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Ethanol and oil firms:

the beginning of a new role for alternative fuels?

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Abstract

Firms are facing increasingly stringent environmental quality specifications for their products, including an increase of biofuel mandates, as a means of reducing emissions of CO_2 and air pollutants. These environmentally related 'new conditions' affect oil firms' fuel production, prompting them, in particular, to integrate biofuels into their operations and, at least in certain cases, to change their overall strategies towards biofuels. This paper seeks to make an empirical contribution to the literature on path-dependency by examining how the introduction of biofuels generates a shift in an oil firm's established technical and production patterns. It analyses in detail the effects of implementing ethanol production in two contrasting oil companies, Petrobras and BP, and draws four main conclusions about the experience.

First, oil companies have become leading players in the development of alternative fuels such as biofuels. Second, there are evident differences among oil majors in their involvement in different biofuels; these arise from the scope and continuity of government policies, from contrasts in the influence of different national ethanol lobbying groups, and from variable levels of proactivity of companies in particular energy options. The third finding is that what seems to be a 'shift in technological paradigm' has begun among the dominant firms in the blending markets, locking the present technical conditions into a pattern of transition which draws alternative non-fossil fuels into the mix. Fourthly, a high demand for flex-fuel cars will further favour the transition to biofuels.

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I. Introduction

Alternative fuels face considerable technical and institutional barriers when attempting to improve their share of markets for established technological fuels. In certain conditions, however, significant alterations to established markets have taken place. Haug (2011) argues that oil can only be substituted by alternative technologies when they are ready to be scaled up, and that the speed of adoption depends on how 'radical' the substitute technologies are. The adoption of such technologies may be triggered by external factors or events which could be associated with strong shifts in factor prices, by major technological breakthroughs in related sectors, or by modifications in societal beliefs, norms, or tastes.

Certain markets can be identified in which external factors have been crucial for the adoption of such fuels; one of these markets is the one for ethanol, which has become the most-used alternative fuel partly due to promotion – largely by supporting government policies. Such policies have acted as an external element which affects the rate of adoption by existing major firms and have provided new 'rules of the game' within the established dominant technological system. Existing leading players, however, are more likely to show hostility and to generate resistance to new technologies, due to fact that, as explained below, their flexibility is limited by what is known as their lock-in dependent path.

Ethanol and ethanol blended with petrol have a long history as automotive fuels (Dimitri and Eikland, 2007) and have recently received growing attention as alternative fuels due to their possible role in reducing problems such as climate change, 'peak oil', high oil prices, and political instability (Solomon, Barnes and Halvorsen, 2007). Increasing interest in ethanol has prompted studies which even see the fuel as a potential threat to petrol, and in the past decade ethanol has experienced an increase in both production and blending volumes in many countries around the world (Szklo, Schaeffer and Delgado, 2007).

This paper focuses on the dynamics of technological change and the role that government policies, institutions, and technological breakthroughs can play in promoting a transformational process of incorporating alternative technologies into current energy and transport systems. At a conceptual level, the paper seeks to contribute to analysis of the particularities of the process of including more biofuel in path-dependent technical systems, focusing on the predominant existing strategies. It draws on the literature of various branches of economic theory – evolutionary economics, transitions theory, and path-dependency – in order to address the impact of the implementation of ethanol production by oil firms.[1] The study also relies on other concerns related to technological change and strategic niche management.[2] As Carolan (2010) argues, the analysis of an emerging ethanol transition in a sociotechnical fuel system could shed light on the causes driving this transition and provide an understanding of the logic of path-dependency in such a system.

The paper uses the case studies of Petrobras and BP to show how the conditions under which these two firms operate have modified their strategy towards biofuels and the extent to which they are investing in this alternative energy option. For Petrobras, government mandates meant that ethanol has been used since the company was established and hence there is a long history of ethanol use in downstream operations. However, it is argued that despite a high rate of adoption of first-generation

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[1] Unlocking or breaking a path-dependency has been dealt with by other authors (Unruh, 2002; Dolfsma and Leydersdorff, 2009; Cowan and Hulten, 1996). They have touched upon breaking carbon lock-in systems that inhibit diffusion of carbon-saving technologies (Unruh, 2000, 2002).

