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Investments of oil majors in liquid biofuels: The role of diversification, integration and technological lock-ins

Daniel Fontana Oberling, Martin Obermaier, Alexandre Szklo, Emilio Lèbre La Rovere*

Energy Planning Program, Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering, Universidade Federal do Rio de Janeiro (UFRJ), Centro de Tecnologia, Sala C-211, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, RJ 21941-972, Brazil

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ABSTRACT

The increasing use of liquid biofuels has been justified by highly volatile and rising oil prices, geopolitical instability of countries that control most of proven oil reserves, growing demand for passenger transportation and environmental concerns, especially climate change. Investments in the sector are increasing steadily, with oil majors being responsible for rising investments into liquid biofuel joint ventures, research and development projects and logistics. This paper analyses the underlying motivations of these investments by evaluating corporate diversification and integration strategies. Findings indicate that vertical integration and diversification are an integral part of oil major's strategic behavior toward biofuels, although strategies differ substantially among companies. In the short term current major oil companies' investments in liquid biofuels are driven by the requirement to comply with binding mandates for biofuels, whereas in the long-term liquid biofuels, if produced on a significant scale, could be classified as non-conventional liquid hydrocarbon reserves for oil majors where access to other (non-)conventional resources is not secured. Finally, given existing technology lock-ins it seems unlikely whether different paths for producing liquid biofuels will be able to co-exist in the long term, or there will be only one dominant path possibly controlled by large oil companies.

1. Introduction

The increasing use of liquid biofuels has been justified by highly volatile and rising oil prices [1,2], geopolitical instability of countries that control most of the known oil reserves [3,4], increased demand for passenger transportation [5] and environmental concerns, especially climate change [6,7].

Energy security, in fact, remains one of the most important driving factors behind the increasing use of alternative fuels in the transportation sector [8]. Maintaining access to reserves continues to be an essential strategy for oil majors as demand for conventional oil is estimated to supply the gross of transportation road fuels, [9]. As such, non-conventional oil resources, including tar sands and shale oil, and even ultra-deep water petroleum resources, have become important as access to more conventional oil is becoming difficult [3,10–12]. For example, as of today Exxon's and Shell's non-conventional oil represents as much as 12% and 11% of the companies' proven oil reserves, respectively. Therefore, it seems acceptable to deduce that liquid biofuels, if produced on a significant scale, could be classified as non-conventional liquid hydrocarbon reserves for oil majors where access to other (non-) conventional resources is not secured.

In terms of environmental concerns, liquid biofuels are considered as one of the major options to curb greenhouse gas emissions in the transportation sector [13–17], although

* *Corresponding author*. Tel./fax: +55 (21) 2562 8805.
E-mail address: daniel@lima.coppe.ufrj.br (D.F. Oberling).
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in some regions concerns still remain related to food-fuel competition [18–22], biodiversity [23] and life cycle emissions [24–27]. However, the main reasons for promoting liquid biofuels continue to differ considerably among countries. The U.S. government has strongly encouraged the expansion of corn-derived ethanol in order to promote energy independence and as a way to reduce air pollution and health problems, particularly through a progressive ban of MTBE [28]. The enactment of the Energy Policy Act of 2005 [29] and the specifications of the Renewable Fuel Standard – RFS [30] brought security and stimulated the growth of U.S. production. From 2000 to 2010 the production grew from 6.4 hm^3 to 49 hm^3 [31]. For 2022, the government aims to reach a value of 492 hm^3. While a specific ethanol target is not mentioned in the RFS – except that 946 dam^3 should be derived from cellulosic biomass by 2013 [32] – reaching this target is believed to imply a large-scale use of ethanol in fuel blends [33].

Europe is another major consumer market for liquid biofuels. The European Union (E.U.) legislation has been mainly motivated by concerns to secure European energy supply, environmental protection, and achievement of the Kyoto Protocol targets [31,34]. Due to the flexibility of E.U. legislation, a variety of biofuel support policies are now in place in the E.U. member countries to reach this target, including standards, quotas, economic and fiscal measures [35].

In the case of Brazil, the Proálcool program launched in the 1970s is a success story, although social and environmental concerns remain [17,36–40]. Current policies on ethanol in Brazil focus on ethanol-gasoline blending mandates, minor tax reductions for blended fuels, and tax incentives to encourage the use of ethanol-powered vehicles [41].

From the end of 2004–2009, annual average growth rates for biofuels reached 20% for ethanol and 51% for biodiesel, despite the global economic crisis of 2008 [42]. According to IEA, biofuels may account for 7% of road transport energy demand in 2020 and 11% in 2030 under its "450 ppm" scenario – on energy equivalent basis. Increases will be initially due to a wider adoption of first generation biofuels, especially sugarcane and corn ethanol. By 2030 first generation ethanol, and to some degree second generation biodiesel, will have begun to substitute first generation technologies [10].

However, while first generation biofuels are less technological risky, second generation biofuels are an R&D priority, particularly in countries or regions where first generation biofuel supply can exacerbate food versus fuel conflicts or environmental degradation. These fuels derive from the conversion of lignocellulosic material through biochemical or thermochemical routes.

Hence, given the strong policy support, investments in the sector are now increasing steadily. Contributions come from government (through support policies such as blending mandates or R&D) or venture capital, but increasingly also from major oil companies such as ExxonMobil, Royal Dutch Shell, BP, and Petrobras [42]. Oil majors are of particular interest given their market position role in the global road transportation sector and the frequent claim that they impede the development and dissemination of renewable transportation alternatives such as biofuels.

