Energy Policy 65 (2014) 7–15

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The future of oil and bioethanol in Brazil

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HIGHLIGHTS

- Cost-benefit analyses of pre-salt and biofuels in Brazil.
- Hubbert model applied to pre-salt oil reserves.
- Sustainable energy scenarios.
- Carbon mitigation accounting based on biofuel scenarios.
- Enhanced oil recovery effect on pre-salt oil reserves.

ARTICLE INFO

Article history:
Received 15 September 2012
Received in revised form
10 September 2013
Accepted 14 September 2013
Available online 14 October 2013

Keywords:
Biofuels
Ethanol
Pre-salt oil
Brazil

ABSTRACT

This work compares the return on investments (ROI) of oil versus biofuels in Brazil. Although several renewable energy sources might displace oil, the country's forte is sugarcane biofuels. In our analysis we carry out simplified benefit–cost analyses of producing oil fields, pre-salt oil fields (without and with enhanced oil recovery), a business as the usual ethanol scenario, and a high ethanol scenario. Excluding the ROI from existing oil fields, which is the highest, when the discount rate is 4% or more, the ROI of the high ethanol scenario is greater than that of the ROI of pre-salt oil. Considering a US$40/t CO_2 tax, the high ethanol scenario's ROI is greater than the pre-salt oil's ROI if a discount rate of 2% or more is adopted. Moreover, the high ethanol scenario throughput up to 2070 compares to 97% of the pre-salt oil reserve without EOR, and demands 78% of its investment. Pre-salt oil production declines beyond 2042 when the country might become a net oil importer. In contrast, ethanol production reaches 2.1 million - boe per day, and another 0.9 million boe of fossil demand is displaced through bioelectricity, yielding a total of 3 million boe (62% of the country's oil demand).

1. Introduction

Although some recent new oil discoveries are noteworthy, the concern that global oil peak production has already been reached is also proclaimed (Murray and King, 2012). In contrast, the potential for renewable energy sources is certainly greater than the present global energy demand (Helena et al., 2011). Currently, the renewable energy source that is responsible for the largest share of primary energy supply is biomass, whereas solar energy presents the greatest technical potential (Edenhofer et al., 2011).

Until 2002, Brazil was able to fulfill its oil demand relying mostly on its internal production. In 2006, the country became self-sufficient, but not yet fully sufficient regarding some oil products (ANP, 2011a, 2011b). Nevertheless, over the last decade, expenses of crude oil and oil products imports have declined substantially and have not been of economic concern. The 2010 production of oil and gas condensates in Brazil achieved 2.2 million bbl/day (Petrobras, 2011a). Since 2009 the perspective for future oil production in the country has substantially changed due to the discovery of potential huge off-shore reserves in the so-called “pre-salt” area (below the thick salt layer and more than 4 km below the sea bed, under a series of layers of rock and salt).

On the other hand, Brazil has shown an important potential for developing modern biomass energy carriers, whose participation in the domestic energy mix is already significant (EPE, 2011a). There is no doubt that biofuels are relevant alternatives to fossil fuels and have significant greenhouse gas mitigation potential. On an energy basis, the substitution of sugarcane ethanol for oil displaces 56 gCO_2 per MJ. Furthermore, if the substitution of bioelectricity for oil is accounted for, 84 gCO_2 per MJ is displaced (EPA, 2010). The displacement of fossil fuels and its CO_2 emissions may be translated into economic value. In our assessment we have

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http://dx.doi.org/10.1016/j.enpol.2013.09.055

considered that 1 t of avoided CO_2 is worth US$20 up to 2011 and US$40 from 2012 onwards, based on studies of several authors (Laude and Jonen, 2011; Audrey and Ricci, 2011; Fabbri et al., 2011; Interagency Working Group on Social Cost of Carbon, 2013).

In this context, the objective of this work is assessing the potential of bioenergy and comparing such potential to the energy obtained from pre-salt oil resources to meet the energy demand of the Brazilian economy up to 2070. In addition, the paper comprises a cost–benefit analysis of both ethanol and oil, and evaluates greenhouse gas emissions implications of these energy sources by internalizing the mitigation costs of CO_2 in the assessment.

Regarding the externalities associated with this two energy sources—oil and ethanol—the scope of this study is limited to CO_2 emissions and environmental impacts due to climate change. Nevertheless, many other environmental impacts can be associated with oil and ethanol production (Edenhofer et al., 2011). Trying to quantify such externalities to include them in this economic analysis would broaden the scope of the present assessment and the results of its conclusions.

2. Oil background

The pre-salt reserves in Brazil which according to the US Security and Exchange Commission (SEC) cannot be yet be fully classified as *reserves*—are expected to be incredibly large. Although the ultimate official quantification has not yet been published, some organizations and researchers claim that the amount of recovered oil in the pre-salt layers can be as large as 90 billion bbl (Brazil Oil, 2010) or as small as 14 billion bbl as quoted in the Brazilian Energy Balance of 2011 (EPE, 2011a, 2011b), or somewhere in between, around 40 billion bbl (Redepetro, 2010; Szklo et al., 2007). Since Petrobras usually keeps its data confidential, the size of the pre-salt reserves in this article was assumed to be 40 billion bbl, following previous assessments.

Petrobras, the Brazilian state-controlled oil company, has proclaimed ambitious oil production plans for this second decade of the century, and official publications convey such expectations (MME/EPE, 2011; Petrobras, 2011b). According to the information released by Petrobras, oil production in Brazil is expected to more than double, jumping from 2.2 bbl per day in 2011 to 5 million bbl per day in 2020 (Petrobras, 2011b, 2013a; MME/EPE, 2011). Since 6–10 years are required to drill and develop new oil wells before they become part of the available supply (Murray and King, 2012), these expectations regarding production up to 2020 seem highly optimistic. As it is shown in Section 5, our model indicates that, in a more realistic scenario, only 4 million bbl per day will be extracted at the production peak, which should be achieved only in 2035, 15 years later than forecasted by Petrobras. Our values are in agreement with a previous assessment (Szklo et al., 2007).