[2] See for instance, David 1985; Dosi 1988; Geels 2002, 2005, 2010; Markard and Tuffer 2006; Unruh 2002.

biofuels, it was not until the flex-fuel car innovation, nearly three decades after the success of the Proalcool programme, that a shift in the dominant fuel in the Brazilian light vehicle market took place. BP, in contrast, has incorporated ethanol into its operations in reaction to regulation in the main markets in which it holds downstream positions. Despite having only 10 years of experience of ethanol expansion in the USA, the company has developed a different strategy from Petrobras. BP has become a first-generation ethanol producer outside its main markets. The company has increased its joint venture agreements for ethanol development and has adopted a leading role in the research and development of other advanced biofuels such as butanol.

Based on these two case studies, the paper shows, first, that oil companies have become leading players in the development of fuel alternatives such as biofuels. Second, there are evident differences between different oil majors in their level of involvement in different biofuels. These differences arise from the scope and continuity of government policies, in differences in the influence of different national ethanol lobbying groups, and from the different levels of activity of oil companies in different energy options. Third, what seems to be a 'shift in technological paradigm' has begun among the already dominant firms in the blending markets, locking the present technical conditions into a pattern of transition which draws alternative non-fossil fuels into the mix. Finally, the paper concludes that a high demand for flex-fuel cars will further favour the transition to biofuels.

Section II looks at the relevance of factors such as path-dependency, technological regimes, and transition, to the current analysis. Section III describes the characteristics of ethanol as a fuel and of the global growth trends in biofuels. Sections IV and V present the two case studies, on Petrobras and BP, and Section VI presents the conclusions. The Appendix summarizes the activities of oil firms in advanced biofuels and related patents.

2. Evolutionary theories of technological change

Theories of evolutionary economics (Dosi, 1982; Nelson and Winter, 1982) emphasize the evolutionary characteristics of economic and technical change. According to such theories, firms, in their growth strategy, focus on established routines and existing competencies, habitually ignoring potential radical innovations. They follow a dominant design and certain new variations are generally favoured over others only if they are in line with prevailing routines established within the existing 'technological regime'. This process considers most variations as being no more than an incremental change to the existing model or design. Dosi (1982) called these 'shared routines' – in other words, forms of further innovation which are constrained within an existing dominant model.

Path-dependency

Arthur (1989), David (1985), and Roehrl and Riahi (2000) have all suggested that initial conditions are often crucial in determining the technological path to be followed. Arthur (1989) states that when two technologies compete for adoption, 'insignificant events' may give one of them a leading advantage that could make their technology dominant in the marketplace. He argues that the existence of increasing returns favours the chances of adopting a new technique, but once a course has been set, it is very difficult to change – meaning that a certain technology could have inferior long-run potential when compared with other technologies which are not selected. In this way, technologies having only small short-term advantages may 'lock' the technical basis of a productive system into technological options that may turn out to have fewer long-term advantages than other technologies; these are consequently 'locked-out'. Such locking-out is likely to affect innovation, since future technological selection and development will most probably follow either the previous path or one that is close to current methods or practices, making it almost irreversible.[3] David (1985) argues that three factors are relevant to the link between path-dependence and technological change: technical interrelatedness, economies of scale, and quasi-irreversibility. All these factors make it more costly and difficult to change technological course. The path-dependent model suggests that past experiences or historical path decisions convert path-dependent technological change into a cumulative process, with little chance of shifting from a specific direction of movement. This process also implies that path-dependent industries and firms have a strong sense of continuity and stability in the process of the technological change which they adopt.

The path-dependent model, however, is by no means without its critics. Some of those have frequently stated that path-dependence theories leave no space for radical innovations, nor do they explain how the system escapes from lock-in conditions. Adopting a central position, Berkhout, Smith, and Stirling (2003) argue that stability and path-dependency are relative, and that firms and other policy actors are subject to competitive pressures which can be strong enough to encourage partial changes. Markard and Truffer (2006) have shed some light on the possibility of unlocking from path dependence, indicating that external stimuli, in the form of market liberalization, may change the environment for selecting innovations, thus allowing for radical innovations.

Neither market conditions nor human agency (Hirsch and Gillespie, 2001) are factors that path-dependency considers to be at the core of its arguments; nor is either of them an effect that external agents or actors could use to modify the direction of the existing technical path. Although path-dependency theory is focused on technical aspects, it does imply the 'embeddedness' of different factors surrounding the concept of technology. It is this embeddedness that binds the possibilities of

[3] As Ruttan (1997, 1523) argues, ' … the strength of the path dependence model lies in the insistence of its practitioners on the importance of the specific sequence of micro-level historical events', and how current conditions may influence future technology and knowledge.

change, considering such factors as: current resources, capabilities, institutional and organizational practices, rules, relevant structures, and other economic factors.