This leads to the following two questions:

1. To what degree can oil major investments in first and second generation liquid biofuels be explained with regard to integration and diversification strategies in the light of more difficult access to conventional oil reserves as well as the rising importance of biofuel blending mandates, which affect the oil companies' downstream markets? In addition, does the possible "greenwashing" or corporate image play a more significant role? – While different studies have analyzed the valuation of corporate sustainability of oil companies [43–47], there is still no agreement on the drivers behind oil companies investments in this sector.

Chandler [48] defines diversification as product diversification and integration as vertical integration. By diversification in this paper we thus mean the inclusion of non-conventional resources into the oil major's energy portfolio. This can include biofuels, but also, for example, Canadian tar sands. Vertical integration is analyzed from the standpoint of strategic access to resources. For example, oil majors have to comply with government blending mandates and may have considerable difficulties in securing supply of cheap biofuel feedstock.

2. Can the quality and amount of current major oil companies' investments in liquid biofuels be explained by existing technological lock-ins [49–51] in the hydrocarbon industry especially for global road transport?

Technological lock-in describes a situation in which an economy remains faithful to a certain type technology or technological system. For further detail, see [49–53].

By understanding the underlying motivations of oil major investments in the liquid biofuels sector this paper does not only aim to give information on their potential role in the future renewable liquid transportation fuels matrix, but also on the development of the biofuel sector as a whole.

The analysis is based on information on investment volumes and quality from four oil majors (BP, Royal Dutch Shell, ExxonMobil and Petrobras), which has been compiled from their respective 20F – BP, Shell, Petrobras (20F is a form issued by the U.S. Securities and Exchange Commission that must be submitted by all private companies out of United States in order to inform company's business and financial conditions) – and 10K – ExxonMobil – reports (10K is an annual report for U.S. firms that offers a comprehensive overview of the company's business and financial conditions), the corporate sustainability reports as well as publicized industry news in technical journals, newspapers or industry blogs.

Following this brief introduction, the remainder of this paper is organized as follows: Section 2 presents the main investment data of the assessed oil companies. Section 3 analyses the investments of the selected oil companies in first and second generation liquid biofuels. Section 4 aims at identifying the mains motivations behind the different strategies of oil companies in the liquid biofuels industry. Finally, Section 5 concludes this paper with a few final remarks on integration, diversification and technological lock-ins.

2. Main investment data of the assessed oil companies

Oil major investments into the biofuels sector need to be put into context with their expenditures in core petroleum business. Any such investments are based on the companies' perceptions of future energy trends and projections of energy potentials. In general, there is broad consensus among oil majors that petroleum has a huge development potential, and that it will remain the predominant global energy source in the coming decades [54].

Table 1 summarizes the main investments (from 2008 to 2010) of the four oil companies selected for this study. It shows that Petrobras' investments grew consistently in all the company's operational areas between 2008 and 2010, increasing from 29.8 G$ to 45.0 G$. In 2010, a total of 49% of Petrobras' overall investments were situated in exploration and production (E&P), and 34% in refining, marketing and transportation. The majority of these investments are occurring in Brazil [63]. A large share of current development is concentrated in the exploration of new frontiers for petroleum reserves, particularly in the large off-shore pre-salt fields (reserves under extensive layers of salt and rocks which can reach a total depth of 7000 m between sea surface and petroleum reservoirs) in the states of Santa Catarina and Espírito Santo [64]. Perspectives for E&P pre-salt are considerable as Petrobras intends to allocate 127.5 G$ (57%) of its overall investments until 2015 into the sector, including the ongoing expansion in the pre-salt layers in the Santos Basin. Furthermore, Petrobras also plans to invest into new refineries and is estimated to reach 8.2 Tg per day of additional distillation capacity in greenfield refineries until 2020 [65]. In sum, the figures in Table 1 indicate a company with large access to petroleum reserves and strong focus on the rapidly growing Brazilian oil products market. This observation, and the fact that Petrobras is a state-controlled company, whose investments are sometimes driven toward less profitable market segments due to strategic reasons (e.g. energy security, fuel pump price control) [66], also explain the company's investments in refining assets, different from the other oil companies assessed in this study.

BP strongly invests into oil and natural gas recovery and sales. From 2000 to the mid-decade alone 26 G$ were invested into exploration and development. Major offshore (Sakhalin, Russia) and deepwater (Gulf of Mexico) discoveries show a commitment to go after increasingly more difficult to recuperate resources [54]. Investments into Canadian tar sands also include huge earmarked financial resources. For example, a 3 G$ joint venture with Husky Energy foresees the development of the Sunrise field in the state of Alberta. Through the same partnership an additional 2.5 G$ will be used to expand heavy oil refining at BP's Toledo refinery in Ohio by 2015 [67,68]. Furthermore, BP is currently also analyzing the development of in situ production on the company's land leases around Kirby (also Alberta). This suggests that

Table 1 – Oil companies' expenditures and geographical distribution of proved reserves.

Investments[a]	Year	E&P	Refining and marketing	Others	Total investments	Financing	Geographical distribution of proved reserves (2010)
ExxonMobil[b]	2008	−19.7	−3.5	−2.9	−26.1	−44.0	USA (43.2%),
	2009	−20.7	−3.2	−3.2	−27.1	−27.2	Asia (17.6%),
	2010	−27.4	−2.5	−2.3	−32.2	−26.9	Canada and South America (12.8%), Oceania (11.2%), Africa (8.0%), Europe (7.2%).
Shell[c]	2008	−28.2	−3.1	−0.1	−31.4	−9.4	Asia (36.6%),
	2009	−22.3	−6.2	−0.3	−28.8	−0.8	North America (22.4%),
	2010	−21.2	−2.3	−0.1	−23.6	−1.5	Europe (23.1%), Africa (8.9%) Oceania (8.2%), South America (0.8%)
BP[d]	2008	−22.2	−6.6	−1.8	−20.6	−10.5	Subsidiaries:
	2009	−14.8	−4.1	−1.3	−20.8	−9.5	US (44.0%),
	2010	−17.7	−4.0	−1.2	−22.9	0.8[f]	South America (15.0%), Africa (11.0%). UK (10.0%), Australasia (9.0%). Equity-accounted entities: Russia (69.0%), South America (20.0%), Rest of Asia (7.0%)
Petrobras[e]	2008	−17.0	−7.6	−5.2	−29.8	2.7[f]	Brazil (95.0%), International (5.0%)
	2009	−18.4	−10.9	−5.8	−35.1	16.9[f]	
	2010	−24.2	−16.0	−4.9	−45.0	35.3[f]	

