare (Alexander, 1985). To date, the results achieved, mainly by hybridization of commercial sugarcane with wild species of *Saccharum officinarum* and *S. Sponteneum* are promising (Matsuoka et al., 2014) and the diffusion of commercial varieties of energy cane is expected soon. All Brazilian sugarcane breeding programs: CTC, IAC, Vignis and RIDESA, are developing energy cane cultivars. As an example of initiative in this field, the Instituto Agronômico de Campinas, associated to GranBio, is developing a set of clones that has about 50% more biomass than the conventional cane (Carvalho-Netto et al., 2014). Figure 19 depicts a comparison of an energy cane cultivar and a conventional one, at 90 days after planting.

Cultivars of energy cane are higher (up to 6 meters) and thinner (1.5 to 2 cm diameter) than commercial sugarcane hybrids, typically present a narrower leaf blade, with large amounts of tillers. They have great adaptability to poor soils and still have a relevant amount of sugar per ton of cane. Currently these varieties are under evaluation to select the best suited for different production contexts, as well as to assess properly aspects of nutrition, response to pests and diseases, harvest and longevity. Energy cane cultivars have been considered mainly for the new frontiers of the sugarcane industry, where the soil and climate conditions are more difficult than in traditional areas.

Figure 19. Example of energy cane (at left) and commercial sugarcane (at right) at 90 days after planting (Carvalho-Netto et al., 2014).

In addition to increased energy production, varieties of sugarcane energy has shown vigorous root systems, as presented in Figure 20, providing good sprouting and great longevity, allowing expand the number of harvests for the same planting, with obvious economic advantages. As indicated in Table 4, it is estimated that between 2010 and 2030 the energy cane cultivars could increase in 140% the annual energy productivity, which can rise from 628 GJ/ha to more than 1,200 GJ/ha (Landell et al., 2010).

Figure 20. Root system of energy cane (at left) compared to one of a commercial-type sugarcane (at right) (Matsuoka et al., 2014)

Table 4. Projected yield for energy cane cultivars improvement (Landell et al.,2010)

Energy cane component	**Year**		
	2010	**2020**	**2030**
Stalks (fresh ton/ha)	81	111	130
Trash (dry ton/ha)	14	19	24
Sugar (%)	15	13	12
Fiber (%)	12	18	23
Total energy (GJ/ha)	628	940	1228
Energy output/input	8	12	14

The development of sugarcane varieties presenting higher energy yield, based on more fiber, certainly is synergistic with the development of processes capable of enhancing lignocellulosic raw materials. However, it should be observed that energy cane creates a new scenario, involving new processes, technologies, resources, and new challenges, as well. The pioneer Alexander three decades ago already recommended to include the production of ethanol in the framework of sugarcane agroindustry and emphasized that the term “energy cane” should not apply to individual plants but rather to a management system (Matsuoka et al., 2014).

7. The decisive role of public-private initiatives

The availability of natural resources, agroindustrial technology and potential demand is not enough to foster investments in advanced biofuels production, mainly due to risk perception inherently associated to new process and market uncertainties. Therefore, the government role is decisive to support properly innovative ventures in bioenergy and bioprocesses, assuring attractive market conditions and reducing uncertainties impacts, especially in the middle of cycle of innovation, after the bench stage and before the commercial production. As can be observed in many cases, in the implementation of a new bioenergy technology, after the initial steps in research and pilot plant, moving to a demonstration unit and following to the first commercial plant presents considerable challenges and risks, in general requiring external support. Such external support can be given fostering the demand, on the supply side, as well as, assuring a demand of the new products, on the consumption side.

Under such concepts, aiming basically to foster the production side, and stimulating public private partnership, the BNDES/FINEP Joint Plan for Supporting Industrial Technological Innovation in the Sugarcane-based Energy and Chemical Sectors (in Portuguese Plano Conjunto BNDES-FINEP de Apoio à Inovação Tecnológica Industrial dos Setores Sucroenergético e Sucroquímico, PAISS), launched in 2011, has induced important investment in second generation bioenergy and energy cane in Brazil, an initiative decisive to overcome starting obstacles and advance in the learning curve. In this section the main features and current result of this program are presented.

The departure motivation for PAISS Plan was essentially the awareness of Brazilian Development Bank (BNDES) and the Brazilian Innovation Agency (FINEP), both institutions in charge of promoting development and innovation in Brazil, of the large delay of the national sugarcane agroindustry in implementing advanced bioenergy technologies, in comparison to other countries, despite of the existence in the Country of a mature and competitive biofuels production, equipment suppliers, and active research institutions in bioenergy. In 2010, while advanced biofuels programs in US and Europe were properly coordinated, with budgets that surpassed US$ 2 billion and several pilot plants in place, in Brazil few projects, lacking integration and coordination, were put forward, representing a small share of BNDES budget applied to bioenergy. Among these projects it could be mentioned the experimental plants of Dedini DHR using acid hydrolysis, CTC and CENPES/Petrobras, both adopting enzymatic hydrolysis.

As stated in its introductory documents, PAISS Plan is a joint innovative initiative of the BNDES and FINEP to select business plans and promote projects that include the development, production and marketing of new industrial technologies for processing biomass derived from sugarcane, assisting good proposals to obtain financial support in the context of both institutions, improving the coordination of development actions and better integration of financial support instruments available. This program is accessible by companies whose corporate purpose understands conducting research, technological development and innovation related to sugarcane processing for energy and biomaterials and who have an interest to undertake the activity of production and/or marketing of the end products resulting from these technologies, focusing mainly the research lines presented in Table 5 (BNDES, 2011). In the instructions to present tenders to PAISS, it is recommended that proposals should involve industry and research institutions, allowing the direct involvement in the projects of the Brazilian Bioethanol Science and Technology Laboratory (CTBE), the National Institute of Technology (INT) and 8 universities. A list of priorities was presented, Table 5 shows the main areas to be explored with regards to process innovatively sugarcane.

Diverse financial instruments were offered by PAISS including: a) credit in special financing lines, b) equity participation, c) non-reimbursable funds for cooperative projects between companies and R&D institution and d) economic support non-refundable (grants) for companies, defined depending on the case (amount, technological risk, involved institutions, etc.). In this context is relevant the BNDES Technology Fund (BNDES Funtec), allowing non-refundable support for projects, with the aim of stimulating technological development and innovation of strategic interest for the country, in line with Federal Government policies.

Table 5. PAISS Plan priorities and main themes (BNDES, 2015b)

Research line	Topics
2nd Generation Bioethanol	1.1 Straw Gathering and Transportation 1.2 Pre-treatment of biomass for hydrolysis 1.3 Processes for enzyme production and/or hydrolysis processes of lignocellulosic material 1.4 Microorganisms and/or processes for C5 fermentation 1.5 Integration and scaling of processes for cellulosic ethanol production
New Products from Sugarcane	2.1 New products from sugarcane biomass 2.2 Integration and scaling up of processes for the production of new products
Gasification	3.1 Pre-treatment of sugarcane biomass for gasification 3.2 Biomass gasification technologies for sugarcane 3.3 Gas purification systems 3.4 Catalysts associated with the conversion of syngas into products

The coordination of the efforts between the BNDES and FINEP permitted to offer initially about US$ 625 million in financing lines, levering investments of US$ 1.7 billion in the end of tenders selection process, developed between 2011 to 2014. The 10-year loans were offered at 4% interest.

A sequence of screening steps was adopted to select projects worth to deserve PAISS funding. After the call for tenders, 57 companies registered proposals, corresponding to a potential investment of US$ 5 billion. Taking into account the adherence of those proposals to the aims and the PAISS rules, a second set of 39 proposals was pre-selected to present business plans, summing up US$ 3 billion. This second group of proposals received support to prepare a financing plan, considering the financial instruments offered by BNDES and FINEP in the frame of PAISS Plan, refining the initial business plan and consolidating the project budget. Finally, considering the economic and financing aspects, a second round of evaluation selected 25 companies, with proposals corresponding to a potential investment of US$ 1.7 billion, distributed among the research lines as indicated in Table 6.

Table 6. PAISS approved projects by research line (BNDES, 2015b)

Research line	**Number of projects**	**Investment** (US$ million)
Cellulosic Ethanol (E2G)	17	703
Renewable Chemicals	22	753
Gasification	1	120
total	40	1,716

Among these 25 companies are large chemical and oil groups as well as technology-based start-ups that saw PAISS as an opportunity to accelerate their entry into Brazil. Many of these business plans selected are dedicated to R&D investments, such as laboratory facilities and pilot plants, but there are also larger investments, mainly focused on demonstration and commercial plants.

These projects include four ethanol 2G plants, listed in Table 7, which total installed capacity reaches 188 million liters per year, two of them already inaugurated. As usual in innovative processes, these plants are facing difficulties and progressively improving their operation. Although the initial concerns were the stability and performance of the core process, the hydrolysis of lignocellulosic feedstock, in the actual operation this stage has presented satisfactory results, with problems arisen in the feedstock logistics and pre-treatment. Particularly the pre-treatment has been a challenging unit operation, due its cost and direct effect on subsequent hydrolysis time and yield. Anyway, it seems that issues are complex, but it is expected that the problems will be progressively solved.

Table 7. Ethanol 2G Plants in Brazil

Company	**Site**	**Scale**	**Capacity** (l ethanol/year)	**Current status**
Granbio	S. Miguel dos Campos, AL	Commercial	80 million	operating
Raízen	Piracicaba, SP	Commercial	40 million	operating
Abengoa	Pirassununga, SP	Commercial	65 million	in construction
CTC	São Manoel, SP	Demonstration	3 million	operating

Other achievements of PAISS worth to mention are the construction of the first two commercial plants in Brazil dedicated to produce valuable renewable chemicals from sucrose and other fermentable sugars from sugarcane: the Solazyme Bunge unit, near Usina Moema mill in Orindiúva/SP, designed to produce annually up to 100,000 ton of bioengineered oils and customized products by advanced fermentation with microalgae, and Amyris unit installed close to Usina Paraíso mill, in Brotas/SP, applying fermentation with modified yeasts to produce fine biochemical products: drugs, cosmetics and farnesene, a product used as fuel in blends with regular diesel.

Figure 21. Plants of Granbio in São Miguel dos Campos (AL) and Raizen in Piracicaba (SP)

The positive outcome of the PAISS program reflects the favorable conditions existing in Brazil and in other similar countries to host investments for new technologies to convert biomass, ranging from R&D Centers to demonstration plants; and enable large investments to establish the commercial plants derived from new technologies that have been globally developed. The main drivers for such attractiveness are presented as follows (Milanez et al, 2012).

- Ready availability and low cost of feedstocks, mainly sugarcane bagasse and straw.

- Locally developed pathways with dedicated technology due to the specific complexity of domestic feedstocks
- Large amount of available land, typically low productivity pastures, that can be converted into agricultural crops for energy or chemical purposes.
- Well-established sugar and ethanol agroindustry, which facilitates the integration of new technologies under low investment and with reduced operational costs.
- Fuel market growth and heavy dependence on imports of chemicals, that creates an excellent opportunity for domestic investment.
- Increasing opportunities for developing a global trade of biofuels and biomaterials, considering the lowest carbon footprint of products derived from sugarcane.

In 2014 the Joint Action Plan Agricultural PAISS was launched, following the PAISS track and aiming also to promote innovation in the sugarcane agroindustry, but focusing the feedstock production and considering the period 2014-2018. Adopting a similar approach with regards financial instruments and procedure for proposals selection, this initiative intends to promote both the development and the pioneering implementation of agricultural technologies, including the adaptation of industrial systems, since it entered the production chains of sugarcane and/or other energy crops compatible, complementary and/or associated with the agro-industrial system of sugarcane. BNDES and FINEP make available US$ 630 million[5] for Agriculture PAISS projects for the period 2014-2018 (BNDES, 2014).

The drivers to put forward this initiative were basically the relative stagnation in the sugarcane productivity during the last decade, due to a lower rate of new varieties introduction and aging of sugarcane fields, associated to the limited supply of modern technologies specific for this culture, compared with other crops occupying larger areas, such as corn and rice, and in the upside, the interesting potential for introducing technologies such as mechanized planting, precision agriculture and advanced logistics (BNDES, 2013). For this program, the priority topics are presented in Table 8.

The first two proposals approved under the Agricultural PAISS Plan were the Biovertis project, located at Barra de São Miguel/AL, which will receive US$ 59.3 million[5] for developing and implementing a proper management system for energy cane production, involving soil preparation, planting, cultivation, harvesting and transportation, and the Raizen project, amounting to US$ 1.91 million[5], aimed at enabling large more agile and efficient technical scale propagation of pre-sprouting of sugarcane seedlings, a technique able to increase the agricultural productivity and reduce costs.

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[5] Original values in Brazilian currency, converted using the average annual exchange rate (2.35 BRL=1.00 USD).

Table 8. Agricultural PAISS Plan priority themes (BNDES, 2014)

Line 1: New varieties, mainly: those related to the production environments of border regions; more suitable for agricultural mechanization; and/or larger amounts of biomass and/or ATR, with emphasis on the use of transgenic breeding.
Line 2: Machines and implements for planting and/or harvesting and straw for collection and/or waste, with an emphasis on expanding the use of precision agriculture techniques.
Line 3: Integrated systems management, planning and control of production.
Line 4: Technical more agile and efficient propagation of seedlings and innovative biotechnological devices for planting.
Line 5: industrial systems adaptation to energy crops compatible, complementary and/or associated with the agroindustrial system ethanol produced from sugarcane.

The industrial and agricultural PAISS Plan has released regularly information, figures and studies about this initiative, an important element for developing and promoting sustainability in the sugarcane agroindustry. An indicator of PAISS positive results is its replication in other sectors, applying its model of inducing public-private partnership, involving research institutions and commercial companies. The rationale is to reinforce at same time, the experience in doing business and the knowledge basis.

Nevertheless, improvements have been considered in simplifying the procedures and increasing the coordination with complementary policies, as well as, addressing the competitiveness of these innovative technologies, introducing mechanisms to encourage the consumption of 2G ethanol, such as a specific tax regime and/or a mandatory quota (Nyko et al., 2013).

8. Main remarks

The sugarcane agroindustry started an important evolution, aggregating advanced technologies and becoming more and more a supplier of renewable liquid fuels and electricity. The conjugated opportunity for implementing processes to convert lignocellulosic feedstock in ethanol and electricity, plus the high potential for increased yields of biomass with energy cane, creates a new scenario, with multiple gains: energy, plus economic, social, and environmental benefits.

In spite of better understanding of this potential, its development depends on proper public policies, reducing risk perception and stimulating efficiency. In this direction, the Brazilian case is a good example: the availability of natural resources, the existence of a well-established sugarcane agroindustry, a proper legislation setting a market for bioenergy, and furthermore, a suitable financing program, promoting innovation, fostering investment and technological and business partnerships, represented a important move forward to consolidate a desirable reality, which first results are appearing. This transformation is starting, with different pathways in evaluation, and learning curves are evolving. But the model is defined, implemented and working. In a few words, it is possible to produce competitive and sustainable energy, as well as customized biomaterials, in the required amounts and with the specified quality.

Part II addresses the impacts and effects carried out by these innovative processes of sugarcane production and processing, for different scenarios for supply and consumption.

Thoughts on the present and the future:

Many wet tropical countries have developed the sugarcane agroindustry for a long time, generating sugar, income and jobs. Now, this agroindustry can go beyond, keeping these achievements and adding energy and environmental protection among its products. About thirty years ago, a visionary man advised:

> “*…for developing nations historically bound together with sugarcane there is still time for constructive and meaningful change. There is time to prepare its place as a future sugar crop, a domestic energy crop, and a multiple-products commodity in service to all future generations*.”
>
> A G Alexander, 1985, Puerto Rico

PART II - Opportunities and Benefits from Sugarcane Biomaterials and Bioenergy 2G

Introduction

Transportation of goods and people, in short and long distances, and the use of modern materials and chemicals such as plastics, agrochemicals and textiles are essential aspects of the everyday life in the contemporary society. However, both transport and industry are relevant GHG producers and the urgent need of dealing with climate change leads to consider seriously innovative and more sustainable alternatives to the fossil energy resources currently adopted. This part of the study presents the potential of advanced processes based on sugarcane, one of the most efficient ways to collect and store solar energy, as feedstock for producing second generation (2G) biofuels and other biomaterials able to supply a relevant share of the global demand, evaluating the associated impacts in terms of GHG emission mitigation and land requirements. These technologies offer today a competitive and sustainable alternative, able to replace large amounts of fossil resources, promoting development and alleviating climate change.

This second part of the study has six sections. In the first one, the prospects for biofuels and biomaterials demand are presented, essentially based on international agencies forecasts and introducing the Brazilian case as an example for the increasing need of ethanol. In the second section, biomaterials are focused, considering current and prospective technologies, and presenting demand perspectives as well. The third section introduces ethanol production models, explaining the different criteria for managing feedstock and the flows of sucrose and lignocellulose and assessing the GHG emission mitigation impact, highlighting the contribution of innovative processes to ethanol production. In the fourth section, based on actual sugarcane yield values the impact on land utilization is assessed, including the expected effect of energy cane introduction. The results of evaluation of GHG emissions and land use impacts associated to innovative technologies for ethanol production are estimated at global level in the fifth section. The last section addresses the main conclusions and recommendations.

The Brazilian actual sugarcane mills are the main reference for data and conditions adopted in this study; they can be considered similar to other tropical countries employing the same state of art technologies, such as Colombia, Guatemala and South Africa.

1. Market perspectives for Biomaterials and Bioenergy 2G

The perspectives for deploying innovative technologies to produce biomaterials and biofuels depend on their current and future demand which is, among other aspects, function of their competitiveness and differential advantages regarding the conventional products, as well as the public policies towards creating and consolidating markets for these products. In this section the potential market for bioethanol as vehicular fuel and some relevant biomaterials that can be produced from sugarcane are reviewed and commented. The Brazilian ethanol market is presented as an example.

1.1. Global market for liquid biofuels

The global market for liquid biofuels is directly related to the demand of conventional fuels in transport. Besides population, motorization and income levels, several other factors must be taken into account, generally difficult to forecast at country level. For instance, the evolution of fuel demand is affect by the taxes applied to fuels and vehicles, the development of suitable public transportation able to compete with individual cars, and the vehicular technology available.

The evolution of world fleet of light duty vehicles has been impressive and mainly in developing countries there is a large room for expansion, if the trend observed in industrialized countries is followed, as indicated in Figure 22 (IEA, 2004). The global rate of motorization in 2013 was 174 vehicles per 1000 inhabitants and it is growing fast; the Chinese and Indian fleets have grown at an annual rate of around 7 to 8% (Ward, 2014).

