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Biofuels and Sustainable Energy Development in Brazil

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Summary. — Through the assessment of three decades of the Alcohol Program in Brazil, the paper shows that adequate public policies regarding biomass production can deliver direct benefits like energy security improvement, foreign exchange savings, and local employment generation, reduced urban air pollution and avoided CO_2 emissions. Moreover, the paper shows that Brazilian produced ethanol has faced economies of scale, technical progress and productivity gains and is no longer dependent on subsidies to be competitive. The paper also examines the potential in Brazil for fostering other biofuels, namely biodiesel obtained from vegetable oils, as well as their implications on sustainable energy development.

Key words — ethanol, biodiesel, biofuels, biomass, sustainable energy, energy for the developing world

1. BIOFUEL DEVELOPMENT POLICIES IN BRAZIL

(a) *The ethanol fuel market*

The Brazilian Alcohol Program was first launched in 1975 due to the bending trend of international sugar prices and to the increasing burden of the oil bill after 1973. The Program is one of largest commercial applications of biomass for energy production and use in the world. It succeeded in demonstrating the technical feasibility of large-scale ethanol production from sugarcane and its use to fuel car engines. It is important to note that experience with ethanol use as a fuel in Brazil dates back to the World War periods in the first half of the 20th Century, with the mandatory use of ethanol in the Brazilian gasoline begging in 1931 (Audinet, 1998).

In 2006–07 season, Brazilian ethanol production reached 18 billion liters, of which 3.5 billion liters were exported. Until 2004, Brazil was the largest producer of ethanol in the world. Since then, and based on maize, the United States moved ahead of Brazil in ethanol production. Taken together, the two countries produce about 70% of the world ethanol supply.

In Brazil, ethanol is used first as an oxygenated additive to gasoline in the form of anhydrous ethanol—99.6 °Gay Lussac (GL) and 0.4% of water. This blend gasoline–ethanol, with 20–25% of ethanol (in volume) is called gasohol. The second use of ethanol in Brazil is direct, in the form of hydrous ethanol (95 °GL) in neat-ethanol (100% powered by hydrous alcohol) and "flex-fuel" cars (0–100% of gasohol and/or 0–100% of hydrous ethanol). In such "flex-fuel" cars, the amount of each fuel is chosen by the drivers when filling up the tank, according to prices and availability, as almost all pump stations in Brazil are equipped with facilities to distribute both gasohol and hydrous ethanol (Goldemberg, Coelho, Nastari, & Lucon, 2004).

A gasohol with 22.4% of anhydrous ethanol content by volume was made mandatory by law in 1975. The second phase of the Program was launched in 1979 with the manufacturing of new cars 100% powered by hydrous alcohol.

Petrobras, the state oil company, has been playing a major role in the blending, stockpiling and distribution of gasohol in Brazil. Since the creation of the Alcohol Program until 1997, prices received by ethanol producers were determined by the federal government. In May 1997, prices of anhydrous ethanol were liberalized, as well as hydrous ethanol prices in February 1999 (Goldemberg *et al.,* 2004).

In the beginning of the Program, ethanol production costs were close to 100 US$/barrel, falling to 50 US$/barrel 10 years later due to economies of scale and technological progress, followed by a slower decline during the nineties (Moreira & Goldemberg, 1999).

In 1999, the production cost of alcohol was still higher than gasoline manufactured from imported petroleum priced at just below US$ 20 per barrel (bbl), less than half of its international price in 1980 when the second phase of the Alcohol Program was launched. This illustrates the main reason for the financial difficulties faced by the program. The amount of sugarcane directed toward ethanol manufacturing also depends on the level of sugar prices in the international market, as most distilleries have now acquired flexibility in using sugarcane either for sugar or ethanol production.

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Production facilities, even in the region of São Paulo, where distilleries are most efficient, require oil prices to be around US$ 30 per bbl in order to make ethanol a cost-effective alternative (Macedo & Nogueira, 2004). Thus, when this price level was again reached on the international market in the year 2000, the cost-effectiveness of ethanol as a substitute for gasoline was re-established. The Brazilian government has taken advantage of this situation to increase the ethanol content of gasohol to 25% in volume, allowing for a reduction in the surplus of stockpiled ethanol.

A major breakthrough was achieved in 2003. Manufacturers of direct fuel injection systems invested in R&D and in the production of systems that can adjust the combustion of the fuel to any proportion of hydrous alcohol and gasohol fed directly into the tank, the so called flex-fuel cars, whose production reached 48,178 units in 2003. In the same year, flex-fuel cars production raised more than five times, jumping to 328,374 units, corresponding to 26% of 2004 demand for new automobiles. And in 2005, flex-fuel new car sales outnumbered the sales of gasohol fueled cars. In 2007, flex fuel cars were already responsible for almost 90% of new car sales in the Brazilian market (ANFAVEA, 2007).

The official Alcohol Program has now been phased out, as ethanol use has become driven by market forces alone, but it is important to recall that the start-up of the Program in the seventies was strongly based on public policies, designed to foster ethanol production. The public financing reached up to 90% of the investment required to build a new distillery and up to 100% of the investment needed to increase the sugarcane-cultivated area. Among the conditions, which were in general extremely favorable to the producer, we can highlight: negative interest rates, 3 years of grace period and 12 years to pay back the loan. Moreover, the government has established ethanol minimum prices, which were more attractive *vis-à-vis* sugar prices. This policy has represented a huge subsidy to sugar cane and ethanol producers. On the consumption side, softer taxation has allowed for ethanol prices at the pump to be always kept at a level corresponding to a lower cost per mileage, compared with gasohol consumers (La Rovere, 1981).

The Program faced a major great supply crisis in 1989, when an important share of the national fleet was composed by ethanol fired cars, whose owners could not find enough fuel for theirs cars. The absence of a steady supply of hydrous ethanol eroded consumers' confidence in the Program. However, consumers' confidence has been progressively re-established thanks to cheaper prices and to a successful penetration of flex-fuel cars in the market, which ensures fuel supply reliability. Therefore, even in the absence of a steady supply of hydrous ethanol, which is not the case for the time being, a flex-fuel car is able to run with gasohol. A similar system is also being used in the United States.

Today, high oil prices and increasing exports due to the enforcement of the Kyoto Protocol to the United Nations Convention on Climate Change are helping to boost the ethanol sector in Brazil and in the world. Foreign demand for Brazilian ethanol has been growing. Replacing part of the gasoline by ethanol—which can easily and immediately be done by blending up to 25% of ethanol in gasohol without any major technological changes in the vehicles—is the fastest and cheapest way to reduce greenhouse gas (GHG) emissions in the transport sector and thus help Annex I countries to meet their GHG reduction targets.

