Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

ELSEVIER

BIOMASS & BIOENERGY

Perspectives on fuel ethanol consumption and trade

Arnaldo Walter[a,*], *Frank Rosillo-Calle*[b], *Paulo Dolzan*[a], *Erik Piacente*[a], *Kamyla Borges da Cunha*[a]

[a]*State University of Campinas—Unicamp (FEM & NIPE), P.O. Box 6122, 13081-970 Campinas, Brazil*
[b]*ICCEPT, Imperial College London, Room 4.02 RSM Building, Prince Consort Road, Kensington Campus, London SW 7 2 BP, UK*

ARTICLE INFO

Article history:
Received 15 January 2007
Received in revised form
21 January 2008
Accepted 22 January 2008
Available online 11 April 2008

Keywords:
Fuel ethanol
International bioenergy trade
Market scenarios
Bioenergy

ABSTRACT

Since the year 2000 or so there has been a rapid growth on fuel ethanol production and consumption, particularly in US and Brazil. Ethanol trade represented about 10% of world consumption in 2005, Brazil being the main exporter. The most important consumer markets—US and European Union (EU)—have trade regimes that constrained the comparative advantages of the most efficient producers, such as Brazil. This paper evaluates the fuel ethanol market up to 2030 together with the potential for international biotrade. Based on forecasts of gasoline consumption and on targets and mandates of fuel ethanol use, it is estimated that demand could reach 272 Gl in 2030, displacing 10% of the estimated demand of gasoline (Scenario 1), or even 566 Gl in the same year, displacing about 20% of the gasoline demand (Scenario 2). The analysis considers fuel ethanol consumption and production in US, EU-25, Japan, China, Brazil and the rest of the world (ROW-BR). Without significant production of ethanol from cellulosic materials in this period, displacing 10% of the gasoline demand in 2030, at reasonable cost, can only be accomplished by fostering fuel ethanol production in developing countries and enhancing ethanol trade. If the US and EU-25 reach their full production potential (based on conventional routes), the minimum amount that could be traded in 2030 would be about 34 Gl. Displacing 20% of the gasoline demand by 2030 will require the combined development of second-generation technologies and large-scale international trade in ethanol fuel. Without second-generation technologies, Scenario 2 could become a reality only with large-scale production of ethanol from sugarcane in developing countries, e.g., Brazil and ROW-BR could be able to export at least 14.5 Gl in 2010, 73.9 Gl in 2020 and 71.8 Gl in 2030.

1. Introduction

Since 2000 there has been a rapid growth in demand for fuel ethanol. Rising oil prices, environmental and climate warming concerns, interests in energy diversity and security has made fuel ethanol an attractive alternative, particularly in industrial countries [1].

In developing countries the focus is more on rural development, jobs creation, savings on foreign currency and improving access to commercial energy [2]. In addition, the agricultural sector, which plays a key role in the early development of ethanol, brings significant benefits to farmers and would be a way to reduce costs and market distortions of the existing farm support policies, estimated as US$ 320 billion/year in OECD countries alone [3]. Finally, limited refinery spare capacity has had an impact on raising prices of oil products [4], which has also some impact on economics of biofuels.

*Corresponding author. Tel.: +55 19 3788 3283; fax: +55 19 3289 3722.
E-mail address: awalter@fem.unicamp.br (A. Walter).
0961-9534/$ - see front matter
doi:10.1016/j.biombioe.2008.01.026

Most experts accept that individual transport will continue to play a key role in the future and oil will continue to be the major energy source for decades to come, despite the efforts to find other alternatives. Biofuels (ethanol and biodiesel) are the best viable alternative in the immediate future, primarily because they can be used in present internal combustion engines and fuel infrastructure, which is one of the major obstacles to introduce other fuels [5]. Ethanol requires few changes or minor ones, particularly with blends of up 10% ethanol (E10). In US, for example, all automakers warranties covered the use of E10 since 1980s [6].

The aim of this paper is to evaluate the ethanol market as automotive fuel up to 2030 and the potential for international biotrade. Ethanol market has been evaluated based on projections of gasoline consumption and targets of ethanol use throughout this period. The potential for international ethanol trade was evaluated by comparing the estimated ethanol consumption according to two scenarios, and the perspectives of domestic ethanol production in the main regions considered in this paper.

2. Potential contribution of biofuels in developing countries

Biofuels can positively impact on the socio-economic development, e.g., by alleviating poverty, through job creation, reducing reliance on imported oil and on increasing access to modern energy services [7]. Many developing countries have a reasonable potential for biofuels production due to the availability of land and cheaper labour force, although they may lack skills, capital and finance. However, large-scale production of biofuels requires careful management to avoid direct competition with food production and constraints on water availability, and preserving biodiversity [8].

For countries that are net importers of crude oil, biofuels can enhance energy security and reduce expenses in hard currency, while providing socio-economic development. Thirty-eight of the world's poorest countries are net oil importers, of which 25 import 100% of their oil and therefore are very vulnerable to supply and price volatility [9,10]. Biofuels offer good possibilities for some of these countries to supply their domestic markets and even to become exporters.

Biofuels production can also induce industrial spin-off, creating job opportunities at low cost; e.g., in Brazil investment for ethanol production is very low compared to other economic activities [11]. The sugarcane industry in Brazil is responsible for about one million direct jobs (about 50% in sugarcane production), plus approximately 2.5–3.0 million indirect jobs [12]. However, job creation in the future will be lower as mechanization of agricultural activities is increasing.

It is accepted by most experts that, on balance, the environmental benefits of ethanol are positive. For example, thanks to ethanol–gasoline blends the removal of lead from gasoline brought considerable health benefits to big cities in Brazil [13]. Lead gasoline is still in use in some African and Asian countries, and thus blending ethanol with gasoline could solve this problem at low cost.

Despite some controversy, it is largely accepted that automotive use of E10 vis-à-vis E0 (pure gasoline) contributes to the reduction of tailpipe emissions of particulate matter and carbon monoxide [14] and reductions on total hydrocarbons and air toxic emissions (especially benzene) can also be achieved as long as vapour pressure control is effective [15]. Nitrogen oxides emissions can be either higher or lower compared to E0 [15], although other studies [16,17] show that the case of ozone formation at worst is neutral. Advantages regarding emissions are more meaningful if the existing fleet is relatively old or its maintenance is poor. With the introduction of more efficient emission control systems in vehicles (i.e., electronic injection, catalytic converters and canisters), final exhaust emissions tend to be roughly the same regardless of the fuel [18].

Large-scale use of biofuels is currently one of the main strategies for the reduction of GHG emissions [19]. The Clean Development Mechanism offers good opportunities despite the fact that no methodology is available for projects of biofuels use in transport. Based on a typical Brazilian figure of 2.7 kg of $CO_{2\,equi}$ avoided per litre of anhydrous ethanol [20], ethanol fuel could represent additional income of US$ 0.02–0.05 per litre (based on credits ranging from US$ 7 to 20 per tonne of $CO_{2\,equi}$); this is meaningful compared with production costs of US$ 0.23–0.28 per litre [21].

3. Ethanol experiences and perspectives

3.1. *Overview on fuel ethanol experiences*

Global ethanol production in 2005 reached 45 billion litres (45 Gl), of which about 33 Gl were used as fuel and the rest for beverage and other industrial applications [22,23], although estimates vary (e.g., 33–37 Gl [24]). In this paper 33 Gl was used although this seems conservative. Global ethanol production in 2006 has been estimated as 51 Gl, of which about 39 Gl as fuel [25]. Fuel ethanol use in 2005 was roughly equivalent to 17.6 Mtoe (0.74 EJ), or approximately 2% of global gasoline consumption. Brazil and US have dominated ethanol production and utilization, representing more than 80%. Brazil has been for decades the world's largest producer and consumer, but was surpassed by US in 2006.

Fig. 1 shows the evolution of fuel ethanol production from 1982 to 2006. Production figures are more reliable for Brazil and US. As shown, prior to 2000 there are some inconsistencies on the total world production, partially explained by the various uses of ethanol. In 2000 fuel ethanol represented about 60% of the total production (17.3 Gl vis-à-vis roughly 30 Gl) [26], about 73% in 2005 (33 Gl vis-à-vis almost 45 Gl) [23,29] and possibly has surpassed 77% in 2006 [25]. A significant growth of fuel ethanol production has occurred since 2000, mainly in US and in Europe (e.g., France, Germany and Spain), as illustrated in Table 1.

In 2005 about 60% of ethanol production was from sugarcane, 30% from grains (mostly corn), 7% from synthetic ethanol (from ethylene, coal, etc.) and 3% from other feedstocks.

Recently, nearly 40 countries have introduced or have shown interest on fuel ethanol. By the end of 2006, mandates

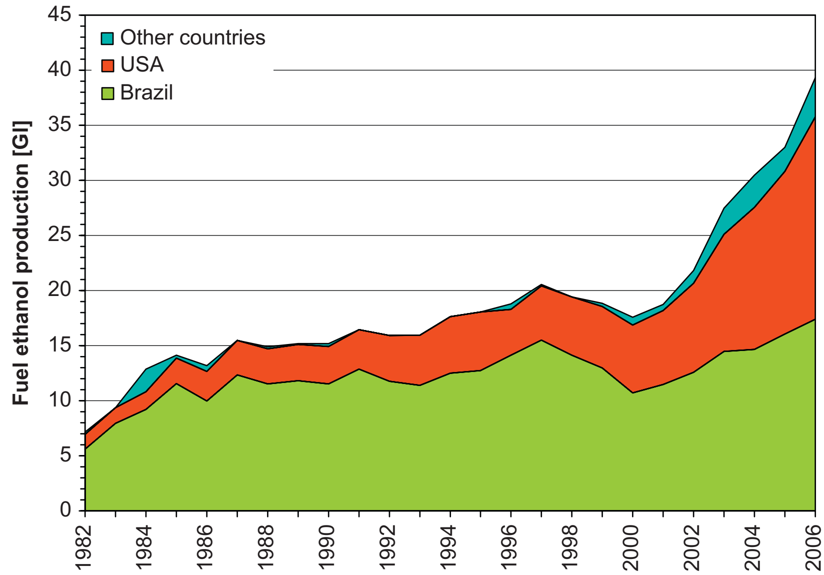

Fig. 1 – Fuel ethanol production from 1982 to 2006. *Sources*: The world [23], US [27], Brazil [28].

Table 1 – World fuel ethanol production (Gl) and average annual growth rates, 2000–2006

	World	Brazil	US	Rest of the world
2000	17.58	10.70	6.17	0.71
2005	33.00	16.04	14.78	2.18
2006	39.31	17.76	18.38	3.17
Average growth rate (%)	14.4	8.8	20.0	28.3

Sources: [23] for the world, [27] for US, [28] for Brazil and [25] for 2006.

for biofuels blending existed in nine countries at national level (Brazil, Colombia, Germany, France, Malaysia, Philippines, Thailand, United States (federal renewable fuel standard), and Dominican Republic) and in four countries mandates were valid in some states/regions (India, China, Canada, and United States—Hawaii, Minnesota, Montana, Washington, Wisconsin) [12,23]. In most countries ethanol is blended with gasoline in proportions that vary from 2% to 10% (volume basis), except in Brazil where this proportion varies between 20% and 25%. Brazil is also the only country where neat ethanol fuel is used in large scale. The main experiences on fuel ethanol use are described below.

3.2. *Brazilian experience and perspectives*

Besides the existence of neat ethanol vehicles, all motor gasoline sold in Brazil contains 20–25% ethanol [on volume basis (E20–E25)]. Neat ethanol vehicles use hydrated ethanol, while anhydrous ethanol is blended with gasoline. In Brazil flex-fuel vehicles (FFVs) can also be fuelled with hydrated ethanol.