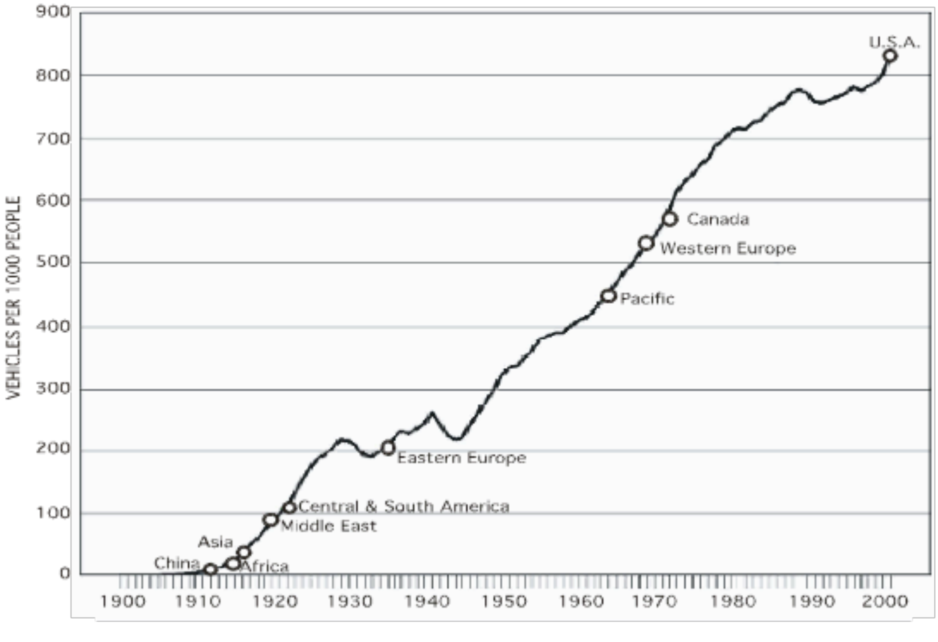


Figure 22. Evolution of motorization in the United States and situation observed in some

countries and regions in 2001 (EIA, 2004)

A detailed assessment of the future global demand for fuels in the transportation sector was developed by the World Energy Council, the Global Transport Scenarios 2050 (WEC, 2011), involving 54 experts from 29 countries, considering the available and emerging technologies and enabling policies, and assessing separately 15 world regions, with two scenarios:

- "Freeway" scenario: envisages a world where market forces prevail to create a climate for open global competition, higher levels of privatization, deregulation, and liberalization.
- "Tollway" scenario: describes a more regulated world where governments and prominent politicians decide to put common interests at the forefront and intervene in markets.

Figure 23 presents the expected evolution for the world light duty vehicle (LDV) fleet, from the 773 million vehicles registered in 2012 to 1,750 million (Tollway) until 2,080 vehicles (Freeway) in 2050, which means to reach globally the same level of motorization observed in US respectively around the 20's and the 30's of last century, as indicated in Figure 22.

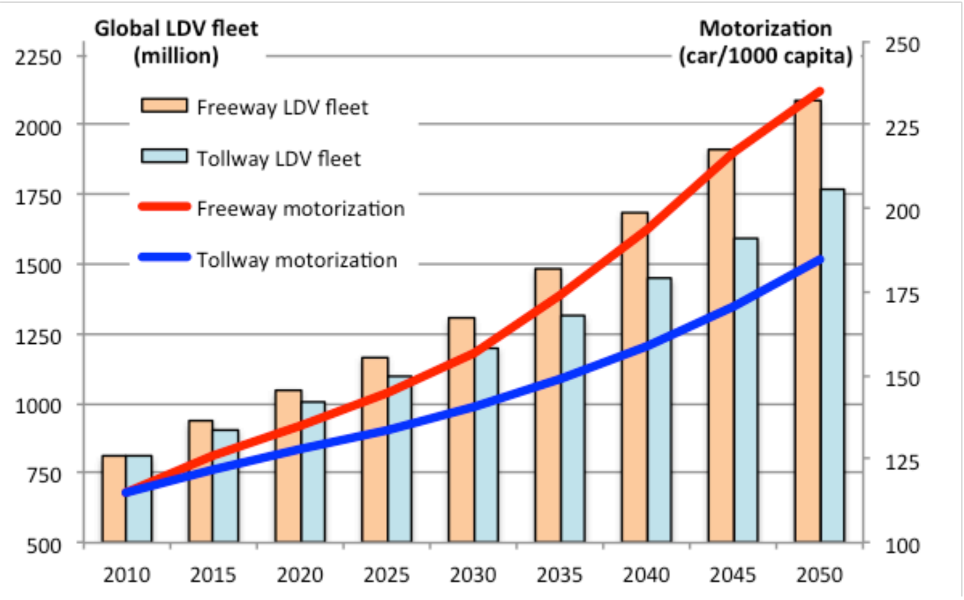
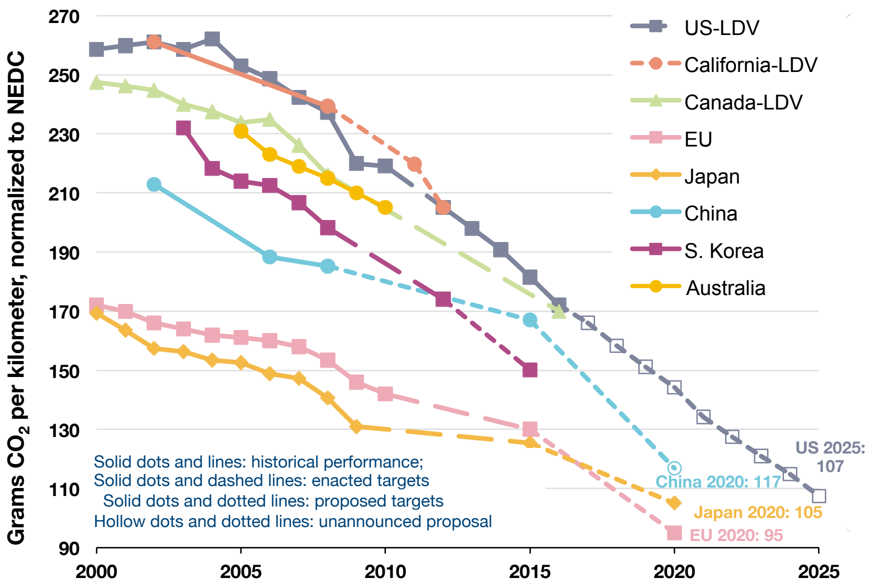


Figure 23. Projections of global fleet and motorization for regulated (Tollway) and non-regulated (Freeway) scenarios (based on WEC, 2011)

On the other hand vehicular technology is improving, pushed by air quality regulation and challenging targets on carbon emissions, in some cases reaching about 130g CO2/km. Advanced motor technologies such as direct injection, variable valve actuation and downsizing and advanced after-burning treatment, imposed by stringent environmental regulation, as well as improvement in transmission systems, tires, vehicle aerodynamics, weight and control have been introduced with good results in light duty vehicles (LDV). Thus, there are positive trends for important reductions in fuel consumption and emissions from road transport in the forthcoming years, as indicated in Figure 24 (Ricardo, 2012).



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

Figure 24. Historic and forecasted specific vehicular CO2 emission in different countries (Ricardo, 2012)

However, in terms of global GHG emission from the transportation sector, the remarkable technology improvements have been not able to compensate the huge expansion of fleet, as pointed out by several studies. As main results from the WEC scenarios to 2050, the total fuel demand in all transport modes will increase by 30% (Tollway) to 82% (Freeway) above the 2010 levels. Transport sector fuel mix will still depend heavily on gasoline, diesel, fuel oil and jet fuel, as they all will still constitute the majority of transport market fuels with 80% (Tollway) to 88% (Freeway) in 2050. The additional transport fuel demand will come from the developing countries where demand will grow by 200% (Tollway) to 300% (Freeway). Therefore, the total GHG emissions from the transportation sector are expected to increase between 16% (Tollway) and 79% (Freeway), confirming the relevance of the government intervention and low carbon fuel systems to face climate change (WEC, 2011).

Accordingly to this WEC study, biofuels will contribute to satisfy that growing demand for transport fuel, as their use will increase almost four fold in both scenarios. Thus, by 2030 the consumption of biofuels could reach about 93 Mtoe, accounting for about 5% of the total road-transport fuel demand, compared with approximately 3% today. Presenting a higher forecast, the BP Energy Outlook

2035 expected that all modes of transport sector will be consuming 2,916 Mtoe in 2030, in which 114 Mtoe as biofuels, corresponding to about 4% of total (BP, 2015). This forecast of expansion of the liquid biofuels market, representing 4.77 EJ/year in 2030, mainly associated to ethanol use in blends with gasoline, must be considered conservative, since there is a large untapped potential for sustainable ethanol production, with a major impact in reducing GHG emission.

The potential sustainable supply of bioenergy and particularly liquid biofuels has been assessed in detail by several institutions, considering different feedstocks and production schemes, as well as the requirement and availability of land in diverse scenarios. One of most authoritative assessment of global bioenergy potential was the Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011), outcome from a large team of experts after reviewing many studies and developing a comprehensive evaluation of natural resources availability and constraints for renewable energy sources. Specifically for bioenergy, this report points out that “the upper bound of the technical potential of biomass for energy may be as large as 500 EJ/year by 2050”, and highlights that to reach “a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimization and other measures. Realizing this potential will be a major challenge, but it could make a substantial contribution to the world’s primary energy supply in 2050” (Chum et al., 2011).

Certainly the role of biofuels in GHG stabilization scenarios can be significantly higher than today. It depends strongly on proper policy frameworks that ensure good governance of land use and improvements in forestry, agricultural and livestock management, together with the adoption of more efficient technology routes, processing high yield biomass. Figure 25 presents modeling results for renewable energy deployment covering a wide range of assumptions about energy demand prospects, cost and availability of RE technologies, including bioenergy, to indicate the expected contribution of liquid biofuels in the next decades for three GHG stabilization ranges, as defined by IPCC Assessment Reports by 2100. The results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results (Chum et al., 2011).

The median levels of biofuels deployment in the most strict mitigation categories (<440 ppm atmospheric CO2 concentration by 2100) in the SREEN report for 2030, about 12 EJ/year, is significantly more elevated compared with the business-as-usual (BAU) expansion indicated in the previous paragraphs. A similar result was presented by IEA in another assessment of liquid biofuels impact on future scenarios for GHG build up: by 2030, for the 450-ppm mitigation scenario, the IEA model estimated that 12 EJ, 11% of global transport fuels, should be provided by biofuels, estimating that second-generation biofuels contribute with 60% of this total (IEA, 2010). Figure 26 gathers projections of liquid biofuel demand by 2030, confirming that higher demands have been envisaged (IRENA, 2014).

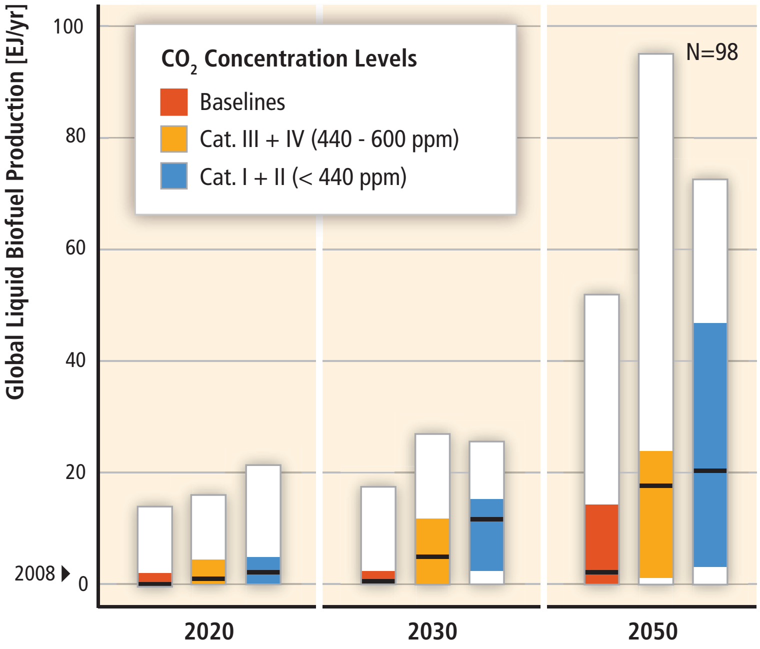


Figure 25. Impact of global biofuels production in IPCC GHG long-term scenarios (median, 25th to 75th percentile range and full range of scenario results) (adapted from Krey and Clarke, 2011, apud Chum et al., 2011).

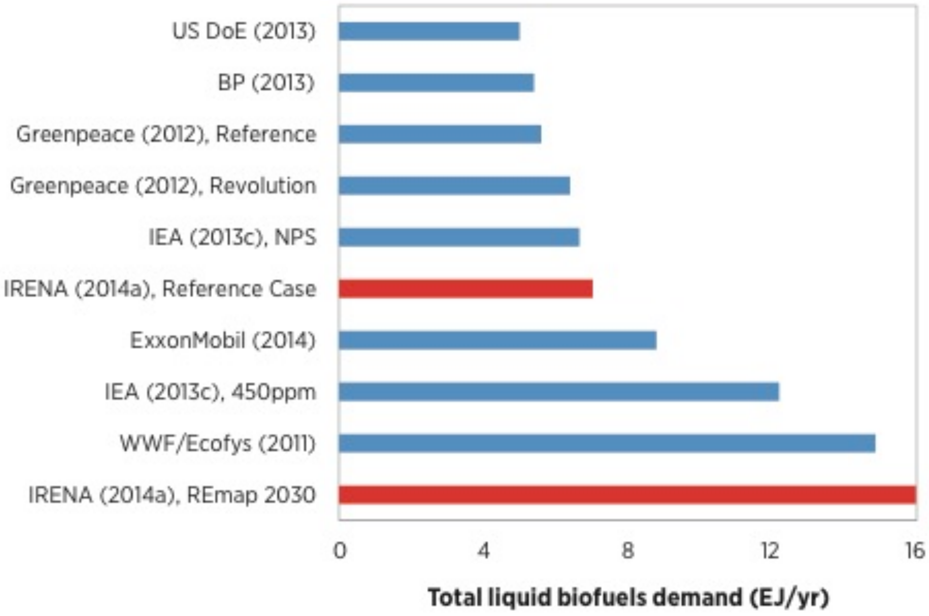


Figure 26. Estimated global liquid biofuels demand in 2030 (IRENA, 2014)

For more distant horizons, when new transport technologies and demand are difficult to forecast, the available studies reinforce the trend to increase biofuels use. For instance, as pointed out in Figure 27, for scenarios including frontiers technologies such as electricity and hydrogen, in order to limit the GHG emission the biofuels share should increase to 43 EJ and represent 42% of transport energy consumption in 2075, leading with electricity the energy supply to move people and goods (Fulton et al., 2015).

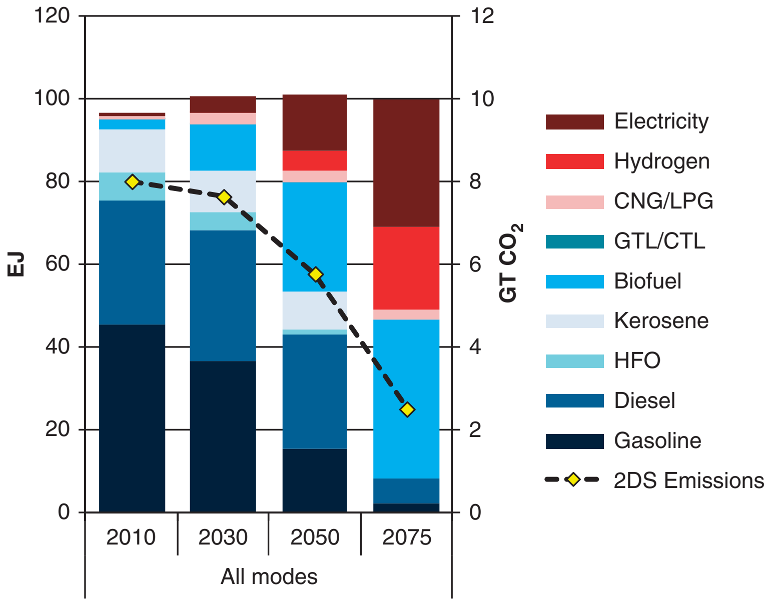


Figure 27. Transport energy use by fuel and year and total CO2 emissions for limiting the average global temperature increase to 2°C (2DS) (Fulton et al., 2015)

Summarizing, it is absolutely necessary a clear increase in the global consumption of sustainable biofuels during the near future, in about 2.5 times the estimated BAU level to 2030, in order to mitigate rationally the GHG emission and reduce the climate change risks. In this context, it is essential to consider that there are already available alternatives able to supply substantial amounts of biofuels economically competitive and presenting significant social and environmental positive side effects. A discussion of land required to accomplish this biofuel production is further presented.

The Brazilian context

The situation in Brazil offers a good reference on the potential of ethanol production from sugarcane in tropical wet regions where this culture have been developed for centuries and corresponds to an important feedstock for sugar production. As in many other countries, sugarcane has been cultivated in Brazil since the 16th century, and in Brazil, since 1931, sugarcane is also a feedstock for ethanol to be used as fuel, as explained in Part I. The Brazilian sugarcane mills produce jointly sugar and ethanol, sharing facilities and optimizing the process, which includes a significant production of electricity in cogeneration schemes burning bagasse, the fibrous by-product resulting from sucrose extraction from sugarcane stalks.

In the season 2013/2014 about 650 Mt of sugarcane were harvested in Brazil, to produce sugar, ethanol and electricity. In 2014 24.4 Mm3 of ethanol were consumed by Brazilian light vehicles, 46% in blends with gasoline (E25) and 54% as hydrous ethanol, used in flexfuel vehicles or vehicles with motors dedicated to pure ethanol use (UNICA, 2015). In some periods, this biofuel represented more than 50% of energy consumption in vehicles with Otto cycle engines in Brazil. However, in recent years, due to a retraction of ethanol demand in flexfuel vehicles caused by gasoline tax reduction and low pricing promoted aiming to control inflation, the biofuel production has stagnated and reduced the ethanol contribution to about 45% of total consumption in light vehicles.

Although measures to recover the competitiveness of the sugarcane agroindustry have been taken and is expected that the ethanol production and use will grow again, there are concerns on increase of external dependence of gasoline in the near future. The actual demand will depend on several factors, but as indicated by Figure 28, from a presentation of Minister of Mines and Energy to the Brazilian Senate in April 2015, is forecasted an expansion on gasoline imports, reaching almost 30% of consumption in the end of next decade, representing a heavy burden to national trade balance and to the Brazilian economy.

This is a condition of potentially unattended fuel demand; and the Brazilian intended Nationally Determined Contribution (iNDC), sets as target to elevate “the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030, by expanding biofuel consumption, increasing ethanol supply, also by increasing the share of advanced biofuels (second generation), and increasing the share of biodiesel in the diesel mix” (Brazil, 2015). So, it is interesting to evaluate the potential of increase the production of ethanol, considering the innovative processes.

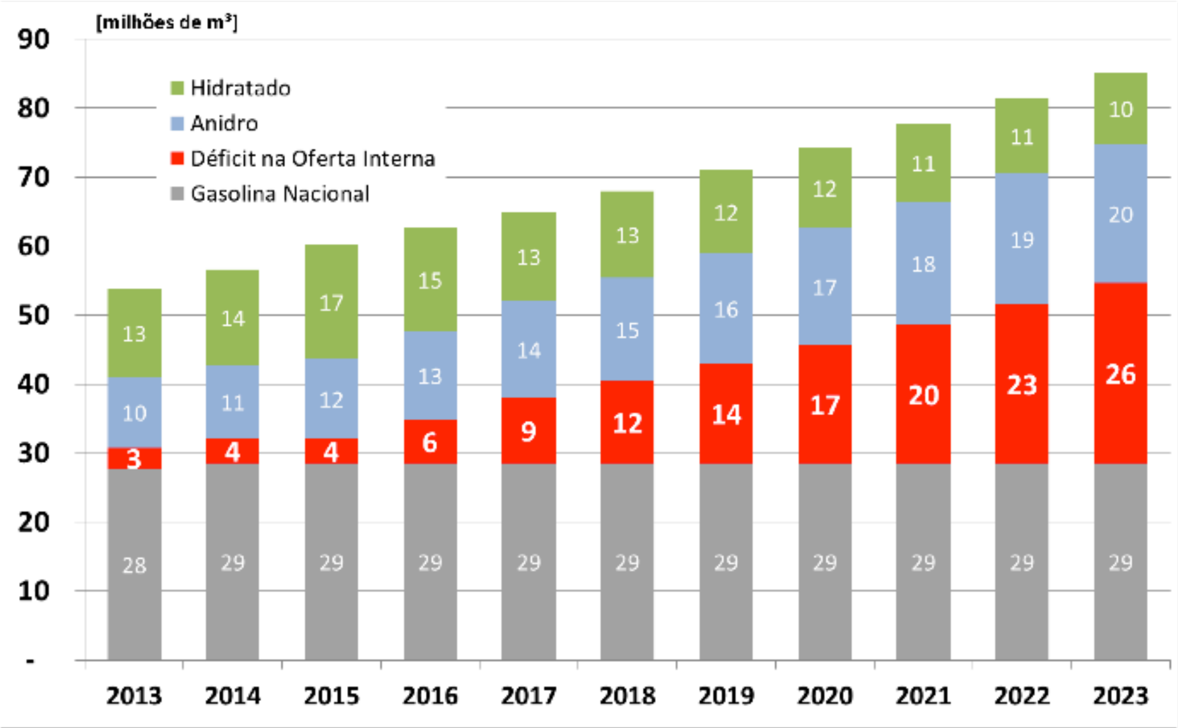


Figure 28. Perspectives for light vehicles fuels market in Brazil (MME, 2015)

According to BNDES estimation, to increment the ethanol production in the Brazilian sugarcane agroindustry, just considering second generation processes, using sugarcane straw and surplus bagasse as feedstock, as well as assuming a proper regulatory framework and public policy measures, more 10 billion liters of ethanol could be produced per year in 2025 (BNDES, 2015). This production is could be reached retrofitting existing mills (50%), expanding existing mills (15%) and implementing greenfield units (35%), as detailed in Annex 1, with a short summary as follows.