a Absolute amount in G$ (Giga $).
b Source: [55,56].
c Source: [57–59].
d Source: [60-62].
e Source: [63].
f Positive values mean that financing activities are providing fund instead of expending cash.

significant future investment may not be far away [68]. Finally, BP has recently increased its focus on shale gas development in the USA by acquiring Chesapeake Energy interests in the Arkoma Basin Woodford Shale (1.8 G$) and Fayetteville Shale (1.9 G$) (both 2008). In addition, the company has signed a product-sharing contract with ENI to develop coal bed methane production in the East Kalimantan's (Indonesia) Sanga–Sanga field [67].

In the last decade, Shell investments have been concentrated in development of petroleum resources and increasing downstream profits, particularly in the refining and chemicals markets. In particular, Shell sees a considerable potential in the development of unconventional resources, including heavy oil, tar sands and shale oil, all of which are likely to require heavy technology investments [54]. For instance, by the time the Athabasca Oil Sands Project (AOSP, includes synthetic crude production at the Muskeg River Mine and the Scotford Upgrader) started in 2003, the company had already invested over 3.6 G$ for its 60% share in the project. Shell has continued to commit considerable resources to AOSP development with a recent upgrading estimated at 7.6 G$ and an additional potential upgrader at 22 G$ [63]. In terms of non-conventional gas, Shell aims to develop an internationally diversified portfolio that follows its long-term strategy for crude oil resources. In 2008, the company invested 0.724 G$ in a partnership (10%) with Arrow Energy for the development of coal bed methane projects in Australia, China, India, Vietnam and Indonesia [69]. This initial investment in Arrow Energy later turned into a joint take-over completed together with Petrochina at a total of 3.2 G$. Following the same strategy, Shell and Petrochina recently signed an agreement for the development of non-conventional gas fields in the Jinqiu block of central Sichuan Province, China [70]. In North America, Shell spent around 5.24 G$ for acquiring Duvernay Oil Corp., a company focused on tight gas reservoirs in Canada [71]. Furthermore, Shell also explores and produces shale gas around Haynesville (through its partnership with EnCana) and has acquired the Pennsylvania-based oil and gas company East Resources for 4.5 G$ [70].

ExxonMobil has a similar strategy to other oil majors. In 2011, investments in E&P were at approximately 89% of all company's investments (33 G$). Expansion of petroleum reserves is done mainly through three strategies. First, the acquisition of new conventional oil reserves in various countries (i.e. Turkey, Vietnam, Nigeria and Angola). Second, the incorporation of non-conventional oil reserves in Australia, Canada and Papua New Guinea. Third, the aggregation of unconventional gas resources, particularly in the USA. This last step has been achieved primarily through the acquisition of XTO for 41 G$ and has turned ExxonMobil into the major U.S. gas producer. From 2006 to 2011, increasing investments in the sector totaled at 138 G$ for E&P [72,73].

Next to considerable investments into non-conventional resources, the financial data of all international oil majors assessed in this study (Shell, ExxonMobil and BP) shows an increasing allocation of free cash flow to purchase the company's own shares in order to maintain a level able to generate higher dividends per share. For instance, between 2007 and 2011 ExxonMobil spent a total of 136 G$ in this kind of activities [72,73]. Together with the increasing investments into non-conventional petroleum resources this strategy may be an indicator hinting at the increasingly difficult access of oil majors to conventional and lower cost petroleum reserves worldwide. How biofuels fit into this picture will be discussed in the following sections.

3. Oil major investments in the biofuels sector

The integration of liquid biofuel-related operations, including three separate industries (agriculture/forest, biofuel production and blending with distribution), is difficult and costly for oil companies. They have to ask themselves at what point they want to enter the liquid biofuels chain: agriculture, biofuels production or only blending and distribution? Questions also include how to deal with new potential by- or co-products from the biofuels chain, including high-grade chemicals [74,75].

There are also no available estimates regarding the costs of such decisions, but they can reach substantial scale. On the other side, given that blends such E10 do not alter significantly the infrastructure installed for refining, transporting or using oil products [29] the infrastructure cost of compliance with first generation biofuel mandates is irrelevant and will not be further discussed.

In general, the information policy of oil majors is very limited: many first and (particularly) second generation biofuels projects have their overall values not disclosed, making the analysis very difficult. However, it is still possible to give strong indications on the main drivers and motivations for oil company investments into the liquid biofuel sector.

3.1. *First generation liquid biofuels*

3.1.1. *BP p.l.c*

BP sees itself as one of the largest blenders and marketers of first generation liquid biofuels worldwide and a market leader in the segment. BP seems to respond mainly to compulsory blending mandates for gasoline and diesel. Existing and planned production facilities are located in the U.S., Brazil and the UK [60]. The company was responsible for blending 10.6 hm^3 of ethanol (2007) and 6.3 hm^3 of biodiesel (2008) for the U.S. market. In Europe, BP production accounted for 14 hm^3 of biofuels or approximately 10% of the global biofuels market [61].