Brazilian experience with ethanol–gasoline blends dates back to the 1930s although it was not until 1975, when the Brazilian Alcohol Program (PROALCOOL) was created, that gasoline began to be replaced in a significant scale in all passenger vehicles. In 1979 the Brazilian government decided in favour of large-scale production of hydrated ethanol fuel in specially modified engines.

Despite its considerable success (i.e., reduction of oil imports, stabilization of the sugar market and enhancement of Brazilian competitiveness), the PROALCOOL was not exempted of controversy partly due to the financial support given by the government, which also benefited inefficient producers. In mid-1980s criticism increased even further due to the decline of the international oil prices, and the large surplus of gasoline. In the 1990s, the government reduced its support due to a debt crises which, combined with other factors, led to ethanol shortages causing serious difficulties to the consumers. Fuel prices were liberalized and by the end of 1990s all subsidies to the sugarcane and ethanol industry were removed.

Sales of neat ethanol-fuelled vehicles started to grow again in 2001 due to a larger price difference between ethanol and gasoline, caused by the combination of higher oil prices and lower costs of ethanol. More importantly, since 2003 with the launch of FFVs a new boom on sales pushed up the demand for ethanol considerably; FFVs reached 85% of new vehicle sales in 2006.

The success of FFVs and the relative low price of ethanol vis-à-vis gasoline are the main reasons why it is predicted that the domestic ethanol market will rise significantly in the near future. In 2006 ethanol production (anhydrous+hydrated) was 17.8 Gl, as illustrated in Fig. 2.

Brazil is the only country in the world with conditions to hugely expand ethanol production capacity rapidly in the short- to mid-term due to the availability of land, technology, capital, know-how and relatively cheap labour force. Currently about 80 new industrial units are in different stages of construction, compared to 335 units in operation; it is

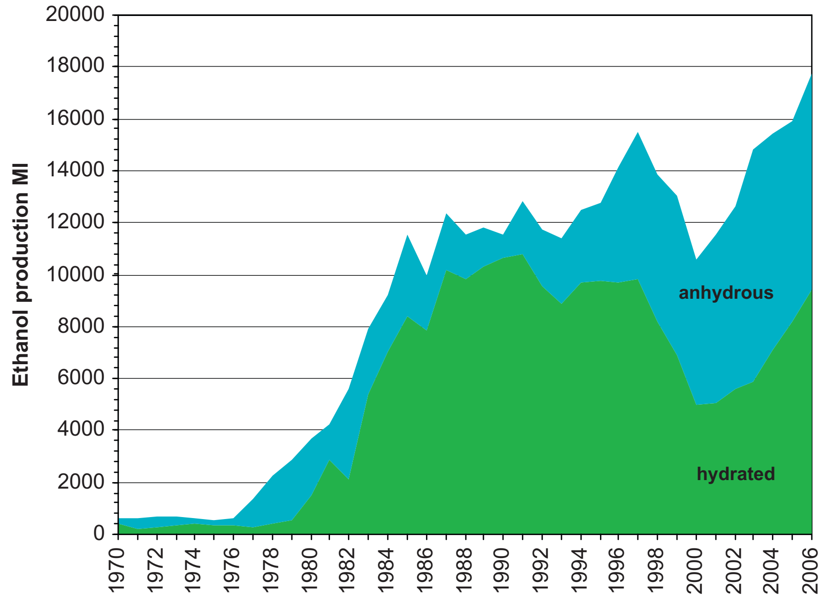

Fig. 2 – Fuel ethanol production in Brazil from 1970 to 2006. *Source*: [28].

expected that ethanol production capacity could more than double by 2015 [29]. This expansion potential is not exempted of criticism both in Brazil and internationally, because concerns with sugarcane monoculture, water use, potential environmental and biodiversity impacts, working conditions and so forth. For an overview of sustainability of ethanol production in Brazil, see the paper by Smeets et al. (this issue).

3.3. *US experience and perspectives*

The US has the world's largest and fastest growing fuel ethanol market, with an estimated production of 18.4 Gl in 2006 [27], a two-fold increase from 2002 to 2006. It is expected that the production capacity could double again between 2007 and 2009. In the past, ethanol was used in niche markets in the Midwest, where production is concentrated, but since 2006 fuel ethanol is consumed countrywide and blended in 30% of the gasoline consumed in the country [30,31]. E85 blends are also used but its expansion is curtailed by lack of infrastructure. Ethanol is sold in most states as octane enhancer or oxygenate blended with petrol and in 2006 represented about 3% of gasoline equivalent [30].

In addition to environmental reasons and the influence of the farming sector, another major driving force is the desire to reduce external oil dependency, together with the phasing-out of methyl tetrabutyl ether (MTBE) as octane enhancer, banned in 23 states in 2005. A major concern with MTBE is water contamination and its health effects.

In August 2005 the US government signed into law the *Energy Policy Act of 2005*, creating a national Renewable Fuels Standard which set targets of 28.4 Gl of renewable fuel to be used in the transport sector by 2012, the vast majority fuel ethanol. In 2006 the Energy Information Administration—EIA [32] estimated that fuel ethanol consumption could reach 55.3 Gl in 2030, but in early 2007 US Federal Government set a new target of 132 Gl of renewable fuels (also mostly ethanol) in 2017 as part of the strategic plan to reduce gasoline consumption by 20% that year [33].

In addition, five states—primarily potential large-scale producers—have introduced local legislation to booster renewable fuels, e.g., Minnesota has adopted the target of 20% ethanol blends to take effect from 2013 [30].

In the US, corn is the prime feedstock for ethanol production [30]. In 2006 the cost of production of fuel ethanol from corn was about 0.33–0.50 Euro/l compared to 0.21–0.29 Euro/l for cost of production from sugarcane in Brazil [24]. The energy balance of ethanol production (the ratio of energy contained in the biofuel to the fossil fuel energy used to produce it) from corn is also far less favourable (e.g., 1.25 [34], 1.32 [35] and 1.34 [36]) than in Brazil—8.3–10 [20]). In the long term, the competitiveness of ethanol from corn will depend on major improvements of all stages of the production chain (i.e., reducing energy consumption, greater energy self-sufficiency, developing new co-products, etc.). It is estimated that production costs could be reduced by 8–15% in the mid-term [24] while the energy ratio could be improved from about 1.3 to 2.9 if fossil fuels used in industrial processes are switched to biomass-based fuels, such as wood chips [37].

However, despite the strong interests of corn producers, the long-term sustainability of fuel ethanol in the US will ultimately depend on the use of new feedstocks. Considerable efforts are being made to develop new routes of liquid fuels from cellulosic material. In 2006 a forecast by EIA [32] stated that by 2030 more than 93% of the ethanol production could still be based on corn and less than 7% on cellulose feedstocks. However, recent estimates are that corn-based ethanol could reach 55–57 Gl between 2012 and 2017, and the remaining from cellulosic material [38]. The estimates of the US DOE are that through RD&D efforts cellulosic ethanol cost could be 0.35 $/l by 2012 and approx. 0.32 $/l by 2017 [33].

3.4. Experiences and perspectives in Europe

European Union (EU) has a strong policy for promoting the use of alternative fuels, particularly biofuels. In 2001 an EU Directive established that by 2005 biofuels should cover 2% of the total transport fuel consumption (energy basis), while the target for 2010 was set at 5.75%. However, so far the average biofuel contribution has been minimum (e.g., 0.5%, 0.6% and 1% in 2003, 2004 and 2005, respectively) and from 2003 to 2005 ten countries did not use either biodiesel or bioethanol as a substitute. The two countries with higher proportions in 2005 were Germany (3.75%) and Sweden (2.23%) [39].

The EU Biofuels Directive has left individual Member States (MS) to decide on policies and measures needed to reach the target, as well as biofuels mix strategies most beneficial to each country. This degree of flexibility makes it very difficult to estimate the long-term potential penetration of biofuels at EU-wide level. In the Energy Policy Document, published in January 2007, the EU has adopted a more conservative estimate for 2020 of 10% based on current trends rather than the 20% suggested in previous documents. However, many believe that even 10% is unrealistic and are calling for a lower percentage for biofuels.

In the EU only a small fraction of ethanol is used as fuel. Total ethanol production (all grades) in the EU is concentrated in some countries and covered about 6% of the world production in 2005 (2.7 Gl) [31]. The main players of fuel ethanol in Europe are Germany, Spain, France, Poland and Sweden, representing about 90% of the production in 2006 (1592 Ml) [40]. Coincidentally, two of the main European producers—France and Spain—consume gasoline blended with ETBE (8–10%). ETBE production is partially renewable when bioethanol is used.

The capacity of fuel ethanol production in Europe in mid-2007 was estimated as 3.3 Gl, distributed in 14 countries, France being the largest (1150 Ml), followed by Germany (706 Ml), Spain (521 Ml) and Italy (302 Ml). An additional new production capacity is estimated as 4.0 Gl, distributed in 15 countries; larger capacity is in France (550 Ml), Germany (480 Ml), Netherlands (480 Ml), Belgium (435 Ml), Spain (420 Ml), UK (400 Ml) and Czech Republic (339 Ml) [40].

The feedstocks used in the EU for ethanol production are sugar beet and wheat; some units under construction will use corn, mainly in new MS. Lately, surpluses of wine have been converted to fuel ethanol. Feedstock cost is a major limiting factor in the EU with prices ranging from 0.74 $/l for wheat to 0.85 $/l from sugar beet, compared to 0.21 $/l in Brazil [41]. The short- to mid-term perspective is that production costs could be reduced 15–20% [24]. The energy ratio of ethanol production from wheat or sugar beet is estimated as around 2 [24].

Given the constraints of ethanol production from the current available technologies and feedstocks, EU is putting a considerable effort in developing second generation of biofuels, based on cellulosic materials. The conversion of ligno-cellulosic material to ethanol has received particular attention in Sweden and to a lesser extent in UK, Spain and the Netherlands. In addition, other routes based on biomass gasification for syngas production and subsequent conversion to biofuels (i.e., methanol, dimethylether (DME)-, Fisher-Tropsch liquids or even hydrogen) are also intensively being investigated in many of the EU MS [42].

The short-term policy is to avoid large-scale implementation of biofuels until feedstock costs can be reduced significantly. Some countries, e.g., Germany and France, have both political and cultural interests in their agricultural sectors and national policies are in favour of local productions of biodiesel and ethanol [42]. However, the high cost of subsidies is prompting some policy rethinking.

3.5. Perspectives in Japan

Japan is one the main consumers of gasoline in the world and is heavily dependent on imported oil. The country has considered large-scale use of fuel ethanol, or ETBE, targeting its energy security and GHG emissions reduction to accomplish its Kyoto obligations. Since 2005 the use of E3 is not mandatory and ethanol blends are used in some regions; an E3 mandate should be defined nationwide and expanded to E10 by 2010. However, there is some resistance due to the low number of large-scale ethanol suppliers and to the interests of oil companies that prefer gasoline blends with ETBE rather than with fuel ethanol [43].

Japan is an important producer of synthetic ethanol but lacks the conditions to produce ethanol from biomass in large scale. In 2005 the country was the second largest importer of ethanol (more than 500 Ml) [31] used primarily as fuel. If mandates are finally implemented, including ETBE blends, Japan will become one of the main markets for fuel ethanol in the world.

3.6. Other countries

More than 40 countries worldwide have shown interest on ethanol fuel. This section looks briefly to some of the most important markets.