Besides foreign demand, domestic sales of ethanol have also been growing in Brazil. This has been allowed by a sharp increase of flex-fuel automobiles sales, which means that a larger number of consumers can choose whatever quantities of ethanol and gasohol they want to buy at the station. Despite some seasonal variation, ethanol final consumers' price per kilometer is rarely higher than gasohol price due to the lower ethanol production costs and to the differential taxation as well. Brazilian gasoline taxation is about two times higher than for ethanol, which is justified by the ethanol positive externalities.

Therefore, the increased flexibility of the domestic ethanol market and the good export prospects, together with the continuous productivity gains in ethanol production, point to an increased sustainability of the program in the future.

Moreover, the Clean Development Mechanism (CDM), under the Kyoto Protocol, has been stimulating Brazilian ethanol producers to increase and improve the use of bagasse as an energy source. Bagasse has already been used to produce the heat and the power needed in the sugar cane transformation process. However, power generation is not the core business of such industry, and there are important opportunities for improving energy efficiency in this process. The financial benefits brought by CDM have been fostering investments in the sector aiming to improve energy efficiency, like for instance replacing old boilers by cogeneration plants and exporting the power surplus to the grid.

Indeed, by April 2008, Brazil was already one of the most active CDM host countries, with 288 projects, of which 124 were at validation and other 126 already registered at the CDM Executive Board. It is important to highlight that, among all of them, 50 are bagasse to power cogeneration projects (23 at validation and 27 registered). However, the contribution in terms of emission reductions of bagasse to power cogeneration projects was less significant, as it accounted for about 5% of the total GHG emissions that may be reduced through all CDM projects hosted in Brazil, which may reach 180 million tons of CO_2 equivalent by 2012 (URC, n.d.).

Brazil was the main ethanol producer for a long time, but recently United States production overcame Brazil's. North-American ethanol however, is produced mainly from corn, with lower productivity, higher costs, and higher energy content. For instance, the average ethanol production in the United States is 3,200 l/ha/year, while in Brazil this figure is more than twice higher (6,800 l/ha/year.). This is reflected in production costs: US$ 0.20/l in Brazil against US$ 0.47/l in the United States, who still strongly subsidizes the production of ethanol with less favorable energy and GHG balances as in comparison to the Brazilian case.

Box 1 The different phases of the Brazilian alcohol policy.

Phase 1—1975 to 1979: Government effort launched with an initial target to blend anhydrous ethanol to gasoline up to 22.4% (by volume).

Phase 2—1979 to 1986: Government support to strong ethanol production increase. Industry agreement to start producing ethanol powered cars, which reached 94.4% of the total automobile production in 1986, allowing to reach a peak fleet of 4.4 million ethanol fueled cars in 1993.

Phase 3—1986 to 1989: Ethanol production stopped increasing in 1986. Major supply crisis in 1989 reduced the share of ethanol fueled cars to 1.02% only of new cars sold in the market by 1989 (due to scrapping, ethanol fueled fleet has fallen to 2.2 million in 2002).

Phase 4—1989 to 2003: Ethanol is mixed up to 24% with gasoline. Local environmental benefits (reduced air pollution in large cities) and employment generation in rural areas have become the main reasons to keep fostering ethanol. After 1999, market forces are the main drivers.

Phase 5—from 2003 on: New and huge investment cycle. High oil prices, energy security, and climate change concerns stimulate world demand, increasing export opportunities. Domestic demand growth thanks to flex fuel cars.

(b) *The National Biodiesel Program*

(i) *Biodiesel production and use as a vehicle fuel*

Biodiesel results from a chemical reaction of a vegetable oil with an alcohol. Either methanol or ethanol can be used. The reaction is called transesterification[1] and the result will, respectively, be a methyl or ethyl ester. Due to the large ethanol capacity already installed, ethyl ester (from vegetable oil and ethanol) would be the most interesting option in the Brazilian context, but so far commercial technology is available for producing methyl esther only.

Biodiesel can be used in blends with diesel oil to fuel trucks and public transportation buses. This blending can significantly reduce air pollutant emissions in large cities, and mainly sulfur emissions. In global terms, its use helps to curb the increase of the greenhouse effect. This approach may have very strong positive effects on a global scale.

Brazil has a large diversity of feedstock available for the production of biodiesel, such as castor beans, palm oil, soy beans, and sunflower, among others, as well as availability of land, especially in less developed regions.

The feasibility of biodiesel requires the implementation of an organized structure for production and distribution. Investment is also needed in order to ensure the supply and quality of biodiesel for use in vehicle engines.

With the implementation of the National Biodiesel Production and Use Program, launched by the Federal government in 2004, the Brazilian Government intends (besides other reasons, like reduction of poverty in the country) to increase energy security. Although Brazil recently reached self-reliance in oil production, the country is still dependent on imports at high costs to meet part of the domestic demand of diesel oil (40 billion liters/year). This is explained by the fact that existing refining capacity in Brazil does not fit Brazilian oil characteristics, which has general low and medium °API. Besides domestic diesel oil production not being enough to attend demand, the quality of the fuel is seen as rather poor, with negative environmental impacts, especially local air pollution, mainly due to its higher sulfur content compared to European standards.

The Brazilian Government, in the process of consolidation of the Program and considering the social and environmental benefits of biodiesel will have to design and use policy tools able to define the best ratio of blending, price caps, improvements in the production process, and utilization of the residues.

The wide availability of ethanol in Brazil (related with the large available area for sugarcane plantations) has stimulated the search of ethyl alcohol routes for biodiesel production, displacing methanol. So far, in spite of the efforts done, such an alternative is in the final development step and the majority current biodiesel production still uses methanol.

The main problems yet to be solved regarding biodiesel production and use are related to the catalytic process to separate glycerin in the chemical process, and also to the production process energy balance.

In fact, the Brazilian biodiesel specification (ANP Order 42/2004) is closer to the European and American ones (DIN 51606 and ASTM D 6751-02). There is no restriction for methyl or ethyl esters and, basically, all fat feedstock are permitted. Allowance is done for biodiesel viscosity and some other parameters, but the biodiesel blend properties should be similar to regular diesel oil. Improvements in biodiesel quality measuring are required, mainly for stability evaluation and the number of cetanes.