Nevertheless, the expectation regarding the reserve increases if *enhanced oil recovery* (EOR) is applied. CO_2 EOR is a well established practice when large amount of low cost CO_2 is available. Based on the US Department of Energy (DOE) results, if CO_2 is re-injected in the wells, it is possible to add to the oil reserves up to 5% of the total oil in place[1] (DOE, 2012). Therefore, considering the size of the reserve and the amount of total oil in place of the pre-salt, up to 11 billion bbl can be recovered through EOR. However, EOR technology is used only when inexpensive CO_2 is available, but the volume of CO_2 available might not be enough to carry out EOR in the Brazilian pre-salt area. In the next paragraph we discuss how much oil can be produced by CO_2 EOR in the pre-salt oil.

According to DOE (2012), in the United States, each bbl of oil on an average required 407 m^3 (0.805 t) of CO_2.[2] Considering CO_2 density equals to 1.98 kg/m^3 and oil equals to 1 kg/l, it means that pumping 805 kg of CO_2 yields 159 kg of oil (or 1 bbl). The expected amount of available CO_2 to be used for EOR depends on the amount of CO_2 mixed to oil and gas, on a mass basis. For our study we assume that 15% (Augusto Batista et al., 2011) of the pre-salt oil mass is CO_2, which is fully removed from oil before transporting it onshore. A significant amount of CO_2 is recovered from the extracted oil and in our calculation we assumed that 85% of the total CO_2 is captured and stored underground until it is required to deploy EOR.[3] In order to extract this extra volume of 11 billion bbl, 8.8 billion t of CO_2 has to be pumped, which requires, at least, 1.3 billion tCO_2 available in the exploration wells, because we are assuming the recovery rate is also 85% and no CO_2 injected is trapped inside the oil field. Considering that CO_2 storage starts as soon as pre-salt commercial oil production begins and the amount stored corresponds to the total CO_2 mixed to oil and gas, this yields only 0.80 billion t, which is below the full EOR′s demand. Under this scenario the conclusion is that not all 11 billion bbl would be recovered due to onsite CO_2 shortage. Consequently, the pre-salt EOR potential is reduced to 8 billion bbl. Accordingly, the ultimate pre-salt reserve, considering EOR, is 48 billion bbl.

There is another option besides EOR to deal with the CO_2 associated to the extracted pre-salt oil. Since the CO_2 content in the oil is above the limits set for oil exportation (ICCT, 2010; Davis et al., 2011) and Petrobras is concerned with environmentally sound practices, this CO_2 could be captured and stored forever underground to satisfy both concerns. Through CO_2 storage it is possible to prevent venting 0.90 billion tCO_2 since we have assumed its share as 15% of the total oil mass. Nevertheless, the remarkable aspect is that Petrobras might invest in this new technology trying to avoid venting 0.90 billion tCO_2 to the atmosphere (Ellsworth and Picinich, 2011). At the same time the extraction and combustion of the 40 billion barrels of pre salt oil will generate around 22.2 billion tCO_2[4] or even 26.9 billion tCO_2 if EOR is considered. However, total emission due to the use of pre-salt oil could reach 21.3 billion tCO_2, when 0.9 billion t is avoided through CCS. Thus, this option, while envisioned by Petrobras, looks very unlikely due the very small net contribution to climate change mitigation (see Fig. 5).

Besides that, reserves expansion is also a function of technology and costs. The cost of finding a new oil well and of producing one barrel of oil per day was ranging between US$5000 in the Middle East to 14,000 in Europe in early 2000s (OECD/IEA, 2003). That same cost was twice as greater in 2007 (OECD/IEA, 2008) and it has continued to increase. Although these figures were not available in Brazil they reflect a global business in which competition is limited to a few players.

3. Ethanol background

In parallel with the oil products expansion, Brazil was able to develop a significant alternative market for ethanol and biodiesel

[1] This amount is calculated using a data proxy from DOE, 2010, which reports that a set of oil producing fields in the US with a total reserve of 27 billion bbl, imply in 148 billion bbl of total oil in place (DOE, 2012). Thus, a simple linear relationship with the pre-salt oil reserve of 40 billion bbl, yields 219 billion barrels of oil in place for pre-salt oil. Thus, 5% more oil extraction through EOR adds up o 11 billion bbl.

[2] According to DOE (2012), in the United States, 237,000 bbl of oil were extracted using 950 BcfCO_2/yr (0.096 Bm^3/day).

[3] It is not our purpose in this paper to quantify energy balance of oil extracting activity, but it is worthwhile to remember that in our CO_2 leakage assumption we must consider leakage due CO_2 mixed to oil and CO_2 emission due the use of fossil fuel as an energy source required to pump CO_2 for EOR and other activities in the extraction process (Gately, 2007).

[4] The value is calculated based on data from EPA (2010), which are 92 gCO_2/MJ, 42 MJ/kg average oil product energy content and 138 (159 × 0.869) kg/bbl. These values yield 534 (0.092 × 42 × 138) kgCO_2/bbl)

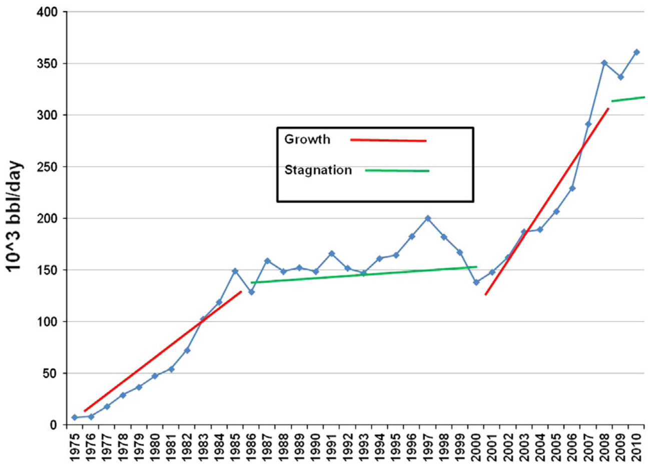

Fig. 1. Historical record of ethanol production in Brazil (MAPA, 2011; DATAGRO, 2012).