China is currently the world's third largest producer of ethanol and is the focus of considerable attention given the potential size of its market. In 2005 the ethanol production capacity (all grades) was estimated as 3.8 Gl [44] while the fuel ethanol consumption reached about 1 Gl [45]. There are four state-designated fuel ethanol enterprises in China with a combined production capacity of 1.3 Gl/year, although there are other plants which are operating [44]. There are three new plants under construction with a combined capacity of 1.5 Gl/year [46]. In China, more than 80% of ethanol is made from grains (corn, rice, etc.); ethanol production from sugarcane represents about 10% [46].

Total capacity could reach 2.5 Gl in 2010 and up to 12.6 Gl in 2020 [45]. Given land constraints, there is a policy of diversifying the feedstock such as cellulose. There are at least two pilot plants in operation producing ethanol through acid and enzymatic hydrolysis of sawdust, rice straw and from the stalks of sweet sorghum [47].

So far it is mandatory to use E10 in nine provinces that account for about one-sixth of that country's vehicles. There are various reasons for supporting ethanol fuel, e.g., reducing oil dependency, improving air quality in big cities, stabilizing grain prices and improving farmer's income. In summary, it can be said China plans to develop fuel ethanol step-by-step, and will prioritize ethanol production from non-food-related crops [46].

India is the world's second sugarcane producer and a large producer of ethanol, mostly used as a chemical feedstock. However, most of the sugarcane production is still aimed at its huge domestic sugar market [48]. Recently, India has been seriously considering fuel ethanol production and a mandate for E10 blends, currently effective in 13 states, will be introduced countrywide by 2010 [44].

India has the potential to be a large-scale fuel ethanol producer from sugarcane but land constraints could be a major limiting factor. In addition, contrary to Brazil, sugarcane is produced by many small farmers and cost reduction will be more difficult.

Thailand imports 90% of its oil consumption, costing 13% of the country's GDP. Thai government is pursuing a policy of domestic production and consumption of biodiesel and fuel ethanol. The withdrawal of MTBE increased ethanol consumption to 340 Ml in 2006 [44]. The main feedstock is cassava as the country is one of the world largest producers. Long tradition, high productivity and experience with this crop, together with the high price of sugar in the domestic market, makes it unlikely that sugarcane will become a major feedstock for large-scale ethanol production. By the end of 2009 there could be at least 24 ethanol plants in operation, with a total production capacity of 1.7 and 1.8 Gl by the end of 2011 [31].

Sugarcane is a traditional crop in many Latin America countries and the potential for ethanol production is quite significant in this region. In Central America and Caribbean all major producers of sugarcane are considering the fuel ethanol option in order to modernize and diversify the sugarcane industry; unlike in most other countries, the main target it to export to the US [48] (see Sections 5.1 and 5.2). The US and Brazil have recently signed a partnership to promote the production of ethanol throughout the region. The US market is also the main target in Peru, where ethanol production has a strong political connotation as new cane plantations are aimed at replacing coca crops. In Colombia a national programme was launched in 2001 where gasoline–ethanol blends are compulsory in cities with over 500,000 inhabitants. Five new ethanol distilleries from sugarcane were established between 2005 and 2006, with a production capacity of about 200 Ml/year [49].

4. Future ethanol markets

4.1. *Trends on gasoline consumption*

The demand for ethanol will be affected by an unbalanced situation between refining capacity, refining structure and the production of gasoline and diesel. For example, in the EU the demand for diesel continues to grow at the expense of gasoline, induced by lower taxes on diesel. The diesel fleet could rise from 30% in 2005 to 43% in 2011 and, as a consequence, gasoline demand is expected to decline by 17.4–23.2 Gl from 2006 to 2011 [4]. On the contrary, in US, with the largest market of gasoline in the world, the short-term forecast is that the demand will continue to rise [32].

In Japan gasoline demand is expected to grow by less than 0.5% annually over 2006–2011 due to a combination of factors, e.g., demand for less, smaller and more efficient vehicles (due to high taxes, aging population, etc.) [50].

On the contrary, in China due its rapid economic development, the demand for vehicles is expected to increase enormously. To reduce gasoline demand, the Chinese government is taxing larger vehicles at higher levels than smaller ones. The prospects are that Chinese transport sector will continue to grow rapidly and so the demand for gasoline; an estimate is that annual energy demand would increase by 5–7% [50] in the next few years. Road transport is the primary factor in China's economic development [32].

In India it is estimated that the demand for road transport fuels would expand by over 5% annually from 2006 to 2011. Currently India's demand on transportation fuels is about 40% of China's current demand [4].

The IEA [4] estimates that from 2006 to 2011 the world demand in the transport sector will grow by approximately 2.5%/year, with relatively smaller growth rates for gasoline than for diesel. By 2050 the IEA estimates that world gasoline consumption can reach 2760 Gl according to a baseline scenario, with an average growth of 1.84%/year [50].

4.2. *Estimates of fuel ethanol consumption*

4.2.1. *Motor gasoline consumption*

To evaluate fuel ethanol consumption by 2030, a simple forecast model was developed based on historical data of motor gasoline consumption of main consuming countries and regions, e.g., US, EU-25, Japan, China, Brazil and the rest of the World. Although Brazil is not a major gasoline consumer, it can become the world's largest exporter of fuel ethanol. The group "Rest of the World—Brazil" (ROW-BR) comprises a large number of countries with heterogeneous features regarding their importance as gasoline consumer and as fuel ethanol producers.

Motor gasoline consumption data were taken from [51–53] while complementary information for Brazil was taken from [28]. Total motor gasoline consumption was estimated as 1213 Gl in 2005 (see Table 3).

The forecast procedure is based on extrapolation of trends of gasoline consumption in each country/region; when available, estimates of future consumption were added to better reflect the expected trends. Complementary data of gasoline consumption are presented in Table 2.

For Brazil a different procedure was used as gasoline consumption is strongly influenced by the market success of FFVs. Firstly, was estimated the energy demand for light-duty vehicles and then deducted from the results the predicted amount of ethanol demand. Estimates of the ethanol market were used for the period 2010–2015 (Table 2). Consumption of fuel ethanol was finally adjusted to the value presented in the National Energy Plan 2030 (50 Gl of fuel ethanol in 2030) [55]. Due to the competition between gasoline and ethanol, the hypothesis assumed by [55] is that the share of ethanol on energy transportation demand will reach almost 55% (volume basis) in 2020 and stabilize thereafter.

As illustrated, Fig. 3 shows the estimated gasoline consumption in US and EU-25 from 2006 to 2030.

Table 3 summarizes estimated gasoline consumption in 2030; for comparison, other estimates from literature are also presented. It is predicted that within 25 years the bulk of gasoline consumption will move from developed countries (US, Japan, EU-25) to developing nations. Consequently, developing countries could have both an important role as producers and also as consumers of fuel ethanol. Fig. 4 shows the estimated evolution of gasoline consumption for the period 2006–2030.

Table 2 – Additional information used to forecast gasoline consumption

Country/region	Information	Sources
US	Motor gasoline consumption = 675 Gl in 2020[a]	[54]
US	Motor gasoline consumption = 745 Gl in 2030	[32]
EU 25	Motor gasoline consumption should drop 20 Gl over 2006–2011	[4]
EU 25	Motor gasoline consumption = 134 Gl in 2020[a]	[54]
Japan	Gasoline consumption must grow just 0.5%/year over2006–2011	[4]
China	Gasoline consumption must grow 5–7%/year over 2006–2011	[4]
Brazil	Fuel ethanol consumption must reach 19 Gl (2010) and 28.7 Gl (2015)	[12]
World	Projected motor gasoline consumption close to 2760 Gl in 2050	[50]

[a] The original estimates take into account the participation of biofuels: 10% in the case of USA and 6% in Europe.

4.2.2. *Fuel ethanol consumption*

In short- to mid-term, fuel ethanol consumption will be induced by mandates in all countries, except in Brazil. In this paper fuel ethanol consumption for the period 2006–2030 was evaluated based on estimates of gasoline consumption, presented above, and on targets of ethanol use in different countries. Two scenarios are proposed, with the main difference between them being the hypothesis that ethanol cellulosic materials will be possible to a large extent from 2020 to 2030. Scenario 1 is more conservative and is based on the targets formerly defined by US administration for the years 2012 and 2030. In this scenario the growth of US ethanol consumption would be constrained by domestic production capacity, considering that large-scale ethanol production from cellulosic materials would be feasible towards the end of the period (2030).

Scenario 2 is based on the targets of ethanol production defined by US government by early 2007, i.e., consumption of about 132 Gl by 2017. This target can only be achieved if large-scale ethanol production from cellulosic materials becomes feasible in short- to mid-term. As a consequence of the commercial availability of such technologies, ethanol consumption would grow more after 2017–2020, both in US and in other countries. Only for US and EU-25 there are differences between Scenarios 1 and 2 on the whole period; for the other countries (China, Japan and ROW-BR) Scenarios 1 and 2 are different just after 2020. There is just one scenario for Brazil. The hypotheses considered in both scenarios are presented in Table 4.

Relative efficiencies between vehicles fuelled with gasoline (E0) and those fuelled with any gasoline–ethanol blend are required in order to estimate fuel ethanol consumption. Except for Brazil, it was assumed that until 2010 fuel efficiency would be 1% lower than an E0 vehicle (i.e., relative efficiency = 99%). Until 2020, and for any fuel blend, relative efficiency would be equal to 100%. Finally, it was assumed

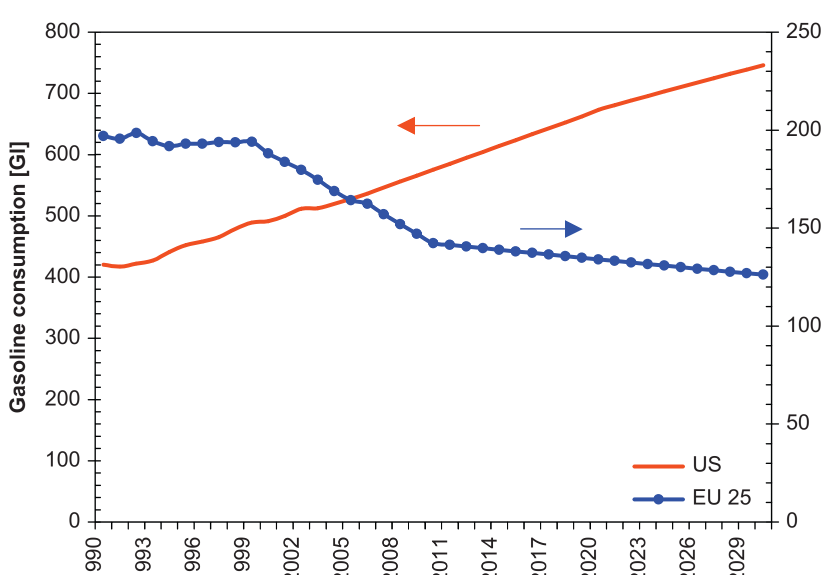

Fig. 3 – Gasoline consumption in US and EU-25—estimated in the period 2006–2030.

Table 3 – World gasoline consumption (data for 2005 and estimates for 2030)

Country/region	Growth rates (%)				Consumption (Gl) in 2005	Consumption (Gl) in 2030
	2006–2011		2003–2030			
	Estimated	Reference	Estimated	Reference		
USA	1.75		1.40		528 (43.5%)	746 (38.8%)
EU-25	−2.71		−1.19		164 (13.5%)	126 (6.6%)
Japan	0.50		0.63		61 (5.0%)	71 (3.7%)
China	6.00	5–7.0[a]	4.10	3.90[b]	53 (5.2%)	166 (8.7%)
ROW-BR	3.26		2.76		378 (31.2%)	771 (40.0%)
Brazil	2.62		3.50	3.50[c]	18 (1.5%)	43 (2.2%)
World	1.91		1.80	1.84[d]	1213	1924

Sources: [a][50], [b][32] over 2003–2030, [c][55], [d][50] over 2003–2050.