Initial rules for introducing biodiesel into the Brazilian fuel market were established in November 2004. The new fuel was authorized by the National Council of Energy Policy (CNPE) for commercial use, by addition to mineral diesel oil in the ratio of 2% by volume (B2). The National Association of the Automotive Vehicles Manufacturers (ANFAVEA) has committed itself to maintaining the diesel engines' warranties even with the addition of 2% biodiesel to mineral diesel, which is compulsory since 13 January 2008. More recently, CNPE mandated an increase to 3% of biodiesel addition from July 1st 2008, and from July 1st, 2009 this addition is of 4% (CNPE, 2009).

With such measures, the government intends to create a biodiesel demand that ranges from 0.8 to 1.6 billion liters per year. From 2012 on, the addition is planned to grow up to 5% (CNPE, 2009). The Program also envisions exporting biodiesel, depending on production levels and on the growth and consolidation of an international market (Macedo & Nogueira, 2004). Therefore, positive impacts on trade balance may come from either replacing part of the imported diesel by domestic produced biodiesel or exporting part of this production. It is expected that Brazilian biodiesel will be used mainly in the internal market replacing mineral diesel oil, but favorable biodiesel export prices may reverse this trend.

Additionally, the government has passed fiscal regulations establishing lower taxes for biodiesel produced by small farmers and/or in the North and Northeast regions (see Table 1).

The idea is to favor the cultivation of castor beans and palm oil by family farmers, and in the less developed regions of the country. Government intervention is required to maximize social and regional development benefits, allowing for a fair competition of small-scale production with soybeans agribusiness. Besides such social concerns, the expansion of large-scale soybean plantations is increasingly menacing the Amazon forest and, therefore, concerns have arisen upon the impact of the biodiesel program if soybean is massively used as its feedstock. That is why federal taxes imposed on biodiesel production under intensive large-scale plantation schemes, such as soybeans, will be even higher than taxes on conventional fossil diesel.

Accordingly, the government guarantees social certificates to producers who encourage the participation of family farmers in the biofuel production process. With these social certificates, producers are eligible for benefits such as tax incentives. Moreover, the Brazilian government established in August 2005 a resolution through the National Council for Energy Policy (CNPE) determining that the certificated biodiesel production will be bought by the National Agency of Oil, Natural Gas and Biofuels (ANP).

The National Economic and Social Development Bank (BNDES) is providing financial support to investments in biodiesel. One of these measures is a 25% extension in the total loan payoff period for the purchase of machinery that uses at least 20% biodiesel fuel.

Table 1. *Federal taxes imposed on biodiesel production and on diesel oil*

Federal taxes	Biodiesel produced from palm oil and castor beans by small farmers in the semiarid, North and Northeast regions	Biodiesel produced by small farmers in general (other regions and/or other feedstocks)	Biodiesel produced from palm oil and castor beans in the semiarid, North and Northeast regions	Biodiesel production in general (large plantations and/or other crops and/or other regions)	Diesel oil
CIDE	Exempted	Exempted	Exempted	Exempted	R$ 0.070/l
PIS/COFINS	R$ 0.00/l (100% reduction)	R$ 0.07/l (68% reduction)	R$ 0.151/l (32% reduction)	R$ 0.222/l	R$ 0.148/l
Total federal taxes	R$ 0.00/l (100% reduction)	R$ 0.07/l (68% reduction)	R$ 0.151/l (32% reduction)	R$ 0.222/l	R$ 0.218/l

Source: Russef (2004).

The most serious problem of fuel consumption in Brazil is the rising diesel oil consumption, reaching next to 40 billion liters per year. Brazilian transport system is mostly based on road transport, which accounts for around 76% of diesel oil demand, against 16% for agricultural production, 5% for power generation, and 3% for other activities (Carvalho, 2008). Within this context, biodiesel production can improve the country's energy security. Another comparative advantage of biodiesel versus diesel oil, a fossil fuel, is the lower emission of air pollutants and the lower GHG emissions in its use. Compared with diesel oil, the use of biodiesel also provides comparative advantages on environmental and social grounds. Family farming in the semi-arid region can get a boost from the biodiesel program thanks to the use of certain crops, especially castor beans, which can be grown easily in dry conditions there. However, social advantages from small scale production biodiesel has not completely materialized yet, since more than 90% of current biodiesel production in Brazil has been based on soybeans which are produced essentially in large plantations (Carvalho, 2008).

(ii) *Biodiesel and vegetable oils use for decentralized power generation*

Besides its use for transport, vegetable oils and biodiesel can also be used to supply electricity to remote communities.

Biodiesel production requires either ethanol or methanol as an input. In remote communities, with constraints, such as long distance from production centers, small demand, and the lack of roads, ethanol or methanol transportation costs may be significant. In such cases, using vegetable oils *in natura* for electricity generation would be more adequate than its use for biodiesel production. Moreover, the transesterification cost would also be avoided whenever the use of vegetable oil *in natura* is feasible for power generation. However, this will not always be the case, due to technical constraints: for example, in the case of castor oil, its viscosity may be a technical barrier.

Vegetable oil production in isolated communities may not only be economically viable but also contribute to local sustainable development. The small scale oil crops fit well with environmental concerns. Vegetable oil can be produced and used locally to replace mineral diesel for power generation, cutting off the need of bringing subsidized mineral fuel from faraway to the community.

The Amazon region in Brazil has an enormous diversity of native oil plants, good soil, and climate conditions for high productivity from these crops (e.g., palm oil), besides environmental and social advantages. There is a significant potential, yet to be assessed, for small communities to extract oil from locally available nuts or other vegetable sources. For power generation applications, palm oil is one of the most readily available sources, as it is already being produced in a large scale, both in commercial plantations and through groups of small farmers, with reliable yields and standardized production. Pilot units for small scale generation (below 200 kW) are being tested in some municipalities in the Amazon region, using *in natura* vegetable oil fired in modified engines, such as in Vila Soledade, in the State of Pará, north of Brazil.

In the North-eastern region of Brazil as well, vegetable oils can be extracted from native plants that are very rough and adapted to the semi-arid climatic conditions, such as castor beans (*Ricinus communis*) and the purging nuts (*Jatropha curcas*) (La Rovere, Monteiro, & Avzaradel, 2007).

The CCC (Fuel Consumption Fund) was implemented in Brazil, aiming to the reduction of power price differences between consumers connected to the grid and in isolated systems. Through CCC, part of the financial resources collected from the energy supply in the grid system is utilized to reduce the price levels in the power supply to isolated systems, allowing for a fair price to final consumers who do not have access to cheaper grid energy, as the price of diesel oil fed into diesel generators is subsidized by the CCC.