(EPE, 2011a). Regarding ethanol, the country is the world's second largest producer with a peak production of almost 30 million m^3 in 2010 (EPE, 2011a). Ethanol has been consumed by a well established fleet of flex-fuel vehicles, which demand either neat ethanol or gasoline, and all "gasoline" sold at the pumps in Brazil is indeed gasohol, which is a blend of gasoline and 18–25% ethanol.

As an alternative to gasoline, ethanol is a more sustainable option because it is possible to extract energy from the same low emission land area every year.[5] Nevertheless, the 36 years history of ethanol production, which is based on sugar cane, shows sequences of fast growing seasons during 10 or 8 years, followed by a stagnation period, which also lasts 10 years (Fig. 1). The last significant growth period was in 2003–2008, followed by the present stagnation (2009–2012). Such high growth periods are driven by different factors, but most of them are related to oil price fluctuation. Sugar prices, climate, and technology improvements are also important drivers.

The stagnation period (2009–2012) is justified by the world economic crisis which started in 2008 and severely impacted the Brazilian sugar cane mills due to the high level of debt of the sector, financed by international loans. At the beginning of the economic crisis in 2008, interest rate on foreign loans increased, and drained the resources needed to sustain the production levels. Between 2009 and 2012, money shortage for the operational costs coupled with unfavorable weather conditions affected the management of the plantations, and consequently, sugar cane production has shown a small decline. Sugar cane is a crop that needs at least 3 years to recover from lack of agricultural care. New seeds require 1 year of growth, and the commercial harvest of a new sugar cane plantation occurs 2 years after crop planting. The interruption of ethanol production growth had a negative impact because demand was escalating due to increasing sales of new flex-fuel vehicles, which was growing at 7% per year between 2006 and 2011(ANFAVEA, 2012). Obviously such recent negative impacts on the Brazilian ethanol production sector might be of concern for short-term forecasts but our study deals with a long time period (2012 to 2070) and the observed trend of the sector since 1975 is a better proxy for long-term forecasts.

The future of sugarcane as an energy crop is based on its potential to produce biofuels and bioelectricity. When all recoverable sugar of the plant (147 kg/t cane on average during harvest season) is converted into ethanol, it is possible to produce 86 l of anhydrous ethanol per tonne of sugarcane (Macedo et al., 2008). However, sugar is only part of the plant's energy. Fibers in the form of bagasse, tops, and leaves are also used to power boilers that produce steam and electricity. Using all the available bagasse, and a share of tops and leaves, it is possible to export 135 kWh of electricity per tonne of sugarcane, using high pressure boilers (Macedo et al., 2008; Conab, 2011).

[5] Several evaluations of the sugarcane crop expansion area in Brazil conclude that the land use change (LUC) contribution is small and even negative since most of the expansion has occurred over pastureland, and cattle head density is increasing and does not put pressure on the expansion to new areas (EPA, 2010; Nassar et al., 2008)

4. Methods

Our assessment comprises a series of simple calculations. Initially, we determine the evolution of oil and bioenergy supply and demand alternatives. Next, we carry out a cost–benefit analysis of the two alternatives. Finally, we include external costs due to CO_2 emissions into the analysis and calculate the implications of EOR on future scenarios. In this section, we briefly describe the model, assumptions, and the algorithms used in the assessment.

Based on likely assumptions and using Hubbert curves we construct a model of the future oil production in Brazil. We determine the costs and carbon emissions due to the deployment of the oil reserves and compare them to a bioenergy case. We build two alternative bioenergy scenarios. One business as usual scenario which considers the average growth rate of sugarcane production over the last 35 years (Low Scenario), and one aggressive scenario which represents the trend observed between 2003 and 2010, when the last significant expansion took place (High Scenario).

The oil production scenario is based on the current Brazilian oil reserves (called from now on producing fields) and the potential pre-salt reserves. Modeling of the two reserve types is achieved by a curve in which 2 Hubbert curves overlap over the analyzed period (Laherrère, 2000). The Hubbert curve, which resembles a normal distribution curve in probability theory, is set for a fixed amount of resource based on its annual production rate P

$$P = 2P_m/(1 + \cos H(5(t - t_m)/c)) \quad (1)$$

The integral of the production function (Eq. (1)) is the ultimate recovery U, P_m is the peak production, t_m is the time of peak production, and c is the duration of the half life from a cut-off at 0.027 P_m.

The value of c is calculated based on

$$c = U/0.8P_m \quad (2)$$

The current oil reserves in Brazil comprise 14 billion barrels (EPE, 2011a) and the pre salt reserves are expected to contain 40 billion barrels. Based on the 2011 production value (2.2 Mbbl/day) (Petrobras, 2011b), and assuming peak production occurs in this year we draw the Hubbert curve representing current reserves. In the case of pre-salt reserves, the assumed peak production equals 4 million bbl/day, and according to Petrobras the production from pre-salt will reach 543,000 bbl/day in 2015 (Petrobras, 2011b). Therefore, the pre-salt Hubbert curve peak occurs in 2035.

Adopting CO_2 injection, it is possible to recover up to 5% more oil from the total oil in place (see justification in Section 2), and this extra volume will start to be exploited just after the production peak in order to extend the production at the peak level for a few more years. Therefore, we extend the ultimate recoverable reserve to 48 billion bbl, with only partial recovery of the technical limit due to limited availability of locally available CO_2.

We have constructed a business as usual scenario of oil consumption in Brazil up to 2070 based on the trend over the period 2001–2010 (EPE, 2011a). We have also determined the cost associated with the producing fields and pre-salt Scenarios. For off-shore ultra-deep reserves (pre-salt) we have assumed an investment of

US$100,000[6] per bbl/day, and usually such expenses occur 4 years before the first revenue starts (DOE/EIA, 2011). For conventional oil already listed in the country′s oil reserve (producing fields) we assumed an investment cost of US$60,000 per bbl/day.