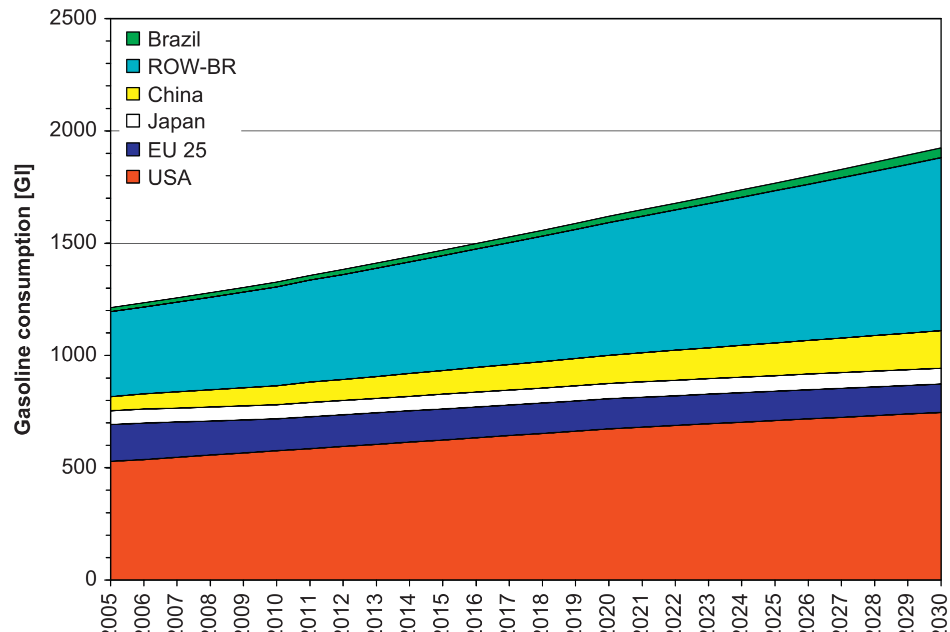

Fig. 4 – Estimated consumption of motor gasoline up to 2030.

that after 2020 relative efficiency would be 101% vis-à-vis an E0 vehicle.

The ratio between the relative efficiency and the volume of ethanol required to displace a given volume of gasoline was taken from [14]. The far right point in each of the lines shown in Fig. 5 corresponds to the estimates of the performance of Brazilian vehicles hypothetically running on E5 and E10. Typical specific consumption (volume basis) of Brazilian vehicles running on E22 is 5.5% higher than a similar E0 model and in case of an E100 model specific consumption is 29.4% higher [18]. As can be seen in Fig. 5, running with E5 and in case of relative efficiency 99%, 8.6 l of fuel ethanol would be required to displace 5 l of gasoline; running with E10 and in case of relative efficiency 100%, 13 l of fuel ethanol would be required to displace 10 l of gasoline.

According to the hypotheses presented above, the estimated ethanol consumption in the period 2006–2030 are shown in Figs. 6 and 7, for Scenarios 1 and 2, respectively. In Scenario 1 consumption of fuel ethanol could reach 272 Gl in 2030 (from 33 Gl in 2005), allowing the displacement of almost 10% of the estimated demand of gasoline (displacement of 190 Gl vis-à-vis estimated consumption of 1924 Gl) (see Fig. 8). In Scenario 2 the consumption of fuel ethanol reaches 566 Gl in 2030, displacing more than 20% of the demand of gasoline (almost 400 Gl) (Fig. 8).

Table 5 shows a comparison between consumptions and their annual growth rates for the different countries and regions for both scenarios. In case of EU-25 (both scenarios) and US (Scenario 2), the high level of ethanol consumption by 2030 (in EU-25 28.5% and 39.3% by volume in Scenarios 1 and 2, respectively, and in US 35% by volume in Scenario 2) could only be reached with a significant share of FFVs or even neat ethanol vehicles.

Table 4 – Targets and assumptions of fuel ethanol consumption from 2006 to 2030 (EU-25 targets in energy basis)

Country	Scenario 1	Scenario 2	Assumptions/comments
US	27 Gl by 2012, equivalent to 4.6% (volume) 55.3 Gl by 2030, equivalent to 7.4% (volume)		Hypothesis assumed by the authors: 95% of the target of 28.4 Gl of biofuels defined by the Energy Policy Act of 2005 Volume of ethanol estimated by US DOE [32]
		70 Gl by 2012	Scenario assumed by [38] in accordance with the target defined by 2017
		132.5 Gl by 2017	Target defined by US government in January 2007; large-scale imports and/or ethanol production from ligno-cellulosic materials would be necessary
		263.7 Gl by 2030	Hypothesis assumed by the authors in accordance with the results achieved up to 2017, considering that ethanol would displace 35% of the estimated gasoline consumption by 2030
EU-25	2.5% by 2010 (energy basis), that corresponds to 3.6% (volume)		Conservative hypothesis assumed by the authors vis-à-vis the EC Directive on Biofuels (5.75% by 2010—energy basis)
	10% by 2020 (energy basis), that corresponds to 14.4% (volume)		EU target defined in January 2007 by the EC Directive on Biofuels [56]
	20% by 2030 (energy basis), that corresponds to 28.5% (volume)		Hypothesis assumed by the authors considering that ethanol would displace 20% of the estimated gasoline consumption by 2030 (energy basis)
		5.75% by 2010 (energy basis)	Target of EU Directive on biofuels [57]
		14% by 2020 (energy basis)	Share feasible to be reached, according to EC [56]
		27.5% by 2030 (energy basis)	Assumed by the authors considering that ethanol production from ligno-cellulosic materials would be feasible and that ethanol would displace 27.5% of estimated gasoline consumption by 2030 (energy basis)
Japan	10% (volume basis) 2015 onwards		Hypothesis assumed by the authors
		15% (volume basis) to be reached by 2030	Based on the hypothesis that ethanol production from ligno-cellulosic materials would be feasible
China	2.5 Gl by 2010, that corresponds to 3% (volume)		Production targets on fuel ethanol; in this case China would be self-sufficient by 2010 [45]
	12.6 Gl by 2020, that corresponds to 10% (volume)		Production targets on fuel ethanol; in this case China would be self-sufficient by 2020 [45]
	2020 onwards—10% (volume) of gasoline displaced by ethanol		Target defined by the Chinese government [46]
		Same hypotheses up to 2030. By 2030, 15% (volume basis)	Based on the hypothesis that ethanol production from ligno-cellulosic materials would be feasible
ROW-BR	1% (volume) of gasoline displaced by 2010		Hypothesis assumed by the authors
	10% (volume) of gasoline displaced 2020 onwards		Hypothesis assumed by the authors
		Same hypotheses up to 2030. By 2030, 15% (volume basis)	Based on the hypothesis that ethanol production from ligno-cellulosic materials would be feasible

In the case of US, Scenario 1 consumption in 2030 (based on [32]) seems to be very conservative based on the current consumption and support policies trends to increase domestic production. The result of Scenario 2—consumption almost five times higher than in Scenario 1—is induced by the target proposed for 2017. In this case, US would remain the main market of fuel ethanol in the world.

To comply with the EU Biofuels Directive by 2010 (Scenario 2) will require a considerable effort to increase ethanol consumption in the short term in Europe. Results of

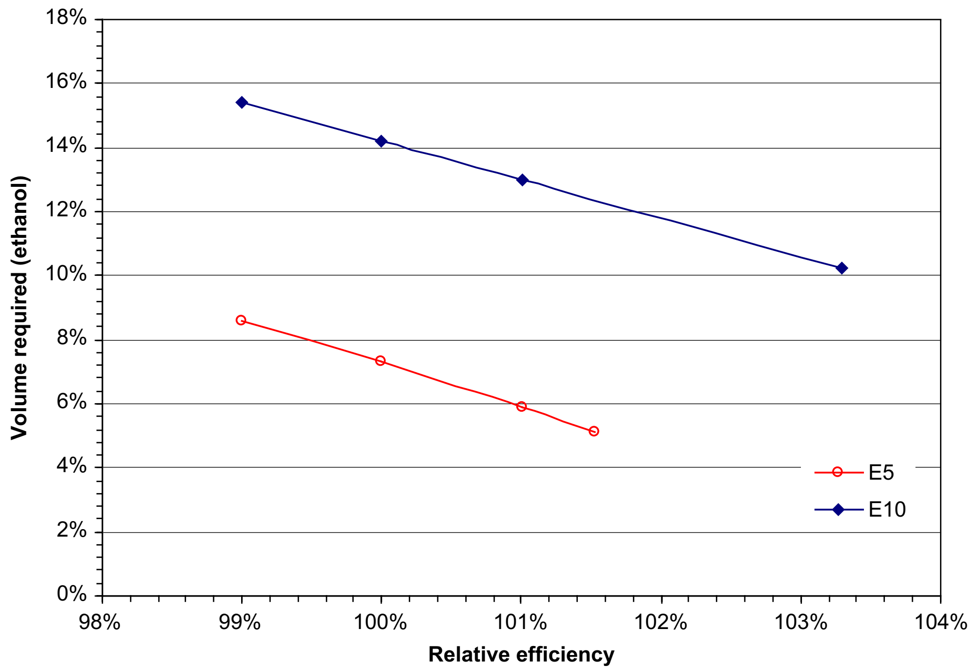

Fig. 5 – Volume of ethanol required as a function of the relative efficiency regarding E0.

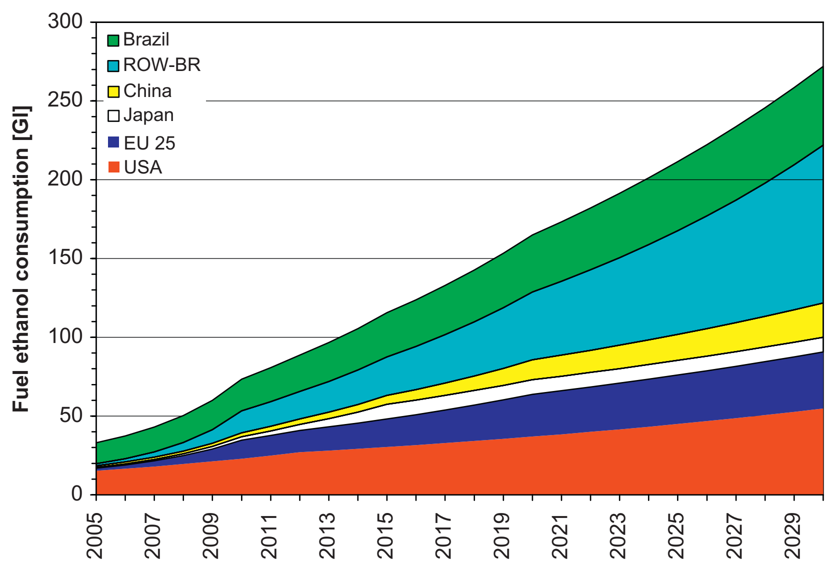

Fig. 6 – Estimated consumption of fuel ethanol in the 2006–2030 period—Scenario 1.

Scenario 2 are on average 40% higher than results of Scenario 1 in the whole period. According to Scenario 2, ethanol consumption in EU-25 by 2030 would be equivalent to the consumption in Brazil in the same year.

For China, Japan and ROW-BR, differences between Scenarios 1 and 2 exist only after 2020. The hypothesis is that fuel ethanol consumption will be equivalent to E10 or E15 by 2030, respectively, leading in both cases to a dramatic growth on consumption, especially in the ROW-BR region. Consequently, the estimated annual growth rates of consumption are very large, mainly in very short term.