It is assumed that the more efficient existing mills, with optimized process steam consumption and collecting 50% of sugarcane straw in 90% of sugarcane fields area could produce about 105 kg (dry basis) of lignocellulosic material (bagasse and straw) per ton of sugarcane processed. Considering the current technology, 217 liters of ethanol/ton cellulose can be produced. Thus, in these conditions, 22,9 liters of ethanol could be produced per ton of sugarcane, in addition to the ethanol produced by the conventional process from sugar (Milanez et al., 2014). The set of 81 mills crushing more than 2 million ton of sugarcane per year and exporting more than 20 kWh/ton sugarcane (used as an indicator of efficiency), processed as a whole 275 million ton sugarcane per year; assuming that 80% of these mills produce ethanol in the above scheme, 5.0 billion liters of ethanol could be produced annually.

For the expanding existing mills case, based on expert's information, is assumed that an additional capacity of 100 million ton cane/year could be installed, and considering that 80% of this capacity operate as in the previous case, more about 1.5 billion liters of ethanol could be produced annually. Finally, as the market conditions for ethanol are assumed favorable, new mills could be installed, operating innovative and high performance agroindustrial production systems, processing energy cane and able to produce about 19,000 liters of ethanol per hectare. Under these conditions, considering that 10 greenfield mills could be built until 2025, cultivating 40,000 ha of sugarcane and producing annually 760 million liters of ethanol (46% from straw and bagasse) and corresponding to a total of more 3.5 billion liters of ethanol per year. The additional ethanol supply from these units could cover 38% of demand gap indicated in Figure 27 for 2023.

The Brazilian case explored in this section, considering also the conventional processes, can be replicated in several other countries. The possibility of implement the production of important amounts of sustainable biofuel in the framework of an existing agroindustry, in a relatively short time, as is possible and feasible in the case of ethanol form sugarcane, characterizes an exceptional alternative to face the climate change challenge.

1.2. Global markets for advanced sugarcane products

In the 90's decade the interest in biological based products (besides bioenergy) was renewed, the main reasons being: cost and risk of oil dependency, reducing local and global GHG emissions, promotion of rural economy, the advances in biological sciences and technologies. The magnitude of the potential market in relevant. In the first years of this century some 140 million ton of carbon based products (excluding energy), worldwide, were derived from petroleum; while products from biological origin, such as textile fibers and pulp and paper (excluding food) were in the same quantity, close to 140 million ton. Many countries and manufacturing companies have established objectives to increase the relative importance of biomaterials, considering innovative processes.

The large variety of processes and products in development were initially considered in two groups:

- Sugar based products: from sucrose (sugar cane, beets) or starch; and, in the future, sugars (C5 and C6) from lignocellulosic hydrolysis (this is the "Sugar Platform" considered here[6]).
- Other biomass products: from lignocellulosic material (through gasification and synthesis, lignin, etc.).

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[6] IEA Bioenergy Task 42 defines 'platforms' as "*intermediate products from biomass feedstocks towards products or linkages between different biorefinery concepts or final products*".

Some products from the Sugar Platform (actually, from the “1st. generation sugars”) have been produced and commercialized worldwide for decades, such as citric acid or lysine. The International Sugar Research Foundation systematic evaluations of sucrose as chemical feedstock were initiated 60 years ago, identifying some large volume products (polymers, surfactants, plastics) and commercial production was progressively established in many application areas. In 1970, more than 200 patents were issued in the U.S. only for the food industry (special sugars), and an equivalent number for sugar esters.

In 1993, 30 products derived from ethanol were commercialized in Brazil; five with production above 400 thousand ton/year. Including starch as feedstock, in 2005 some products reached 1 million ton/year. They supplied 23% of the sweeteners market; 0.7 million ton/year organic acids (citric, gluconic, lactic, ascorbic, 1998); 1.4 M ton/year poliols; and started commercial trials in plastics (PLA, PHAs, 3-GT) aiming at 10 million ton/year only in packaging.

The perspective of producing 2G sugars worldwide (and eventually competing in cost with the 1G sugars) led to large efforts to increase products portfolio and production in the Sugar Platform, with specific research programs in most developed countries, including the cellulosic derived sugars. The effort has increased in the last years, due in part to the delay in achieving fully developed processes at competitive costs for ethanol from second generation processes (E2G), and then looking for higher value, even if lower volumes, products from cellulosic derived sugars.

Although certainly relevant, particularly as way to reinforce the introduction of innovative processes and collaborate to promote development of advanced bioenergy schemes in the framework of sugarcane agroindustry, the importance of biomaterials in terms of GHG emissions and land use with sugarcane is reduced compared with ethanol as fuel current and prospective impact.

2. Production of biomaterials in sugarcane biorefineries

This section considers the production profile, level of technological readiness and demand perspectives for advanced biomaterials based in sugarcane as feedstock. The several schemes of ethanol production chain are presented separately in the next section, due to high volumes involved and potential impact in GHG emissions.

2.1. Technology assessment for advanced bioproducts from sugarcane

In 2003 a comprehensive survey was conducted in Brazil for the most important (worldwide) existing products from the Sugar Platform (sucrose and starch) and the in course developments, aiming at implementation in the Brazilian sugar cane mills (Nastari, 2003). From 36 initial products in ten categories (Sweeteners; Poliols; Solvents; Plastics; Ethanol derived products, etc.) a screening was conducted, looking at some criteria: level of protection/availability of industrial property; required quality of the feedstock (juice, high test molasses (HTM), crystal sugar, etc); adequacy of production scale and energy needs to an "average" sugar mill, as well as synergy with the effluent treatment; commercialization issues, including the world market. The released results have shown (Macedo, 2005) that good possibilities exist for selected products, and two points must be carefully considered:

- Competition at global level has to be considered; the relative feedstocks competing costs, worldwide, included crystal sugar, HTM and sucrose in juice, in Brazil; glucose from corn, USA; sucrose from sugar beets, and sugars from wheat, Germany; and "future" prospects for cellulosic derived sugars. Sucrose production costs in Brazil indicate a strong position to implement new products in sugar mills, looking ahead for fully developed 2G sugars from cane residues.
- Strong commercialization arrangements (aiming at global markets) are needed.

From a global context, a recent survey looking at the European competitiveness in the emerging markets based on the Sugar Platform (EC-DGE, 2015) selected for deeper analyses of opportunities/barriers to implementation, and impact mitigation, the 25 primary products listed in Table 1 (Alcohols and Organic acids & other) plus eight downstream bio-based products. The initial survey considered 94 products (projects in EU, Asia, South America and USA); first screening summarizes the stage of the technology deployment (manufacturing, research/pilot, demonstration) and the corresponding TRL (Technology Readiness Level). The main results include the number of companies working on each product, the maximum TRL currently achieved, where any manufacturing (M), demonstration (D) or research/pilot (R) facilities are located globally, and a list of the most advanced developers. The TRL (Technology Readiness Level) is a relative measure of the maturity of evolving technologies on a scale of 1 to 9; TRL 1 corresponds to basic research on a new invention or concept, TRL 5 to pilot scale testing, whilst TRL 9 corresponds to mass deployment of a fully commercialized technology.

Table 1. Some products selected for further analysis, (EC-DGE, 2015)

Alcohols	Organic acids & other	Polymers
Ethanol	Acetic acid	PLA (via lactic acid)
n-butanol	Lactic acid	PET
ABE/IBE	Itaconic acid	PBS (via succinic acid and BDO)
Isobutanol	Succinic acid	PEF (via FDCA)
1,3-propanediol (PDO)	Levulinic acid	PE (via ethylene)
1,4-butanediol (BDO)	para-xylene	PMMA (via itaconic acid)
Xylitol	3-HPA	PHAs (direct), including PHB/PHBV
Sorbitol	Acrylic acid	Polyisoprene (via isoprene)
	Adipic acid	
	Furfural	
	5-HMF	
	FDCA	
	Iso-butene	
	Farnesene	
	Algal lipids	

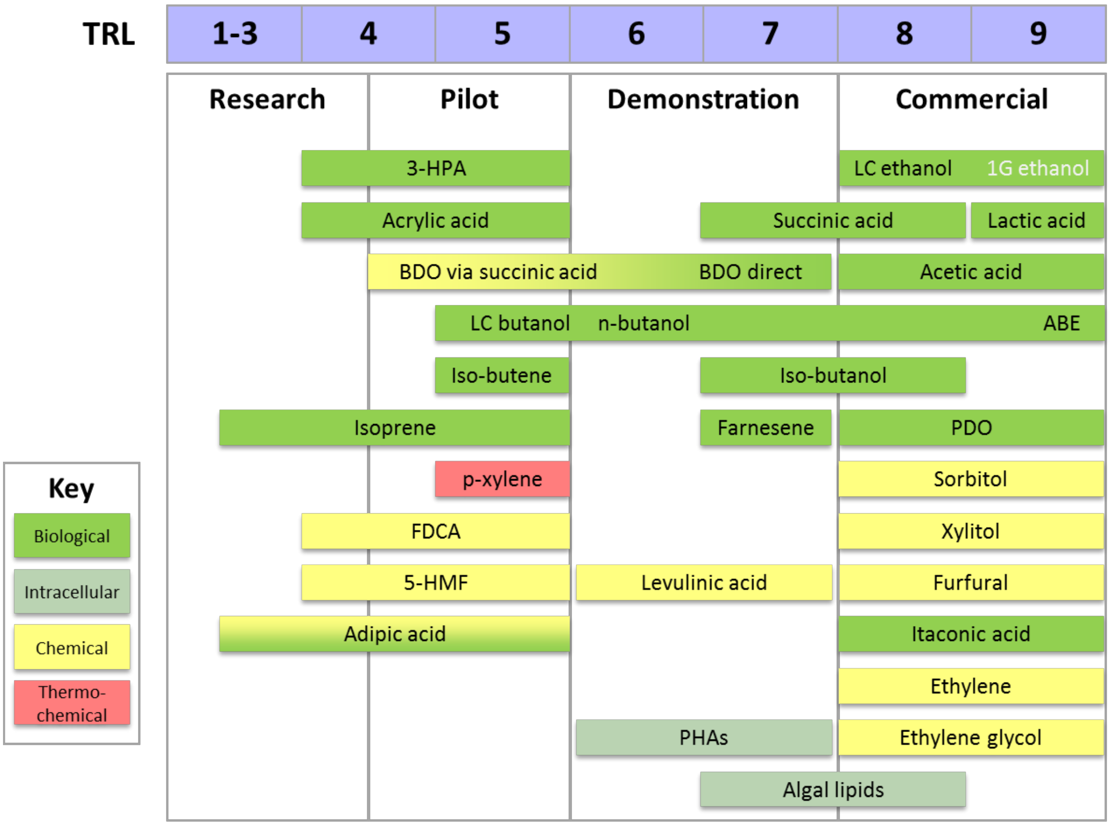


Figure 29. Development stage selected sugar platform products, (EC-DGE, 2015)

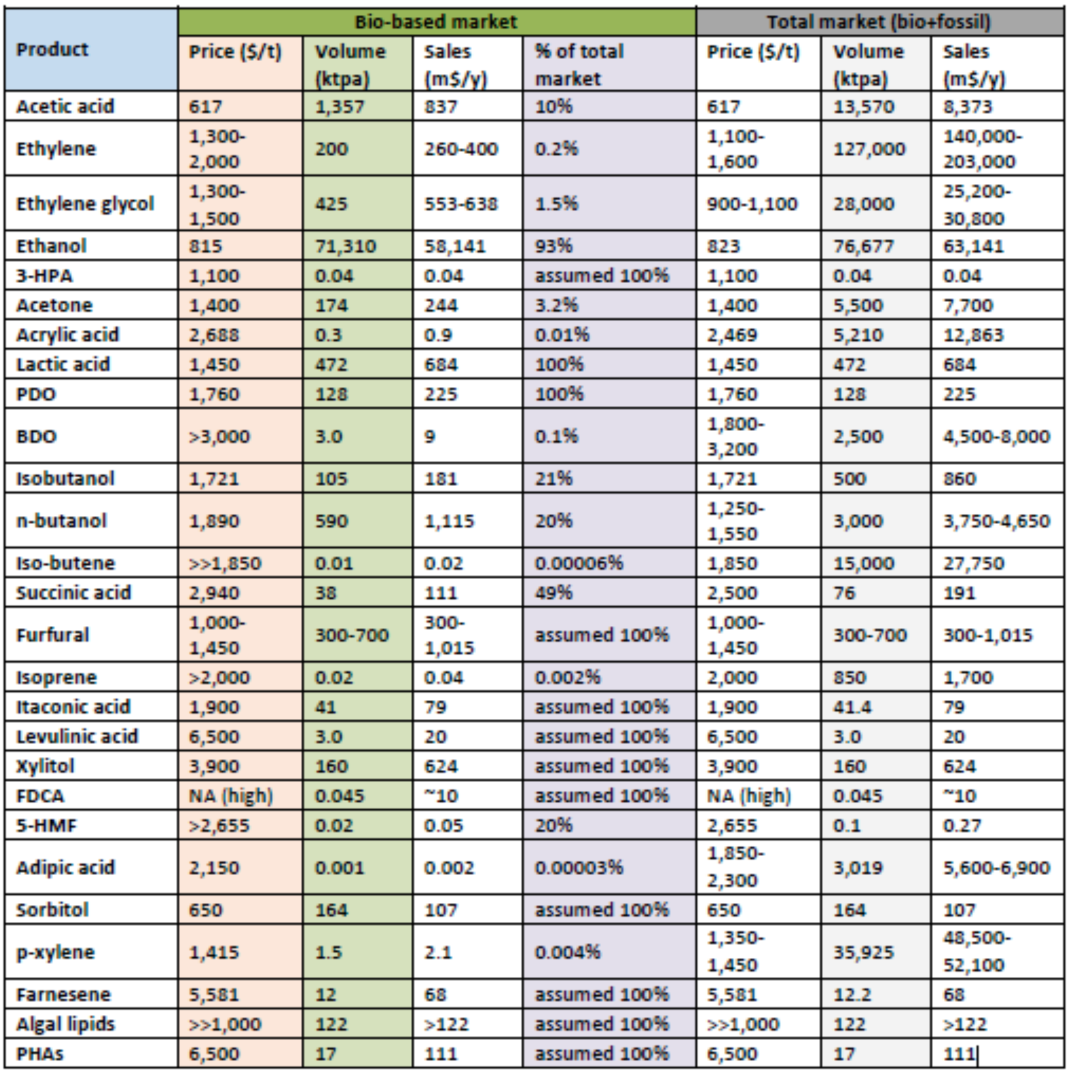
The importance of using TRL adequately (to decide on the use of the technology) must be always emphasized; some of the problems with E2G implementation today are clearly related to a low TRL. Skipping the intermediate levels (mostly related to Demonstration plants) and going directly to full commercial stage may present high risks. The TRL assigned for all the 94 cases, as indicated in Figure 29, show that a large number of projects are in the research/pilot plant stage, another large number is ready for commercialization, but very few (circa 15%) are in Demonstration: the “valley of death” is clear

2.2. Production scenarios of advanced bioproducts from sugarcane

Although the mentioned Sugar Platform review (EC-DGE, 2015) understandably does not cover all projects (for Brazil, no mention of lysine, acetic acid, butanol, special yeasts and other already existing are included) it brings an updated review of global markets (bio + oil based), biological production, and prices for the 25 selected products.

It must be noted that some of those products will create their own markets (the market sizes and prices here refer, in general, to substitution of products from oil). So, the listing in Table 2 is only a reference, subject also to regional conditions

Table 2. Prices and volumes estimated: bio-based and total product markets (EC-DGE, 2015)



Product	Bio-based market				Total market (bio+fossil)		
	Price ($/t)	Volume (ktpa)	Sales (m$/y)	% of total market	Price ($/t)	Volume (ktpa)	Sales (m$/y)
Acetic acid	617	1,357	837	10%	617	13,570	8,373
Ethylene	1,300-2,000	200	260-400	0.2%	1,100-1,600	127,000	140,000-203,000
Ethylene glycol	1,300-1,500	425	553-638	1.5%	900-1,100	28,000	25,200-30,800
Ethanol	815	71,310	58,141	93%	823	76,677	63,141
3-HPA	1,100	0.04	0.04	assumed 100%	1,100	0.04	0.04
Acetone	1,400	174	244	3.2%	1,400	5,500	7,700
Acrylic acid	2,688	0.3	0.9	0.01%	2,469	5,210	12,863
Lactic acid	1,450	472	684	100%	1,450	472	684
PDO	1,760	128	225	100%	1,760	128	225
BDO	>3,000	3.0	9	0.1%	1,800-3,200	2,500	4,500-8,000
Isobutanol	1,721	105	181	21%	1,721	500	860
n-butanol	1,890	590	1,115	20%	1,250-1,550	3,000	3,750-4,650
Iso-butene	>>1,850	0.01	0.02	0.00006%	1,850	15,000	27,750
Succinic acid	2,940	38	111	49%	2,500	76	191
Furfural	1,000-1,450	300-700	300-1,015	assumed 100%	1,000-1,450	300-700	300-1,015
Isoprene	>2,000	0.02	0.04	0.002%	2,000	850	1,700
Itaconic acid	1,900	41	79	assumed 100%	1,900	41.4	79
Levulinic acid	6,500	3.0	20	assumed 100%	6,500	3.0	20
Xylitol	3,900	160	624	assumed 100%	3,900	160	624
FDCA	NA (high)	0.045	~10	assumed 100%	NA (high)	0.045	~10
5-HMF	>2,655	0.02	0.05	20%	2,655	0.1	0.27
Adipic acid	2,150	0.001	0.002	0.00003%	1,850-2,300	3,019	5,600-6,900
Sorbitol	650	164	107	assumed 100%	650	164	107
p-xylene	1,415	1.5	2.1	0.004%	1,350-1,450	35,925	48,500-52,100
Farnesene	5,581	12	68	assumed 100%	5,581	12.2	68
Algal lipids	>>1,000	122	>122	assumed 100%	>>1,000	122	>122
PHAs	6,500	17	111	assumed 100%	6,500	17	111

3. Innovation in ethanol production from sugarcane and impact in GHG emission

In addition to its positive impact on the energy and agroindustrial sectors, and the benefits in the social and environmental dimensions, one remarkable feature of ethanol from sugarcane is its reduced carbon footprint, possibly the lower among the alternatives available to transportation. This section explores initially some conceptual aspects of GHG emission in biofuel production, then introduces the ethanol production routes including innovative processes and presents evaluations of GHG emissions.