Furthermore, we have accounted for exploitation, transportation and refining oil costs. Such costs are similar for producing fields and pre-salt oil, with the respective values of US$15,[7] 5 and 10 (DOE/EIA, 2011. For the average lifetime of wells we adopted 15 years and an exponential decreasing curve (WEO, 2008). With these assumptions oil costs already transformed in oil products range from US$41.4 to US$49.0/bbl, for the producing fields and the pre-salt oil, respectively. The former value is compatible with US$42/bbl, which corresponds to the cost of finding oil in South/Central America between 2004 and 2006 (IEA ETSAP, 2010). The last value is higher than those unofficially published (Brazil Oil, 2010) but is compatible with recent estimates for deep water reserves (IEA, 2011).

Moreover, we assume that oil products market value at the refinery gate is 2.1 times its production cost[8] (note that taxes and obligations, which impact consumers′ final price, are not accounted for). Accordingly, oil products market price from current reserves and the pre-salt are respectively US$86.9 and US $102.9 per bbl. In addition, we have included in the economic analysis the externality due to CO_2 emissions.

The economic analysis is further extended because Petrobras is willing to reduce CO_2 emissions associated with the exploitation of pre-salt oil (Brazil Oil, 2010; OXAN, 2010). For imported oil, a major concern is the total amount of CO_2 associated with the well to tank fuel, which is usually below 10 gCO_2/MJ (roughly 400 gCO_2/liter of oil). This implies in very low emissions during oil extraction (ICCT, 2010). Thus, assuming that 15% of the pre-salt oil mass is CO_2 (Kennedy, 2010; De Souza, 2010),[9] it is quite reasonable that Petrobras is planning to reduce such emissions, either to be exported or to be marketed as a green company. The most probable route to be used is Carbon Capture and Storage (CCS). Under this process, CO_2 is separated from oil and gas and pumped back underground so that it is stored until productive wells start to decline. This technology is being used in a few other oil fields but storage in pre-salt region has never been performed. Even when favorable economic CCS condition exists e.g. pumping CO_2 in depleted oil wells to promote EOR, globally only 170 wells were using this approach in 2010 (DOE 2010). A major reason to avoid this technology is cost. It is remarkable that even after oil prices had been near values between US$80 and 100 during the last few years, oil companies still prefer to search for new wells instead of using EOR. In our analysis we have assumed a pre-salt CO_2 storage cost of US$30/t$CO_2$ (IEA, 2006). On top of that a degree of CO_2 losses due to process limitations and the necessity of generating electricity and heat required in the CO_2 separation process, and for its pumping into the well justifying the 85% CO_2 recovery efficiency adopted

Regarding the ethanol cost some important assumptions are (1) TRS is delivered to the mill at R$0.40/kg[10]; (2) average sugar cane amount of TRS = 147 kg/t cane, yielding a production of 86 l/tcane, since from 1.709 kgTRS we can produce 1 l of anhydrous ethanol (Macedo et al., 2008); (3) net heat content of anhydrous ethanol = 21.18 MJ/l (EPA, 2010); (4) ethanol production cost is driven by the feedstock cost, which represents 62% of the cost (, Van den Wall Bake et al., 2009; CONSECANA, 2006); (5) ethanol sales price at the sugar mill gate is 1.5 times its production cost (this choice is done in order to avoid the evaluation of taxes, duties and profit, because this would extend the article); (6) average delay between revenue collection, investments and expenses is 1 year; (7) bioelectricity is produced as a byproduct from ethanol production; (8) bioelectricity sales price is US$70/MWh (EPE, 2011b); (9) money cost for financing energy generation is 9%/yr; (10) revenue obtained from the difference between the bioelectricity sales price and cost is accounted as cost reduction for the ethanol production cost. Other important assumptions are different for the High and Low Scenarios. For the High Scenario, we assume that 135 kWh/tcane will become available for exportation by the sugar mill, using all the available sugar cane bagasse and 50% of tops and leaves, which are usually burned or dumped on the soil; (1) electricity generation cost defined by the investment cost in the cogeneration plant (steam + electricity), is US$1500/kW[11] plus an operational cost of US$5/MWh.[12] For the Low Scenario we assume: (2) 90 kWh/tcane will become available for exportation by the sugar mill, using the available sugar cane bagasse and 50% of tops and leaves, which are usually burned or dumped on the soil; (3) installed electricity capacity cost is US$800/kW[13] plus an operational cost of US$5/MWh.

5. Results

Fig. 2 shows the past and future production of oil and ethanol in Brazil, in the period of 1975 until 2070. Based on our model results, present known reserves with a peak in 2011,[14] have already produced 12 billion bbl up to 2011 and are expected to supply another 13 billion bbl. Pre-salt reserves, which total 40–48 billion bbl, without and with EOR, respectively, will peak in 2035[15] at a production rate of 1.46 billion bbl per year, and will then start to decline. During the period 2012–2041 or 2012–2051, depending on the adoption of EOR or not, Brazil will be a net exporter of oil. The most optimistic scenario, which is the one with EOR, indicates that the country will depend on imported oil after 2052, comparison of the domestic supply evolution to the annual demand up to 2070, is also shown on Fig. 2

It is very clear, under these circumstances, that Brazil′s oil production allows the country to be a net oil exporter during three or four decades but this is not enough to supply the market beyond 2052. Fig. 2 also presents the High and Low ethanol Scenarios, each one represented by 2 curves. The lower one on

[6] Based in average well lifetime of 15 years and exponential decay, used in our model, this means an upstream cost of US$14.99/bbl, modest compared with global average, onshore and offshore, upstream costs of around US$30/bbl (DOE/EIA, 2011). Since upstream cost includes exploration and production costs and the global average production costs is US$8/bbl, also quoted in the same source, the exploration cost is around US$7/bbl. These figures are optimistic for pre-salt activities since they are all located offshore.