In general the company's investments in biofuels can be viewed as integrated into BP's strategy for entry into other segments of the energy market related to climate change. Indeed, although Shell had already previously incorporated climate change actions into its corporate strategy, it has been supposed that BP's position has put pressure on other international oil majors, such as ChevronTexaco, to incorporate concerns about climate change into their strategy [76,77].

Investments into first generation biofuels have only started recently: as late as 2005, BP had not disclosed any specific first generation biofuels strategy, although the company had already experiences with biodiesel blends and, to a limited degree, ethanol blends in the European market [78].

In terms of investments, since 2007 BP has committed more than 1.5 G$ to build upon existing operations and R&D, but it is unclear to what degree first generation technological routes have benefited from this. In terms of disclosed projects, BP is a major shareholder in an ethanol plant in Hull, Great Britain. Partners of the project include British Sugar/ABF and DuPont (45% BP, 45% ABF and 10% DuPont). The plant is valued at 0.4 G$ with an annual capacity of 420 dam^3 of ethanol. The plant is to run on wheat feedstock.

In Brazil, the company achieved majority control (83%) of the Companhia Nacional de Açúcar e Álcool (CNAA), one of the largest domestic ethanol and sugar producing companies. The estimated value of the deal is 0.680 G$, in which BP also took on the refinancing of all CNAA's long-term debt as the economic crisis of 2008 has left many Brazilian sugarcane and ethanol producers in financial difficulties [31]. The deal will augment BP's overall Brazilian production capacity to an annual 1.4 hm^3 of ethanol equivalent [79]. Also in Brazil, the Tropical BioEnergia S.A joint venture including Santelisa Vale and Grupo Maeda (BP 50%, Sanelisa Vale 25%, Grupo Maeda 25%) foresees investments in the range of 1 G$ for the construction of two ethanol refineries, of which the first started operating in 2008, producing an annual 435 dam^3 of ethanol. At the time of the joint venture (2008) this investment was the largest yet made by any international oil major in Brazilian ethanol production (BP's initial contributions reaching 0.560 G$).

Finally, a smaller joint venture on biodiesel development is the D1-BP Fuel Crops Limited, together with D1 Oil. The project started in 2007 with a budget of 0.160 G$ (0.09 G$ on behalf of BP) for a five-year timeline aims to develop *jatropha* biodiesel in India.

While these strategies focus on first generation biofuels, they also offer considerable second generation opportunities. This is also an issue for Shell and Petrobras, and will be dealt within greater detail in Sections 3.2 and 3.3.

3.1.2. *ExxonMobil Corporation*

ExxonMobil is an efficient company in terms of its financial controls and expertise in the exploration of mature oil fields [80], but conservative in terms of renewable energy investments, including biofuels [78]. Although the company had been studying renewable energy for decades, ExxonMobil concluded only a few years ago that their potential markets would be too small and thus not worth the investment as they could generate larger profits in exploring oil and gas opportunities [81]. While this view has now changed, the company is one of the few oil majors that openly considers liquid biofuels as a risk: in its recent 10K filing, it is stated that "the continued growth in biofuels mandates [along with climate and carbon policies, but also government sponsorship of alternative energy] could have negative impacts on the refining business" [82]. Furthermore, the company also works with more conservative biofuels diffusion scenarios: future global transportation fuel demand is to be met mainly by oil (95% in 2030), with only limited space for biofuels [72].

In terms of first generation biofuels, ExxonMobil, as other oil majors, attends to governmental or state-wide blending mandates. This seems especially the case where downstream business is large, e.g. in Germany where the company has been leader in production and diffusion of biofuels [78]. However, the company does not openly divulge such information, which is contrary to other oil majors analyzed in this paper. A research sponsorship of the Global Climate and Energy Project at Stanford University may have first generation components, but this investment is likely to be only marginally relevant.

3.1.3. *Royal Dutch Shell p.l.c*

Shell is the largest distributor of liquid biofuels worldwide, with 9.6 hm^3 sold in 2009 [83]. In the U.S., Shell alone was responsible for the sale of 30% of all ethanol consumed, having distributed more than 5 hm^3 in 2007 [57]. Shell owns a highly diversified investment portfolio beyond fossil fuels [78,80].

Despite its relatively strong renewables focus, first generation biofuels were portfolio as far as 2005. However, according to Eikeland [78], Shell had previously focused on bioenergy activities. In the 1990s, the company had plans for biomass extraction at company-owned plantations in Africa and Latin America, but these plans were later removed from the company's renewable energy portfolio [78]. This indicates that Shell, at various points in time, overhauled its biofuel assessment and strategic planning with regard to the sector.

Shell has recently changed its strategy and now shows more optimistic scenarios for biofuel dissemination, largely driven by the introduction of low carbon fuels policies for road transport in Europe and the U.S. Accordingly, the company has augmented its resources in the biofuels sector while reducing its investments in other renewables such as solar energy. Furthermore, Shell has also considerably changed its liquid biofuels portfolio with strongly growing investments in sustainable first generation biofuels instead of relying exclusively on second generation R&D [84].

This is mainly evidenced by Shell's recent announcement regarding the 12 G$ joint venture with Cosan S.A. Indústria e Comércio, Brazil's leading sugarcane and ethanol producer. The partnership, which has been named Raízen, joins Shell's considerable Brazilian retail and marketing units and a financial contribution of 1.6 G$ with Cosan's sugarcane crushing capacity, its annual 2 hm^3 production capacity, cogeneration units as well as downstream and logistical assets (including export facilities) [84,85]. Cosan also enters with a net debt of 2.5 G$ which are to be carried on Raízen's balance sheet. The company's downstream assets include ESSO's former commercialization assets which Cosan had bought in 2008 for an estimated 0.826 G$. Based on the investment value Raízen now marks the single largest commitment to biofuels that any oil major has made to date [87].