The body of the path-dependence literature does not help to show what the factors driving change are, nor how the system destabilizes or enters a transition to technological change, or how radical this change might be. It is nonetheless very useful in understanding the current state and in calculating the number and size of the barriers preventing radical technological change. Hughes (1983; 1989) argues that a large technical system (LTS), such as the electricity supply sector, groups a capital-intensive infrastructure along with many complex components and structures, exhibiting path-dependencies which in fact become forbiddingly high barriers to radical innovations. A similar case can be seen in the oil and gas industries, where exploration facilities are set to last for decades and cannot be converted to low-carbon fuel use (Scrase and Mackerron 2009). Within such an LTS there is an interdependence of technologies, components, and practices which makes large-scale changes difficult. An oil-based-fuelled vehicle production system can be characterized as a large technical system with increasing returns, economies of scale, and path-dependence where, over the past century, innovations have been incremental rather than radical. Systemic interactions of actors and institutions along the dominant path create a lock-in system (Unruh 2000).

In order to understand any possible deviation from path-dependency, or how a lock-in may be broken, one needs to consider a broader definition of a technological system, one similar to the socially embedded technological regime defined by Kemp, Rip, and Schot (2001, 272):

> … the grammar or rule set comprised in the complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of the technology or mode of organization.

The 'social embeddedness' of the concept adds variables such as: value of past investments, interests of firms, government policies, and intra- and inter-organizational relationships to the previous definition (Kemp, Rip and Schot (2001, 272).

Transition literature

Berkhout (2002) emphasized the importance of focusing on actors affecting or pushing for change, not only of individual technologies but, at a higher level, for change in technological systems. The use of the transitions literature complements the analysis of the potential unlocking of oil-based path-dependency, as it integrates the role played by actors and institutions as well as providing possible answers to the questions of where radical innovations come from, and what effect they have on stabilized regimes. When looked at from this perspective, transition literature is in substantial conflict with path-dependency and lock-in, as it aims to show how lock-in may be broken rather than reinforced.

'Transition' can be defined as a passage from an earlier to a later stage of development. The literature on transitions focuses not only on technological aspects of change but also on how actors, social groups, institutions, and markets will interact in a wider societal context. Kemp, Schot, and Hoogma (1998) broaden the technological regime concept by redefining it as one that is socially embedded. Geels (2004) refined the concept and added a distinction between sociotechnical systems, rules, and actors, and introduced the term 'sociotechnical regimes' in which he includes all policy, science, technological, and sociocultural regimes. Geels (2005) uses a multi-level perspective (MLP) to consider the interaction among three levels: niches, sociotechnical regimes, and the sociopolitical landscape. Niches are the breeding place for developing new technologies and radical innovations, as well as for realizing regime shifts. The existence of niches, therefore, explains how radical innovations come about and how a new technological regime emerges. Sociotechnical regimes include a network of public and private actors as well as the rules, artefacts, and technological systems of a sector – all of which provide structure and stability to technological development. The sociopolitical landscape refers to political and cultural values, macroeconomic aspects, and other factors that are part of a wider context. Each of these multiple levels has its own set of interrelated actors and characteristics, and technological change occurs as linkages between them.

Strategic Niche Management (SNM) is a concept which has been used to investigate the introduction of sustainable technologies into established markets. This approach has helped to analyse innovations with potential environmental effects.[4] Transition theory is designed to help explain regime transitions as changes that derive from protected sociotechnical niches which attempt to replace existing practices and become 'market niches'. 'Niche development' has evolved from a new concept: shifting a regime to achieve broad implementation of an emerging technology. Using SNM as a policy tool could help a normally protected technological niche to become a market niche, even by forcing its way into the regime, for example:

> when public authorities exert external pressure on industries to develop technologies with certain (sustainable) characteristics, by a specific deadline. (Raven, 2005, 54).