[7] This value is compatible with lifting oil costs from (IEA ETSAP, 2010), mainly considering cost increases in the last few years

[8] This figure is obtained from the ratio between Petrobras gross revenue and total costs in the period 2006–2010 (Petrobras 2011a, 2011c).

[9] This is the average TRS market price between 2007 and 2011 (UDOP, 2012)

[10] The real cost is US$2500/kW, but we assume that the first 1000 is already included in the ethanol cost since the mill needs steam for processing sugar cane.

[11] The real cost is US$2500/kW, but we assume that the first 1000 is already included in the ethanol cost since the mill needs steam for processing sugar cane.

[12] The cost is US$10/MWh, but since heat is produced and consumed for ethanol production we share the cost in equal parts between electricity generation and ethanol production

[13] The real cost is US$1800/kW, but we assume that the first 1000 is already included in the ethanol cost since the mill needs steam for processing sugar cane (Dos Santos, 2012).

[14] This assumption is in agreement with the observed amount of oil production by Petrobras in Brazil, excluding the Pre-salt oil (ANP, 2013). Apparently, investments in Pre-salt oil are draining financial resources from the more traditional oil fields.

[15] The abrupt decline on EOR Pre-salt is consequence of our assumption that CO_2 associated to oil will be stored until Pre-salt production peaks and used after that in order to preserve the peak production volume as long as possible. Once stored CO_2 is depleted, EOR will stop because we are not assuming any technological advance in EOR present practice.

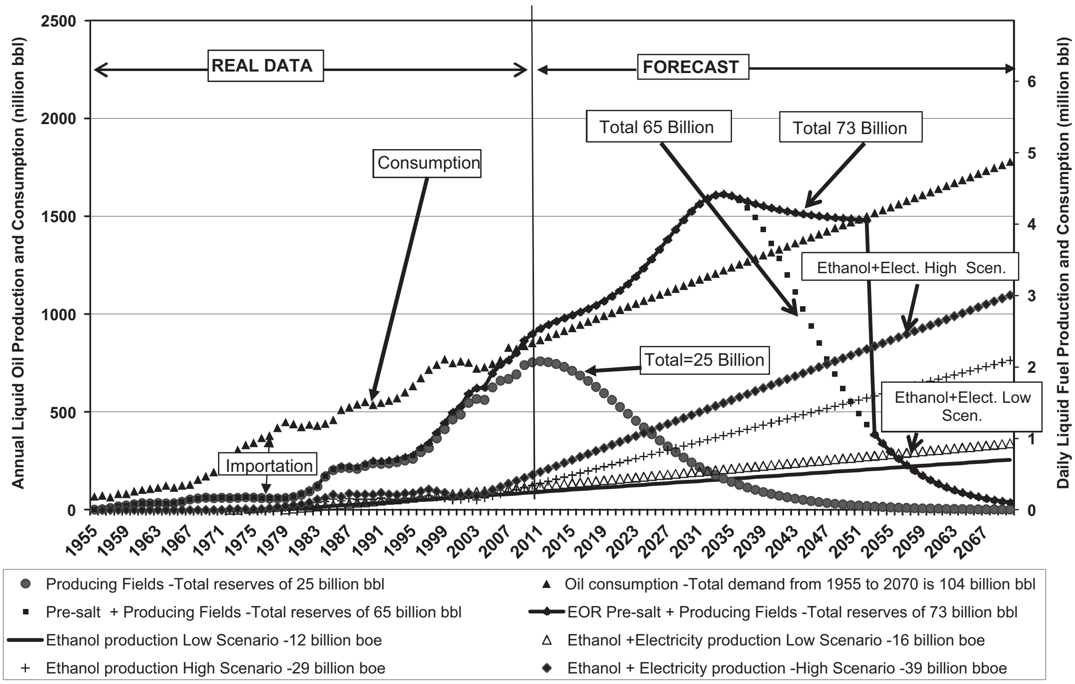

Fig. 2. Past and future oil and ethanol scenarios.

each scenario shows the amount of ethanol (on energy equivalent basis to gasoline) that will be produced. The upper one indicates the total amount of energy produced not only as ethanol but also as bioelectricity generated from sugar cane bagasse and part of tops and leaves. The bioelectricity is converted into bbl of oil equivalent because bioelectricity displaces oil and natural gas, which would be required to run thermoelectric plants.[16]

The lower curve of the High Scenario presents an annual production of 764 million boe[17] in 2070, whereas the Low Scenario, 256 million boe of ethanol fuel. Ethanol productivity is a function of sugar cane yield and its Total Reducible Sugars (TRS) content. Through technological improvement, we can expect average yields of 118 t/ha and TRS of 169 kg/t cane in 2039 (Pacca and Moreira, 2009), which means 11,700 l/ha/yr, yielding an increase of 67% when compared to the average productivity of 7000 l/ha in 2009. We assume constant technology after 2039, which means that the total amount of land required by 2070 is 16 Mha, which equals to 67% of the worldwide land used to grow sugar cane crops in 2011 (FAO, 2011). In addition, ethanol can also be used to power Diesel engines as it occurs in countries like Sweden and Brazil (Carlsson, 2010). However, to travel the same distance, Diesel engines consume either 1.6 l of ethanol or 1 l of diesel. Thus, one barrel of diesel equivalent corresponds to 254.4 l of the renewable fuel being used in Sweden and Brazil Assuming that the future road travels share by car, using gasoline, and trucks, using diesel, is similar to the 2010 values, the global average amount of hydrous ethanol necessary to replace 1 barrel of oil is 237 l. Therefore, 41% of the ethanol annually consumed displaces gasoline and 59% displaces diesel.

We compared the costs of oil production used in our model to the Petrobras values, Fig. 3 shows a comparison of cost estimates based on Petrobras total net revenue[18] between 2005 and 2011 (Petrobras, 2012) and the expected expenditure based on oil cost values used in our assessment. As we can see costs are compatible with the figures assumed for existing oil reserves (producing fields) and for pre-salt fields. Note that the cost has increased faster over the last 3 years, which might indicate that pre-salt oil is more expensive than oil extracted from producing fields.