3.1.4. *Petrobras S.A*

Despite an initial reluctance to enter the liquid biofuels sector within the Proálcool ethanol fuel program, the company has since long supported the logistics of distribution and sale of biofuels in Brazil, including the acquisition of biofuels, blending and distribution of hydrated ethanol through its intermodal network and selling through its retail network [87,88]. The creation of Petrobras Biocombustível S.A. in 2008, subsidiary of the Petrobras S.A. group, led to the centralization of all biofuel-related operations except transport and

distribution, and indicates a further commitment of the company to the biofuels sector.

Recent investments include 2 G$ in the *corredor do etanol* (ethanol corridor), an intermodal transport system (road, railway and water) to facilitate increasing ethanol exports. Petrobras has also entered in several joint ventures, including a strategic partnership with Japan on ethanol supply [89].

Petrobras' *Visão 2020* (Vision 2020) is to turn the company into a world reference in biofuels. Investments between 2009 and 2013 are to reach 2.8 G$ in this segment, which is an 87% increase compared to the previous plan (2008–2012) [90]. The plan foresees an investment of 0.4 G$ for infrastructure, including ethanol pipelines, and 0.53 G$ are earmarked for biofuel research. Most of the expenditure is linked to domestic ethanol development (80%), with the remainder going to biodiesel (20%). Petrobras aims to increase ethanol production to an annual 3.8 hm^3 by 2013. Finally, Petrobras is also exploring a potential partnership with foreign and domestics firms to develop four new ethanol plants in Brazil and may take stakes in existing plants [91]. It is assumed that first generation ethanol will take a considerable share of the planned investments given its large-scale commercial potential for domestic and export purposes.

Finally, Petrobras has also invested into three biodiesel plants within the Brazilian Program on Biodiesel Production and Use (PNPB) and has begun to enter domestic palm oil production with high potential for biodiesel production.

3.2. *Second generation biofuels*

3.2.1. *BP p.l.c*

BP systematically invests in R&D of technologies for production of ethanol from cellulosic material and to biobutanol production [62].

Its main investment was the 0.098 G$ acquisition of the research project on cellulosic ethanol from Verenium Corporation (now called Vercipia); BP took total control of the project, including infrastructure and the patent, in 2010. They had previously already invested 0.045 G$ in the same project. Down the same technological route, BP became a shareholder of Mendel Biotechnology in 2007, which aims to develop more efficient raw material in cellulosic production. The investment value was not disclosed.

Also in 2007, BP sponsored the creation of the Energy Biosciences Institute (EBI), a partnership with the University of California Berkeley, the University of Illinois at Urbana Champaign, and the Lawrence Berkeley National Laboratory. They agreed to make scheduled investments of 0.5 G$ over 10 years; the aim of the institute is to develop new raw materials, new production methods and bioprocessing in oil exploration. BP also founded the Global Biofuel Technology Center, which aims to find feasible technologies for the transformation of biomass into cellulosic ethanol [60,62]. In addition, in 2009, BP agreed to a 50/50 joint venture with DuPont to create Butamax Advanced Biofuels LLC, a partnership to develop biobutanol fuel. The values of these investments were not revealed [62].

Another initiative is the Joint Development Agreement with Martek Bioscience Corporation to develop biofuels via microbial fermentation, converting sugars into diesel. Signed in 2009, the agreement provided an initial injection of about 0.01 G$. The partnership continues, but no information about the volume of investments after 2009 were disclosed [60,62].

A conservative estimate of spending on projects still in progress indicates that BP has invested at least 0.355 G$ in research related to second generation biofuels over the past four years. This figure considers the 0.05 G$ per year over four years EBI partnership as well as all investments for the purchase of and investment in Vercipia Martek.

3.2.2. *ExxonMobil Corporation*

In second-generation liquid biofuels, ExxonMobil focuses on the development of micro-algae as anew raw material for biofuel production. It supports the Global Climate Change and Energy Project at Stanford University. This research group, started in 2007 and is funded by four companies: ExxonMobil, General Electric, Schlumberger and Toyota. It aims at conducting technological research to develop a new energy system with significantly lower greenhouse gas emissions [32]. ExxonMobil are expected to invest 0.1 G$ over a 10 year period. In 2009, Exxon joined Synthetic Genomics Inc. (SGI) to develop biofuels from photosynthetic algae; they intend to invest more than 0.6 G$ dollars, if research goals are consistently achieved [55].

3.2.3. *Royal Dutch Shell p.l.c*

Traditionally, Shell invested in a broad technological portfolio that includes bio-oil from photosynthetic algae, ethanol from cellulose, biomass gasification to produce synthetic fuels, among others. In 2010, Shell changed its strategy in order to invest in more mature technologies. They suspended higher risk investments, such as algae production, which was carried out by HR Biopetroleum and Cellana; and suspended their partnership with Choren, which started in 2008, and aimed to improve Biomass-to-Liquid technology (BTL) [58].

Currently, Shell places more emphasis on the enzymatic hydrolysis of cellulosic biomass represented by their partnership with Iogen Energy Corporation, started in 2002, and which aims to develop this technology for application to agricultural waste. Between 2002 and 2006, 0.05 G$ were invested [57]. In 2008, Shell announced an increase in the shareholding of the company, jumping from 26.3% to 50% [58]. Little information is available about the volume of investment.