Aspects of evolutionary economics used in the case studies

In summary, there are key elements from evolutionary economics – path dependence and transition theories – that support the analysis of the two case studies in this study. The first, is technological interrelatedness and interdependence (path-dependency) in energy systems, which act as a barrier for radical innovations; these barriers are embedded and possibly limit the adoption of new technologies if they are not compatible with existing practices and infrastructure. Second, technological paradigm lock-in, in which there is inertia in technological development and a powerful lock-in effect that guides the search and innovation process to follow a trajectory which inhibits transition. Third, strategic niche management – since niches are frequently sources of radical innovations. Sociotechnical niches are often protected and can later become market niches, although they need to be 'strategically managed' to overcome regime lock-in barriers. Fourth, incumbent/regime strategies ('Regime Shift'), in which (established) incumbent firms are part of the sociotechnical regime, in which their strategies and trajectories co-evolve; they become relevant actors in shaping and directing the speed of adoption of new technologies and possible paradigm shifts. These incumbent regime strategies could also incorporate the developing niches which can appear as a market opportunity – or way of solving a problem. Finally, as part of external technological breakthrough (Landscape/Regime), government policies may facilitate conditions for occasional regime change through authoritative mandates that provide relevant stimuli for technological breakthroughs.

How does this body of literature help us understand the evolution of ethanol implementation by the oil firms? This study considers that oil firms are immersed in an oil-based path-dependent fuel production system, in which investments are generally large and have high fixed costs. There are economies of scale, technological interrelatedness, and learning coordination effects which make investments generally irreversible, and any decision to incorporate biofuels would be unlikely to come from their 'internal' search for adaptations or variations to their fuel production system. Hence, a transition to the incorporation of ethanol into an oil firm is likely to come from external sources and not from the technological paradigm. This was clearly the case for Brazil's Proalcool Programme, a policy implemented by the Brazilian government in the 1970s, that stipulated the development and deployment of cars with ethanol-run Otto engines, in an attempt to trigger a changeover from oil-

[4] SNM emerged from two bodies of literature: evolutionary theories of technical change, and constructive technology assessment (CTA). SNM can be used either as a research model or a policy tool (Raven, 2005).

based transportation fuels. The programme, which has become regarded as one of the most successful and ambitious of renewable undertakings, made national R&D centres develop engines which would run on higher mixtures of alcohol with petrol, and later on alcohol alone. This policy was supported by generous subsidies given to both producers and users. The Brazilian example illustrates how, through a policy-driven programme, a technological paradigm and trajectory were challenged by a large-scale implementation of an ethanol-based strategy. The transitions approach could be useful in analysing the Brazilian case in particular, as it will help explain and analyse the role of different actors involved at different levels (regime, niche, landscape).

Moreover, the use of biofuels probably has an effect on its technological path, and this effect could vary depending on the extent and rate of ethanol implementation; this in itself could lead to a new direction in its trajectory, perhaps unlocking or decreasing a firm's path-dependence. Thus, it will be relevant to ask: what are the main characteristics of oil firms' ethanol implementation, and are these are common among oil firms? To what extent have oil firms modified their original oil-based path-dependent trajectory as providers of fossil fuels, and what elements, if any, could determine the path direction? It is assumed that higher implementation[5] (total ethanol volume used) would mean a more significant change and deeper impact. This study will therefore analyse the question of whether this transition is reflected in the oil firms' path. It will be relevant to show whether, in implementing ethanol programmes, there are differences among oil firms in the degree of modification of their path, and what features make firms more likely to implement biofuels.

This paper begins to provide some answers to these questions by drawing on the theories discussed above – in particular by analysing the strategies followed by Petrobras and BP after confronting biofuel mandates – in order to assess whether there has been any significant change in their oil lock-in path.

[5] Biofuels can be used either as an additive or as a fuel substitute, with different implications for oil firms. When used as an additive, ethanol is blended up to 25% in motor fuel.

3. Technological change and the growing interest in biofuels

Although there have been various studies analysing the relationship of oil firms with climate change or sustainability,[6] there has been a lack of emphasis on the 'new conditions' affecting oil firms' fuel production.[7] Firms are facing increasingly stringent environmental quality specifications for their products (Szklo et al., 2007), including an increase of biofuel mandates, as a means of reducing emissions of CO_2 and air pollutants. These environmentally related 'new conditions' affect oil firms' fuel production, prompting the companies in particular to integrate biofuels into their operations and, at least in the case of certain oil firms, to change their strategies towards renewable energy. Few studies exist which address the effects of biofuels blending on the operations of oil firms, or on the extent to which the introduction of biofuels has affected changes in their investment decisions.