3.1. GHG evaluation issues in biofuel production

The objective of achieving and demonstrating efficient GHG emissions reduction with biofuels involves challenges in technical development, methodological difficulties and the need for reliable and diversified data. Today, the main issues associated with methodology are:

- the Life Cycle Assessment (LCA) approach, which can be implemented either by a process-based analysis or by the Consequential Life Cycle Assessment (CLCA), incorporating economic modeling methods, as well as social and environmental interactions (Brander et al., 2008);
- the treatment of co-products in LCA's, needing the adoption of substitution or allocation criteria, to share the common emissions by mass, energy or economic value;
- the estimation of Soil Organic Matter stock changes, which demands long duration field studies in actual conditions at diverse soil horizons;
- the aggregation level of Land Use Change, which can be assessed at different areas, for one or many production units;
- the estimation of the CH_4 and N_2O emissions coefficients in many situations.

Other technical issues, such as related to new agronomic practices and new processes, still require basic research (Macedo et al., 2015). So, any evaluation of GHG emissions for a proposed biofuel production system must state carefully all the hypotheses used, and expect for "trends" and "order of magnitude" results.

Indirect effects associated to land use changes and a comprehensive view on biofuels impacts on land resources, soil quality and water use have clear technical components, but are strongly based on broader organizational aspects. The impacts on land use, soil and water are hardly separable between biofuels feedstocks and other (much larger) agricultural products, and their minimization must be pursued recognizing that their magnitude is generally associated to policies out of the scope of biofuels policies. Figure 30 synthetizes the broad and complex field of interactions and fluxes associated to the evaluation of GHG emission in the ethanol production from sugarcane.

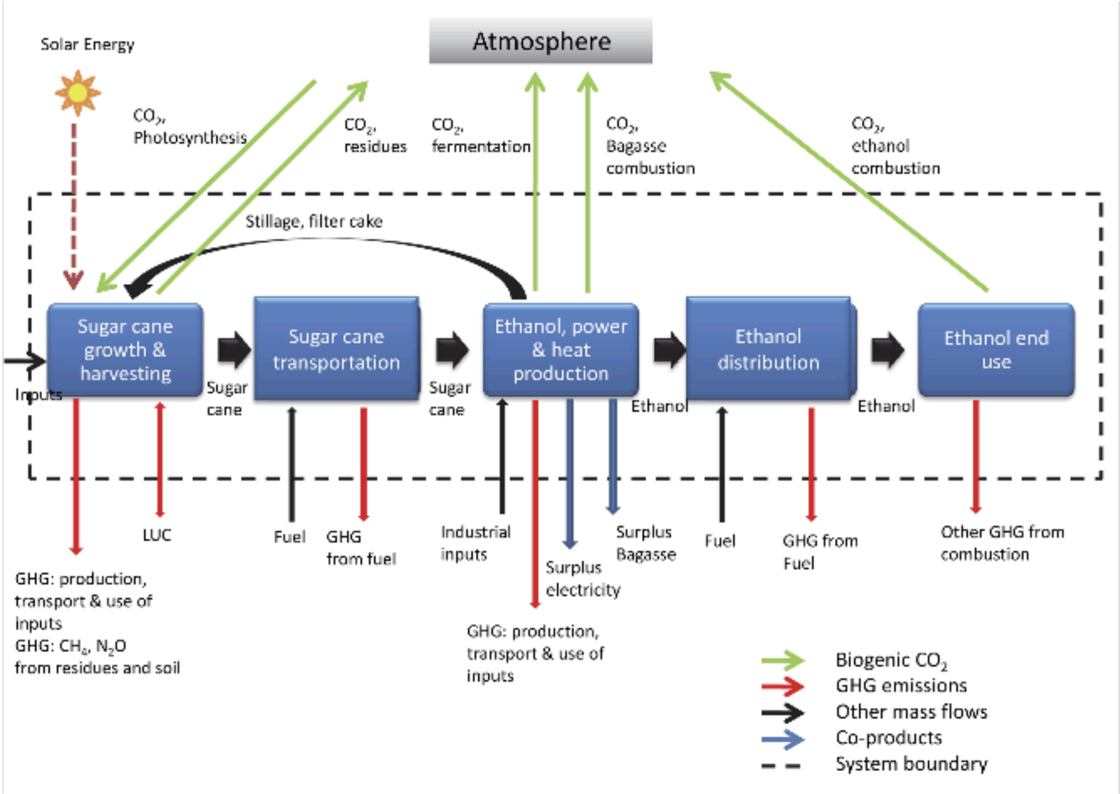


Figure 30. Mass flows and life cycle GEE emissions in production of ethanol from sugarcane (Macedo et al., 2015)

3.2. Ethanol production systems configuration and operation

Sugar cane to ethanol plants in Brazil produce ethanol (from sucrose) and some electricity surplus, beyond process energy needs (from bagasse, eventually some straw). This is called a “first generation system” (1G). In 2007 a comparison among conventional E1G and prospective E2G production schemes in a typical sugar mill processing sugarcane (considering varieties selected for sugar production) and 40% of the cane residues (Seabra et al., 2011) included the GHG emissions expected, which requires a clear definition of plant configuration and operation hypothesis. Second generation ethanol production competition with first generation optimized to produce electricity have also been assessed by Dias et al. (2011), leading to the conclusion that E2G will become economically competitive with bioelectricity when sugarcane straw is used and when low cost enzyme and improved technologies for 2G production become commercially available.

Processes in development and early commercialization for cellulosic feedstock (from bagasse and straw) sacharification to C5 and C6 sugars, followed by their fermentation, may be designed to maximize ethanol production, reducing surplus electricity production. This is called a “second generation system” (2G). This option can be developed with an integrated system (both E1G and E2G produced at the same factory) or in a Stand Alone unit (Dias et al., 2012).

Both processes, conventional and innovative, will produce more energy (for the same area of cane) in the medium – long terms, when using much higher productivity sugar cane (“energy cane”), now in experimental stage. The ratio of lignocellulosic material/sucrose is much higher in this case, thus process energy needs are also different, as are the conversion parameters.

All those options were analyzed by CTBE for their GHG emissions/mitigation, since they may all occur in the implantation of new units or adaptation of existing sugar/ethanol mills (Milanez et al., 2015; CTBE, 2015). Scenarios for E2G production were adopted BNDES, 2015; CTBE, 2015) for two periods: 2015 – 2020 e 2021 – 2025. Assuming a proper context, the total E2G production could reach 3.25 million m3 in 2020 and 10 million m3 till 2025, as commented in Section (1.1). Integrated and Stand Alone plants are considered in new units and in adaptations of existing sugar mills (depending on the characteristics of the sugar mill; the introduction of energy cane as portion of the feedstock would happen only in the second period (2021–2026). Besides the associated E1G in the E2G units, some new production of E1G is also considered.

A summary of the results for the different options used (*without energy cane*) from (Milanez et al., 2015, CTBE, 2015) is depicted in Figure 31.

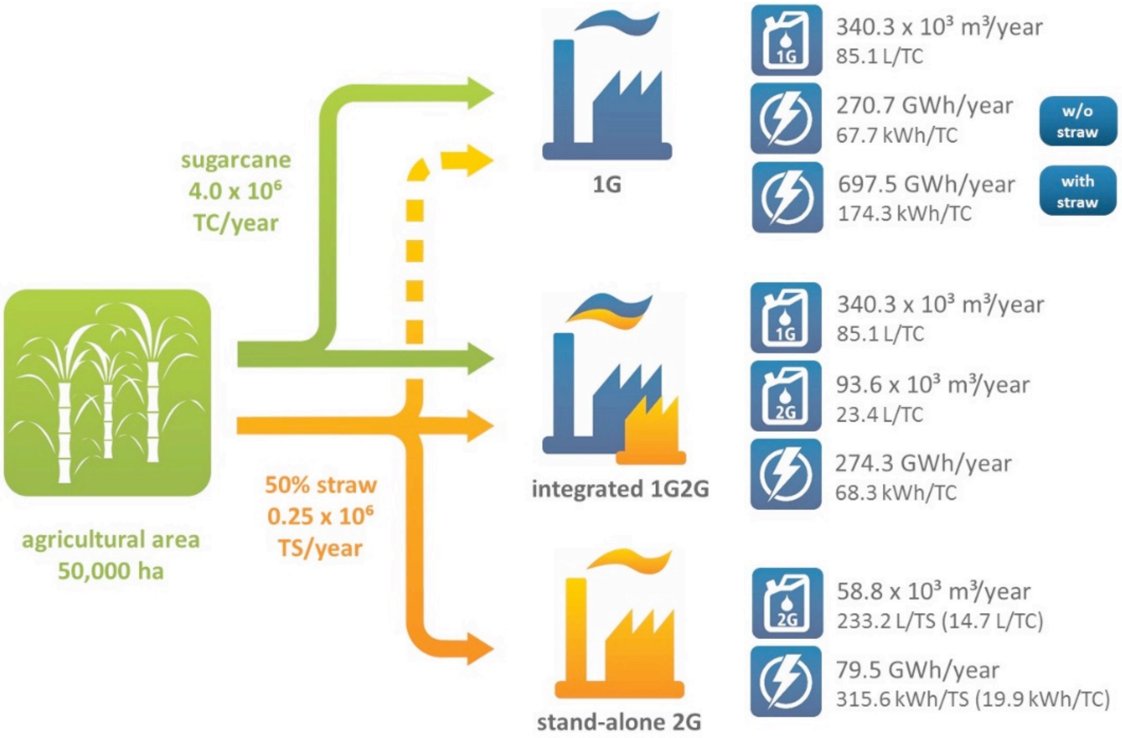


Figure 31. Scenarios with “conventional” cane, feedstock and energy outputs (Milanez et al., 2015, CTBE, 2015)

In this figure, all scenarios (except one) consider the same basic condition: a mill processing annually 4.0 million ton of sugarcane, cultivated in 50,000 ha, plus 50% of cane straw available. Exception is one of the 1G scenarios, were no straw recovery is included. All scenarios consider also modern mills, with high pressure boilers and low process steam consumption. The Integrated 1G2G scenario takes the 50% straw plus the surplus bagasse (available after supply the demand of fuel in the cogeneration plant for power and process steam) to produce E2G. The Stand Alone 2G scenario uses all the 50% straw to produce E2G, meeting its process energy needs with the lignocellulose remaining from the process.

3.3. GHG emissions in ethanol from sugarcane production systems

Particularly with regards to GHG emissions associated to ethanol production in the context of sugarcane mills, in addition to the conditions presented for operation, other important hypotheses are:

In all cases, since two products are obtained (electricity and ethanol), the emissions were distributed between them. This can be done either by allocating the emissions based on mass, energy or the economic relation between them, or assigning all the emissions to the main product (here, ethanol) and computing for it the "credit" related to the emissions reduction when the co-products (here, electricity) substitute for market products which would have emitted GHG in their life cycle (here, the electricity from the grid). In Brazil, credits for electricity may correspond to the emissions assuming the Marginal Operation value, associated to thermal power plants (since the sugarcane harvest season and therefore the electricity generation occur during the dry season, when the thermal plants run at full load), but conservatively the Grid Mix is also used.

The GHG emissions from straw production, for 1G2G integrated and the Stand Alone 2G scenarios, *are not allocated to straw (as a part of sugar cane)* except for the processes of collecting and transporting it; the full allocation would increase E2G emissions, and decrease E1G emissions in both processes.

Implementing models for simulating the several mills configurations (presented in Annex 1) under those representative operational conditions and following the procedures above, the main results obtained by CTBE (2015) indicated that:

1. Results for the specific processes indicate that the use of energy based allocation or economic base allocation makes very little difference in this case; but changing from allocation to substitution (electricity as co-product) greatly reduces the emissions for Scenario E1G (with straw).

2. Using energy allocation, E1G (with straw) shows emissions of 21.1 g CO_2eq/MJ; against 20.3 g CO_2eq/MJ for the (combined) production of ethanol in the integrated 1G2G scenario. When substitution is used, even against the electricity grid mix, not the margin, the E1G (with straw) scenario emissions are 8.5 g CO_2eq/MJ, and the E1G2G (combined) scenario emissions are 16.4 g CO_2eq/MJ. This is, clearly, due to the mitigation provided by the much larger electricity surplus.
3. The energy ratios, relating the renewable energy production and the fossil energy direct and indirect input, for the Integrated 1G2G scenarios present a value of 7.0 $MJ_{renewable}/MJ_{fossil}$; and the Stand Alone scenario yields 6.3 $MJ_{renewable}/MJ_{fossil}$. The Scenario 1G (with straw) presents 8.1 $MJ_{renewable}/MJ_{fossil}$.
4. Looking at the mitigation related to the area used (plantation), each hectare of sugar cane, in the 1G (with straw) scenario, mitigates 11.2 ton CO_2eq/year; the integrated 1G2G scenario leads to 12.9 ton CO2eq/year. Adding the results from the Stand Alone 2G scenario and the corresponding 1G (no straw) scenario yields 12 ton CO_2eq/year, confirming the advantages of integration 1G2G.
5. All the above results do not include the direct effects of Land Use Change on biomass stocks (Soil Organic Carbon, Above Ground Biomass or Below Ground Biomass). Those effects were evaluated, considering the basic IPCC methodology and ethanol produced from recently converted areas and the recent sugarcane expansion profile, i.e., 69.3% over pasture; 14.8% over soybeans, 2.8% over corn, 2.8% over orange, 0.4% over coffee, 0.8% over native vegetation, and 9.0% over other cultures. Results indicate a small decrease in GHG emissions mainly due to the increase in carbon stocks in soil and biomass due to land conversion from pasture (including degraded pastures) and annual crops to sugarcane.

The above results correspond to the processes used in the first period (2015 – 2020), according to the rate of penetration of the different options for E2G and some growth in E1G, leading as said, to a total E2G production reaching 3.25 million m^3 in 2020, in line with BNDES (2015) production estimate.

The evolution in 2021-2025 would include, also, the introduction of some energy cane, reaching 10 million m3 till 2025, also accordingly BNDES (2015). Since this would lead to rather different process conditions (sugar contents in cane, sugar losses in bagasse, milling strategies) and long term energy cane cultivation (productivities, equipment, harvesting and logistics of biomass handling) the results present higher uncertainty. This study indicates the possibility for E2G GHG net emissions reaching 10 g CO_2eq/MJ in the period (2021-2025), and 7.4 g CO_2eq/MJ in (2026-2030). With a production of 10 million m^3/year (50% in Stand Alone plants and 50% in integrated 1G2G plants) in 2025, the corresponding avoided GHG emissions would be 16.7 million tCO_2eq/year. In the next section, these values will be used to estimate the impact of implementing E2G from sugarcane in global terms. Still, total accumulated avoided emissions reduction due to ethanol production in Brazil since 1980 has already reached 709.7 Millions of tons of CO_2, as shown in figure 32.

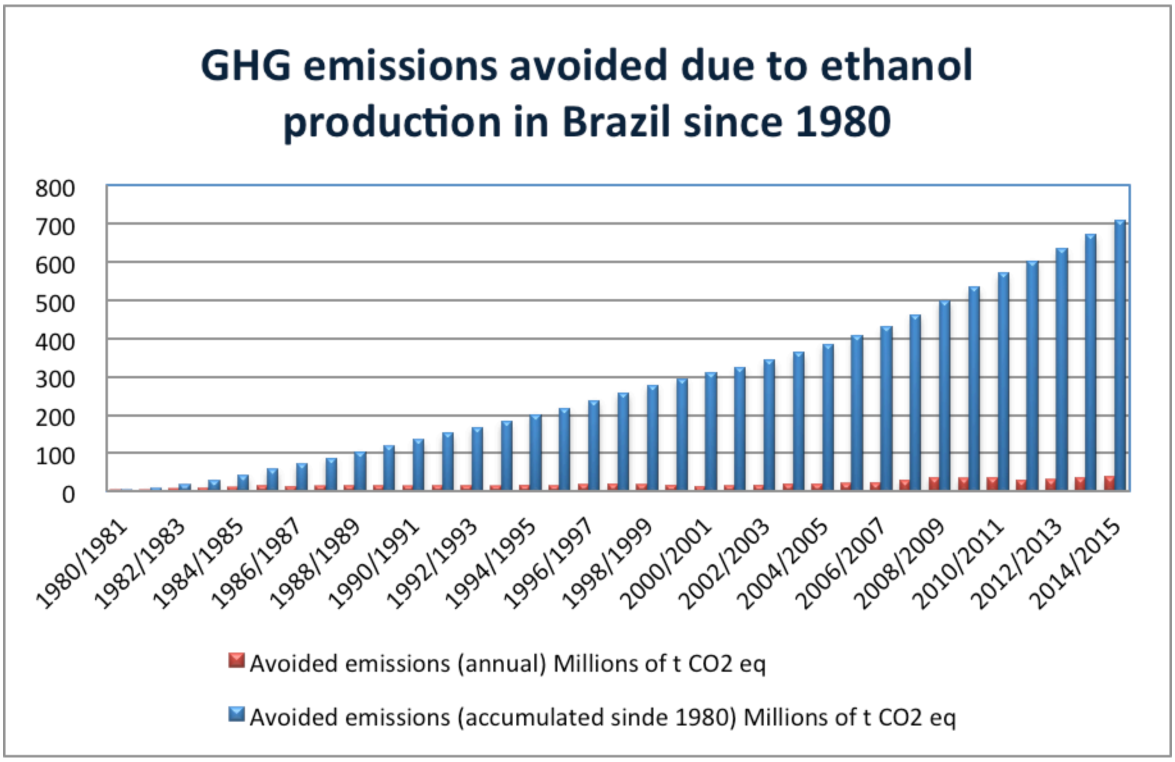


Figure 32. GHG emissions avoided due to ethanol production in Brazil since 1980

(based on CTBE, 2015)

Also, no indirect land use change (iLUC) impacts are included; the reason is that there is no consensus yet about methodologies (except that the values found today are many times smaller than the proposed values in 2007) (Macedo, 2014). Also, the Environmental legislation in Brazil today leads to still smaller effects.

In summary, the introduction of E2G and energy cane reinforce the potential of sugarcane ethanol mitigate substantially GHG emissions when substituting gasoline, with an excellent energy ratios ($MJ_{renewable}/MJ_{fossil}$) and high agroindustrial productivity, which means relatively reduced area requirement, as commented in the following section.

4. Land requirement: impacts of efficiency, E2G and energy cane introduction

A prime feature for sustainability in bioenergy production systems is the efficiency in using natural resources, such as land and water. The amount of land to be cultivated for producing biofuel for a given demand is determined essentially by the agroindustrial productivity, which combines the feedstock yield and its further conversion in biofuel. Although the conventional ethanol from sugarcane is already acknowledged as an efficient biofuel, considered as an "advanced biofuel" by EPA/US, there is room for relevant improvements in the agroindustrial productivity. The impact of the innovative technologies on land use for ethanol production based on sugarcane is estimated in the following paragraphs.

Two innovations to be taken into account in this context, aiming at increasing the biofuel yield and reduce the area required are: a) the E2G processes, allowing to produce ethanol not only from sugar content in sugarcane but also from its fiber and leaves, and b) the introduction of energy cane, increasing significantly the production of biomass per hectare. Table 3 presents the productivity values assumed in CTBE studies modeling different configuration of sugarcane mills.

Table 3. Ethanol agroindustrial productivity for different mill technologies (CTBE, 2015)

Technology scenario	**Agroindustrial productivity** (m^3/ha)
Current 1G mills (2015 average)	6,49
1G existing mills integrated to 2G	8,28
1G greenfield mills (optimized to power production)	6,48
(1G+2G) greenfield mills (improved technology)	8,70
(1G+2G) integrated (conventional cane plus energy cane)	13,25
(1G+2G) mills (energy cane)	18,61

CTBE (2015) evaluated both effects combined in the Brazilian context, distributing the total production of ethanol among the different configurations (as indicated in Annex 1) and concluding that, for the scenarios evaluated for the next decade, the current average agroindustrial productivity, 6.49 m^3 ethanol/ha, could rise to 7.26 m^3 ethanol/ha (+12%) due to gains in the conventional E1G process and energy cane introduction (supplying partially the raw material processed), and reach 8.66 m^3 ethanol/ha (+33%) when E2G process are implemented, always in average figures, as indicated in Figure 33.