The benefits of CCC were recently expanded to renewable sources by law. However, current regulations state that only generators who have a concession or authorization of the Energy National Agency (ANEEL) are qualified to receive CCC benefits. These authorizations and concessions are required and given only to hydropower plants of minimum 1 MW and thermal power plants of minimum 5 MW. Therefore, current regulations do not benefit isolated communities yet and are a barrier to the development of small-scale projects.

Aiming to enlarge the use of CCC, biodiesel was included as a potential fuel to replace diesel oil. However, whenever feasible, it would be better to generate electricity directly using vegetable oil *in natura* in small generators rather than biodiesel. So, an improvement to the referred law would be the use of the term "biofuel" instead of biodiesel, allowing for the eligibility of vegetable oil use as a fuel to get CCC support.

2. EXTERNALITIES OF BIOFUELS PRODUCTION AND USE IN BRAZIL

(a) *Social, environmental, and economic impacts*

During its initial phases, the Alcohol Program was quite controversial. Negative perceptions from stakeholders had arisen not only from the ethanol supply crisis in 1989 but also from some negative environmental and social impacts. The Program has been also criticized as a mechanism of transferring at about US$ 10 billion of public funds in subsidies to a single sector.

Among environmental concerns arisen by the Program, we can highlight the risk of competition of sugarcane plantations with food production, water pollution caused by the runoff of cane-washing water and the leaching of stillage, as well as local air pollution due to pre-harvesting burning of the plantation, required for manual harvesting. Civil society and academia have been watching the social and environmental implications of ethanol production and use (La Rovere, 1981; La Rovere & Audinet, 1993; La Rovere & Simões, 2004).

Water and air pollution have been considerably reduced throughout the implementation path of the Program, as environmental protection laws and regulations were progressively enforced by State agencies. The pre-harvesting burning of the plantation (source of air pollution in cities nearby) is being progressively banned by law in the state of São Paulo (where 60% of the sugar cane production is located), as it can be avoided thanks to the penetration of mechanical harvesting (Moreira & Goldemberg, 1999).

In 2002, and due to the air quality problems near the plantations, the government of São Paulo state established a law phasing out the pre-harvesting burning by 2021 in areas where mechanization is possible and by 2031 in areas where mechanization is not possible (slope higher than 12%). A protocol was signed between the São Paulo Environmental Agency and the producers, anticipating the deadlines to 2014 and 2017, respectively. In 2007, about 41% of the sugar cane area in São Paulo state was mechanically harvested (Fredo, Vicente, Baptistella, & Veiga, 2008).

Indeed, the development of energy markets for sugarcane crops residues helped to advance technologies that were needed to harvest green cane and to collect these residues more efficiently, thus eliminating the need to burn before harvesting. Nowadays such residues are burnt much more efficiently for cogeneration of heat and electricity, replacing fuel oil burning. Such a practice has become common in ethanol processing industry and has helped to increase the relative participation of sugarcane products in domestic energy supply (Moreira & Goldemberg, 1999).

Sugar cane fields in Brazil need little irrigation. Moreover, quality problems related to irrigation (such as nutrients and agro-chemicals carrying, as well as soil erosion) and industrial use of water are not found in São Paulo, which holds, in this regard, a level 1 classification (zero impacts) from the Brazilian government's agricultural research organization EMBRAPA (Macedo, 2007).

Also in São Paulo state, effluents from sugar cane distilleries are treated with an efficiency of 98% and widely spread back into the fields, helping to fertilize and to irrigate them (Macedo, 2007). Such practice is current all over the country and has helped to increase sugarcane crops productivity and to reduce not only production costs but also water pollution.

Moreover, water caption and consumption by the distilleries has dropped, respectively, from 5.6 to 1.8 m^3/ton sugar cane in 1990 to 5.07 and 0.92 m^3/ton sugar cane in 1997 (Macedo, 2007).

There are 200,000 ha of permanent protected areas in the sugar cane fields in São Paulo, which represents 8.1% of the total sugar cane cultivated area in São Paulo. This share of 8.1% can be split in: primary vegetation (3.4%), abandoned (2.9%), secondary vegetation (0.8%), and sugar cane crops (0.6%).

It is possible to say that sugar cane crops expansion verified since 1972 has caused very low impact in deforestation and biodiversity loss. Sugar cane crops occupy only 0.7% of the 850 M ha of total Brazil area, of which 55% are occupied by forests, 35% by pastures, and only 7% by agriculture (soy and corn using half of total agriculture area). Nowadays there is 12% of the Brazilian territory available with good conditions for sugar cane cultivation. In the last 40 years, agriculture has expanded mostly in Cerrado biome (savannas and discontinuous forests).

The area used to increase sugarcane production has mainly replaced pasture lands, without harming staple food production. Part of sugar cane crops occupies nowadays areas that used to be occupied by Atlantic rain forest (only 7% of original area remains). However this biome has been lost far before the growth of sugar cane expansion in the seventies. In the last 25 years, sugar cane crops expansion was concentrated in the middle-south of Brazil and faraway from the Amazon rain forest, from Pantanal and from the Atlantic rain forest, which represents, along with the Cerrado, the main Brazilian ecosystems. In São Paulo, where the sugar cane fields are concentrated, sugar cane basically replaced pasture and other crops (Macedo, 2007).

The increase in the area used for pasture and crops has concentrated in Cerrado land. So far, sugar cane has not been extensively cultivated in Cerrado, but this picture is now changing with the new growth cycle starting. Cerrado occupation (also but not only by sugar cane) should be based on sustainable practices regarding biodiversity, water resources, and soil preservation, maximizing, on the other hand, economic and social gains. Taking into account the available technology, land and water resources, Brazil can increase sugar and ethanol production without losing protected ecosystems and biodiversity, and preserving, at the same time, soil and water resources.

Air quality in Brazilian large cities and particularly in São Paulo (the most polluted urban area) has benefited from reduced emission of local air pollutants by gasohol and ethanol fueled cars, compared to gasoline fueled cars (prior to the introduction of direct fuel injection systems). Brazil was also able to be one of the first countries to ban the use of leaded gasoline, thanks to the blending of anhydrous ethanol, which acts as an octane booster of gasoline (Moreira & Goldemberg, 1999; La Rovere & Simões, 2004).

Positive social impacts of ethanol production include the generation of nearly one million jobs, mainly in rural areas: more than 700,000 direct jobs (Moreira & Goldemberg, 1999) and more than 200,000 indirect rural jobs (Macedo & Nogueira, 2004). However, bad working conditions for manual harvesting workers, especially in the North-eastern region, have been a major source of criticism. On the other hand, compared to working conditions in other sectors and considering data for workers in São Paulo State, the labor force employed in sugarcane fields is paid higher wages than workers employed in other agricultural sectors and even than those employed in services or industrial sectors (Moreira & Goldemberg, 1999).