In 2006, Shell began a partnership with Codexis Inc, which is searching to develop more powerful enzymes to accelerate the conversion of biomass into ethanol or other fuels. In 2007, there was a reclassification of this partnership, in which Shell augmented available resources, with an advance of 0.02 G$. Over the past three years, Shell's investments have been growing fast. In 2008, 2009 and 2010 they spent 0.03 G$, 0.063 G$ and 0.066 G$ respectively. At the end of 2010, Codexis Inc. had already achieved some goals that encouraged additional investment of 0.02 G$. Thus, in the last four years, Shell has invested approximately 0.195 G$ in enzyme development [92].

The partnership with Virent Energy Systems Inc., explores a new technology that converts biomass' sugars into hydrocarbons similar to those produced in the petroleum refining processes (in the same class as hydrocarbons from gasoline and conventional diesel). Since March 2010, a pilot plant has already been working in the U.S. with a capacity of 38,000 L of gasoline annually. In June 2010, a total of 0.05 G$ was invested

Table 2 – Selected investments by four oil majors in first and second generation biofuels.

1st generation	Purpose	$	2nd generation	Purpose	$
BP					
Joint venture with British Sugar/ABF and DuPont	Ethanol plant in Hull with annual capacity of 420 dam^3	0.4 G$	Partnership with Verenium Corporation	Research on cellulosic ethanol. Infrastructure and patent dominion	0.098 G$
83% majority control of Brazilian CNAA	Brazilian production capacity to an annual 1.4 dam3 of ethanol equivalent	0.680 G$	Partnership with Mendel Biotechnology (since 2007)	Development of more efficient cellulosic raw material for bioproducts	n/a
Joint venture with Santelisa Vale and Grupo Maeda	Construction of two ethanol refineries (annual 1 dam3 ethanol capacity)	Total 1 G$. Initial: 0.560 G$	Funding of Energy Biosciences Institute (EBI)	Development of new raw material and methods for research on bioprocessing in petroleum exploration	0.5 G$ in 10 years
Joint venture with D1 Oil forming D1-BP Fuel Crops Limited		0.16 G$ in five years	Global Biofuels Technology Center	Similar to EBI funding (see above)	n/a
			Joint venture (50/50) with DuPont	Creation of Butamax Advanced Biofuels LLC	n/a
			Joint development agreement with Martek Bioscience	Development of biofuels via microbiotic fermentation (conversion of sugar into diesel)	Initial investment of 0.01 G$(2010)
ExxonMobil					
n/a			Global Climate Change and Energy Project at Stanford University	Research on energy systems that can have high GHG emissions reduction potential	0.1 G$ in 10 years
			Partnership with Synthetic Genomics Inc.	Development of biofuels based on photosynthetic algae	0.6 G$
Petrobras					
Corredor do etanol	Intermodal transport system to facilitate export	2 G$	CENPES research institute	Ethanol from cellulosic matter, bio-oil from microalgae, ethanol from vegetable oils and synthetic biofuels (BTL)	0.477 G$ until 2014
Brazilian Program on Biodiesel Production and Use (PNPB)	3 biodiesel facilities (several new facilities planned)	0.115 G$			
Total investment in sector (2009–2013)	Turn the company into a world reference in biofuels.	2.8 G$			
Shell					
Joint venture with Cosan (Raizen)	Create world-wide trading synergies	12 G$	Partnership with Iogen Energy Corporation	Development of enzymatic hydrolysis process for production of ethanol from agricultural wastes	Between 2002 and 2006 0.05 G$ (newer values not available)
			Partnership with Codexis Inc.	Development of enzymes that speed up conversion of biomass into ethanol and other fuels	Approximately 0.195 G$
			Partnership with Virent Energy Systems Inc	Conversion of sugar into hydrocarbons	0.046 G$
			2–5 year research partnerships with different universities (2008)	Partnerships with MIT, U.S., UNICAMP, Brazil; IMCAS, China; CoEBio3, Great Britain; and School of Biosciences Exeter University, Great Britain	n/a

Source: elaboration by the authors based on research data
*n/a is not available.

jointly by Shell and Cargill, but the percentage share was not disclosed [59].

All these partnerships have a specific focus on the development of new fuels from cellulosic biomass. However, it still lacks quantitative information on Shell's investments. Assuming that (1) the levels of investments in Logen for the quadrennium 2002–2006 were maintained through 2006/2010 (0.05 G$); (2) investment in Virent Energy Systems Inc. was restricted to the aforementioned 0.02 G$; and (3) the total invested in Codexis was 0.195 G$, an estimate indicates that over the past four years, Shell may have invested at least 0.268 G$ in research on enzymatic hydrolysis, in spite of cutting investment in other high-risk technologies.

3.2.4. *Petrobrás S.A*

Investments in second-generation liquid biofuels are still well below those of first generation. They are carried out through partnerships within Brazilian public education institutions, mainly the federal universities, and developed by their own research center, CENPES. Petrobras focuses on bioethanol from cellulosic material, bio-oil from microalgae, bioethanol from vegetable oils and synthetic biofuels via gasification processes, BTL. In 2008, Petrobras opened a research laboratory in molecular biology and photosynthetic algae on their own facility, the investment for which was not disclosed. In addition, Petrobras has a pilot plant in their research facility, but again investment value remains undisclosed [63]. In 2010, the Petrobras Biofuels unit announced intentions to invest 0.477 G$ by 2014 in R&D focused solely on biofuels [86]. The company has also its H-Bio process in which a soy oil stream is blended with mineral gasoil fractions and the mixture is hydrotreated in a severe HDT unit, which aims to yield mostly hexadecane streams.