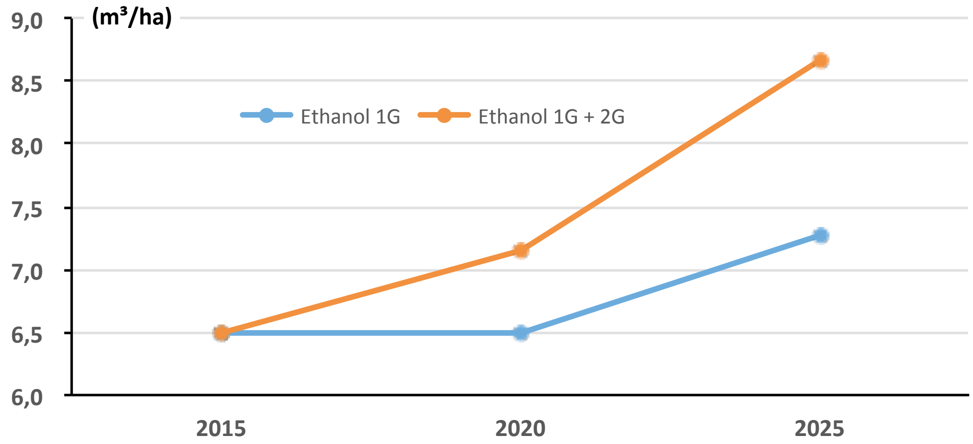


Figure 33. Average agroindustrial productivity of ethanol estimate for Brazilian mills (based on CTBE, 2015)

This increase in productivity depends of course on the accomplishment of the intense efforts to achieve the expected performance in energy cane and E2G processes, as well as that the required investments in brownfield and greenfield mills will be done. Assuming these conditions to produce the volume of ethanol indicated by BNDES for 2030, 55.3 million m^3 (as detailed in Annex 1), the area planted with sugarcane (only the fraction used for ethanol production) this year would be 7.61 million ha without E2G process and 6.39 million ha (-16%) for (E1G+E2G) production, as depicted in Figure 34.

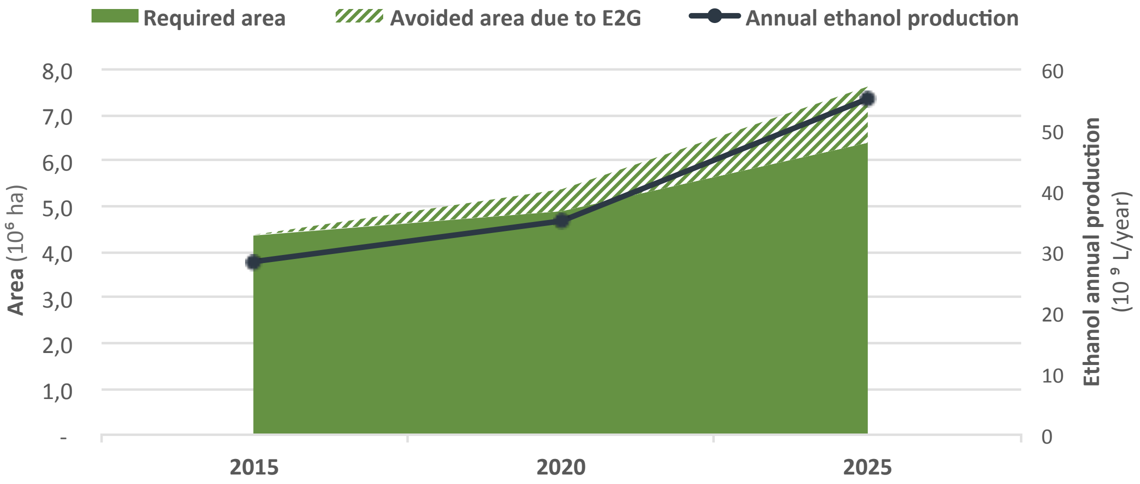


Figure 34. Land required for sugarcane plantation and expected ethanol production in Brazil (based on CTBE, 2015)

5. Global impacts of innovative bioethanol from sugarcane: GHG emissions mitigation and land use

It is recognized the remarkable features of sugarcane as energy vector, with good perspectives to expand its use abroad as feedstock for sustainable bioenergy production in large amounts and relatively limited use of land (Leal et al., 2013). In this section, assuming that the Brazilian sugarcane agroindustry is similar to the existing in several other countries, where the ethanol production can be possibly implemented in the same way, associated to sugar production and power generation, the main results from the previous sections are used for evaluating GHG emissions and land use impacts associated to innovative technologies for ethanol production at global level.

Thus, replicating in a large scale the Brazilian case, two scenarios were adopted: the Business as Usual, taking into account the current (2015) situation and average indicators of Brazilian mills, and the Needed scenario, considering the adoption of innovative technologies in this agroindustry and adopting parameters as estimated in CTBE (2015) for Brazilian mills to 2025. Naturally this analysis should be taken as an exercise under clear hypothesis to evaluate of the potential for promoting ethanol from sugarcane using modern and innovative technologies.

Although many other scenarios could be explored, it can be assumed that the Business as Usual scenario represents adequately the existing production and use paradigm to the near future, while the Needed scenario looks for considering the IPCC requirements for GHG mitigation, with higher ethanol demand and better production technology, assuming that integrated 1G2G processes will be deployed and energy cane plantation will be available as well. Therefore, the Needed scenario means also that proper public policies and regulation will be in place to foster ethanol production (including specific measures for E2G) and its use will be promoted to help to stabilize GHG concentration at 450 ppm, level expected to limit the increase of average global temperature increase to 2°C, as pointed out by IPCC (2011).

Taking into account the ethanol global demand perspectives discussed in Section (1), two conditions were assumed, as indicated in Table 4, representing the Business as Usual perspective, typically assuming ethanol use in blends; and the Needed scenario, which requires a more intense expansion of ethanol use. Since biofuels include also biodiesel, it was assumed that ethanol represents 75% of whole biofuel estimate in every case. For each scenario a mill technology configuration was assumed, with the respective mitigation effect on GHG emissions, resulting the impact presented in Table 5.

The mitigation factors presented in Table 5 come from CTBE (2015) studies. For the Business as Usual scenario they correspond to the values calculated for the current average emission observed in the Brazilian mills (from 2015 data: 28.4 million m^3 ethanol production and 43.6 million ton CO_2eq emission avoided). For the Needed scenario it was assumed the situation expected at the end of next decade, after the introduction technological improvements: E2G processes, straw use, partial adoption of energy cane and general improvement in mill's efficiency, as indicated in Annex 1 for Brazilian mills in 2025 (55.3 million m^3 ethanol production and 91.0 million ton CO_2eq emission avoided). Compared to the gasoline emission, in energy units, these mitigation factors mean that about 75% of GHG emission from this fossil fuel could be avoided.

Table 4. Ethanol demand scenarios in 2030 for evaluating GHG emission mitigation

Scenario	References	Biofuels demand	Commentary
Business as Usual	BP Energy Outlook 2035 WEC Global Transport Scenarios 2050	4.77 EJ	Biofuels will represent about 5% of energy consumed in transportation sector in 2030.
Needed	IPCC/SREEN, 2011	12.00 EJ	Required to stabilize GHG concentration at 450 ppm. Biofuels will cover 11% of energy for transport.

Table 5. Global ethanol demand in 2030 for evaluating GHG emission mitigation

Scenario	Business as Usual	Needed
Ethanol demand	161 million m^3	404 million m^3
Mitigation factor	1,53 t CO_2 eq/m^3 ethanol	1,65 t CO_2 eq/m^3 ethanol
Avoided emission	246 Mt CO_2 eq/year	667 Mt CO_2 eq/year

The total emission mitigated in higher ethanol demand scenario, covering 11% of energy demand in the world transport sector, represents respectively approx. 1.4% of global anthropogenic GHG emissions estimated for 2010 (49 Gt CO2 eq) and 9.5% of global transport GHG emissions estimated for the same year (7 Gt CO2 eq) (IPCC et al, 2014). This scenario could be considered technically feasible under the standpoint of final utilization since in Brazil biofuels have been supplying more than 50% of transport energy consumption for many years, with good results. Initially low ethanol blending in gasoline was adopted (1931), increased during the

70’s progressively to E25 (25% ethanol), then vehicles with engines dedicated to pure hydrous ethanol were introduced (1979) and more recently, flexfuel vehicles, able to use any ethanol and gasoline blend were successfully introduced (2003). Nowadays practically all global automakers produce and commercialize flexfuel vehicles in Brazil and all cars equipped with gasoline engine, including imported models, are using regularly E27.

Regarding land use, the introduction of energy cane plays a relevant role and two situations were assessed, considering the average productivity estimated by CTBE (2015) for Brazil in 2025, as presented in Figure 32. Again these productivity hypothesis must considered reasonable, since today several Brazilian mills present greater yields using conventional technologies. The results are presented in Table 6, indicating that the use of innovative process, adopted in the Needed scenario, could increase the production in more than 2.5 times, while expanding about twice the cultivated area.

Table 6. Land use for ethanol production in 2030

Scenario	Business as Usual	Needed
Ethanol demand	161 million m3	404 million m3
Ethanol productivity	7,26 m3/ha	8,66 m3/ha
Land necessary	22,1 million ha	46,7 million ha

The area estimated to be occupied with sugarcane in the Needed scenario, about 47 million ha, can be compared with the land potentially available for bioenergy production. According to FAO (2012), the land available for rainfed agriculture is estimated to be 1,400 Mha of ‘prime and good’ land and a further 1,500 Mha of marginal land that is ‘spare and usable’. Around 960 Mha of this land is in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha) with much, if not all of it, currently under pasture/rangeland (SCOPE, 2015). Thus, the area values presented in Table 6 actually represents a small share of land available.

The evolution of ethanol from sugarcane technology, either in the agriculture side and the industrial processes, improving the efficiency in solar energy harvesting, reinforces this culture as the option of choice for producing large volumes of biofuel with relevant GHG mitigation effect and an acceptable land use. Indeed, properly managed, in our planet there is land enough for all human needs, including sustainable biofuels production.

6. Main remarks

The potential of sugarcane as renewable energy resource has been increasingly developed. Today, for instance, most of Latin American cars run using gasoline blended with ethanol, improving environmental conditions and generating income. But the current technology adopted can be substantially enhanced, by diffusing already available methods and procedures, together with the deployment of innovation in final stage of development. As an example of the first case, the rapid introduction of green cane harvest (without the traditional pre-harvest burning) in Brazil, allowing to use (still partially) the straw incremented significantly the electricity surpluses sold by the mills to the grid. The second group of more intense changes, represented by energy cane plus E2G processes commented in this study, corresponds to real breakthroughs and deserves more attention of energy planners and decision makers. The high GHG mitigation impact is certainly a relevant differential, in addition to other sustainability advantages, recently reassured by a large group of international experts (SCOPE, 2015).

Today, especially in the conditions observed in Brazil and considering the availability of proved technologies, the use of bagasse and sugarcane straw for power production is marginally more attractive than E2G. In other sugarcane producing countries the situation is more or less similar, with the trade-off electricity versus ethanol determined by the power sector supply/demand condition and the ethanol demand configuration. However, the emergence of other alternatives for electricity generation, such as wind and direct solar systems, as well as the effective opening of the global trade of biofuels, the progressive performance gains in E2G, associated to proper energy policy measures, can shift the attractiveness towards ethanol in the forthcoming years. Besides, the development of competitive innovative biomaterials production in the framework of Sugar Platform can reinforce the feasibility and interest in new process based on sugarcane as a whole, including its sugar and fiber content.

It is important to observe that the scenarios explored in this study correspond to reasonable volumes of ethanol. The ethanol demand indicated to 2030, 161 million m^3 (Business as Usual scenario) to 404 million m^3 (Needed scenario), compared to the current global ethanol production, about 80 million m^3, represents respectively an increase of 100% and 400%. Certainly are significant growth rates, but considering the time span (15 years) and the historic Brazilian and US experience, it seems feasible, since these countries already implemented successfully large expansion in their ethanol programs.

Another way to consider the feasibility of such expansion is observing that today an enormous amount of sugarcane straw is still left on field after harvesting and bagasse is burned mostly in low efficiency boilers. Admitting to collect 50% of available straw and obtain a 20% surplus bagasse from sugarcane mills, about 95 kg of lignocellulosic material (dry basis) per sugarcane ton could be diverted for ethanol 2G production; assuming a yield of 217 liters of ethanol/ton cellulose (current technology), the current global production of sugarcane, circa 2 billion ton, would produce more than 41 million m³ ethanol. Just using “residues”, without planting any additional ha. Of course that considering the prospective improvements, this figure can be even greater. In fact, the potential for expanding sugarcane use for ethanol production is not only a huge one, as well as it is closer than appear at a first glance.

To accelerate the maturation and deployment of innovation in sugarcane energy agroindustry the government role is crucial, considering the clear externalities of this route and proportioning a stable environment for new ventures, based on regulatory and financing schemes able to reduce the risk perception and stimulate initiatives with a potential relevant socio-economic-environmental return.

The context currently observed in several countries with good potential for modern sugarcane agroindustry shows that still technical support and demonstration efforts are required to proceed in the learning curve; this can benefit from cooperation at international level. The relatively long experience of Brazil with sugarcane bioenergy demonstrates how rewarding can be and actually is, in a broad sense, to bet in this green energy.

Part III - Guidelines and Recommendations

Introduction

Part III highlights some of the principal points developed in this study in order to consolidate its main conclusions and to address recommendations for the formulation of strategies and measures to foster innovation oriented to accelerate the development and diffusion of low-carbon fuel technologies for transport and industry.

The development of modern society and the achievement of a comfortable living standard in terms of access to services and consumer goods for much of the planet's population are essentially based on a large access to energy, predominantly from fossil energy sources. However, the production and use of energy are currently recognized as a source of serious environmental problems, including climate change, with great impact on our planet and our life.

The progressive awareness of the dimension of this problem and the proposition and implementation of suitable measures to face properly this situation bring significant challenges, among which is the necessary transition to more sustainable energy systems on a global scale. Indeed, it is a complex task to transform national energy matrices traditionally based on oil, coal and natural gas, primary sources with high emissions of greenhouse gases (GHG) in new supply schemes based on socially acceptable and environmentally correct renewable energy sources. Although there is enough natural potential, to build new energy infrastructure requires high investment and relatively long maturity periods, characteristic of energy systems. This energy transition is even more acute and complex in the transport sector, where vehicle technologies impose, with limited exceptions, the use of liquid fuels, due their logistical advantages and end-use readiness. To make this situation more difficult, the expansion of global vehicles fleet and the associated energy requirement is a clear trend, mainly in developing countries.

To the World Energy Council, the world light duty vehicle fleet, about 773 million vehicles registered in 2012, will grow strongly and reach in 2050 a total of 1,750 million vehicles in a conservative and regulated scenario or even beyond, 2,080 million vehicles, in a more liberal and favorable market for individual cars (WEC, 2011). Of course that the fuel demand will grow proportionally, basically to supply internal combustion engines, which should remain during the next decades as the main prime mover in the transportation sector, to be progressively replaced by other technologies. IEA forecasts that around 2050 vehicles moved by electricity and hydrogen will represent less than 20% of transport energy demand (Fulton et al., 2015).

Thus, while is remarkable the increased use of renewable energy technologies in the production of electricity, with the deployment of modern hydropower schemes and a major expansion of wind and solar power, allowing to meet an increasing share of energy demands in industrial, commercial and residential sectors, the transportation of people and goods, by all modes, remains largely dependent on petroleum-based fuels, responsible for large part of current anthropic GHG emissions. Nevertheless, there is an option to supply transport energy needs and reduce substantially carbon emissions: modern liquid biofuels such as ethanol and biodiesel have been occupying an increasing share of energy demand for transport and in dozens of countries its use is already mandatory, usually blended with conventional petroleum-derived fuels. Currently, the IEA estimates that about 3% of global energy consumption in the transport sector is met by biofuels, corresponding to an annual production of 80 billion liters of ethanol, with expectations that this volume will double by 2030, rising to account for 5% of the sector consumption.

However, and very important, given the risks determined by climate change, expanding the production and use of biofuels should be accelerated. According to reports from the IPCC (2011), to limit the rise in average global temperature to 2°C, considering the most probable scenarios of energy demand and the portfolio of available energy technology alternatives, the production and use of biofuels must reach about 11% the energy market in the transport sector, requiring an annual production of around 400 billion liters of ethanol.

1. The search for low-carbon advanced biotechnologies

In this context, adoption of innovations by the agribusiness of sugarcane can offer a competitive and sustainable alternative, reinforcing the comparative advantages already presented by conventional ethanol production from sugarcane, particularly its economic competitiveness and its high capacity of GHG emissions mitigation. Such innovations cover since the introduction of high yielding sugarcane varieties (energy cane) to the use of industrial processes capable of producing ethanol from lignocellulosic materials and production of advanced bio-products (such as biodegradable plastics and chemical intermediates). These disruptive technologies are able to improve agroindustrial productivity and sustainability in a broad sense, reducing environmental impacts and allowing better economic competitiveness, reinforcing the positive indicators of an agroindustry already efficient and productive. It is worth to remark that although representing relevant improvements, these innovations has been introduced progressively, as a synergistic complement to the current productive environment of conventional sugarcane agroindustry, taking advantage of existing plants and infrastructure, reducing costs and environmental impacts.

1.1 Innovative processes and products from a traditional agroindustry

During the last decades, the sugarcane agroindustry has developed several processes and products, beyond the traditional sugar and including many sucrose products, such as bioenergy (biofuels and bioelectricity), chemicals and plastics, in some cases introducing them in market with good results. A large room has been opened by advanced biotechnology techniques, allowing to producing specialized biomaterials for food, feed and industrial applications.

Among such diversity, conventional and second-generation biofuels represent the most important in terms of potential feedstock consumption. Although second generation biofuels represent a breakthrough for bioenergy development, innovative biochemical and the thermo-chemical processes are taken longer time to reach mature technologies than expected 15 years ago. In the first half of the last decade large (public and private) investments in the US and Europe motivated the implementation of many projects, today still in R&D (or closed), starting demo plants and a few "first of the kind" commercial scale plants. Still today activities are mostly motivated by government policies (mandates and incentives). Thus, the Brazilian initiatives can be considered timely and in line with similar efforts. Although this delay, relevant advances have been observed, with cost reductions and yield gains, increasing the economic competitiveness with regards other applications of lignocellulosic feedstock.

A comprehensive analysis presented by the NREL in 2013 on the goals and achievements of the E2G developments in the US looked to a "standard" conceptual plant processing corn stover to produce 2,000 ton ethanol/day, adopting SSCF (Simultaneous Hydrolysis and Co-Fermentation of C5 and C6 sugars) process; following the advances (projected mostly from lab and pilot scale) from 2000 to 2012, very interesting results are shown, confirming the advances towards feasibility (NREL, 2013):

- Production cost (projected): 2.42 US$/liter (2001) to 0.57 US$/liter (2012).
- Technology improvements achieved in all five process steps: Biomass Supply, Feedstock logistics, Pretreatment, Enzymatic Hydrolysis, and Fermentation.
- All the biomass processing steps were validated at pilot scale (1 ton/day continuous; and 8 m^3 for batch fermentation).