For Brazil, fuel ethanol consumption has been estimated close of its maximum. It seems very improbable that in a competitive market (induced by a large fleet of FFVs) fuel ethanol consumption could be higher than 55–60% vis-à-vis the total fuel consumption (volume basis).

Based on present trends, even the estimate of Scenario 1 seems very optimistic. It is clear that on a global scale, displacing 10% of gasoline by ethanol in 2030 will be a considerable achievement.

4.3. *Evaluating fuel ethanol production and trade*

Future fuel ethanol production in a specific country will depend on a set of circumstances, such as supportive policies to local farmers, concerns with energy dependence, food

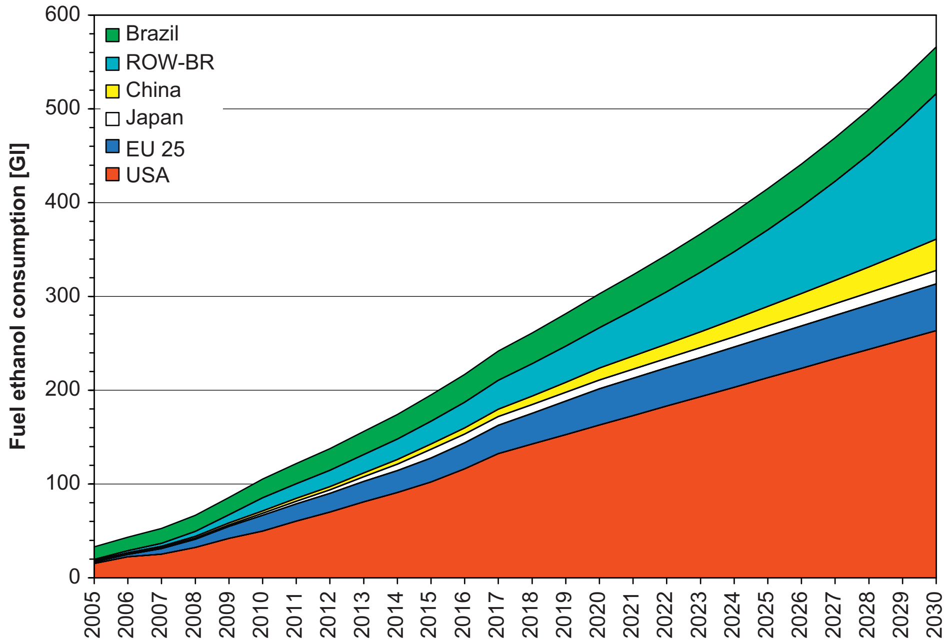

Fig. 7 – Estimated consumption of fuel ethanol in the 2006–2030 period—Scenario 2.

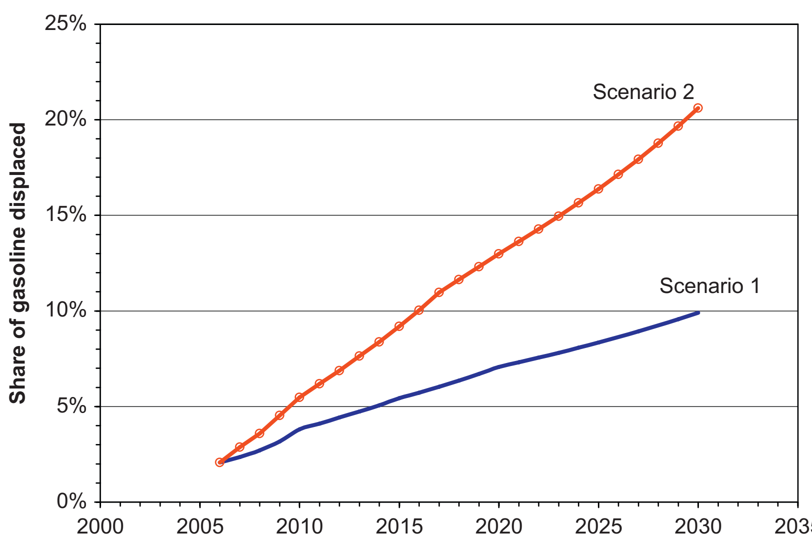

Fig. 8 – Estimated share of gasoline displaced due to fuel ethanol use.

supply, future costs of oil and ethanol production, availability of land, environment and so forth.

Assessing the magnitude of fuel ethanol trade in the short- to mid-term with any degree of accuracy is a difficult task due to the large number of variables involved and lack of reliable data. The evaluation presented in this paper is based on comparing ethanol consumption (previously presented) and estimates of domestic production capacity.

Production capacity was evaluated according to the following procedure. Firstly, we evaluated the capacity for fuel ethanol production in 2005. Secondly, the production capacity in 2020 was estimated based on trends of increasing capacity and estimates available in the literature. Finally, projections were done for each region/country in order to estimate the capacities in 2030. In some cases projections were also carried out for 2020. Although uncertain, the estimates of ethanol production capacity based on conventional feedstocks and technologies are more accurate than in the case of production from cellulosic-based materials. In case of Japan it was assumed as a way of simplification that no conditions exist to produce ethanol from biomass; this hypothesis is reasonable in case of ethanol production from conventional feedstocks, but this is not necessarily the case of cellulose-based ethanol. The estimates of production capacity of fuel ethanol from 2005 to 2030 are presented in Table 6.

Table 5 – World fuel ethanol consumption in 2005 (data and estimates) and 2030 (estimates)

Country/ region	Consumption (Gl) in 2005	Scenario 1			Scenario 2		
		Consumption (Gl) in 2030	Annual growth rates 2005–2010 (%)	Annual growth rates 2005–2030 (%)	Consumption (Gl) in 2030	Annual growth rates 2005–2010 (%)	Annual growth rates 2005–2030 (%)
USA	15.3 (46.4%)[a]	55.3 (20.3%)	8.4	5.3	263.7 (46.6%)	26.7	12.1
EU-25	1.6 (4.9%)[b]	36.0 (13.2%)	26.0	13.2	49.6 (8.8%)	59.9	14.7
Japan	0.5 (1.5%)[c]	9.3 (3.4%)	34.3	12.5	14.3 (2.5%)	34.3	14.5
China	1.0 (3.0%)[d]	21.6 (7.9%)	20.4	13.1	33.5 (5.9%)	20.4	15.1
ROW-BR	1.3 (3.9%)[e]	100.2 (36.8%)	60.8	19.0	154.9 (27.4%)	60.8	21.1
Brazil	13.3 (40.3%)[f]	50.0 (18.3%)	8.6	5.4	50.0 (8.8%)	8.6	5.4
World	33.0	272.4	15.1	8.8	566.0	26.1	12.0

[a] [27].
[b] Consumption estimated as the domestic production of about 900 Ml [40] plus the imports of 700 Ml [31].
[c] Consumption in 2005 estimated equivalent to the net volume of imported undenatured ethanol [31].
[d] [45].
[e] Consumption calculated per difference, considering the world fuel ethanol consumption equal to 33 Gl.
[f] [28].

Average annual growth rates on the production capacity are presented in Table 6 (see also notes). In all cases the growth percentages are reduced along the period, reflecting constraints on fuel ethanol production based on conventional feedstocks and conversion process. In this sense, the assumptions are not ambitious. Considering global production capacity, average annual growth rates fall from 17.2% from 2005 to 2010 to 5.5% from 2010 to 2020 and to 2.85% from 2020 to 2030. In contrast, the average annual growth percentages are very high in the case of fuel ethanol from cellulosic materials (34.8% and 35.7% for US and the World, respectively, in the period 2020–2030). This is a very ambitious target and it is clear from these results that to achieve this level of ethanol production from cellulosic material is going to be a major challenge.

A complementary step was taken to verify whether it would be possible to reach the estimated production capacities (e.g., land availability could be a serious constraint). Results presented by [60] were used for this purpose. The study considers that up to 2020 only current commercial technologies of ethanol production would be available (from sugarcane, grain, beet, etc.) and that after 2020 some ethanol plants will start using cellulosic material. This hypothesis is on-line with Scenario 1 of ethanol consumption, but not with Scenario 2. The evaluation carried out by [60] considers constraints on land availability (food crops and biodiesel production), evolution and limits on yields and a steady and feasible growth of ethanol fuel production capacity. Table 7 presents the estimated limits of fuel ethanol production based on current commercial technologies for the main regions/countries according to [60]. In case of US and EU, the maximum capacity of ethanol production using traditional technologies and feedstocks would be 68.2 and 27.3 Gl, respectively. Once these targets are achieved, no further expansion could take place. The maximum capacity in Brazil in 2010 (21 Gl) estimated by [60] is lower than the figure presented by the Brazilian government (25–26 Gl) and, thus, 21 Gl was not considered a constraint.

The comparison between Tables 6 and 7 indicates that the estimated production in EU-25 by 2030 (40 Gl; see Table 6) is well above the maximum possible from conventional technology (27.3 Gl) (Table 7). Thus, 27.3 Gl is the limit to be considered once this production is achieved between 2020 and 2030.

In case ethanol from cellulosic materials is available only toward the end of the period, US DOE [32] estimated for 2030 about 4 Gl of ethanol would be produced in US, increasing the maximum production capacity from 63 Gl (Table 6) to 67 Gl. For the EU it was also assumed that the production of 4 Gl from cellulosic material by 2030, pushes its maximum capacity to 31.3 Gl. For China, only ethanol from sugarcane has been considered by Fulton [60] and here it was assumed that the difference would be produced from other feedstocks.

The estimated capacity of ethanol from conventional feedstocks along the period is shown in Fig. 9, which could reach 180 Gl in 2030. Roughly, one third of the estimated capacity would be in US, one third in Brazil and another third in the rest of the world. As mentioned, a further 8 Gl from cellulosic materials could be expected by 2030.

It is worth noticing that from 2020 onwards the estimated production capacity through conventional feedstocks would be close to its maximum in EU-25 and China. Thus, without ethanol production from cellulose and significant imports, this tight situation could result in risky shortage and high costs. In the US in the same period the production capacity will be close to 55 Gl, the maximum can be produced from corn according to some experts (e.g., [38]). In Brazil, by 2030 the production capacity would be about 50% of its possible

Table 6 – Estimates of production capacity—fuel ethanol (Gl)

Region/country	2005	2010	2020	2030
Conventional feedstocks				
US	16.2[1]	45.0[a]	58.0[b]	63.0[b]
EU-25	2.1[2]	9.5[c]	24.8[d]	40.0[d]
China	1.3[3]	2.5[4]	12.6[4]	18.2[e]
ROW-BR[f]	1.0	2.5	6.0	10.3
Brazil	18.0[5]	26.0[6]	44.7[g]	62.0[g]
World	38.6	85.5	146.1	193.5
Cellulosic materials				
US	–	–	9.0[h]	178.0[7]
World	–	–	9.6[i]	203.0[8]

Sources: [1][27], [2][40], [3][44], [4][45,46], [5][28], [6][58], [7][59], [8][60].
[a] Assumed by the authors based on predicted production capacity of 40–42 Gl by 2009 [25].
[b] Calculated by the authors based on an adjusted logistic function to the recent data of production capacity [25], considering the estimate by 2010 and the hypothesis that ethanol production from corn must reach 55 Gl by 2017. The annual growth rates on production capacity would be 2.57% from 2010 to 2020 and 0.83% from 2020 to 2030. As comparison, the annual growth rates from 2004 to 2007 were 21%.
[c] Authors assumptions based on predicted production capacity of 7.7 Gl by the end of 2008 [40]. The average annual growth rate from 2007 to 2010 would be slightly larger than 27%, while the predicted annual growth rate on production capacity from 2005 to 2007 was 48% [40].
[d] Authors calculations based on an adjusted linear function [$-3072.5+1.53$ (year)] to the current production capacity and considering estimate capacities in the years to come [40]. Average annual growth rates would be 10% from 2010 to 2020 and 4.9% from 2020 to 2030.
[e] Authors calculations based on a polynomial function [$13{,}942-14.185$ (year)$+3.6\times10^{-3}$ (year)^2] adjusted to the data of previous years. Average annual growth rates would be 17.6% from 2010 to 2020 and 3.7% from 2020 to 2030.
[f] Authors estimates. Average annual growth rates would be 20.1% from 2005 to 2010, 9.1% from 2010 to 2020 and 5.6% from 2020 to 2030.
[g] Authors estimates based on an adjusted function to previous years. Average annual growth rates from 2005 to 2010 are 7.6%. From 2010 to 2020 it was estimated to 5.7%, and 3.3% from 2020 to 2030.
[h,i] Authors calculations based on an exponential function adjusted to the production capacity by 2030 estimated by [59,60], supposing the commercial production at 1 Gl scale will start in 2012.

maximum [60]. For ROW-BR the adopted procedure leads to a very low production capacity (10.3 Gl) in 2030 compared to the estimated potential capacity (ca. 172 Gl of which 161 Gl would be from sugarcane). The potential of ethanol production in ROW-BR is huge and should be the object of further studies.