5.1. Model results for oil

Fig. 4 shows ROI values for the several scenarios considered as a function of CO_2 prices (US$0 or 40/t$CO_2$) and the expected annual social interest rate of 4%. The box in the Figure informs the results are valid when assuming a delay of 4 years between oil investments and oil production, as well as the price of Total Reduced Sugar (TRS) for sugarcane feedstock of R$0.4/kg (US$0.2/kg) Economic results are surprising because there is a common sense that the oil industry provides excellent returns on investment (ROI). Defining ROI as the present value of "(revenue minus cost)/cost",[19] producing fields ROI is 1.23 considering an average price of US$86.9/bbl (see Fig. 4) for the oil products sold at the refinery gate. For the pre-salt oil, ROI is much lower, 0.56, when the barrel is sold at an average price of US

[16] Thermoelectricity in Brazil, is usually based on heavy oil and natural gas as feedstock with an operational efficiency of 40% but could be fully replaced by bioelectricity from sugarcane due to its lower operational cost.

[17] Hydrous ethanol, which contains 95% of ethanol and 5% water (ANP, 2011b), is used in Brazil and its performance in cars (km/l) is accepted as 30% lower than gasoline for flexfuel cars. Nevertheless, for neat ethanol cars its performance is 25% lower, since the engine compression rate can be significantly increased when compared with conventional gasoline cars (Larsen et al., 2009). In our model we used the latter index since flexfuel cars can achieve better performance with turbo charging. We assume that for large ethanol use in the future turbo compressor cars will be popular. Thus 1 boe is equal to 212 (159/0.75) liters of hydrous ethanol.

[18] The net revenue is used as a proxy for total expenditures since Petrobras profit used to be a roughly constant and small percentage of its net revenue through the years 2005–2011 (Petrobras, 2013b).

[19] In order to calculate the ROI we need the present value of all annual costs and revenue during the production and commercialization period of oil and ethanol. Unitary costs and revenues are constant over such period because we consider that inflation equally impacts all values; however total annual costs and revenues vary over the analyzed period due to the volumes of ethanol and oil that are sold. Because a 4% social discount rate was adopted, ROI values are close to 1, which means that revenues are twice the production cost. This outcome renders a modest result for entrepreneurs used to invest in large projects. Usually these projects are attractive at IRR around 15% in developing countries based in national currency, but around 10% based in hard currency.

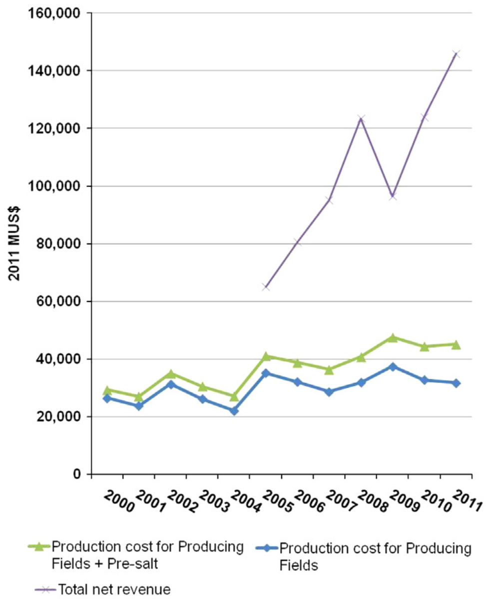

Fig. 3. Petrobras total expenditures versus oil production costs.

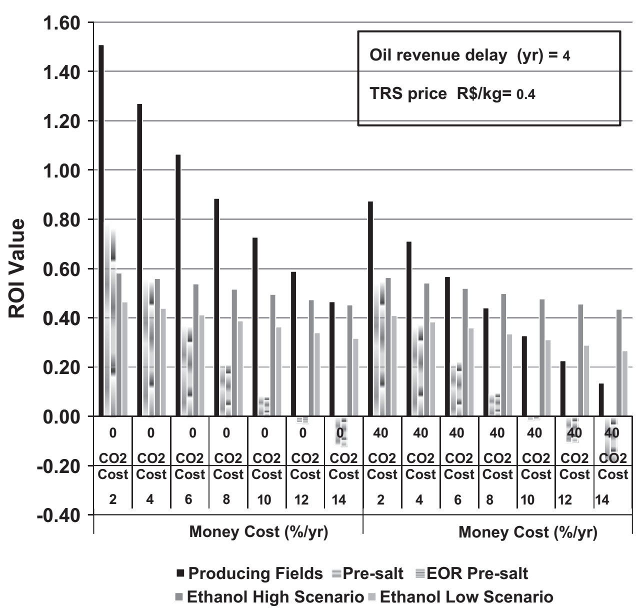

Fig. 4. ROI for different biofuel sources, discount rates, and CO_2 taxes.

\$102.9. These values are based on the net present value analysis (for the year 2011) assuming an annual discount rate of 4%[20] and neglecting the CO_2 emission costs.

The producer sales price of final oil products derived from our model—US\$86.9 and US\$102.9, respectively, sounds quite realistic when checking the present sales price of oil products in Brazil[21] (ANP, 2013). Although investing in pre-salt provides a reasonable return, mainly if low discount rates are applied, they are not as profitable as investing in producing fields (see Fig. 4).

Nevertheless, we must remember that oil production and consumption emit CO_2 to the atmosphere, increasing climate change impacts and implying in external costs, which ultimately should be added to the product cost. From Fig. 4, when CO_2 costs are accounted for, the ROI of producing fields and pre-salt oils are 0.69 and 0.36, respectively, for the final oil products prices of US \$108.3 and US\$124.3/bbl. The price increase per barrel compared to the values presented in the previous paragraph is explained by the CO_2 cost. One barrel of oil products emits more than 0.5 tCO_2 (DOE/NETL, 2008), and this means an increase of a little over 50% in the value of 1 tCO_2 added to the original bbl oil cost. This cost equals US\$21.4 added to the pre-salt value of US\$102.9. Under this new scenario, considering a discount rate of 12%/yr ROI becomes 0.20 for producing fields and negative for pre-salt (-0.11). Fig. 4 illustrates the results of a sensitivity analysis for 7 discount rates and 2 different CO_2 costs.