Mechanical harvesting has been increasing due to, among other factors, environmental concerns, especially with air quality in cities around sugarcane fields. This has put pressure on harvest workers, who need to increase their productivity in order to remain competitive, and, therefore, has been reducing even more the quality of their work. Moreover, mechanical harvesting reduces the number of rural jobs, creating a necessity to absorb a huge mass of unemployed and unskilled rural workers. On the other hand, new and higher quality jobs—however fewer—are created in the equipment production and operation chains. Therefore, mechanical harvesting implies a clear trade-off between positive environmental impacts on the one hand and negative social impacts on the other.

Regarding macroeconomic impacts, it must be highlighted the investment of five billion US dollars (2001 US$) from 1975 to 1989 in the agricultural and industrial sectors for expanding the production of ethanol for automotive use. Moreover, savings with foregone imports evaluated at international prices have amounted to US$ 52.1 billion (January 2003 US$) from 1975 to 2002 (Goldemberg *et al.,* 2004).

If on the one hand the Ethanol Program has been criticized as a mechanism of transfer of subsidized public funds, on the other hand, the stable framework ensured for ethanol production has settled the basis of private investment in R&D, leading to substantial productivity growth.

Box 2 Economic impacts of ethanol production and use in Brazil.

Production costs = 100 US$/barrel (1979), 50 US$/barrel (1989), 30 US$/barrel (1999);
Average productivity: 6,800 l/ha/year against 3,200 l/ha/year in United States;
Public subsidies: US$ 10 billion over 20 years;
Job creation: more than 700,000 direct jobs and more than 200,000 indirect rural jobs;
Direct investment in the agricultural and industrial sectors: five billion US dollars (2001 US$) from 1975 to 1989;
Savings with foregone imports: US$ 52.1 billion (January 2003 US$) from 1975 to 2002;
Progress ratio: 93% in the period 1980–85 and 71% from 1985 to 2002.

The main R&D effort was made in agronomical research and in the capital goods production, allowing for the impressive technical progress and productivity growth recorded by Brazilian ethanol industry, both in sugarcane yields (tons/ha) and in ethanol conversion (liters of ethanol per ton of sugarcane). Indeed, 91 Mt of sugarcane were produced in Brazil in 1975, yielding 6 Mt of sugar and 0.56 M m^3 of ethanol. Sugarcane production grew 3.5 times in 2002 *vis-à-vis* 1975, reaching 320 Mt. While sugar production also grew at the same rate (3.7 times), ethanol production grew almost seven times faster (22.5 times) in the same period (Goldemberg *et al.,* 2004) (see Table 2).

Regarding technical progress, the development of an ethanol fired engine and more recently the development of flex-fuel motors must also be highlighted.

The progress ratio (PR), defined as the unit cost decrease according to cumulative sales, recorded for sugarcane ethanol in Brazil was 93% in the period 1980–85 and 71% from 1985 to 2002 (Goldemberg *et al.,* 2004).

Energy supply diversification allows for an important ancillary benefit: increased energy security. The path to a cleaner and more diversified energy supply requires the research for alternative efficient fuels for transportation (Tolmasquim, Szklo, & Soares, 2002).

Table 2. *Productivity gains in ethanol production*

	Circa 1975	2004
Crushing capacity (tons of cane/day)	5,500	13,000
Fermentation time (h)	24	4–6
Beer alcohol content (OGL)	7.5	10.0
Extraction yield (% sugar)	93	97
Fermentation yield (%)	80	91
Distillation yield (%)	98	99.5
Total yield (liter hydr. alc./ton cane)	66	86
Total steam consumption (kg/ton cane)	600	380
Steam consumption—hydrous (kg/l)	3.4	2.0
Steam consumption—anhydrous (kg/l)	4.5	2.8
Boiler—efficiency (% PCI)		
Pressure (bar)/temperature (°C)	66	87
	21/300	85/530
Surplus bagasse (%)	Up to 8	Up to 78
Biomethane from stillage (N m^3/l alcohol)	–	0.1

Source: DEDINI (2004).

Regarding environmental benefits of Biodiesel at the national level, its use reduces emissions of carbon monoxide by 40% and of sulfur dioxide by 100% (Tolmasquim *et al.,* 2002). On the other hand, emissions of nitrogen oxides (NO$_x$) slightly increase. In the social arena, the production of 800 million liters/year is expected to generate about 150,000 jobs, especially for family farmers, promoting a labor intensive development pattern (Macedo & Nogueira, 2004).

(b) *Avoided GHG emissions*

Another positive environmental impact of ethanol is related to climate change mitigation through greenhouse gas emissions reduction. The use of ethanol and bagasse as a fuel has allowed for avoiding a substantial amount of GHG emissions in the last 30 years (up to a peak of 10 million tons of carbon per year—MtC/y). Indeed, the net amount of GHG emissions avoided by sugarcane ethanol and bagasse in Brazil has been evaluated at 9.45 MtC for the year 1990–91. The carbon released into the atmosphere when bagasse and ethanol are burnt as fuel is compensated for by an equivalent quantity of carbon that the sugarcane absorbs during its growth. Accounting only for the replacement of gasoline, the use of ethanol has avoided the release into the atmosphere of an average of 5.86 MtC per year from 1980 to 1990 (Macedo, 1998). Results are summarized in Table 3 below using 1990–91 as a base year.

As well as for ethanol *vis-à-vis* its fossil equivalent (gasoline), greenhouse gases (GHG) emissions from biodiesel *vis-à-vis* mineral diesel depend on several factors, such as local climate condition, energy used in crops production (mechanization, fertilizers), crops productivity and others. Ethanol and biodiesel net GHG emissions are very case specific.

Studies show that GHG emission reduction due to one liter of ethanol replacing one liter of gasoline ranges from 19% to 47% per kilometer (well-to-wheels, from biomass production to the vehicle) in the case of corn ethanol, from 35% to 56% in the case of sugar beet and of 92% in the case of sugarcane ethanol, thanks to its more favorable energy balance (Macedo, 1998).