Finally, the comparison between the estimated consumption of fuel ethanol over the period 2005–2030—according to Scenario 1 (see Section 4.2)—and the results of production capacity shown in Fig. 9 allow the evaluation of deficits and surpluses in each region/country, as illustrated in Fig. 10.

In the short term (2010), as can be seen, the balance is basically zero for China, negative for Japan (2.1 Gl which would have to be met by imports) and EU-25 (2.3 Gl also to be imported), but positive for US and Brazil. The balance in EU-25 is also negative in 2020 (2.0 Gl) and in 2030 (4.7 Gl), even considering the maximum possible production from grains and sugar beet, and including the production of 4 Gl of ethanol from cellulose (in 2030). In China the balance is still zero in 2020, but negative in 2030 (3.4 Gl). Japan would have to import about 9.3 Gl in 2030.

In the case of US, in Scenario 1 fuel ethanol consumption in 2030 corresponds to an average consumption lower than E10. In this case the surplus capacity would be sizeable (21 Gl in 2020 and 12.2 Gl in 2030) and at least partially the most expensive production could be avoided. But in case of E10 blend, even with 4 Gl of ethanol from cellulose the supply deficit would be significant (9.3 Gl in 2020 and 16.6 Gl in 2030).

The results show that Brazil can export 12 Gl in 2030, although the export potential is much larger. In 2006 the average ethanol production was 5609 l/ha [29]; based on a growth rate yield of 0.9%/year [60], producing 62 Gl in 2030 would require less than 9 Mha, compared to 3.1 Mha in 2006 [29]. About 90 Mha surplus lands can be used in Brazil without displacing food production or preserved areas. Thus, to produce 100 Gl (50 Gl for domestic consumption and 50 Gl for exports) 14.4 Mha would be required of which 11.3 Mha would be new lands.

For the ROW-BR case, large deficits of fuel ethanol supply can be observed in Fig. 11, ranging from 11 Gl in 2010 to 90 Gl in 2030. However, the potential for ethanol production in this region is high as India alone could produce between 6 Gl in 2010 and 50 Gl in 2030 from sugarcane [60]. Fig. 11 also compares the deficits estimated in this paper with the potential estimated by [60] for ethanol production from sugarcane. Depending on the year, 45–65% of the potential ethanol production capacity from sugarcane would be enough to match the estimated demand, except Brazil.

According to the estimates presented in Table 6, it will be impossible to match the consumption predicted in Scenario 2. Table 8 presents the balance between demand and supply in US and in the rest of the world, bearing in mind the evolution of ethanol from cellulosic materials as presented in Table 6. In case it would not be possible to accelerate and increase ethanol production from second generation, the only way to make Scenario 2 a reality (displacement of about 20% of predicted gasoline consumption by 2030) would be large-scale production of ethanol from sugarcane in developing countries. To match the demand predicted in Scenario 2, Brazil and ROW-BR would have to export at least 14.5 Gl in 2010, 73.9 Gl in 2020 and 71.8 Gl in 2030, i.e., 13% (2030) to 25% (2020) of the whole ethanol demand.

In case no significant cellulose ethanol production occurs in this the period, if US goes for E10 in 2030 (Scenario 1 for other countries), and based on the optimistic assumption that US and EU-25 can reach their full ethanol production potential, the amount of fuel ethanol that could be traded to match demand in 2020 (in US, EU-25, Japan and China) is estimated at about 21 Gl, and close to 34 Gl in 2030, i.e., 24% and 28%, respectively, of their combined consumption. In this case local production in US and EU would be very expensive.

In case of no significant production of ethanol from cellulosic materials, an alternative scenario assumes that

Table 7 – Limits on fuel ethanol production—2010–2030 (Gl)

Region/country	Comments	2010	2020	2030
US[a]	Ethanol produced from corn	28.9	68.2	68.2
EU-25	Production from grain+beet	12.1	27.3	27.3
China	Ethanol produced from sugarcane	1.9	7.6	16.0
ROW-BR[b]	From different feedstocks	22.4	96.1	171.9
Brazil	Ethanol produced from sugarcane	21.0	61.3	121.2
World[c]		86.3	260.5	404.6

Source: [60].
[a] Information from [60] corresponds to the maximum production in North America, that was used here as a proxy of the maximum production capacity in US.
[b] Calculated as a difference.
[c] Calculated from the total estimated maximum production capacity minus the estimated production capacity from cellulosic material.

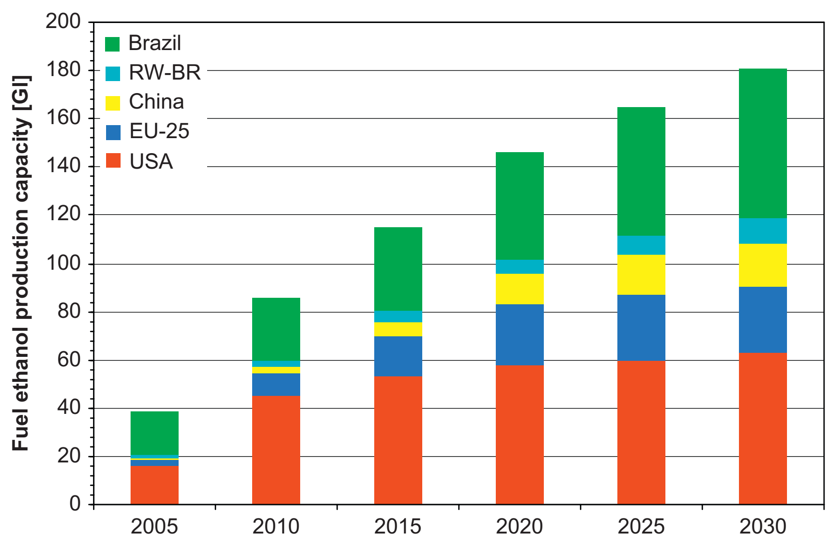

Fig. 9 – Estimated capacity of production of fuel ethanol without significant production from cellulosic materials.

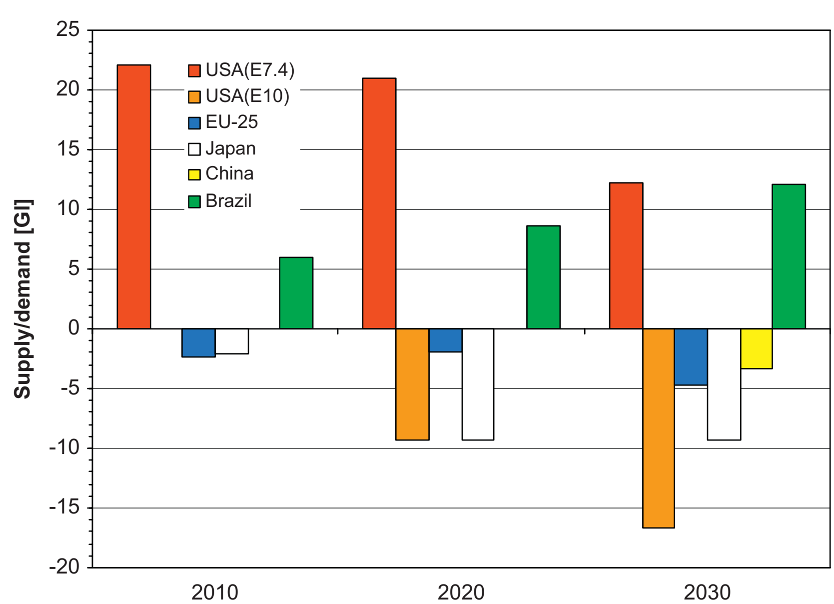

Fig. 10 – Estimated balance between potential supply and demand (Scenario 1) of fuel ethanol [Gl].

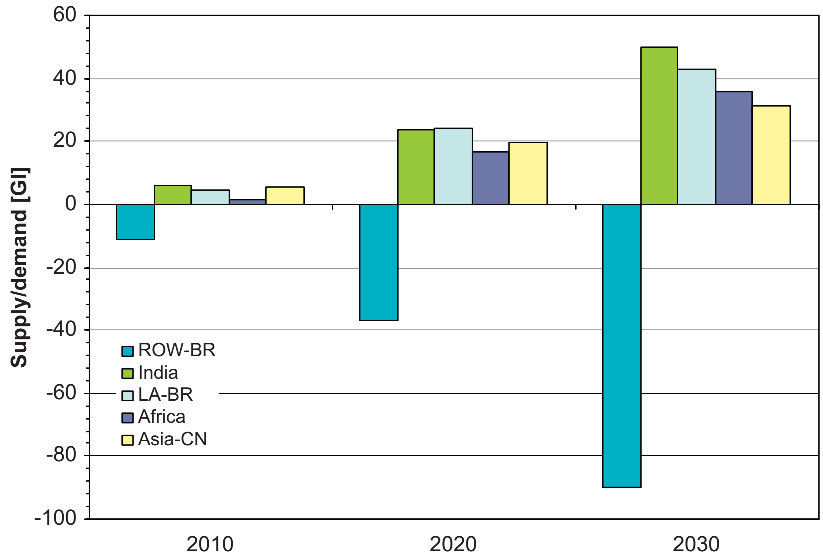

Fig. 11 – Estimated balance between potential supply and demand of fuel ethanol [Gl]—ROW-BR. *Source*: The potential supply [60].

Table 8 – Balance Demand–Supply according to consumption predicted in Scenario 2—2010–2030 (Gl)

	Comments	2010	2020	2030
US	Considering production of cellulosic ethanol from 2012 onwards (see Table 6)	−5.0	−95.8	−22.7
World	Considering production of cellulosic ethanol from 2012 onwards (see Table 6)	−19.9	−146.7	−182.2
World	Considering production of ethanol from cellulose and large-scale production from sugarcane[a]	0.0	4.3	16.4

[a] Production of 26 Gl in Brazil and 22.4 Gl in ROW-BR in 2010; 61.3 Gl in Brazil and 96.1 Gl in ROW-BR in 2020; and of 121.2 Gl in Brazil and 171.9 Gl in ROW-BR in 2030.