3.3. *Verified investments by the four oil majors in liquid biofuels*

Table 2 summarizes the investments of oil majors in both technological routes of first and second generation liquid biofuels. First generation investments are far more relevant in terms of their investment value. However, it includes infrastructure physical assets, which may facilitate first steps into future second generation biofuels production and distribution. This observation, in fact, seems to be validated by the oil companies' own stakeholder reports which essentially point in that direction. Furthermore, most of the analyzed companies (except ExxonMobil) see Brazil as a major opportunity for biofuels development.

It is insightful to compare the oil major investments into liquid biofuels with their core petroleum business (presented in Section 2). Overall disclosed investments into first generation by the four companies attain 19.3 G$ compared to only 1.9 G$ for second generation liquid biofuels. While these numbers are significant also for oil majors, they are clearly yet not as relevant as investments in conventional petroleum or even unconventional resources. For example, ExxonMobil's capital and exploration expenditures in 2009 alone were rated at 27.1 G$, and its earlier acquisition of XTO alone was estimated at 41 G$. Shell's capital investment for 2010 was 26 G$ including 11 G$ in exploration expenditure. Finally, larger-scale biofuels projects such as Petrobras' investment into the ethanol corridor (2 G$) or BP's 0.400 G$ joint venture investment in Hull are comparatively smaller than investments into non-conventional petroleum, and also smaller in number. All oil majors divert considerable resources to the development of fossil fuel resources across a variety of projects. In comparison, only eight first generation and eight second generation liquid biofuel projects have been identified in our review. Hence, under the petroleum industry perspective, liquid biofuels investments are still a minor activity.

Nevertheless, for the renewable industry, these oil companies' investments into liquid biofuels play an important role. Especially first generation liquid biofuels expenditures seem to be relevant for the development of the biofuels sector: in 2010 asset finance dropped by to 19% to 4.7 G$ which is considerably below the 20 G$ investments in 2007 [42]. While these numbers do not include mergers and acquisitions, and thus exclude, for example, Shell's joint venture with Cosan, it becomes clear that BP's focus on ethanol refineries (valued an initial 0.560 G$) or Petrobras' biofuels investment plans (2.8 G$ until 2013) play a very important part in overall biofuel sector investments, a role even more emphasized given the recent downturn of the sector.

4. Main drivers for oil major investments in liquid biofuels

The compiled database indicates that oil majors follow differentiated strategies. ExxonMobil invests very little in first generation liquid biofuels, except for those investments in its downstream business and refinery upgrades in order to comply with current biofuel mandates (mostly below E20-25 for ethanol and seldom above B5 for biodiesel). The previous sections show that Exxon focused mainly in adding petroleum reserves, including the non-conventional resources in USA.

The other three companies analyzed show higher investments in first generation liquid biofuels, which exceed those in second generation biofuels. BP and Shell show considerable expenditures in Brazilian ethanol, especially Shell with its COSAN joint venture worth 12 G$. But BP's investments in Brazil are also notable, and likewise Shell has a focus on access to Brazilian ethanol. Petrobras is an exception given its status as state-controlled oil major. Its strong support for first generation sugarcane ethanol can be linked in part to political influence which directs the company to control ethanol production and promote the country's national biofuels targets, also in the case of biodiesel. The company has already been involved in ethanol biofuel for a long time (particularly since the 1980s) and its recent development plans suggest a considerable upgrade of its biofuels investments, especially regarding domestic ethanol.

The focus on investments in Brazil by European-based oil majors can be linked to two arguments. First, current production of biofuels for transport is still inefficient in many temperate regions regarding energy balance and production per hectare. Strategic access to low-cost biofuel resources under these conditions is a principal driver behind biofuel investments. Second, the discussion on food conflicts due to first generation biofuels expansion has raised considerable

skepticism regarding sustainability [93,94]. In this context, Brazil offers considerable advantages given its potential for expanding agricultural production without compromising food production [17,18,39]. Actually, Shell and BP as major blenders of first generation biofuels have now taken initiatives to demand contractual sustainability standards by feedstock providers. This gives further evidence of the socio-environmental concerns surrounding biofuels including Brazil, making it unlikely that oil majors primarily use their biofuels investments as greenwashing.

In addition, several oil companies are attempting to increase their petroleum reserves by investing in technologies to prolong exploitation of current oil fields, establishing partnerships with national oil companies and adopting production-sharing agreements [95]. However, it is still unclear if biofuels (given their current growth rates) could help extend petroleum reserves. Even under optimistic assumptions, Castro [96] found that an attenuation of peak oil decline would require annual growth rates in production of non-conventional oil above 10% until 2030. Therefore, using biofuels as a way to extend petroleum reserves is unlikely to be a primary driver behind investments into biofuels, at least for the first generation.

Particularly, for second generation biofuels there is much uncertainty given the considerable time span required before they will become commercially viable. In terms of market entrance price syncrudes from Canada's tar sands are still more advantageous than advanced biofuels [97,98]. Indeed, high costs remain a considerable barrier to commercialization, with estimated cellulosic ethanol prices two to three times above that of conventional gasoline (if compared on an energy equivalent basis). For algae biodiesel, the current range is even higher. In the case of cellulosic ethanol the share of raw material is estimated to decline, but the costs of converting biomass are still considerable [99].

The analysis of investments in innovation in the biofuels industry shows great variety, with a large diversity of projects, which include: new raw materials (lignocellulosis, algae, waste, etc.); new processes (hydrolysis, synthetic biology, new fermentation processes, gasification, pyrolysis); and new products (biobased products).

This range of alternatives and strategies in R&D indicates the still experimental level of second generation biofuel technologies, and shows that as of yet, there is no dominant one. This diversity is related to different future visions by each market player. In this range of actions, some companies are concentrating their bets, while others are diversifying their investments in various technologies. There is thus a technological race on among a wide range of private sector players such as biotech companies, chemical companies, agribusiness, oil companies, and others.