Oil companies have a history of making investments away from their mainstream or core activities. For example, BP in the period 1955–70 expanded its business in chemicals and plastics and diversified into other non-fuel related activities such as nutrition and computing (Bamberg 2000). The British company also entered into the solar business for several decades, until it divested from it in 2012. With only a few exceptions (such as the Shell Solar Energy programme and BP's solar adventure) however, oil companies have historically divested from large-scale, and long-term non-core activities. This situation has very slowly and slightly shifted as environmental concerns have grown. As an example, from 2000 to 2010 the US oil and gas industry invested about $71 billion in technologies to reduce greenhouse gas emissions; only 1/8 of this, however, about $9 billion, went to renewable technologies (American Petroleum Institute 2011).

Of these renewable technologies, it has been biofuels and solar which have attracted most of the investment. Biofuel is a liquid fuel derived not from petroleum, but produced, conventionally, from plant crops such as sugar (cane and beet), corn, rapeseed, palm oil, soya oils, and wheat. Although biofuel can be a petrol or diesel substitute, it is only in Brazil where it is both used as a substitute and blended in proportions of up to 25 per cent with petrol. Fuel ethanol must be rendered undrinkable by the addition of a denaturant (usually 2–5 per cent volume petrol). Oil firms have used anhydrous ethanol as an octane enhancer (as an additive to petrol, similar to the use of the ether MTBE), while the use of hydrous ethanol involves potential corrosion problems. Ethanol cannot be transported in the same pipelines as oil-based products because contamination may occur if it is mixed with petrol, due to ethanol's affinity for water. When used as a fuel, ethanol is often classified by its water content: hydrous ethanol (used as a petrol substitute) contains at least 5 per cent water; while anhydrous ethanol (blended into petrol in percentages of up to 25 per cent) is manufactured using additional processing that further dehydrates it in order to conform to regulatory specifications, which require a maximum water content of 1 per cent by volume.

The development of ethanol as a fuel and an additive, both in Brazil and the rest of the world, was associated with the development of the internal combustion engine in cars. When cars were first invented and developed in the late 1800s and early 1900s, they were tested with different power

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[6] Skjærseth and Skodvin (2003), Rowlands (2000), Kolk and Levy (2001), and Van den Hove et al. (2002) have all studied energy firms' reaction to climate change. Skjærseth and Skodvin (2003) analysed the strategies of Exxon Mobil, Statoil, and Shell towards climate change, stating that it took ten years after the United Nations Convention on Climate Change (1992) for companies such as BP and Shell to change their position toward climate change, at least rhetorically, and begin to invest in renewable energy, while Exxon opposed the Kyoto Protocol and has only recently started to invest in alternative energy. Rowlands (2000) looked at oil companies' strategies, drawing comparisons between Exxon Mobil and BP.

[7] There have been some exceptions; Bel and Bourgeois, 2003 and Enos, 1958, have focused on depicting the major innovations that occurred in the oil refining industry, and have identified a technological path and oil-based trajectory followed by the majority of firms,

sources. As early as 1876, Nikolas Otto, the German engine inventor, used pure alcohol in his first internal combustion engine – which later emerged as the dominant petrol combustion engine – while several studies were also undertaken in Britain on the use of alcohol in the internal combustion engine (Rothman et al., 1983). Hence, the use of alcohol as a transportation fuel dates back to the initial development of engines. Fuel ethanol, as Lynd (1990) argues, has properties similar to methanol, and is in many ways superior to petroleum fuel for spark-ignited engines. Ethanol has a higher octane number than conventional petrol, it is safe in storage, and has good thermal efficiency. However, ethanol has unfavourable properties for petrol engines as it generates starting problems, overheating, increased cylinder wear, and it also has a lower energy density of about a third that of petrol. The lower density factor, however, is offset by its high octane and greater volumetric efficiency when blended in proportions of up to 25 per cent with petrol (Rothman et al 1983). A fundamental problem for petrol blended with ethanol is that alcohol is soluble in water, while most petrol and fossil fuel distribution systems are not.