Indeed, for each unit of fossil energy used in sugar cane production, harvesting, and transportation, as well as in the ethanol processing, 9.3 units of renewable energy are produced in 2005–06. This may reach 11.6 in 2020 with the spread of already commercial technologies. For anhydrous ethanol production, the total GHG emission was 436 kg CO$_2$ eq/m^3 ethanol in 2005–06, decreasing to 345 kg CO$_2$ eq/m^3 ethanol in 2020. Regarding hydrous ethanol, the avoided GHG emissions depends on the final use. Still in 2005–06, 2,181 kg CO$_2$ eq/m^3 ethanol in neat-ethanol cars and 2,323 kg CO$_2$ eq/m^3 ethanol in E25 cars.[2] These figures are based on the best available and comprehensive data for the Brazilian Center-south Region,

Table 3. *Brazil net CO$_2$ emissions avoided by ethanol and sugarcane bagasse production and use, 1990–91*

	MtC/year
Ethanol substitution for gasoline[a]	−7.41
Bagasse substitution for fuel oil burning as heat source in other industries	−3.24
Fossil fuel utilization in sugarcane industry	+1.20
Net contribution (uptake)	−9.45

Reproduced from Macedo, (1998).

[a] Includes both the blending of 22% ethanol in gasoline and 4.2 million pure ethanol-fired cars.

which accounts for the bulk of ethanol national production (Macedo, Seabrab, & Silvac, 2008).

Regarding biodiesel GHG net emissions, there is not a study available yet for the Brazilian specific conditions. However, it is possible to say that there is a great potential for GHG emission reductions due to biodiesel production and use in Brazil. Studies applied to the colza biodiesel in Europe show that GHG emission reduction from its use for replacing one liter of mineral diesel ranges from 44% to 66% per kilometer (well-to-wheels) (IEA, 2004). The Brazilian agricultural circumstances influencing GHG emissions, especially climate, crops variety, and energy intensity in oil crops cultures are more favorable than in Europe. Using methanol (from fossil fuels—naphtha) in the transesterification process for biodiesel production, CO_2 emissions are reduced by 78% compared with diesel oil displaced. When ethanol is used for biodiesel production, CO_2 emissions reductions made possible by substituting biodiesel for diesel oil may reach nearly 100%, as in the case of ethanol substitution for gasoline.

3. LESSONS LEARNED AND BIOFUELS PROSPECTS

The menace of a serious crisis of the balance of payments and low sugar prices at the international market were key driving forces for launching the Ethanol Program in Brazil. Governmental leadership was crucial to ensure the support to the Program by key stakeholders: Petrobras, sugarcane, and ethanol producers, the car industry, and consumers. Oil and sugar prices in the international market have been the most important factors of success and crises of the Ethanol Program in Brazil.

Public subsidies, now phased out, were fundamental for the success of the Program in its initial phase. Such public effort would be in vain if the subsidized sector had not invested in R&D looking for productivity growth and technical progress, which have been recorded in sugarcane crops, in sugarcane processing, and in ethanol fired and flex fuel cars manufacturing. High level oil prices and opportunity for increasing ethanol exports thanks to CO_2 emissions reduction efforts abroad make prospects of future sustainability of the Ethanol Program look even brighter today. Indeed, recent domestic production and exports have been steadily growing. However, new challenges are also to be tackled. The big challenge is to increase ethanol production in a sustainable way in order to meet the fast demand growth expected both in the sugar and ethanol domestic and international markets. Kyoto treaty is fostering ethanol exports to Europe, as already mentioned. The recent Japanese government decision of allowing for an initial 3% blending of ethanol to gasoline opens up a new market for Brazilian ethanol exports. It can become huge as the blending is progressively increased (up to 10%) and bilateral negotiations succeed on joint ventures for expanding ethanol production in Brazil.

In this context, it is relevant to mention the cases of South Korea and China. In South Korea, the same Japanese position may be adopted. Considering a blend of 10% of ethanol and 90% gasoline, the market is estimated as 1.9 billion liters. And, in China, a blend of ethanol and gasoline may be adopted soon. The Chinese market in 2010 is estimated as 4.8 billion liters, with local production able to reach 2.5 billion liters.

The potential European demand is estimated at 13 billion liters in 2010 for EU-25. The demand can be met by internal production, but production costs are in average almost three times higher than in Brazil.

It is too soon to evaluate how much of biofuel production growth has been a response to climate change, to high oil prices, or to energy security concerns. Even though, it is possible to say that ethanol production and use in Brazil can continue to grow without subsidies, even if oil prices fall to US$ 40/barrel. At this level, ethanol production would still be cost-effective even if ethanol prices fall to follow a gasohol price reduction.

Some scenarios elaborated by the authors of this paper show that ethanol domestic demand in Brazil may reach 43 billion liters in 2025 in the highest scenario (4% growth rate for Otto cycle vehicles annual sales, and average annual content of 60% of hydrous ethanol in the tank—Scenario HGVS-HCA, Figure 1). To meet this demand, which does not include exports, the land used for sugar cane cultivation would have to increase 130% in 20 years.[3] However, the potential demand does not necessarily mean that this production level is feasible or desirable, which will depend on the impacts of this expansion in land prices (and consequent impacts on cost production), on its externalities, and on the required investment in production

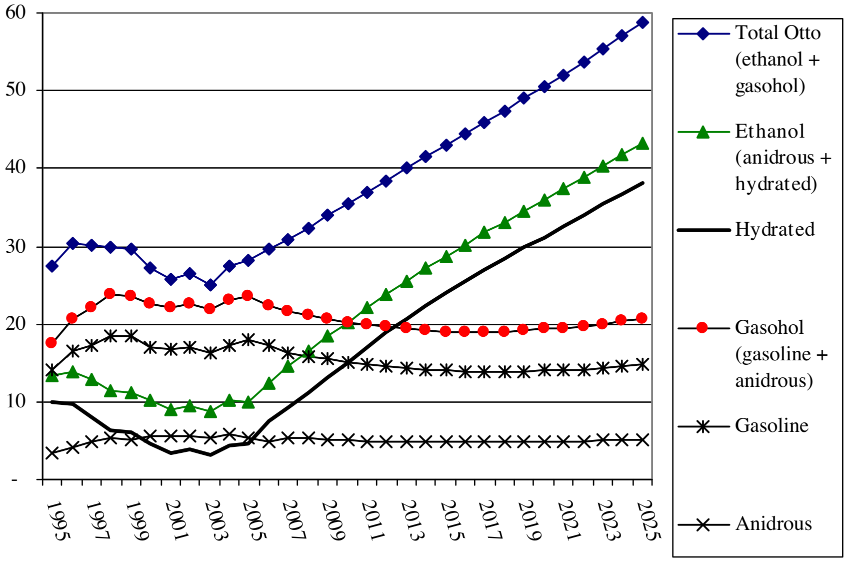

Figure 1. *Domestic consumption of fuels for otto cycle engines, Scenario HGVS-HCA (billions of liters).*