Some companies focus their research on technological options that have possible interactions with their industrial expertise, such as bio-oil extracted from microalgae (surveyed by Exxon, BP and Petrobras). Under this option, the oil extracted from algae could be refined in its own structure, further enhancing integration with current activities. That would be the most natural way of integrating biofuels into the existing chain, practically regarding them as non-conventional oils. However, this technology is still in the early development stage and there are great risks, explaining ExxonMobil's believes that liquid biofuels will play a role only in the long run. Indeed, its investments in algae technology demonstrate that the company does not intend to incorporate the large scale production of biofuels in their short and medium term strategy. Exxon is rather looking to expand capacity in terms of natural gas and non-conventional oil in order to maintain high levels of profitability.

In the case of other technologies, such as enzymatic hydrolysis or chemical conversion, investigated by Shell, BP and Petrobras, existing expertise is not a driver for investments. For the medium-term strategy, companies plan to include second generation biofuels because these technologies are more closely paired with currently exploited economies of scale and marketing skills.

In addition, the commitment of Shell, BP and Petrobras to a range of technologies, converge on their strategies to get involved in ethanol production in Brazil. Shell's joint venture with Cosan (Raízen) allows the company to establish a direct contact with the agricultural and biofuels sector, a step most oil companies have avoided in the past preferring to base their biofuels investments exclusively on complying with government biofuels mandates. It also marks a change in strategy toward options that are economically competitive and can provide large scale, short-term, cost-effective greenhouse gas (GHG) emissions reductions – generally considered to be the case for Brazilian sugarcane ethanol. Finally, the deal has also considerable second generation implications, a position acknowledged by Shell, which aims to continue R&D efforts to achieve commercialization of second generation biofuels derived from sugarcane residues (mostly bagasse). Shell's strategy seems to bet on enzymatic hydrolysis, that has great marketability in the medium term, along with major investments in Brazilian ethanol.

5. Final remarks on integration, diversification and technology lock-ins

Vertical integration aims to guarantee access to strategic resources. In the short term oil majors have to increasingly comply with government blending mandates, securing supply of low-cost feedstock or biofuels. In the medium- to long-term, when second generation biofuels eventually become commercial this strategy will be even more relevant. Therefore, early movers are likely to have considerable advantage. While biofuel mandates above 10% (on a volume basis) are uncommon (only in Brazil), meeting blending obligations in major consumer markets with low cost resources is a concern for most oil majors, especially European ones. Ethanol exports are only feasible in regions which can produce biofuels without subsidies. Brazilian ethanol from sugarcane can be produced in a very cost-effective way, and is likely the best option [36,100]. This also explains the considerable interest of Shell and BP in Brazilian joint ventures.

Diversifying supply sources is another important issue. Replacing reserves has proven difficult for several oil majors,

not only due to political instability in countries that hold most of current reserves, but also given the surge of nationalized oil companies [3]. In this scenario the role of unconventional petroleum (crude oil and natural gas) has become increasingly important for some oil companies, such as Exxon (e.g. unconventional gas) and Petrobras (e.g. pre-salt petroleum reserves). Other oil companies are still looking for ways to add to their petroleum reserves. Liquid biofuels can become one of the answers to this issue in the long term.

Lock-ins: Companies' investments in research on advanced biofuels are facilitated by their ability to coordinate their strengths in technology projects. They have greater capacity (financial and technological expertise) to absorb the risks associated with investments in innovation. National government policies that drive investments toward road infrastructure, as well as compulsory blends for biofuels that are fueled in internal combustion engines, strength the role of oil companies in liquid fuels compared to, for example, electric vehicles. This is an open way for oil companies to invest in second generation biofuel technology. None of the companies analyzed invest in disruptive technologies that go far beyond their core business. Therefore, technological lock-ins related to the current fuel supply system are unlikely to disappear.

On the contrary, biofuels increasingly play a part in a fossil fuel dominated techno–institutional complex. In the short term the quality and amount of current major oil companies' investments in liquid biofuels are driven by the requirement to comply with binding mandates for biofuels. The oil majors' strategy is increasingly emphasizing widening access to low cost first generation biofuels (e.g. sugarcane bioethanol). In the long term the emphasis continues to be on the introduction of liquid biofuels (even advanced ones) in the infrastructure of the oil industry.

However, there is not yet a dominant path for introducing advanced biofuels in the long term. Oil companies are testing different paths, although all of them tend to follow the perspective of a large firm: the aim to benefit from scale and scope economies. Interestingly, some advanced biofuels do not fit entirely in with this aim and are being developed by small and highly technological firms. These firms, however, are unlikely to be prepared to compete in a world of increasing large scale demand for liquid fuels. A different, but unlikely, world based on decentralized centers for liquid fuel supply and demand could be to their benefit, but has to face strong technological systemic lock-ins. In fact, our analysis shows that when small specialized firms overcome the R&D phase for advanced liquid biofuels, and try to reach the market, they are frequently acquired by or enter into joint venture agreements with oil majors. This happened, among other, with Synthetic Genomics Inc. (SGI), Choren, Iogen Energy Corporation, Codexis Inc, Virent Energy Systems Inc, Verenium Corporation (now called Vercipia), Mendel Biotechnology, Butamax Advanced Biofuels, and Martek Bioscience Corporation.

Therefore, it seems unlikely whether different paths for producing liquid biofuels will be able to co-exist in the long term, or whether there will exist only one dominant path, possibly controlled by large oil companies such as BP, Shell, Petrobras or ExxonMobil.

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