US and EU would impose quotas for imports to avoid expensive supply. If these quotas were 30% of their domestic market in 2030, the traded volume required to meet the combined demand of US, EU, Japan and China is estimated as about 46 Gl (38% of the estimated consumption in Scenario 1). In this case US would have to import 22.4 Gl and EU 10.8 Gl.

The relatively modest target to displace 10% of the gasoline demand in 2030 (Scenario 1), at reasonable cost, can only be accomplished fostering fuel ethanol production in developing countries and, most importantly, enhancing ethanol trade. An even greater challenge will be to replace 20% of the gasoline demand by 2030; this will require the development of second-generation technologies and a considerable expansion of international trade.

5. Fuel ethanol trade

Traditional trade theory argues that economies gain from trade by specialising in products where they have a comparative advantage [61]. Thus, those who produce at lower costs and with higher quality should have trade advantages. In practice, however, this is not the case because countries impose trade barriers to protect local production.

Fuel ethanol trade is still in its infancy and there are still many barriers which, unless removed or changed, will hinder the development of bioenergy in countries with comparative advantages and encourage the development of biofuels production where it is more expensive [3].

5.1. *Recent trade flows*

Ethanol trade data are imprecise due to various potential uses and lack of proper codes for biofuels in the Harmonized System Commodity Description and Coding System (HS) [62]. Estimates [31] indicate that ethanol trade (all grades) has grown steadily from about 3 Gl in 2000 to 6 Gl in 2005 (i.e., about 13% of the world production, estimated as 44.9 Gl). From 1995 to 2002 this varied between 2.8 and 3.8 Gl; assuming that the rise in recent years was primarily fuel ethanol, it is reasonable to estimate that in 2005 about 10% of the fuel ethanol consumption was traded.

Fuel ethanol is traded under HS code 2207, which covers denatured and undenatured alcohol. Both can be used as fuel but denatured ethanol is often used as a solvent [62]. In this case a chemical substance is added to make ethanol undrinkable and its removal is expensive [48]. From the 6 Gl traded in 2005, 4.7 Gl (almost 80%) was undenatured ethanol with at least 80 degrees strength [31]. Denatured ethanol, 20% of the traded volume in 2005, remained basically unchanged during 2000–2004 [62].

FO Licht data [31] show the origin of 5.5 Gl exported in 2005 and the destination of 4.5 Gl imported, i.e., roughly 92% and 75% of the volume traded (all grades), respectively. Brazil was by far the main exporter (48%), followed by US, France and South Africa (6% each). US was the main importer with 18%, followed by Japan (11%), India, Germany and Netherlands (8% each).

Almost 97% of the Brazilian exports in 2005 were undenatured ethanol with high-degree strength, of which about 96% was fuel ethanol. In 2005 Brazil exported to 47 countries but the bulk of the trade was with just 12 countries (almost 92% of the total volume) [12]. The increase on Brazilian exports from 2003 to 2004 was 1.6 Gl, that was almost the whole expansion of world trade. The growth was much lower from 2004 to 2005 (190 Ml vis-à-vis an increase of about 1 Gl on trade); South Africa presented an increase of 871 Ml on its exports from 2004 to 2005 [63]. Table 9 shows exports of ethanol from Brazil from 2004 to 2006.

Fig. 12 shows the evolution of Brazilian exports/imports of fuel ethanol from 1980 to 2006. In the 1990s, during a critical period of ethanol production, Brazil was forced to import a significant amount of ethanol (mostly from US and South Africa) which in most cases was of poor quality.

From 2002 to 2005 US imported small quantities of ethanol mainly from Central America and Caribbean countries. However, in 2006 US imported almost 2.5 Gl (about 12% of the fuel consumption) [25], 1642 Ml from Brazil and 628 Ml from Jamaica, Costa Rica, El Salvador and Trinidad Tobago, of which at least 480 Ml (76%) was also originally from Brazil [12]. Up to 7% of the US ethanol demand may be imported duty-free under the Caribbean Basin Initiative (CBI), even if the ethanol comes from outside these countries [62].

5.2. *Trade regimes on biofuels*

In 2005, the net amount of ethanol imported by US was estimated as 600 Ml or about 5% of domestic consumption. Net imports by EU-25 in 2005 were equivalent, or 19% of total consumption [31].

US impose most-favoured nations (MFNs) import duties of 142.7 US$/m^3 plus a 2.5% *ad valorem* (according to value) tariff on ethanol. MFN basically means normal trade rules, with no special advantage and no special constraint. In many cases

Table 9 – Brazilian exports of ethanol (all grades), 2004–2006

2006			2005			2004		
Country	(Ml)	US$/m^3	Country	(Ml)	US$/m^3	Country	(Ml)	US$/m^3
US	1749.2	504.43	India	414.2	278.07	India	478.6	194.24
Netherlands	344.5	439.35	Japan	317.9	292.75	US	424.6	189.46
Japan	227.7	418.15	Netherlands	264.3	301.01	S. Korea	278.4	201.19
Sweden	201.3	394.04	US	260.6	297.28	Japan	223.2	198.73
El Salvador	182.7	439.41	Sweden	245.1	286.03	Sweden	193.4	238.98
Total/avg	3416.6	469.69	Total/avg	2598.5	294.29	Total/avg	2408.3	206.68

Source: [12].

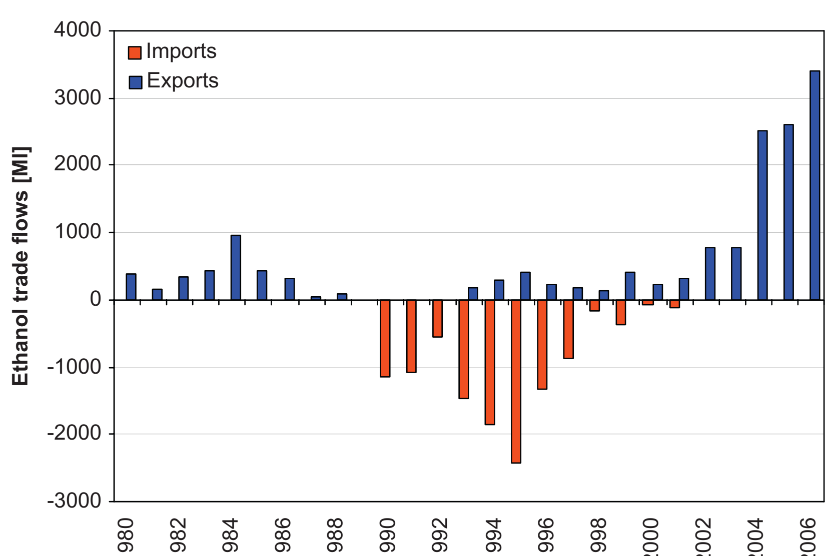

Fig. 12 – Brazilian trade flows of fuel ethanol—1980–2006. *Source*: [28].

this tariff offsets lower production costs and imposes a significant barrier to imports. An argument seldom presented in US is that these tariffs ensure that the benefits of the domestic US ethanol tax credit do not accrue to foreign producers [64].

US gives special treatment under the CBI agreement but the amount traded under this regime has been far below the 7% cap (e.g., about 3% in 2005). However, the situation may change as new investment is going into ethanol plants in Caribbean [62].

Despite the small market, duty-free treatment of ethanol in US has raised some concerns. Some experts believe that trade liberalization would induce modernization of the US industry and could act as safeguard against supply disruptions. Nonetheless, an attempt to get rid to the MFN import duties on ethanol in 2006 failed due to strong opposition from the Midwest senators [31]. In addition, the numerous state-level subsidies provide so many incentives to domestic production that barriers to imports would remain even if the import tariffs were to be removed [62].

The economic impacts of full ethanol trade liberalization in US were analysed by Elobeid and Tokgoz [65]. Their conclusions are that in US the consumption should increase by 3.2% (about 500 Ml in 2005), with 7.5% reduction of the domestic production and 14.1% decrease of the domestic prices. Net ethanol imports to US should increase 192.8% (about 1.2 Gl, based on imports figures in 2005). The authors also evaluated the impacts on Brazilian ethanol production and estimated that it could lead to an increase of 8.8% (1.4 Gl) and about 62% increase on exports (1.6 Gl) and a 3.2% reduction in the domestic consumption (425 Ml in 2005).

Based on the European Commission [31], 45% of the ethanol imported by EU in 2005 was under the MFN regime; 29% under reduced duty regimes and 26% was duty-free. Under MFN regime EU imposes a duty of 192 Euro/m^3 on undenatured alcohol (102 Euro/m^3 in case of denatured alcohol); e.g., all import from Brazil are under MFN rules. Reduced duty and duty-free regimes operate under preferential trade arrangements between EU and developing countries. Many countries of Africa, South and Central America and Asia are included in these preferential trade arrangements that aim at drug diversion, sustainable development and good governance [62].

Other countries, such Australia and Canada, have MFN duties on ethanol imports, and even Brazil, which often complains against trade duties imposed by US and EU, imposes a tariff of 60 Euro/m^3 on imported ethanol.

Part of the difficulties of biofuels trade liberalization has roots in agricultural policies and the need to protect farmers, e.g., ethanol is internationally classified as an agricultural product, but biodiesel is classified as industrial [62]. After the failure of the Doha Round, in 2006, opportunities for trade agreements have subsided and confined primarily to bilateral agreements.

5.3. *Market requirements*

5.3.1. *Standardization of the final product*

One of the current constraints for fuel ethanol trade is the lack of an internationally agreed standard. Standardization will have a direct impact on international ethanol trade as it is vital to establish agreed fuel characteristics (e.g., maximum water content, aldehydes, flash point, explosion limits, pH, etc.). For example, even EU MS do not have harmonized standards on ethanol which complicates trade (currently a specification often used is that of Swedish company Sekab [66]). The EU is currently developing an ethanol fuel standard along the lines of the American Society of Technical Material (ASTM) D4806 (Standard Specification for Denatured Fuel Ethanol for Blending with Gasoline) adopted in many US states [66].

In Brazil, the National Petroleum Agency (ANP) is responsible for specifying and supervising the quality of all commercial fuels, including biofuels. Other agencies, e.g., the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), are developing methods and procedures for quality testing of ethanol. An important aim of the agreement signed between US and Brazil in 2007 is to set standards for ethanol. Brazilian INMETRO and ASTM are responsible for this task.

5.3.2. *Sustainability and certification*

Certification schemes can play a key role in the future to ensure fuel ethanol is sustainable, particularly in EU where consumers tend to be more sensitive to environmental and social issues [62] and where some initiatives are being investigated [67–69].

Despite divergences, most experts agree that the following issues should be considered to ensure the sustainability of biofuels [67]: (i) a minimum reduction of GHG emissions should be reached vis-à-vis life cycle of conventional fuels; (ii) biofuels production should not jeopardize food production or contribute to significant raise of food prices; (iii) production of biofuels should not impact negatively on natural ecological systems or contribute to the reduction of water availability; (iv) biofuels production should not cause any important impact on soil and water bodies as consequence of the large-scale use of agrochemicals; (v) biofuels production should impact positively in the region where they are produced; and (vi) biofuels production should have a positively social impact on the employees and the local population.

Certification issue is rather complex, firstly because the diversity of views on sustainability, and secondly because there is a growing perception in many developing countries that certification schemes could end up as technical barriers to international trade. At this stage it is not clear what will be the impacts of certification schemes on production costs and trade of biofuels. There is a danger that stringent certification will hinder rather than enhance the biofuels industry, which is being subjected to unprecedented scrutiny. It is crucial that sustainability criteria are widely agreed among producers and consumers. Smeets et al. (this issue) provide some insights for ethanol from sugarcane under Brazilian conditions.

Given the importance of GHG emissions reduction and concerns with food prices [70], certification of biofuels production could impact negatively on ethanol produced from corn and cereals and provide some advantage to ethanol from sugarcane and lingo-cellulosic materials.