At this time, many plants (demonstration, and some actually commercial scale) were being built. It seems that in some cases by-passing steps in the development led to problems. Many projects were canceled, at risk, or incomplete (BCG, 2014); still some commercial scale plants are starting in the US (Abengoa, DuPont, Poet-DSM); in Europe (M&G); in China (Shandong), and in Brazil (Granbio, Raizen, Abengoa) (BNDES, 2015a). Recent public-private partnership (PPP) conducted by BNDES and FINEP, further commented, have enhanced the development of E2G technologies in Brazil; two commercial plants and one demonstration plant are starting to produce the biofuel. Anyway, great progress has been made (costs and performance) and it is expected that, given the proper development time, E2G processes will succeed in bringing large ethanol volumes to the market.

An important advantage of these new processes is their higher efficiency in converting the solar energy stored in the sugarcane in useful forms of energy, which may lead to important changes in the sugarcane agroindustry. In this context, energy efficiency can be assumed as the ratio between the total commercial energy output (including ethanol, electricity, and other biofuels) and the energy input (energy available in whole cane: sucrose and other reducing sugars, bagasse and 40% of the trash), as shows Figure 18, Part I, based on the expected performances and considering a reference mill in Brazil (Seabra and Macedo, 2011).

To define the most interesting processing route for a given context, besides energy efficiency, additional considerations should be made, taken into account aspects such as the commercial energy cost and value (local), local policies, the resulting emissions, and of course the technology availability. Financing mechanisms are an important issue, and they may be different in each case, as in Brazil, today. In the last years, almost all greenfield sugar mills in Brazil have opted for high pressure boilers and turbo-generators with some condensing capacity, to allow for more electricity production and using bagasse efficiently. Both uses of lignocellulosic materials, for liquid biofuels and electricity production can be developed synergistically, allowing energy benefits as a whole.

1.2 Energy cane: a leapfrog in energy productivity

During centuries, sugarcane breeding had promoted high sucrose content and reduced fiber in cane stalks, in order to increase sugar production and facilitate milling operation. Such usual paradigm of sugarcane breeding has imposed to backcross commercial Saccharum officinarum hybrid varieties with sugary and low fiber ancestral species, reducing its vigor and limiting its productivity. The potential field productivity of sugarcane is estimated to be about 400 ton of fresh biomass per hectare per year in optimum conditions (Souza et al., 2013), while the world commercial average productivity is less than 25% of that value. In fact, despite the significant increase in productivity and diversification of varieties observed in recent decades, the genetic potential of sugarcane still allows additional significant gains, with clear implications to overall agroindustry performance and prospects for lignocellulosic feedstock processing.

A revision of the usual paradigm focused on sugar was pioneering recommended by A. G. Alexander during the 1980’s in Puerto Rico, indicating that the fiber content should be re-evaluated, with global gains in productivity and performance. In his proposal, aimed to recovery the economically depressed Puerto Rican sugarcane industry in that time, Alexander’s group always stressed the possibility of using the whole plant: the juice, the fiber and also the top and the leaves, from the more productive cultivars (Matsuoka et al., 2014).

The new varieties of sugarcane, optimizing the whole plant energy products are called energy cane. It is essentially a cane with a lower sucrose content and higher fiber content than usual sugarcane varieties, and most importantly, presenting higher yields in ton of plant material per hectare, resulted of hybridization of commercial sugarcane with wild species of Saccharum officinarum and S. Sponteneum (See figures 19 and 20, Part I). It is estimated that between 2010 to 2030 the energy cane cultivars could increase in 140% the annual energy productivity, which can rise from 628 GJ/ha to more than 1,200 GJ/ha (Landell et al., 2010).

The diffusion of commercial varieties of energy cane is already in place, although the processing of this high fibrous feedstock imposes develop new processes for harvesting, preparation and extraction. The same challenging situation is observed in the sugarcane straw collection and use, associated to sugarcane green harvest, requiring new equipment and technologies. It should be stressed that the interest in energy cane is also associated to the innovative processes able to convert cellulose in valuable products, presented the previous topic.

2. The opportunity for public-private initiatives

It has been proved that availability of natural resources, agroindustrial technology and potential demand are not enough to foster investments in advanced biofuels production, mainly due to risk perception inherently associated to new process and market uncertainties. Indeed, the government role is decisive to support properly innovative ventures in bioenergy and bioprocesses, assuring attractive market conditions and reducing uncertainties impacts, especially in the middle of cycle of innovation, after the bench stage and before the commercial production. As can be observed in many cases, in the implementation of a new bioenergy technology, after the initial steps in research and pilot plant, moving to a demonstration unit and following to the first commercial plant presents considerable challenges and risks, in general requiring external support. Such external support can be given fostering the demand, on the supply side, as well as, assuring a demand of the new products, on the consumption side.

Taking account these concepts, aiming basically to foster innovation in the production side and stimulate public private partnership, the Joint Plan for Supporting Industrial Technological Innovation in the Sugarcane-based Energy and Chemical Sectors (PAISS), put forward in 2011 by the Brazilian Development Bank (BNDES) and the Brazilian Innovation Agency (FINEP), has been a decisive initiative to overcome starting obstacles and advance in the learning curve. The main motivation for the Plan was the awareness of these two institutions about the large delay of the national sugarcane agroindustry in implementing advanced bioenergy technologies, in comparison to other countries, despite of the existence of a mature and competitive biofuels production, equipment suppliers, and active research institutions in bioenergy. Until this initiative, few and limited second generation processes projects were deployed.

To date, the PAISS concept was implemented in two rounds, the first one essentially directed towards industrial processes (Industrial PAISS, launched in 2011) and the second one more focused on agriculture (Agricultural PAISS, launched in 2014). The aim of this plan is select business plans and promote projects that include the development and implementation of innovative technologies for producing and processing sugarcane to bioenergy and bioproducts, assisting good proposals to obtain funding, improving the coordination of development actions and better integration of support instruments available. Its guidelines stimulated joint projects from industry and research institutions and pointed out a list of priorities, covering: second generation ethanol, new products from sugarcane, and gasification of lignocellulosic by-products in the Industrial PAISS, and new sugarcane varieties (for new production environments and energy cane), agro-machinery, integrated systems management, planning and control of sugarcane production, planting techniques, and adaptation of industrial systems for energy crops in the Agricultural PAISS.

The financial instruments offered by PAISS include: a) credit in special financing lines, b) equity participation, c) non-reimbursable funds for cooperative projects between companies and R&D institution and d) economic support non-refundable (grants) for companies, defined depending on the case (amount, technological risk, involved institutions, etc.). After the call for tenders and a sequence of thorough screening steps to select the projects worth to deserve funding, Industrial PAISS granted about US$ 625 million[7] in financing lines, levering investments of US$ 1.7

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[7] PAISS investments converted from original values in Brazilian currency, using the average annual exchange rate (2.35 BRL=1.00 USD).

billion, to be deployed between 2011 to 2014 (BNDES, 2011), while Agricultural PAISS offered US$ 630 million projects for the period 2014-2018 (BNDES, 2015).

The Industrial PAISS projects include four ethanol 2G plants (see Table 7, Part I), which total installed capacity reaches 188 million liters per year, two of them already inaugurated (showed in Figure 21, Part I). As usual in innovative processes, these plants are facing difficulties and progressively improving their operation. Although the initial concerns were the stability and performance of the core process, the hydrolysis of lignocellulosic feedstock, in the actual operation this stage has presented satisfactory results, with problems arisen in the feedstock logistics and pretreatment. Particularly the pretreatment has been a challenging unit operation, due its cost and direct effect on subsequent hydrolysis time and yield. Although that issues are complex, it is expected that these problems will be progressively solved.

The positive outcome of the PAISS program reflects the favorable conditions existing in Brazil and in other similar countries to host investments for new technologies to convert biomass, ranging from R&D centers to demonstration plants; and enable large investments to establish the commercial plants derived from new technologies that have been globally developed. The main drivers for such attractiveness are presented as follows (Milanez et al, 2012).

- Ready availability and low cost of feedstocks, mainly sugarcane bagasse and straw.
- Locally developed pathways with dedicated technology due to the specific complexity of domestic feedstocks.
- Large amount of available land, typically low productivity pastures, that can be converted into agricultural crops for energy or chemical purposes.
- Well-established sugar and ethanol agroindustry, which facilitates the integration of new technologies under low investment and with reduced operational costs.
- Fuel market growth and heavy dependence on imports of chemicals, that creates an excellent opportunity for domestic investment.
- Increasing opportunities for developing a global trade of biofuels and biomaterials, considering the lowest carbon footprint of products derived from sugarcane.

3. Main conclusions

In this study a brief technology assessment was developed, identifying and characterizing the innovative processes in different level of matureness to produce ethanol from lignocellulosic feedstock and other valuable bioproducts from sugarcane. Particularly with regards to bioenergy from sugarcane, the prospects of increasing the production of ethanol by adopting second generation processes and promoting energy cane cultivation can represent a real contribution to supply the increasing demand of energy in the global transport sector, and at the same time, mitigate significant amounts the emissions of GHG gases to the atmosphere.

The following paragraphs present the findings of this study with respect to impact of ethanol from sugarcane production and use on global GHG emissions, as well as the land necessary to produce cane in this context. The Brazilian situation is the basic reference for evaluating the technology scenarios, after extended to the global context, assuming two forecasts of energy demand for light vehicles, as explained in the previous parts of this study.

It is well recognized the potential of sugarcane as energy vector, with good perspectives to expand its use abroad as feedstock for sustainable bioenergy production in large amounts and relatively limited use of land (Leal et al., 2013). In order to evaluate the impact of expanding ethanol production abroad, it was assumed that the sugarcane agroindustry existing in several other countries is or can be similar to the Brazilian one, and the ethanol production can be possibly implemented in the same way, associated to sugar production and power generation. In fact, this assumption seems very feasible since today there is sugarcane agroindustry in other countries, such as Colombia and Guatemala, presenting in some cases performance indicators similar or even better than the Brazilian good mills.

Under this assumption, it was possible to consider different technological scenarios, including first and second generation processes, considering units under typical conditions of raw material supply, incorporating sugarcane straw and energy cane scenarios. Thus, several scenarios were assessed to evaluate GHG emissions and land use impacts associated to innovative technologies for ethanol production, initially for Brazil then estimated at global level, as described as follows.

3.1 Production scenarios

The potential for producing ethanol from sugarcane using modern and innovative technologies was assessed in two scenarios: the Business as Usual scenario representing the existing production and use paradigm to the near future, while the Needed scenario looks for considering the IPCC requirements for GHG mitigation, with higher ethanol demand and better production technology, assuming that integrated efficient processes will be deployed in the feedstock production and conversion. Therefore, the Needed scenario means also that proper public policies and regulation will be in place to foster ethanol production (including specific measures for promoting E2G) and its use will be stimulated to help to stabilize GHG concentration at 450 ppm, level expected to limit the increase of average global temperature increase to 2°C, as pointed out by IPCC (2011).

Aiming at increasing the biofuel yield, two innovations were considered: a) the E2G processes, allowing to produce ethanol not only from sugar content in sugarcane but also from its fiber and leaves, and b) the introduction of energy cane, increasing significantly the production of biomass per hectare. The productivity values assumed in CTBE studies modeling different configuration of sugarcane mills are presented in Table 3, Part II.

To evaluate the average impacts of adopting these technologies in an actual park of mills, the total production of ethanol was shared among the existing and projected mill's configurations in the Brazilian sugarcane industry (CTBE, 2015). In this conditions, for the scenarios evaluated for the next decade, the current average agroindustrial productivity, 6.49 m^3 ethanol/ha, could rise to 7.26 m^3 ethanol/ha (+12%) due to gains in the conventional E1G process and energy cane introduction (supplying partially the raw material processed), and reach 8.66 m^3 ethanol/ha (+33%) when E2G process are implemented, always in average figures for the whole sugarcane agroindustry (see Figure 33, Part II). This increase in productivity depends of course on the accomplishment of the intense efforts to achieve the expected performance in energy cane and E2G processes, as well as that the required investments in brownfield and greenfield mills will be done.

3.2 Ethanol consumption scenarios

Regarding the global ethanol demand perspectives, two conditions were assumed, representing the Business as Usual perspective, typically assuming ethanol use in blends, in line with BP (2015) and WEC (2011); and the Needed scenario, which requires a more intense expansion of ethanol use, accordingly to IPCC (2011) forecast. Table 4, Part II, summarizes these assumptions and Table 5, Part II presents for each scenario the ethanol demand, the mitigation factor estimated by Life Cycle Analysis on the considered technologies (CTBE, 2015) and the resulting impact on GHG mitigation. Compared with the production observed in 2013 (83 million m^3), these demand forecasts require increasing the global ethanol supply in 94% and 387% for the Business as Usual and Needed scenarios, respectively.

3.3 Main results

For the time horizon considered, 2030, the total GHG emission mitigated in the higher ethanol demand scenario (Needed), covering 11% of energy demand in the world transport sector, represents approx. 1.4% of global anthropogenic GHG emissions estimated for 2010 (49 Gt CO_2eq) and 9.5% of global transport GHG emissions estimated for the same year (7 Gt CO_2eq) (IPCC, 2014), as indicated in Table 7 and Figure 35.

Table 7. Global ethanol consumption and impacts in 2030

Indicator	2030 BAU	2030 Needed	Needed/BAU
Liquid biofuel production (million m^3)	161	404	+250%
Emission mitigation (Mt CO_2eq/year)	246	667	+271%
Land use (million ha)	22.1	46.7	+211%

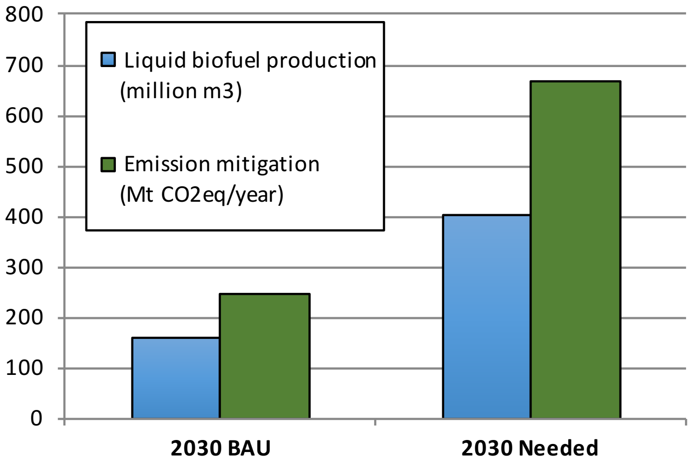

Figure 35. Scenarios to 2030 for ethanol production and GHG mitigation

The area estimated to be occupied with sugarcane in the Needed scenario, about 47 million ha, should be compared with the land potentially available for bioenergy production. According to FAO (2012), the land available for rainfed agriculture is estimated to be 1,400 Mha of ‘prime and good’ land and a further 1,500 Mha of marginal land that is ‘spare and usable’. Around 960 Mha of this land is in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha) with much, if not all of it, currently under pasture/rangeland (SCOPE, 2015). Thus, such area actually represents means 1.6% of land available for rainfed agriculture.

The evolution of ethanol from sugarcane technology, either in the agriculture side and the industrial processes, improving the efficiency in solar energy harvesting, reinforces this culture as the option of choice for producing large volumes of biofuel with relevant GHG mitigation effect and an acceptable land use, as indicated in this study. Indeed, properly managed, in our planet there is land enough for all human needs, including sustainable biofuels production. Figure 6 synthesizes the land issue, indicating that the area required for ethanol production in the Needed scenario represents a very limited portion of total land available for economic purposes.

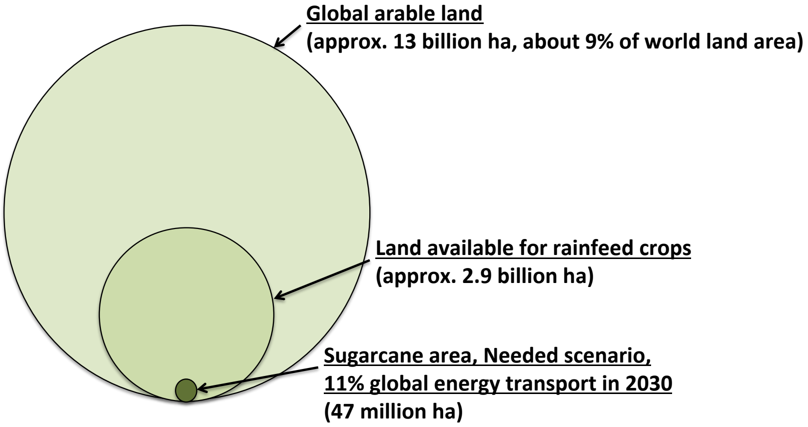

Figure 36. Land required for ethanol production in the Need scenario

3.4 On feasibility and perspectives

It is important to observe that the scenarios explored in this study correspond to reasonable volumes of ethanol. The ethanol demand indicated to 2030, compared to the current global ethanol production, means an annual cumulative growth rate of 4.7% (Business as Usual scenario) and 11.4% (Needed scenario). Certainly are significant growth rates, but considering the time span (15 years) and the historic Brazilian and US experience, it seems feasible, since these countries already implemented successfully large expansion in their ethanol programs, with similar expansion. Nevertheless, represents a clear challenge to deploy such ethanol production, thus innovation has a clear role: increase bioenergy (fuel and electricity) yield and improve GHG mitigation.

Another way to consider the feasibility of such expansion is observing that today an enormous amount of sugarcane straw is still left on field after harvesting and bagasse is burned mostly in low efficiency boilers. Admitting to collect 50% of available straw and obtain a 20% surplus bagasse from sugarcane mills, about 95 kg of lignocellulosic material (dry basis) per sugarcane ton could be diverted for ethanol 2G production; assuming a yield of 217 liters of ethanol/ton cellulose (current technology), the current global production of sugarcane, circa 2 billion ton, would produce more than 41 million m^3 ethanol. Just using “residues”, without planting any additional ha. Considering the prospective improvements, this figure can be even greater. In fact, the potential for expanding sugarcane use for ethanol production is not only a huge one, as well as it is closer than appear at a first glance.

Although the current and innovative biomaterials produced in the framework of sugarcane agroindustry, based on thermochemical processes or bioprocesses, have an expanding global market, either as intermediate or final products, their impact with regards to GHG mitigation and land use is still limited compared with biofuels. Nevertheless, these products increment the diversification of mills, aggregating value to some low cost by-products and can play an important role in improving, as cogenerated electricity does, the overall feasibility of sugarcane agroindustry.

4. Recommendations

The sugarcane agroindustry started an important evolution, aggregating advanced technologies and becoming more and more a supplier of renewable liquid fuels and electricity, and opening a broad field of opportunities for producing innovative bioproducts, such as bioplastics and chemical intermediates. The conjugated opportunity for implementing processes to convert lignocellulosic feedstock in ethanol and electricity, plus the high potential for increased yields of biomass with energy cane, creates a new scenario, with multiple gains: energy, plus economic, social, and environmental benefits. Due its large and pioneer experience in modern liquid biofuels (from feedstock production to modern processing routes) and well developed R&D institutions active in bioenergy, Brazil and other similar countries with proper climate and available land have a privileged position to promote these technologies of global interest.

In spite of better understanding of this potential, considering the most feasible scenarios, its development depends on proper public policies, reducing risk perception and stimulating efficiency. In this direction, the Brazilian case is a good example: the availability of natural resources, the existence of a well-established sugarcane agroindustry, a proper legislation setting a market for bioenergy, and furthermore, a suitable financing program, promoting innovation, fostering investment and technological and business partnerships, represented an important move forward to consolidate a desirable reality, which first results are appearing. This transformation is starting, with different pathways in evaluation, and learning curves are evolving. But the model is defined, implemented and working. In a few words, it is possible to produce competitive and sustainable energy, as well as customized biomaterials, in the required amounts and with the specified quality.

To accelerate the maturation and deployment of innovation in sugarcane energy agroindustry the government role is crucial, considering the clear externalities of this route and proportioning a stable environment for new ventures, based on regulatory and financing schemes able to reduce the risk perception and stimulate initiatives with a potential relevant socio-economic-environmental return. In this direction, measures must be taken in two directions: reinforcing the attractiveness of introducing innovation in production ("technology push") and promoting the use of products made in this context ("demand pull"), as commented as follows.