Since emission reductions due to CO_2 presence in the exploited oil poses a small contribution to the environment when compared to oil consumption and refining (NETL, 2008), and its cost is significant (see next two paragraph), it is possible to infer that CO_2 storage is justified by EOR aiming to extract more oil from the pre-salt, once its production starts to decline.

The economic cost associated with the EOR activity was evaluated based on a cost of US\$30/tCO_2 stored underground (Carbo, 2012).[22] This means that the CO_2 associated with one barrel of oil extracted from pre-salt, which weights 24 kg, requires an additional cost of US\$0.72/bbl to be stored. But for EOR, the amount of CO_2 pumped is 0.805 tCO_2/bbl, which cost 24.2US\$/bbl. Thus, total cost of this extra oil, transformed in oil products, obtained through CO_2 EOR is (24.15+15+5+10)=US\$54.16/bbl,[23] instead of US\$49.0, since there is no further exploration cost, which has been replaced by the EOR cost. In principle, we could conclude that CO_2 EOR improves the project because it extends reserves from 40 billion to 48 billion bbl. This is not true for the project economics since our model concludes that under this circumstance the ROI has a value of 0.55 (see Fig. 4) for money cost at 4% and CO_2 value equal zero, while without EOR the ROI is 0.56. The economics is impaired but very sensitive to some parameters. If the pumped CO_2 recovery rate increases from 85% to 90%, the ROI are equal to 0.56 for both cases.

With our model we can verify that adding the CO_2 external cost of US\$40/t the ROI for pre-salt oil decreases from 0.56 to 0.36 without EOR (see Fig. 4) while it also decreases from 0.55 to 0.37 with EOR, assuming a 85% CO_2 recovery rate. Total emissions with EOR emitted into the atmosphere are larger than without CCS (see Fig. 5) by 4700 Mt. Also it is worthwhile to remember that these emissions are related to the production of 48 Bbbl, while without EOR but only with CCS, total oil production would be 40 Bbbl and CO_2 emissions 21,300 Mt. For EOR we have total lifecycle emissions of 26,900 $MtCO_2$ for 48 Bbbl or 0.560 tCO_2/bbl and production price of US\$49.9/bbl,[24] while without EOR we have 0.534 tCO_2/bbl

[20] The cost of money value (discount rate) looks low, but it represents the social cost of money, which is a better index for long-term projects, mainly the ones with significant impact in the quality of life of generations (Borken-Kleefeld et al., 2009).

[21] In January 2011, when 1US\$=1.7602R\$, average gasoline price to final consumers were R\$2.67, from which Petrobras received 28%, Distributers and Service stations 11%. Ethanol share (with 25% presence per volume) was 22%, State tax (ICMS) 26% and Federal taxes (CIDE, PIS/PASEP, COFINS) 13%. Gasoline fraction was 0.75 l/l of gasohol and was sold at the refinery gate at R\$1.00/l (Petrobras, 2011d). Thus, gasoline was sold by Petrobras at US\$0.568/l (US\$90.3/bbl). This price should pay oil cost, transportation and refining, while providing a profit of around

(*footnote continued*)
20% and covering taxes expenses around 10%. Note that Petrobras pays roughly US \$10/bbl as royalties. Thus, oil producing cost should be around US\$58/bbl while our model assumes US\$41. This difference is quite reasonable since total Petrobras operational costs involve other costs on top of the oil cost.

[22] The author quotes US\$66/tCO_2 captured for the biomass carbon capture project being tested in Decatur, Illinois involving 2.5 $MtCO_2$. We prefer to half this value considering the volume of CO_2 captured in the pre-salt oil reserve is much bigger.

[23] Such value is compatible with recent EOR oil production cost estimated by IEA (IEA, 2011).

[24] This value is the average cost of EOR deployment obtained from the cost of 40 billion bbl at US\$ 49.0 and 8 billion bbls at US\$54.2.

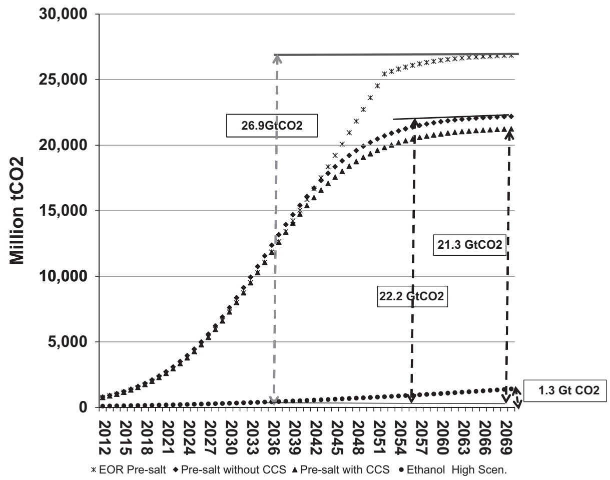

Fig. 5. Total emissions of 4 liquid fuel scenarios.

and a slightly lower production price—US$49.0, but the ROIs are very much similar (0.37 and 0.36).