Biofuels certification is not the main target of this paper (see Dam et al., this issue). It is essential that certification should not become an obstacle to the international bioenergy trade [62] and ant sustainability criteria can only be widely accepted if it is developed through transparent discussions between consuming and producing countries.

6. Conclusions

Ethanol production and demand has grown rapidly in recent years, largely spearheaded by policies rather than by genuine market forces. Worldwide, fuel ethanol is currently equivalent to about 2% of the gasoline consumption and its share could reach 10–20% by 2030.

To achieve these targets is a major challenge. For instance, this will require increasing production capacity from about 38 Gl (estimated as of 2005) to at least 275 or 570 Gl in 2030 (a seven-fold increase in 25 years). Considering that 60% of this capacity would have to be built in developing countries, the challenge is even greater. The initial cost of producing and using biofuels are high and a new biofuel industry needs the support of investors, farmers, fuel distributors, car manufacturers, not to mention a strong cooperation among countries and companies [8].

International ethanol trade is still in its initial stage and there are many barriers to be overcome. It seems clear from this paper that even a 10% displacement of the gasoline by biofuels in 2030 can only be possible through international ethanol fuel trade, as all major consumers lack the capacity to produce ethanol in large scale and at lower costs.

Second generation of ethanol would be vital if 20% of the gasoline demand is to be replaced by biofuels by 2030, although a significant contribution would have to come from conventional feedstocks mainly from developing countries. On the other hand, large-scale production of biofuels in developing countries would require the removal of trade barriers and technical and financial international cooperation.

Acknowledgements

The authors acknowledge the reviewers' comments on the draft version of this paper.

REFERENCES

[1] BP. The global ethanol industry is going through a period of rapid growth; 2006 Available at ⟨www.bp.com⟩.
[2] ESMAP. Energy sector management assistance programme. Potential for biofuels for transport in developing countries. Washington: The World Bank Group; 2005.
[3] Hazell P, Pachauri RK. Bioenergy and agriculture: promises and challenges—Overview. Focus. International Food Policy Research Institute—IFPRI; 2006 Available at ⟨http://www.ifpri.org/pubs/catalog.htm#focus⟩.
[4] IEA. Medium term oil market report. Paris: International Energy Agency; 2006.
[5] Romm J. The car and fuel of the future. Energy Policy 2006;34:2609–14.
[6] WSDA. Bioenergy: frequent asked questions. Washington: Washington State Department of Agriculture; 2006 Available at ⟨http://agr.wa.gov/bioenergy/faqs.html⟩.
[7] United Nations Foundation. The United Nations biofuels initiative. New York: United Nations; 2006 Available at ⟨www.unfoundation.org⟩.
[8] Hazell P, von Braun J. Biofuels: a win–win approach that can serve the poor. International Food Policy Research Institute—IFPRI Forum; 2006 Available at ⟨http://www.ifpri.org/pubs/catalog.htm#focus⟩.
[9] Hunt S, Förster E. Biofuels for transportation: global potential and implications for sustainable agriculture and energy in the 21st century. Renewable Energy World 2006;9(4).
[10] World Bank. Clean energy and development: towards an investment framework. Report DC2006-0002. Washington: World Bank; 2006.
[11] Goldemberg J. The Brazilian energy initiative-support report. Paper presented at the Johannesburg 2002 world summit for sustainable development, 2002.
[12] Unica—União da Indústria de Cana de Açúcar; 2007 Available at ⟨www.unica.com.br⟩.
[13] Thomas V, Kwong A. Ethanol as a lead replacement: phasing out leaded gasoline in Africa. Energy Policy 2001;29:1133–43.
[14] IEA. Biofuels for transport—an international perspective. Paris: International Energy Agency; 2004.
[15] Niven RK. Ethanol in gasoline: environmental impacts and sustainability review article. Renewable & Sustainable Energy Reviews 2005;9:535–55.
[16] Whitten GZ, Reys S. Air quality and ethanol in gasoline. Presented at the ninth annual national ethanol conference: policy & marketing, 2004.
[17] Nastari P, Macedo IC, Szwarc A. Observations on the draft document entitled "Potential for biofuels for transport in developing countries". Washington: World Bank; 2005.
[18] Joseph Jr H. Long term experience from dedicated & flex fuel ethanol vehicles in Brazil. In: Clean vehicles and fuels symposium, Stockholm; 2005.
[19] IPCC. Intergovernmental panel on climate change. Climate change 2001: the scientific basis. Cambridge: Cambridge University Press; 2001.
[20] Macedo IC, Leal MRLV, Silva JEAR. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. São Paulo: Secretariat of the Environment; 2004.
[21] Nastari P. Etanol de cana-de-açúcar: o Combustível de Hoje. Presentation at Proalcool—30 anos depois, São Paulo, 2005.
[22] Licht FO. World ethanol & biofuels report, vol. 3(2), 2005.
[23] REN21. Renewables—global status report—2006 update. Renewable energy policy network for the 21st century; 2006 Available at ⟨www.ren21.net⟩.
[24] Worldwatch Institute. Biofuels for transportation. global potential and implications for sustainable agriculture and energy in the 21st Century. Prepared for the German Ministry of Food, Agriculture and Consumer Protection in coordination with the German Agency for Technical Cooperation and the German Agency of Renewable Resources, Washington, 2006.
[25] RFA. Renewable Fuels Association. Statistics data; 2007 Available at ⟨http://www.ethanolrfa.org/industry/statistics/#C⟩.
[26] Berg C. World fuel ethanol analysis and outlook; 2004 Available at ⟨http://www.distill.com/World-Fuel-Ethanol-A&O-2004.html⟩.
[27] RFA. Renewable Fuels Association. Statistics data; 2006 Available at ⟨http://www.ethanolrfa.org/industry/statistics/#C⟩.
[28] Brasil. Balanço Energético Nacional. Brasília: Ministério de Minas e Energia; 2006 Available at ⟨www.mme.gov.br⟩.
[29] Carvalho EP. VI Conferência Internacional da Datagro. Presentation of Unica, São Paulo, 2006.

[30] RFA. Renewable Fuels Association. From niche to nation—ethanol industry outlook 2006. RFA; 2006.
[31] Licht FO. World ethanol & biofuels report, 2006, various issues.
[32] EIA. Energy Information Administration. Annual energy outlook. Washington: US Department of Energy; 2007 Available at ⟨www.eia.doe.gov/oiaf/ieo/index.html⟩.
[33] DOE. US Department of Energy. Biomass multi-year program plan. Washington: US-DOE; 2007.
[34] Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States 2006;103(30):11206–10.
[35] Wu M, Wang M, Huo H. Fuel-cycle assessment of selected bioethanol production pathways in the United States. Chicago: Argonne National Laboratory; 2006.
[36] Shapouri H, Duffield JA, Graboski MS. Estimating the net energy balance of corn ethanol. Agricultural Economic Report Number 721. Washington: US Department of Agriculture; 1995.
[37] Wang M, Wu M, Huo H. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environmental Research Letters 2007;2:1–13.
[38] Flavell R. Biotechnology options for bioenergy crops: prospects for 2nd generation feedstock technologies. USDA Global Conference on Biofuels, Minneapolis; 2007.
[39] Rosillo-Calle F, Silveira S, Duic N. Chapter in the book "Fuel ethanol in Brazil—past, present and future," forthcoming.
[40] EBIO. Bioethanol fuel in numbers. European Biofuel Association; 2007 Available at ⟨www.ebio.org⟩.
[41] USDA. The economics of bioethanol production in the EU 2006. Washington: United States Department of Agriculture; 2006.
[42] Faaij A. Bio-energy in Europe: changing technology choices. Energy Policy 2006;34:322–42.
[43] Piacente EA. Perspectives for Brazil in the bio-ethanol market. MSc dissertation, State University of Campinas, Campinas, 2006.
[44] DSD. Feasibility study on an effective and sustainable bioethanol production program by least developed countries as alternative to cane sugar export. Dutch Sustainable Development Group; 2005.
[45] Martinot E. Biofuels global market and policy overview. In: World biofuels symposium—China, Beijing; 2006.
[46] Liu D. Chinese development status of bioethanol and biodiesel. In: World biofuels symposium—China, Beijing; 2006.
[47] Zhenhong Y. Bio-fuels industry in China: utilization of ethanol and biodiesel today and future. In: World biofuels symposium—China, Beijing; 2006.
[48] Rosillo-Calle F, Walter A. Global market for bioethanol: historical trends and future prospects. Energy for Sustainable Development 2006;X(1):18–30.
[49] Beltrán COB. Structural and environmental aspects of bioethanol production in Colombia. International Sugar Journal 2007;109(1297):41–5.
[50] IEA. Energy technology and perspectives 2006—scenarios & strategies to 2050. Paris: International Energy Agency; 2006.
[51] BP. BP statistical review of world energy; 2006 Available at ⟨http://www.bp.com/statisticalreview⟩.
[52] IEA. IEA statistics. Paris: International Energy Agency; 2006 Available at ⟨http://www.iea.org⟩.
[53] IEA. Annual statistical supplement. Paris: International Energy Agency; 2003 Available at ⟨http://www.iea.org⟩.
[54] Ayoub PM. Biofuels for Shell—biomass based blending components for transport fuels (gasoline and diesel). In: World biofuels symposium—China, Beijing; 2006.
[55] EPE. Plano nacional de energia 2030—estratégia para a expansão da oferta. Brasília: Empresa de Pesquisa Energética; 2006.
[56] Rodson P. EU policies and targets for biofuels. In: Symposium on fuels standards and regulation, Brussels; 2007.
[57] EC. A EU strategy for biofuels, COM (2006) 34 Final. Brussels: European Commission; 2006.
[58] Brasil. Estatísticas. Brasília: Ministério de Agricultura, Pecuária e Abastecimento; 2006 Available at ⟨www.agricultura.gov.br⟩.
[59] Oak Ridge National Laboratory. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge: US DOE; 2005.
[60] Fulton L. Recent biofuels assessments and two new scenarios. Paper presented at the IEA seminar assessing the biofuels option, Paris, 2004.
[61] The Economist. More pain than gain. The new titans, September 2006. p. 12–5.
[62] Zarilli S. The emerging biofuels market: regulatory, trade and development implications. In: UNCTAD—United Nations conference on trade and development, Geneva; 2006.
[63] COMTRADE. United Nations commodity trade statistics database; 2006 Data available at ⟨http://contrade.un.org⟩.
[64] The economic effects of significant US import restraints—fourth update. United States International Trade Commission, Washington, 2004.
[65] Elobeid A, Tokgoz S. Removal of US ethanol domestic and trade distortions: impact on US and Brazilian ethanol markets; 2006 Working paper 06-WP 427 2006. Available at ⟨www.card.iastate.edu⟩.
[66] Rosillo-Calle F. The role of biofuels (ethanol and biodiesel) in the transport sector of European Union until 2025: implications for Brazil. London: Imperial College London; 2007.
[67] Cramer J, Wissema E, de Bruijne M, Lammers E, Dijk D, Jager H, et al. Testing framework for sustainable biomass—final report from the project group Sustainable Production of Biomass, Amsterdam, 2007.
[68] Frei C, Gnansounou E, Püttgen HB. Sustainable biofuels program—the need for biofuel certification/labelling. Lausanne: École Polytechnique Fédérale; 2006.
[69] Fritsche UR, Hünecke K, Hermann A, Schulze F, Wiegmann K. Sustainability standards for bioenergy. Frankfurt: WWF Germany; 2006.
[70] The Economist. The end of cheap food, 2007. p. 77–9.