4.1 Technology Push measures

The BNDES/FINEP Joint Plan for Supporting Industrial Technological Innovation in the Sugarcane-based Energy and Chemical Sectors (PAISS), launched in 2011, represents a landmark to promote innovation in the Brazilian sugarcane agroindustry, acknowledged of strategic interest, in line with Federal Government R&D policies. It has induced important investment in second generation bioenergy and energy cane, and an indicator of its positive results is its replication in other sectors, applying its model of inducing public-private partnership, involving research institutions and commercial companies. The rationale is to reinforce at same time, the experience in doing business and the knowledge basis. Regardless the PAISS outcome, two recommendations can be made:

- Improvements can be considered in simplifying the procedures and increasing the coordination with complementary policies, involving other Federal and state level R&D and innovation agencies, which objectives include in many cases the promotion of sustainable bioenergy.
- A continuity of this plan should be evaluated, with a third round of PAISS possibly covering both industrial and agricultural subjects and opening room for to overcome the obstacles found in the previous phases and the conditions observed in the new frontiers of sugarcane agroindustry development, where the soils and climate are posing challenges to obtain good and stable yields.

Also in the category of Technology Push actions, should be considered to intensify the international cooperation with developed and emerging countries, with several institutions already active in advance processes for lignocellulosic feedstock to biofuels and biomaterials. This cooperation could be fostered in the framework of existing bilateral and multilateral programs and focusing human resources development and training. The objective in this cooperation should be to reinforce the local capacity in these technologies.

In a complementary direction, it should be take into account the context observed in several developing countries, mainly in Latin America and Africa, presenting good potential for modern sugarcane agroindustry deployment, but still lacking of initiatives in this field. In this case, cooperation, technical support and demonstration efforts could move such agroindustry to proceed in the learning curve, following the way that some countries are already developing, such as Peru, Angola and Ecuador. The relatively long experience of Brazil with sugarcane bioenergy demonstrates how rewarding can be and actually is, in a broad sense, to bet in “green energy”.

4.2 Demand Pull measures

Promoting and in some cases assuring the market for products have been a kind of measure largely adopted to reinforce the competitiveness of innovative technologies, as the case of advanced biofuels. Some measure in this direction should be considered in Brazil, to encourage the consumption of 2G ethanol, such as a specific tax regime and/or a mandatory quota. Considering the size of the Brazilian biofuels market and the current capacity of 2G production units, the support necessary would comparatively small (Nyko et al., 2013). Currently, in USA and EU the advanced biofuels receive clear and relevant support by marketing drives, in both cases associated to environmental policies and aiming at to mitigate GHG emissions. It is worth to review them, as follows.

The Renewable Fuel Standard (RFS) program was created in the United States of America under the Energy Policy Act of 2005 and further amended and expanded. This program is implemented by the Environmental Protection Agency in consultation with Department of Agriculture and the Department of Energy. The RFS program is a national policy that imposes a certain volume of renewable fuel to replace or reduce the consumption of petroleum-based transportation fuel, heating oil or jet fuel. The renewable fuel categories under the RFS are: a) biomass-based diesel, b) cellulosic biofuel, c) advanced biofuel (able to meet a 50% GHG reduction), and d) total renewable fuel. Long-term consumption goals have been established and a system of compliance was implemented, obliging refiners or importers of gasoline or diesel fuel to blend renewable fuels into transportation fuel, or by obtaining credits (called “Renewable Identification Numbers”, or RIN’s) to meet an EPA-specified Renewable Volume Obligation (RVO). Cellulosic biofuels have special regime and quotas, and must mitigate 60% of GHG emission compared with fossil fuels (EPA, 2015). The RFS is certainly the main foster of advanced biofuels market in the USA.

The European Union implemented in 2009 a more complex regulatory and legal framework, including the Renewable Energy Directive, creating a 10% quota for renewable energy in transport to be accomplished until 2020 and requiring sustainability indicators, the Fuel Quality Directive, and the Directive to reduce indirect land use change (ILUC) for biofuels and bioproducts, a quite controversial issue. After a long debate, in April 2015, the European Parliament rejected ILUC due its insufficient scientific basis and approved a revision of this legislation, creating a cap of 7% on the contribution of biofuels produced from “food” crops8, and adding emphasis on the production of advanced biofuels from waste feedstocks. Member States must then include these provisions in national legislation by 2017, and show how they are going to meet sub-targets for advanced biofuels. The other 3% (“non-food biofuels”) will come from a variety of multiple counted alternatives: biofuels from used cooking oil and animal fats (double counted), renewable electricity in rail (counted 2.5 times), renewable electricity in electric vehicles (counted 5 times), and advanced biofuels (double counted and with an indicative 0.5% sub-target) (EC, 2015). Although the implementation of these Directives are more time demanding and the subsidiary legislation is still in progress, it is visible their positive role in promoting and developing the European market for advanced biofuels.

The mature experience and consequent legislation promoting advanced biofuels demand in USA and EU offers important references on the opportunities for measures in such direction in other countries. A baseline for these measures is the mechanisms for promoting biofuels in general, that can “pave the road” for promoting the advanced biofuels, creating an adequate logistic and distribution system able to be used either for conventional or advanced biofuels, as well as, reducing possible cultural obstacles against biofuels introduction. In any case blending mandates or quotas specific for advanced biofuels should be considered, as they have been proved to be effective. However, such targets should be realistic, based on local perception of biofuels market growing potentiality, and fundamentally designed to promote steady and incremental contribution of biofuels to energy supply, in a sustainable basis.

Concluding these remarks on mechanisms to foster sustainable advanced biofuels production and use, is worth to observe that although both Demand Pull and Technology Push measures are important drivers of innovation for biofuels production and use, their effectiveness depends on some aspects that needs attention:

- The coordination between technology and environmental policies is crucial and can promote interesting synergies. This is particularly relevant after the COP 21 guidelines and Intended Nationally Determined Contributions (INDC’s) pledges.
- The continuity and stability of programs, creating stable research groups and medium term goals, as well as imposing intermediate following and

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[8] The real competition food versus bioenergy occurs not at feedstock level, but at basic inputs for production, such as money, labor, land, water, etc. Sustainable bioenergy is necessarily associated to efficient production and conversion processes, using rationally natural and human resources.

evaluation activities, when the contribution from external reviewers are highly recommended.
- The balance and tuning of measures to spur innovation must consider properly the existence and needs of endogenous technological support, able to absorb and process in a rational rate the available information.

As a final remark on this study, it should be stressed that, based on several independent studies (SCOPE, 2015), when properly implemented and managed, the production and use of liquid biofuels is not a threat to food security, biodiversity and ecosystem services. Indeed, the evolution of this agroindustry has been done mostly achieving environmental, economic and social benefits, such as improving soils, integrating production chains, delivering co-products, generating income and jobs. Introducing innovative feedstock and processes, such as lignocellulosic material and ethanol 2G, can reinforce this positive record, allowing climate mitigation much more effectively while improving economic performance to accomplish broader societal needs.

References

Alexander, A G, 1985. *The Energy Cane Alternative*. Elsevier. Amsterdam.

ANFAVEA, 2015. *Yearbook of Brazilian Automotive Industry*. National Association of Motor Vehicle Manufacturers. São Paulo

BCG, 2014. Comments on Low Carbon Fuel Standard Re-Adoption. The Boston Consulting Group, *Fuel Availability Workshop*, Western States Petroleum Association, October 2014

Bioplastic, 2015. *Biocycle: Company History*, available at http://www.biocycle.com.br/site.htm, consulted in August 2015.

BNDES, 2015. *Estimativa de produção de Etanol 2G no Brasil até 2025*, Preliminary Note, National Social and Economic Development Bank, Rio de Janeiro.

BNDES, 2011. Plano Conjunto BNDES-FINEP de Apoio à Inovação Tecnológica Industrial dos Setores Sucroenergético e Sucroquímico – PAISS. Introduction and Basic Information in Portuguese, available at http://www.bndes.gov.br/SiteBNDES/bndes/bndes_pt/Areas_de_Atuacao/Inovacao/paiss/, consulted in September 2015

BNDES, 2013. O desempenho das atuais tecnologias agrícolas do setor sucroenergético: estagnação passageira ou crise estrutural?, by Nyko, D; Valente, M S; Milanez, A Y; Tanaka, A K R; Rodrigues. BNDES Biofuels Department. August 2013.

BNDES, 2015a. Second Generation Ethanol as an Opportunity for Sustainable Development, by Milanez, A Y. BNDES Biofuels Department. July 2015.

BNDES, 2015b. PAISS - BNDES/FINEP Joint Plan to Support Industrial Technology Innovation for the Sugarcane Industry, by Milanez, A Y. BNDES Biofuels Department. August 2015.

BNDES/CGEE, 2008. *Ethanol from sugarcane – Energy for sustainable development*. BNDES Brazilian Development Bank and CGEE Center of Strategic Studies (co-edited with ECLAC and FAO). Brasília.

BP, 2015. BP *Energy Outlook 2035*, London.

Brander, M., Tipper, R., Hutchison, C., Davis, G., 2008. Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels, *Econometrica Press*, April 2008.

Brazil, 2015. *intended Nationally Determined Contribution towards achieving the objective of the United Nations Framework Convention on Climate Change*, Brasilia, 2015.

Carvalho-Netto, O V; Bressiani, J A; Soriano, H L.; Fiori, C S, Santos, J M; Barbosa, G V S; Xavier, M S; Landell, M G A; Pereira, G A G, 2014. The potential of the energy cane as the main biomass crop for the cellulosic industry. *Chemical and Biological Technologies in Agriculture*. Vol 1.

CGEE, 2012. *Sustainability of sugarcane bioenergy* - Updated edition. – Brasília, DF : Center for Strategic Studies and Management (CGEE), 2012.

Chum et al., 2011. Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: *Bioenergy*. In (IPCC, 2011), op cit.

CTBE, 2015. 2G ethanol life cycle assessment. Final presentation of project results to the members of the board of ABBI, São Paulo, November 12th, 2015, and executive summary “The contribution of cellulosic ethanol for reducing carbon emissions and fossil energy use in the transportation sector”. A. Bonomi, O. Cavalett, Tassia L. Junqueira and M. F. Chagas, Campinas.

Dias, M. O. S., Cunha, M. P., Jesus, C. D. F., Rocha, G. J. M., J. G. C. Pradella, Rossell C. E. V., Maciel Filho, R., Bonomi, A. 2011. Second generation ethanol in Brazil: Can it compete with electricity production? Bioresource Technology 102.

Dias, M. O. S., Junqueira, T. L., Cavalett, O., Cunha, M. P., Jesus, C. D. F., Rossell C. E. V., Maciel Filho, R., Bonomi, A. 2012. Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. Bioresource Technology 103.

EC-DGE, 2015. *From the Sugar Platform to biofuels and biochemicals*. Final report for the European Commission Directorate-General Energy, E4Tech, RE-CORD (Consorzio per la Ricerca e la Dimostrazione sulle Energie Rinnovabili), Wageningen University and Research Center, ENER/C2/423-2012/SI2.673791. V2.1., April 2015.

EC, 2015, Biofuels, European Commission, available at https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels, consulted in November 2015

EPA, 2015. Renewable Fuel Standard Program, US Environmental Protection Agency, available at http://www.epa.gov/renewable-fuel-standard-program/, consulted in November 2015

EPE, 2013. *Decennial Energy Expansion Plan 2022*, Energy Research Agency, Ministry of Mines and Energy, Brasília.

FAO, 2012. *World agriculture towards 2030/2050*. ESA Working Paper No. 12-03, by Alexandratos, N; Bruinsma, J. Food and Agriculture Organization of United Nations, Rome.

FAO, 2015, FAOSTAT, available at http://faostat3.fao.org/home/E, consulted in July 2015

Fulton, L.M., Lynd, L.R., Körner, A., Greene, N, Tonachel, R.L., 2015. The need for biofuels as part of a low carbon energy future, *Biofuels, Bioproducts and Biorefining*, Wiley Online Library, DOI: 10.1002/bbb.1559

Goldemberg, J; Coelho, S T; Guardabassi, P., 2008. The sustainability of ethanol production from sugarcane. *Energy Policy*, Vol 36.

IEA, 2004. *Advanced Motor Fuels*, Fuels Update Newsletter, Vol 7 (1), January 2004

IEA, 2014. *World Energy Outlook 2014*. International Energy Agency. Paris.

IPCC, 2011, *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S.

Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. Cambridge University Press, Cambridge.

IPCC, 2014. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva.

IPCC, 2012. *Special Report on Renewable Energy Sources and Climate Change Mitigation*. Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge.

IRENA, 2014, *REmap 2030: Summary of Findings*. International Renewable Energy Agency. Abu Dhabi.

IRENA, 2014. *Global Bioenergy: Supply and Demand Projections*, Working Paper for REmap 2030, International Renewable Energy Agency, Abu Dhabi, September 2014

Landell, G A; Pinto, L R; Creste, S; Chabregas, S M; Burnquist; W L, 2010. Technical road map for ethanol: genetic improvement and biotechnology. in: *Sugarcane Bioethanol: R&D for Productivity and Sustainability*, Cortez, L A B (editor). Ed Blucher. São Paulo.

Leal, M R L, 2010. Energy cane. in: *Sugarcane Bioethanol: R&D for Productivity and Sustainability*, Cortez, L A B (editor). Ed Blucher. São Paulo.

Leal, M R L, Nogueira, L A H, Cortez, L A B, 2012. Land demand for ethanol production. *Applied Energy*. Elsevier. Vol. 102.

Macedo, I.C., 2005. *Some diversification options in Brazil*. International Sugar Organization/Datagro International Seminar, “Sugar and ethanol: a magic combination for the future”. S Paulo, May 2005.

Macedo, I. C. , Nassar, A.M., Cowiec, A.L., Seabra, J.E.A., Marelli, L., Otto, M., Wang, M.Q., Tyner.W.E., 2015. Greenhouse Gas Emissions from Bioenergy. Chapter 17, *SCOPE 72 (Bioenergy & Sustainability: bridging the gaps)*. Edited by G M Souza, R L Victoria, C A Joly , L M Verdade; S Paulo.

Macedo, I C, 2005. Sugarcane’s Energy: Twelve Studies on Brazilian Sugarcane Agribusiness and its Sustainability. UNICA. São Paulo

Matsuoka, S; Kennedy, A J; Santos, E G D; Tomazela, A L; Rubio, L C S, 2014. Energy Cane: Its Concept, Development, Characteristics, and Prospects. *Advances in Botany*. Vol 2014, Article ID 597275

Milanez, A. Y., Nyko, D., Valente, M. S., Sousa, I. C., Bonomi, A., Jesus, C. D. F., Watanabe, M. D. B., Chagas, M. F., Rezende, M. C. A. F., Cavalett, O., Junqueira, T. L., Gouvêia, V. L. R., 2015. De promessa a realidade: como o etanol celulósico pode revolucionar a indústria da cana-de-açúcar – uma avaliação do potencial competitivo e sugestões de política pública. *BNDES Setorial 41*, Rio de Janeiro.

Milanez, A Y; Nyko, D; Cavalcanti, C E, 2012. Brazil’s race towards second generation biofuels. *Biofuels International*. Issue 5, volume 56, june 2012.

MME, 2015. *National Energy Balance*. Ministry of Energy and Mines. Brasília.

NREL, 2013. T. Foust, A. Bratis . Biomass 2013: Cellulosic Technology Advances, July 31, 2013. National Renewable Energy Laboratory. Boulder.

Nastari, P. (coordinator), Macedo, G. A., Macedo, I. C., 2003, *Novos Produtos da Sacarose*, Internal Report to CrystalSev – Cargill, June 2003.

Neves, M F; Trombin, V G; Consoli, M, 2009. Mapping the productive chain: a panoramic portrait of sugarcane agroindustry. In: Souza, E L and Macedo, I C. *Ethanol and bioelectricity: the sugarcane in the future energy matrix*. UNICA. São Paulo.

Nyko, D; Valente, M S; Dunham, F B; Milanez, A Y; Costa, L M; Pereira, F S; Tanaka, A K R; Rodrigues, A V P. 2013. Planos de fomento estruturado podem ser mecanismos mais eficientes de política industrial? Uma discussão à luz da experiência do PAISS e seus resultados. *BNDES Setorial, Inovação*, n. 38.

Oxiteno, 2012, Innovation and Green Chemistry in Oxiteno. *Workshop for Sustainable Production of Biopolymers and other Bio-based Products*. FAPESP São Paulo Research Foundation. São Paulo.

Ricardo, 2012, *Greenhouse Gas Reduction Potential: estimations for Light-Duty Vehicle Technologies in 2020–2025*, ICCT International Workshop, Brussels, February 2012

Schuchardt U; Ribeiro M L; Gonçalves A R, 2001, A indústria petroquímica no próximo século: como substituir o petróleo como matéria prima?. *Química Nova*, v. 24(2)

SCOPE (2015). *Bioenergy & Sustainability: Bridging the gaps* (Vol. 72, p. 779). Souza, G. M., Victoria, R., Joly, C., & Verdade, L. (Eds.). Scientific Committee on Problems of the Environment. Paris.

Seabra, J E A, 2008. *Technical-economic evaluation of options for whole use of sugar cane biomass in Brazil*. PhD Thesis. Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica. Campinas.

Seabra, J E A; Macedo, I C, 2011. Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. *Energy Policy*. Elsevier. Vol. 39.

Seabra, J.E.A., Macedo, I.C., 2011. Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil, *Energy Policy*, 39 (2011)

Souza, A P; Grandis, A; Leite, D C C; Buckeridge, M S, 2013. Sugarcane as a bioenergy source: history, performance, and perspectives for second-generation bioethanol. *Bioenergy Research*, Vol. 7, no. 1.

Technip, 2013, ￼*Global Ethylene Market Outlook*, by Eramo, M. (IHS Chemical). Technip Inaugural Ethylene Forum. Los Angeles.

UNICA, 2015, UNICADATA, available at http://www.unicadata.com.br, consulted in July 2015

UNICA, 2015. *UNICADATA*, available at http://www.unicadata.com.br, consulted in September 2015

WEC, 2011. *Global Transport Scenarios 2015*, World Energy Council, London

Annex 1

Ethanol production estimate in Brazil (CTBE, 2015)

	2015	2020	2025	Technological scenario
Ethanol 1G	**28.4**	**31.7**	**45.3**	
Current 1G mills (2015 average)	28.4	22.54[4]	22.54	Scenario 1 - without straw
1G mills integrated to 2G		5.86[4]	5.86	Scenario 4
1G greenfield mills (optimized to power production)		3.25[5]	3.25	Scenario 1 - with straw
1G greenfield mills (improved technology)			3.25[6]	Scenario 2
1G integrated (conventional plus energy cane)			6.46[7]	Scenario 5A
1G mills (energy cane)			3.93[8]	Scenario 8A
Ethanol 2G[1]		**3.25**	**10.0**	
2G stand alone plants (straw from 1G mills)		1.625[2]	1.625	Scenario 7 - straw
2G plants integrated to 1G mills		1.625[2]	1.625	Scenario 4
2G plants integrated (conventional plus energy cane)			3.375[3]	Scenario 5A
2G stand alone plants (energy cane)			3.375[3]	Scenario 8A
Total	**28.4**	**34.9**	**55.3**	

Hypothesis and assumptions

[1] It was adopted the total ethanol 2G production estimated by BNDES (2015) 3.25 billion liters by 2020 and 10 billion liters by 2025.

[2] It was assumed that half of the short-term production increase would occur in integrated plants (Scenario 4) and half in independent plants (Scenario 7 - straw).

[3] For the production volume increased from the previous period (6.75 billion liters) was assumed that half would be produced in integrated plants (Scenario 5A) and half on independent cane power plants (Scenario 8A).