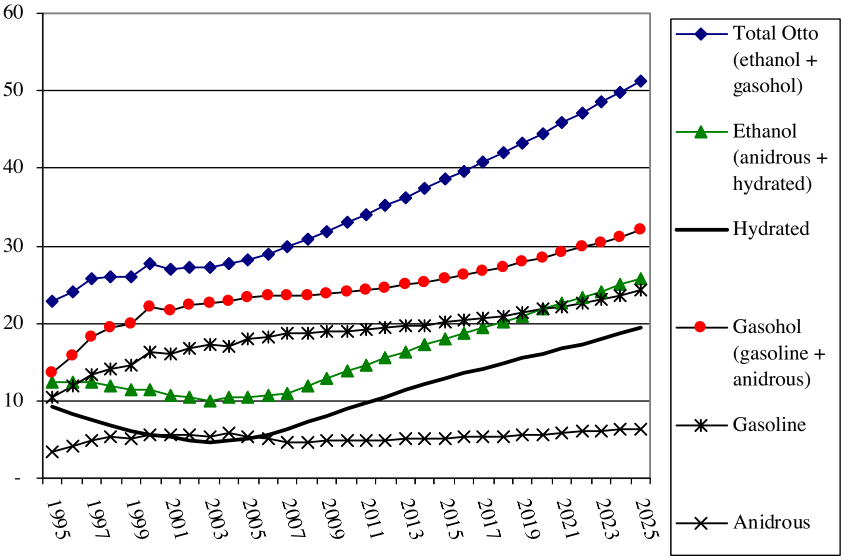

Figure 2. *Domestic consumption of fuels for otto cycle engines, Scenario HGVS-LCA (billions of liters).*

capacity and infra-structure, which are still to be quantified (La Rovere *et al.,* 2006).

Another scenario considers an average annual content of hydrous ethanol in the tank of 30%. Considering the same hypothesis for the vehicles sales growth, the demand would reach 25 billion liters in the same period (Scenario HGVS-LCA, Figure 2). This simply shows that the scenarios are very sensitive to the hydrous ethanol prices relative to gasohol prices at the pump, and its implications on hydrous ethanol and gasohol demands (La Rovere *et al.,* 2006).

Sugar market, oil prices, land prices, and GHG abatement opportunity costs and public subsidies are some key variables. Kojima and Johnson (2005) show that gasoline/anhydrous ethanol blend is heavier taxed than hydrated ethanol in Brazil. This taxing policy is a very good example of how government may act to have some influence on ethanol demand levels in Brazil. The question is to know if the current policy of taxing gasoline/anhydrous ethanol blend heavier than hydrated ethanol would be enough to foster a demand closer to the HGVS-HCA scenario levels (Figure 1) than to the HGVS-LCA scenario levels (Figure 2), or if this policy would have to be deepened in order to do so.

Sugar exports are also bound to increase in the short and medium term due to general commodities demand expansion in the world markets and recent WTO decisions on phasing out subsidies to sugar exports by European countries, therefore, expanding Brazilian world market share prospects. Sugar prices are also increasing in the international market. At equivalent price levels, sugar production may be more convenient for sugarcane producers than ethanol due to better cash flow and lower stockpiling expenses. As most plants have acquired flexibility to produce either ethanol or sugar, the security of ethanol supply may be jeopardized, as it was the case back in 1989. This would harm ethanol foreign market. Lack of transport infra-structure also limits ethanol exports possibilities.

A technological breakthrough in ethanol production would be using the cellulose contained in the bagasse as an input. This may double or triple ethanol productivity per ha, and also reduce land needs in a high production scenario. It would also be a possible way out of a new ethanol supply crisis in a high sugar price and production scenario. The perspective of a higher profits rate has been attracting several huge investors to the so-called second generation biofuels, such as ethanol made from cellulosic feedstocks.

For instance, the main ethanol production equipment manufacturer in Brazil claims that after 20 years of development, flash acid hydrolysis is now able to deliver 109–180 l of additional ethanol per ton of bagasse, at competitive costs, based upon results obtained at its 5,000 liters/day demonstration plant (yet to be scaled-up to 50,000 l/day). This may nearly double the ethanol output per hectare, supplying additional outputs up to 5,600 liters/ha/year on the top of current 6,800 liters/ha/year yield (Fairbanks, 2003). This new market for bagasse would also favor an optimization of energy use at the distilleries, allowing for maximizing bagasse surplus after meeting the heat and power process needs.

However, even in the case of a successful technological breakthrough, it has become evident that a new regulatory framework is needed to ensure a successful new phase of the Brazilian ethanol program in the future. After the deregulation of the late nineties, government ability to influence the market is limited to establish the level of ethanol blending in gasohol.

Increased domestic and international demand has already started to put pressure on ethanol prices. In early 2006, gasohol prices were raised in the domestic market due to ethanol price increase. This happened soon after an official announcement that oil products prices would not be increased thanks to national self-sufficiency in oil production reached in this year. The issue is particularly sensitive as Brazilian government is very keen to curb inflation rates.

In view of the price increase in early 2006, the government has considered to reduce again this level of ethanol in the blend back to 20%. Another measure considered is to increase BNDES funding of ethanol stockpiling. In 2003, President Lula had also met the industry to ask a commitment to security of supply and reasonable prices, but with positive reply from producers representing only 60% of the national production.

In short, a new enabling environment must be built in order to avoid the problems faced in the past. It is no longer possible to rely on the spot markets only for ethanol sales. Firm contracts at least on a yearly basis must be enforced to ensure security of ethanol supply at non-volatile prices. On the long run, it is important to conduct a strategic environmental assessment of sugarcane production expansion, with an appropriate zoning, in order to ensure the environmental and social sustainability of the program.

In Brazil, not only ethanol production tends to increase. Biodiesel has also a great potential to be developed (Figure 3). As for the ethanol case, at the beginning, public policies and investments are necessary and desirable to foster investments and futures economies of scale, productivity growth, and to improve its contribution to sustainable development. The Biodiesel National Program intends to fill this gap, learning from the ethanol program experience. However, much has to be done yet in further detailing its guidelines to reach a consistent regulatory framework.

The task is even more challenging for biodiesel than for ethanol. Its economic competitiveness is not yet there. Some vegetable oils have high opportunity costs as industrial feedstock with small but profitable niches in the international market. The need for capacity building is huge if small farmers are to be the basic feedstock suppliers. Policy tools will have to go beyond public funding and tax exemptions. The level of involvement of Petrobras and Eletrobras in building the infrastructure required for appropriate functioning of biodiesel and vegetable oil markets will be absolutely crucial.