In those crucial early years of car development, petrol and alcohol competed to become the dominant fuel for the internal combustion engine on both sides of the Atlantic. As Dimitri and Effland (2007) argue, ethanol failed to become the dominant fuel in the USA primarily due to economic factors, rather than to technical suitability for engines. In fact, Henry Ford's first automobile in 1896 ran on pure alcohol, while in 1908 his famous Model T was a flexible-fuel vehicle that ran on both alcohol and petrol, or a combination of the two. Despite the initial competition between the two fuels, the petrol engine became the dominant technology for cars, generating investments and establishing appropriately scaled infrastructure for distribution and consumption of this fuel (for example, petrol stations, pipelines, and roads).

Ethanol is the most widely used type of biofuel in the world. In terms of usage, biofuels are the largest renewable energy source in road transport, biofuels accounting for about 3 per cent of road transport energy consumption (International Renewable Energy Agency, 2013), and 22 per cent in the Brazilian transport sector. The USA is the largest consumer of biofuels in the world followed by Brazil. The three major producers in the world are the USA, Brazil, and the European Union. The production and use of biofuels in the USA and the EU are predominantly driven by biofuels support policies, including the US Renewable Fuel Standard (RFS2) final rule and the EU Renewable Energy Directive (OECD-FAO 2012). In 2011, the total US production of ethanol amounted to 13,900 million gallons (a nearly eight-fold increase from 2001) which represents approximately 10 per cent of US petrol ('gasoline' in the USA) supply, and alcohol can be found in about 96 per cent of all petrol sold in the USA. It is estimated that ethanol displaced 462 million barrels of imported crude oil in 2012 (RFA, 2013). On the other hand, the world biodiesel market is considerably smaller than the ethanol market, both in production and use: it is estimated that total world biodiesel production in 2012 accounted for over 25 billion litres, in contrast with the approximately 110 billion litres of ethanol for the same year (OECD-FAO, 2012). The largest share of biofuels in any transport market is found in Brazil, where ethanol accounts for 57 per cent of the total petrol-type fuel market on a volume basis. The largest relative size of biodiesel in any market is in the EU, where biodiesel accounts for no more than 6.3 per cent of the volume of the diesel market.

The production of ethanol in Brazil has huge potential, given its access to a substantial arable area. Brazil comprises 850 million hectares and nearly 360 million hectares can be used for agriculture. Sugar cane production uses 7.0 million hectares of arable land, while ethanol production demands 3.2 million hectares, representing less than 1 per cent of total arable land in Brazil. Ethanol production amounts to 7,000 litres per hectare per year, while the USA produces at less than half this rate, that is, 3,300 litres per hectare per year (Silva and Fischetti, 2008). In contrast to the USA, Brazil has a surplus of ethanol production and exports ethanol to different parts of the world. The country exported 5,118.7 million litres of ethanol in 2008, although in 2011 it had to import ethanol from the USA due to a shortage in supply which was related to high sugar prices, government policy, poor harvests, and lack of investment in sugar cane cultivation.

In addition, the use of ethanol has been promoted by governments due to its lower greenhouse gas emissions (GHG) in comparison to petrol. Brazilian sugar cane-based ethanol is calculated to have saved more than 50 per cent of GHG in comparison to petrol use.

4. The Brazilian case

The purpose of this section is to refer both to the lock-in characteristics of large technical systems explained earlier in Section II, and to the role of niches which permit or encourage regime modifications or shifts. By looking at both of these it is possible to suggest a coherent explanation of a possible qualitative shift in the technological trajectory of Petrobras after nearly six decades of ethanol production.

Phase 1: The first biofuel mandate and the beginning of large-scale implementation

The Brazilian experience with ethanol as a fuel or additive from sugar cane production is a pioneering one, strongly associated with both the initial development and expansion, and then the subsequent crisis, of the sugar industry in Brazil, in both the north-east and south-east of the country. At the same time as the expansion of sugar cane-derived fuel use by cars there was enormous growth and development of the sugar cane industry in south-east Brazil. After World War I came an expansion of the *usinas* (sugar cane factories) in the south-east, which within a few years surpassed the production of the more traditional sugar producing region up to that time, the north-eastern region of the country (predominantly Pernambuco and Alagoas). The expansion of the sugar industry continued in the south-east, and generated an economic crisis for the north-eastern producing sector, forcing the national government to intervene in order to restore economic equilibrium to the sugar industry, as well as to develop the production of a new product, anhydrous ethanol. The Government formed the Sugar Production Defence Commission and the Alcohol–Motor Studies Commission, which led to the establishment of the first official mandate for ethanol on 20 February 1931 (Official Decree 19.717). The Decree made it obligatory to add 5 per cent anhydrous alcohol to all petrol (all being, at that time, imported). These policies stimulated the development and growth of alcohol capacity through new distilleries producing alcohol from sugar cane. By 1 June 1933, these two Commissions were merged into the IIA (Institute of Sugar and Alcohol) which was allocated the task of promotion, development, and expansion of a large alcohol distribution network across the whole of the country. This was a primary response to the need to find new conditions and markets to alleviate the over-production of sugar generated at that time (Netto, 2007). Among the principal IIA policies were quotas for sugar and alcohol production.