[4] It was adopted that the production of 2G ethanol in integrated plants (2) occur in retrofits 1G plants (Scenario 1 - without straw). Thus, part of 1G plants that existed in 2015 would be converted into integrated plants 1G2G (Scenario 4). The amount of ethanol produced in 1G integrated plants (5.86 billion liters/year) is proportional to ethanol 2G (1.625 billion liters/year), enough to keep the production ratio E1G/E2G calculated for this scenario.

[5] It was assumed that in the short term there would be also ethanol 1G production increased in new plants optimized for Electricity (Scenario 1 - with straw), with the same volume of ethanol 2G ethanol (3.25 billion liters/year).

[6] It was assumed that the same short-term ethanol 1G production increase (3.25 billion liters/year) also occur in the medium term, but with plants with 1G technology in this time frame (Scenario 2).

[7] Likewise in the short term picture ([4]), this would be the production of ethanol 1G in the integrated mill processing conventional and energy cane to produce ethanol 2G ([3]) to maintain the production ratio E1G/E2G calculated for Scenario 5A.

[8] Likewise in the short term scenario ([4]), this would be the production of ethanol 1G in mills processing energy cane and producing ethanol 2G ([3]), in order to maintain balanced the production ratio E1G/E2G calculated for Scenario 8A.

Annex 2

Brazil country profile[9]

Low-Carbon Fuels Policy, Regulation and Enforcement

Mandates

All gasoline blended with anhydrous ethanol in the range E18 to E27, most frequently E25, currently E27.
Ethanol hydrated also available in all 39,000 gas stations.
All vehicular Diesel blended with biodiesel, B7.

Tax policy

There are differential tax regimes for biofuels, with lower taxes (IVA and CIDE, a federal tax on fuels), charging the negative externalities associated to fossil fuels.

Sustainability criteria and requirements

There is strict environmental legislation regarding water use, effluents disposal, pre-harvest burning of sugarcane fields, which promoted progressive improvement of environmental indicators. Agroindustrial units are monitored and enforced in cases of no accomplishment of legislation. Regarding protection of natural forests and biodiversity, two important measures have been taken: a Federal law implemented an agro-ecological zoning (2010), defining the areas where bioenergy production can be developed, and a revised Forest Code was approved (2014), reinforcing protection of sensible areas (rivers borders, slopes, etc.) and setting permanent protected areas in every farm.

Enforcement of biofuels legislation

Progressively implemented and improved since 1931, a broad framework of legislation and regulatory orders define and organize the biofuel production, trading and commercialization, under Federal surveillance and enforcement, through agencies and ministries such as Federal Environmental Agency and National Agency of Petroleum, Natural Gas and Biofuels, complemented by State legislation and agencies.

Relevant renewable energy and climate change mitigation policies

10 years Energy Plan (PDE), Long-term Energy Plan (PNE), Proálcool, PNBiodiesel, Low-carbon Agriculture Plan (Plano ABC), Climate Change Law, Decree, Fund, Climate Change National Plan (PNMC).

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[9] Prepared for Low-Carbon Transport Fuels LCTF/WBCSD

Policy stability

for ethanol: 40 years E15-27 mandate

for biodiesel: 10 years B3-B7 mandate

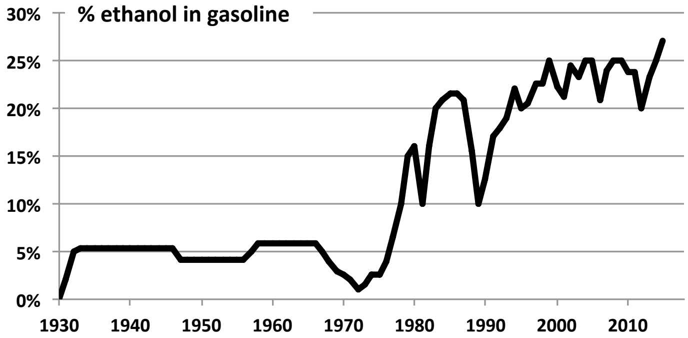


Figure 1. Mandatory ethanol content in Brazilian gasohol (BNDES/CGEE, 2008, updated)

Current Low-Carbon Fuels Production and Use

Sustainable biofuels in the Brazilian energy transport sector corresponds to 17.6% in 2014.

(*Sources: DCR Monthly Inform, Ministry of Mines and Energy (MME) and National Energy Balance (BEN) 2015*)

Status of Low-Carbon Fuels markets – supply and demand

<u>Ethanol</u>

- production/consumption: 28.6 billion liters of ethanol (2014), 57% ethanol hydrated
- installed capacity: about 30 billion liters/year in almost 400 facilities
- 3 commercial E2G units, 185 million liters production capacity

<u>Biodiesel</u>

- production/consumption: 3.4 billion liters of biodiesel (2014)
- installed capacity: about 7.3 billion liters/year in 50 facilities

<u>Vehicular fleet</u> (2014)

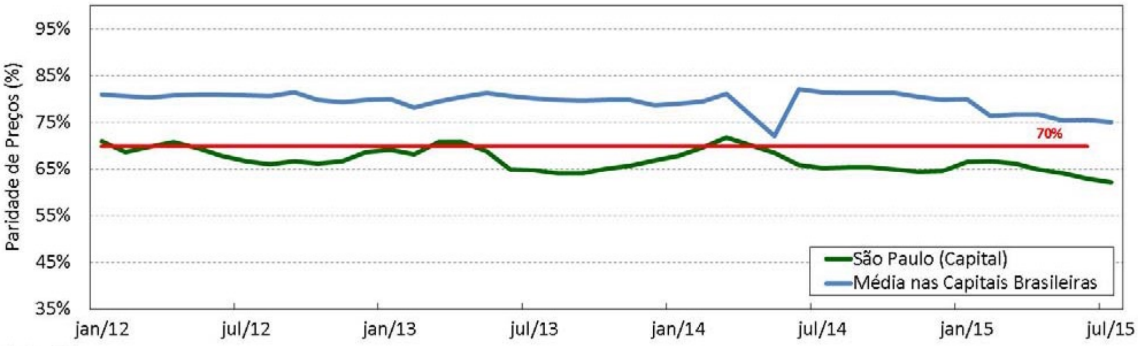
- light vehicles, Otto cycle: 35.4 million cars (70% flexfuel) (it is not allowed to use diesel in light vehicles in Brazil)
- motorcycles, Otto cycle: 15.2 million motorcycles (27% flexfuel)
- trucks, buses, tractors, Diesel cycle: 4 million vehicles
- total fleet: about 44 million vehicles

<u>Jetfuel production</u>

- still at experimental level

Price attractiveness of Low Carbon Fuels and sector profitability

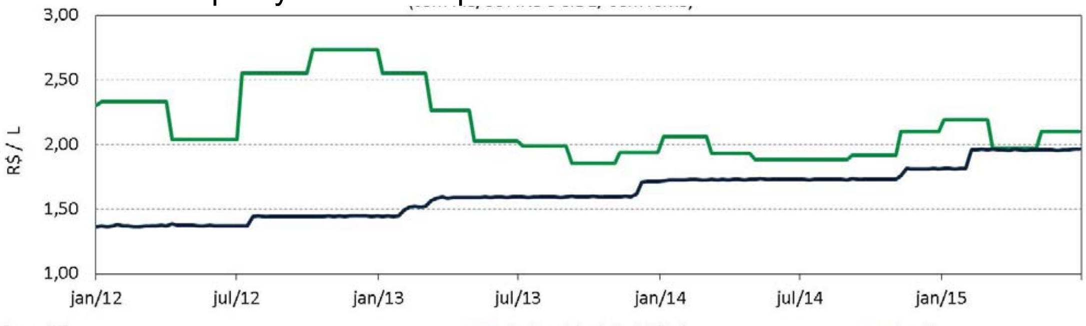
Bioethanol: parity with gasoline prices



Fonte: ANP
Elaboração: MME

Figure 2. Bioethanol prices compared to gasoline

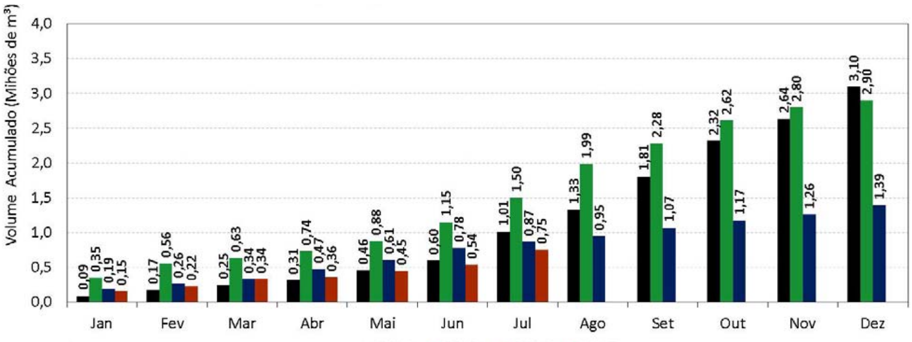
Biodiesel: parity with diesel prices



Fonte: ANP
Elaboração: MME *OBS: A partir de jul/2012 os preços de biodiesel consideram os valores realizados pelo produtor/importador de diesel na oferta para a distribuidora.*

Figure 3. Biodiesel and diesel prices paid for producers (MME, 2015)

Role of exports and imports



Fonte: ALICE/MDIC
Elaboração: MME *Obs.: Os valores mensais são acumulados.*

Figure 4. Ethanol exports from Brazil (MME, 2015)

Potential for Additional Low-Carbon Fuels Production

Low-Carbon Fuels feedstock resource assessment (competition for resources)

- ethanol: 100% sugarcane, energy-cane (still at experimental level)
- biodiesel: 78% soya, 20% beef tallow

The land currently dedicated to production of liquid biofuels (ethanol and biodiesel) in Brazil is about 8.8 million ha or 1.0% of total national area. The agro-ecological zoning, a thorough study developed by EMBRAPA, the National Agriculture Research Agency, and that involves dozens of researchers and agricultural and environmental institutions and considering maps of soil, climate and rainfall, topography, classified the areas of highest potential yield while respecting environmental regulations and areas that should be preserved, as well as seeking to reduce competition with areas dedicated to food production.

This zoning supports the actions of the Brazilian government in ensuring that bioenergy production will not occur in environmentally sensitive areas or reduce the areas currently dedicated to other agricultural products. According to this assessment, for the cultures of choice to liquid biofuels production, sugarcane (for ethanol) and oil palm (for biodiesel) there are respectively 65 million ha and 30 million ha suitable area for expanding biofuel production.

(Nogueira, L.A.H.; Capaz, R.S., 2013. Biofuels in Brazil: Evolution, achievements and perspectives on food security. Global Food Security, Elsevier. Vol 2)

Low-Carbon Fuels supply chain logistics

- Production, transport, distribution, retail (39,000 gas stations)
- Modals: road, rail, ducts, waterways

Barriers to Low-Carbon Fuel production

- Fossil fuel subsidies and administrated prices, …

Market size expectation

- Growth of light vehicles: 6,0% a.a. (reaching, in 2021, 56 millions units; flex fuel share count for 75%, or 42 million units).
- Flex-fuel vehicles (FFVs) currently represent approximately 90% of sales of new cars in Brazil, and pure ethanol can be used nowadays by 23.8 million Brazilian vehicles.

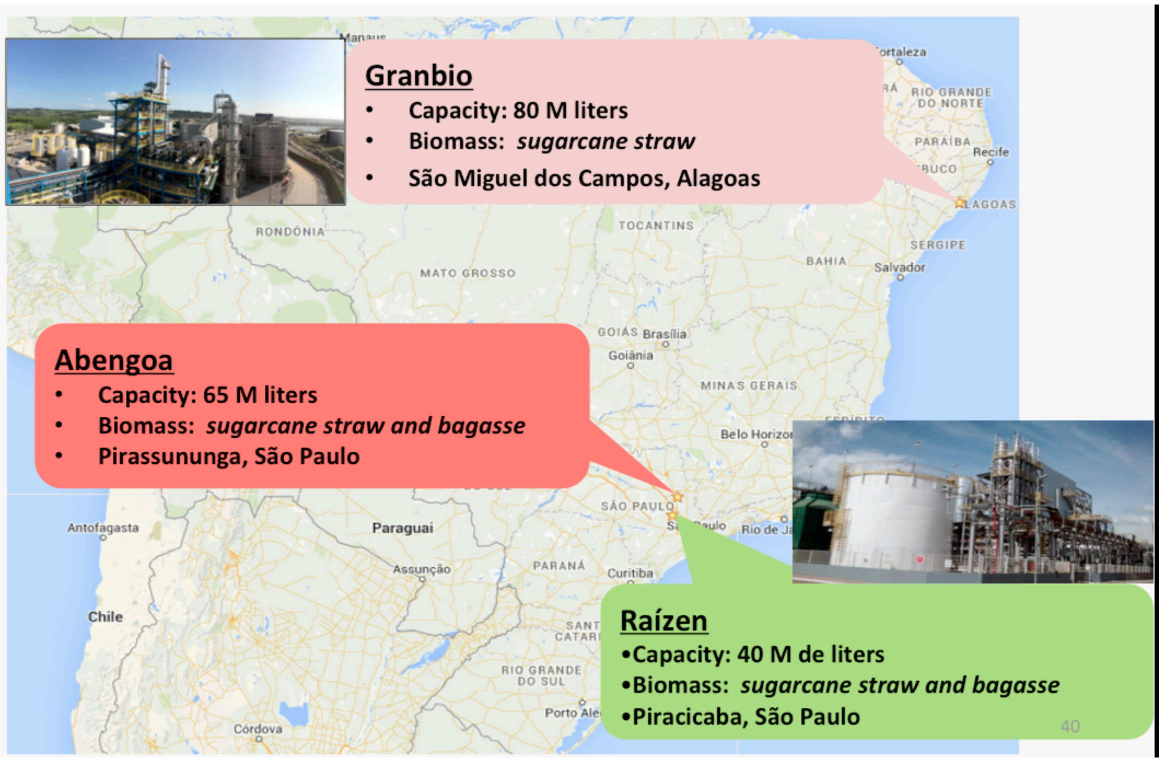
Investment Environment for second-generation biofuels

The Joint Plan for Supporting Industrial Technological Innovation in the Sugar-based Energy and Chemical Sectors (PAISS) was first implemented in 2011, when the main focus was the development of 2nd generation ethanol and renewable chemical technologies. In 2014, a new edition of PAISS was launched, in this time focused on agriculture technologies dedicated to bioenergy. As a result, a total investments derived from these two editions of PAISS amounted more than $2 billion.

Among the selected companies are large chemical and oil groups as well as technology-based startups that see PAISS as an opportunity to accelerate their entry into Brazil. Many of these business plans selected are dedicated to R&D investments, such as laboratory facilities and pilot plants, but there are also larger investments, mainly focused on demonstration and commercial facilities.

Company	**Site**	**Scale**	**Capacity** (m^3 ethanol/year)	**Current status**
Granbio	S. Miguel dos Campos, AL	Commercial	80 million	operating
Raízen	Piracicaba, SP	Commercial	40 million	operating
Abengoa	Pirassununga,SP	Commercial	65 million	in construction
CTC	São Manoel, SP	Demonstration	3 million	operating

Horta (2015)



Granbio

- **Capacity: 80 M liters**
- **Biomass: *sugarcane straw***
- **São Miguel dos Campos, Alagoas**

Abengoa

- **Capacity: 65 M liters**
- **Biomass: *sugarcane straw and bagasse***
- **Pirassununga, São Paulo**

Raízen

- **Capacity: 40 M de liters**
- **Biomass: *sugarcane straw and bagasse***
- **Piracicaba, São Paulo**

The positive outcome of the PAISS program reflects the favorable conditions existing in Brazil and in other similar countries to host investments for new technologies to convert biomass, ranging from R&D centers to demonstration plants; and enable large investments to establish the commercial facilities derived from new technologies that have been globally developed. The main drivers for such attractiveness are presented as follows (Milanez et al, 2012).

- Ready availability and low cost of feedstocks, mainly sugarcane bagasse and straw.
- Locally developed pathways with dedicated technology due to the specific complexity of domestic feedstocks.
- Large amount of available land, typically low productivity pastures, that can be converted into agricultural crops for energy or chemical purposes.
- Well-established sugar and ethanol agroindustry, which facilitates the integration of new technologies under low investment and with reduced operational costs.
- Fuel market growth and heavy dependence on imports of chemicals creates an excellent opportunity for domestic investment.
- Increasing opportunities for developing a global trade of biofuels and biomaterials, considering the lowest carbon footprint of products derived from sugarcane.

Such conditions will accelerate the establishment of a new technological pattern for the sugarcane industry, in which traditional sugar and ethanol production will be partly replaced by the higher added-value products. As a result, Brazil's traditional sugarcane mills will be transformed into diversified industrial complexes, closer to the concept of bio-refineries.

Milanez, A Y; Nyko, D; Cavalcanti, C E (2012). Brazil's race towards second generation biofuels. Biofuels International. Issue 5, volume 56, june 2012.

Technological Capacity for Low-Carbon Fuels

National research capacity

- Technology research and development institutions: most relevant and internationally renowned include CTBE, Nipe/Unicamp, CNPAE/Embrapa, CTC, IAC, Ridesa, Vignis, Canavialis, IPT.
- S&T support agencies: Several federal and state-level agencies, including BNDES, FINEP, Fapesp, CNPQ, Capes
- Science and technology development programs: Bioen, Sugarcane Genoma, Inova Energy.
- Scientific publications: Scope, Blucher, BNDES, Embrapa, Fapesp, CGEE.

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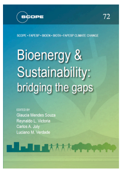
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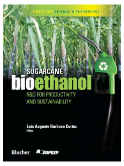
(6)


(1) Bioenergy & Sustainability: bridging the gaps. Souza, G. M., Victoria, R., Joly, C., & Verdade, L. (Eds.). (Vol. 72, p. 779). Paris, SCOPE, 2015.
(2) Roadmap for Sustainable Aviation Biofuels for Brazil: a Flightpath to Aviation Biofuels in Brazil. L. A. B. Cortez (Org.). São Paulo, Blucher, 2014.
(3) Flightpath to Aviation Biofuels in Brazil: Action Plan. Boeing/Embraer/Fapesp and Unicamp. São Paulo, Fapesp, 2013.
(4) Sustainability of sugarcane bioenergy. Center for Strategic Studies and Management (CGEE) and National Laboratory for Bioethanol Science and Technology (CTBE). Brasília, CGEE, 2012.
(5) Sugarcane Bioethanol: R&D for productivity and sustainability. L. A. B. Cortez (Org.). São Paulo, Blucher, 2010.
(6) Sugarcane-based bioethanol: energy for sustainable development. BNDES and CGEE (Org.). Rio de Janeiro, BNDES, 2008.

Trained workforce

- 845 thousand people working in the biofuel agroindustrial and logistic chain (IRENA 2015)

Experience with liquid fuels

- 95 years E5 (1920), 40 years E15 (1975), 35 years E100 and E25 (1979), 13 years flex (2002), 10 years B3-B7

Greenhouse Gas Management Activities

Current emissions

- Total transport sector emissions in the energy matrix 2014 (BEN 2015): 221.9 Mt CO_2eq (45,7% of energy emissions)

Emissions of GHG avoided with the production of Ethanol in Brazil since 1980.

- Avoided Emissions from ethanol production 2014/2015 (CTBE 2015): 38.8 Mt CO_2eq
- Accumulated avoided emissions from ethanol production 1980/2015 (CTBE 2015): 709,7 Mt CO_2eq

Intended Nationally Determined Contributions (NDCs)

- Increase the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030, by expanding biofuel consumption, increasing ethanol supply, including by increasing the share of advanced biofuels (second generation), and increasing the share of biodiesel in the diesel mix.