In fact, the Brazilian government's biodiesel program—based on vegetable native oils production to benefit poor family farms—in a preliminary analysis, may be considered a charitable thought but not feasible. The small castor bean production, for example, appears to be insufficient to meet the demand—according to Petrobras (2008), Brazil will need 871,000 m^3 of biodiesel during 2008 (Figure 3). However, the entry in the biodiesel market of large players like the state-run oil and gas company Petrobras can change this view. The emergence of new biodiesel plants and retail outlets via the distribution arm of Petrobras appears to have Brazil on course to meet forecast demand in 2015, that is, 2,771 m^3 (Carvalho, 2008). In 2006, Petrobras sold biodiesel at 500 of its filling stations and in 2007, this figure already reached around 7,000.

What is less clear is the amount of biodiesel that will be possible to get from small-scale family farmers producing locally available vegetable oils. The difficulties to ensure the required technological capacity-building, social organization, and logistics should not be underestimated. Conflicts have already been reported between private owners of biodiesel production plants and small farmers supplying the feedstocks to these plants. These conflicts are arising from the difficulty of timely delivery of seeds, technical assistance, and general infrastructure to small farmers by the industrialists, who are not managing to respect their contractual engagements. Meanwhile, soybeans international prices were low, after peaking in 2003, and the biodiesel market supplied an excellent opportunity for large-scale soybean oil producers. That was similar to what happened at the very launching of the Alcohol Program, when the attempts to develop small-scale ethanol production from different feedstocks (manioc and sweet sorghum, besides sugarcane) were killed by the availability of large-scale sugarcane plantations in a period of low sugar prices in the international market. The social benefits of such a biodiesel program would be much lower than expected today. Environmental benefits may also be reduced if additional soybean production to meet biodiesel plants induces deforestation in the Amazon region. Apparently, tax exemptions alone will not be sufficient to create a new paradigm of vegetable oils production based upon small farmers, in a time frame required to supply the huge amounts of biodiesel required to meet the ambitious targets established by the government. New policy measures and tools will be required to harmonize biodiesel demand with a sustainable supply from small producers as envisaged to maximize the social benefits of the program. Another key issue is the development of appropriate technology. Toward this end, Petrobras recently engaged in R&D of transesterification technology, in an attempt to increase the productivity of small-scale plants for biodiesel production from vegetable oils other than soybeans.

There is also scope for a potential synergy between biodiesel and ethanol programs since building a biodiesel transesterification unit integrated to an ethanol distillery may reduce investment costs by 20–25%. Moreover, using ethanol as an input for biodiesel production will also improve technological self reliance and profitability thanks to increased carbon credits potential (Olivério, 2005).

In general, biofuels development contributes to energy supply diversification. Moreover, it also contributes to improve reliability of internal energy supply, to reduce balance of payments problems related to fossil fuel imports to foster sustainable long term energy supply, and to reduce local pollution and GHG emissions. If production can be ensured from small-scale family farmers, it may also promote regional and social development.

The outcome of Petrobras efforts will be crucial to the success of biodiesel production based on small-scale family farmers. The role of governmental policy tools will also be fundamental—so far, economical viability of small-scale decentralized production is not there. The sustainability of Brazilian biodiesel production will depend basically on the path adopted to overcome the barriers above discussed.

Even though the positive externalities brought by biofuels production and use can be obvious, at least in the Brazilian case, they are very difficult to be quantified. If quantified and included in biofuels price, these externalities might foster even faster biofuels development. Biofuels development supplies a major opportunity to rethink rural development and to promote a new rural development cycle, especially in Brazil due to its comparative advantages, which include its biodiversity, the largest land availability for expanding agricultural activities (without necessarily requiring further deforestation

Figure 3. *Biodiesel demand forecast in Brazil (1,000 m^3/year): 2006–15. Source: Carvalho (2008).*

in the Amazon region), several different climates, and excellent water resources availability. These factors show that Brazil is well placed to be the leader in the production and use of biofuels (Sachs, 2004).

It is important to notice that biofuels are only a part of biomass use. Biomass can be used to produce not only biofuels but also food, fibers, plastics, construction materials, industrial feedstock, and pharmaceuticals. Several developing countries can foster their development on the condition of exploring their biodiversity. Biotechnology should be used both to enhance biomass output and to widen the spectrum of its by-products. In this way, such countries "may engage ahead of industrial countries into a genuinely sustainable and fairly labor intensive development pattern, on the condition of respecting the rules for an ecologically sound management of forests, land, and water" (Sachs, 2004). Similarly, the Sustainable Biofuel Consensus provides a vision of "…a landscape that provides food, fodder, fiber, and energy; that offers opportunities for rural development; that diversifies energy supply restores ecosystems, protects biodiversity, and sequesters carbon; and that contributes to global peace. When produced responsibly, increased global biofuels trade, transport use, and production can be cost-effective, equitable, and sustainable" (Rockefeller Foundation, 2008).

Finally, the Brazilian experience with production and use of biofuels, namely sugarcane fuel ethanol, has more than 80 years. Nowadays, due to several reasons, there is a great interest in replicating the same approach in Brazil with biodiesel from vegetable oils, and in other countries as well. However, national circumstances may vary widely across different potential biofuels and producer countries. Lessons learned from the Brazilian Ethanol and Biodiesel programs may help to highlight the key sustainability factors required for a careful assessment of new national biofuel programs.

NOTES

1. The main reaction for converting oil to biodiesel is called transesterification. The transesterification process react an alcohol (like methanol) with the triglyceride oils contained in vegetable oils, animal fats, or recycled greases, forming fatty acid alkyl esters (biodiesel) and glycerin. The reaction requires heat and a strong base catalyst, such as sodium hydroxide or potassium hydroxide. The simplified transesterification reaction is "Triglycerides + Free Fatty Acids (<4%) + Alcohol → Alkyl esters + glycerin." It's possible to say that transesterification is a chemical reaction between a vegetable oil *in natura* with an alcohol (ethanol or methanol), which usually produces 90% of biodiesel and 10% of glycerin by volume.

2. E_x means a blend with x% v/v of ethanol blended with gasoline. E_{25} is thus a blend with 25% v/v ethanol with 75% v/v gasoline. E_x blends are also known as gasohol.

3. We have assumed an increase of 20% in the average crop productivity (from 66 tons of sugar cane per hectare to 80 tons per hectare) and an increase of 7% in the average industrial yields (from 86 to 92 l of ethanol per ton of sugar cane) during the period.

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