5.2. Model results for ethanol

Examining the ethanol scenarios, the ROI has the value 0.57 for the High Scenario and 0.45 for the Low Scenario, ignoring the CO_2 costs (see Fig. 4), when ethanol sales price is US$127.9/boe. Remembering that under these circumstances the ROI for oil are 1.23 and 0.56 for producing field and pre-salt oils sold at US$86.9 and US$102.9/bbl, respectively. The result is quite interesting since the High Scenario provides almost the same return on investment as the pre-salt. The different sales price (ethanol 127.9 and gasoline 102.9) are, presently in Brazil not a high disadvantage because the existing legislation taxes increase domestic sales of oil products than ethanol. In some regions, state taxes are 33.3% for gasoline and 13.6% for ethanol. Considering only such taxes pre-salt oil price to final consumer is U$137.2/bbl and for ethanol is US $145.4/boe. Adding, federal taxes, which are also higher for oil than ethanol, ethanol price to the consumers will be 10% lower than the gasoline price. Another important index is the amount of money required for ethanol supply, whose present value in 2011 are US$740 and 323 billion for the High and Low Scenarios, respectively, while for pre-salt it is US$933 billion.

When CO_2 costs are included the ROI is 0.55 and 0.39 for the High and Low Scenarios (see Fig. 4), at a cost of US$129.3 and US $133.8/boe, respectively, while for pre-salt oil it is 0.36 at US $124.3/bbl. The difference between pre-salt gasoline producer price and High Scenario ethanol consumer price vanishes due to higher gasoline state and federal taxes. High and Low Scenarios total costs are US$756 and 350 billion, respectively, and 1287 billion for pre-salt. Total costs are more favorable to ethanol and again the supply is much better met by ethanol than oil after 2050. It is worthwhile to note that the CO_2 cost has an impact on both oil and ethanol sales price. The reason is that land use changes GHGs emissions are included in the overall emissions of sugar cane plantation and processing. Nevertheless, for the High Scenario the impact is smaller than for the Low because 135 kWh/tcane is being accounted as a byproduct of ethanol production and this electricity replaces the use of Natural Gas, thus avoiding its GHGs emissions (EPA, 2010).

Comparison between ethanol and pre-salt can also be made when EOR used. ROIs are 0.57 and 0.45 for High and Low Scenarios and 0.55 for pre-salt assuming no CO_2 tax. Including CO_2 tax they are 0.55, 0.39 and 0.37, respectively.

6. Conclusions

Considering the higher production sales price of ethanol compared to oil products, ethanol is only cost effective if appropriate policies exist. This is the major issue that has to be analyzed by energy policy makers. However, the difference between ethanol and oil ROI is very small, and if discount rates above 4% are considered, ethanol ROI is always greater than pre-salt oil′s ROI. Furthermore, if the value of carbon is taken into account, ethanol becomes more attractive even for a discount rate of 4%. Thus, ethanol production might be more economically attractive than oil, which is finite. Once the pre-salt reserve is over, even assuming that other reserves could replace pre-salt oil in the future, it is necessary to consider that new investments would have to be made, starting from scratch and further costs due to decommissioning would have also to be accounted for (World Bank, 2010).

On the other hand, for sugar cane plantation the soil used for ethanol production in 2012 will still be productive in 2070 and beyond. New initial investment in new areas will only be required to expand the planted area, but operation and maintenance costs apply annually to keep the total productive area, sustaining production and jobs. Thus, it is very important that energy policy makers take a wise decision on the allocation of energy investments now. Shall they be directed only to the oil sector, due its traditional image of being very economically attractive, or shall they go to the ethanol sector, a renewable energy producer, with the traditional image of being probably less economic attractive but with a longer life, or to both? Considering the latter case, what is the share for each one?

We were able to show that these oil and ethanol traditional economic images are far from reality. Regarding oil extracted from producing fields its economic return is unequivocally better than ethanol production for both High and Low Scenarios, in the absence of the CO_2 tax. Nevertheless, half of these reserves have already been used and its contribution for the liquid fuel supply in the future is limited. For the pre-salt oil, which is presented to Brazilian society as the major future source of oil supply, the evidences pointed out to a different direction. The results derived from our model show that ethanol in the High Scenario, has a 2% economic return higher than the pre-salt oil, and 4% higher than the EOR pre-salt oil, while requiring less investment than both oil scenarios.

Additionally, when the CO_2 tax is included, ethanol in the High Scenario presents better economic return to investors, while ethanol in the Low Scenario presents the same return. And this conclusion stands the same even when pre-salt CO_2 is captured and stored or used for EOR.

Another important finding is that the oil option will not be enough to attend to Brazil′s demand beyond 2043 (or 2052 if EOR is deployed). This will threaten the country′s energy security, as well as drag significant amount of hard currency to guarantee importation after these years. Ethanol supply will guarantee partial liquid fuels supply for the period analyzed. In particular the High Scenario will meet 62% of total fuel demand by 2070 and, even more after that, provided land availability is not a barrier for further sugar cane modest area expansion. It is worthwhile to mention that the total ethanol produced in the High Scenario between 2012 and 2070 is equivalent to 38.5 billion boe and for the Low Scenario 13.7 billion boe. The High Scenario production capacity is almost as big as the pre-salt reserve (97.5%) without EOR.

Finally, CO_2 impact on climate change is not only a matter of cost. Real reduction on CO_2 emission has to be achieved by many countries, mainly the ones with high emission level and some medium to high economic development standards. The High Scenario reduces emissions up to 2070 by 20.0[25] billion t of CO_2, compared with pre-salt oil, even when pre-salt CCS is deployed, which represents two thirds of the 2010 CO_2 global emission.

Appropriate government policies are needed to enhance the interest in ethanol production and slow down oil production expansion. One of the best measures would be fostering energy sector transparency, providing better information to society regarding the physical magnitude of production, economic costs and prices of energy products. This can be achieved by requiring official and detailed annual reports prepared by experts and independent auditors.

The level of uncertainty related to oil cost is significant. On top of the production costs there are many taxes and obligations charged, which are added to the consumer′s price; however, in this paper we ignored this point considering essentially the producers sale price. Considering the array of taxes, obligations, and additional costs related to special treatments for liquid fuels, they could be the objective of another analysis aiming to cover this complex spectrum. Nevertheless, the results are even more robust since without considering the total cost burden that is higher in the case of fossil fuels, biofuels still offer similar or better economic returns to society.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2013.09.055.

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