Although Brazil was not the only country producing alcohol fuel at that time,[8] its successful use of alcohol mixture since the 1930s marks the initial steps in the formation of the world's only large-scale implementation of both anhydrous and hydrous ethanol. Subsequent developments are shown in the list of events in Table 1.

[8] In 1927, Germany and France produced 17 and 17.5 million litres of fuel alcohol, and by 1932 this production had increased to 120 and 85 million litres respectively (Netto, 2007).

Table 1: Brazilian ethanol implementation (main events)

1931	First ethanol blend mandate	1989	Oil prices drop and petrol price equals that of ethanol
1954	Formation of Petrobras	1990s	Ethanol comprises 20% to 25% of the petrol sold in fuel stations
1973	First oil crisis	2003	Flex-fuel biofuel cars debut
1975	Beginning of Proalcool Program	2005	The National Program for Biodiesel is launched
1977	Blend of 4.5% ethanol	2008	B2 becomes mandatory (B2 is 2% biodiesel blend)
1979	Blend of 15% ethanol	2010	Ethanol consumption equals that of petrol
1979	Second oil crisis	2010	B5 usage starts
1985	Ethanol mixed in petrol reaches 22%	2011	ANP* starts regulating the production of ethanol, now considered a fuel. Proportion of ethanol in petrol may go from 18 to 25% and is established by the government

Notes: Agência Nacional do Petróleo

The Second World War brought another crucial change and a new opportunity for Brazil to expand its sugar production. This second era of expansion generated fresh interest in modernizing the industry especially in the state of Sao Paulo (Netto 2007), and in creating associations to defend sugar cane producers' interests, such as Copersucar which was created in 1959. Furthermore, for the first time in 400 years, the Sao Paulo region surpassed the hegemonic sugar cane production in the north-east and expanded its capacity by a factor of six. These events mark the initial stages of what became the politically strong and highly concentrated Sao Paulo sugar cane industry.

Ethanol as a fuel developed in Brazil along a distinctive path, in harmony with the expansion of the sugar cane industry and of the foreign-owned car and oil industries. Contrary to the position in the rest of the world, sugar cane-based ethanol has been produced along with petrol since the early stages of Brazil's fuel industry, and has remained as an oxygenate for Brazilian petrol since 1931, when the first blending mandate was decreed by the government. The number of sugar cane distilleries producing fuel-grade ethanol increased substantially during the first (5 per cent) blending mandate – rising from one in 1933 to 54 in 1945 (Hira and de Oliveira 2009). This growth in ethanol production, which became a constant additive to the petrol mix, accompanied the expansion of the sales of cars and their fuels. Up to 1950, all the cars in Brazil were imported, as was the petrol to run them, thus increasing substantially Brazil's dependence on imported oil and its derivatives. By 1957, 1166 cars were registered in the country and three years later the number had grown to 42 619, of which 40 980 were manufactured in Brazil (Anfavea 2011). Brazil favoured highway development over railroads, further promoting the automobile industry (Sperling 1989).

Car expansion also facilitated the development of infrastructure for the distribution of oil-derived products such as petrol. The existence of a distribution and retail network designed specifically for a liquid fuel such as petrol, in addition to the lack of interchangeability with other fuels, was one of the main technical and cost barriers to overcome when introducing a new fuel in the USA and the EU. Since Brazil's 1931 decree on petrol use, the continuous use of ethanol in the petrol mix shows a unique example of a successful agro-industry being favoured as a supplier of fuel additives, capable of overcoming cost and technical barriers. In later decades (the 1970s) it was to become a large-scale producer of the petrol substitute, hydrous ethanol.

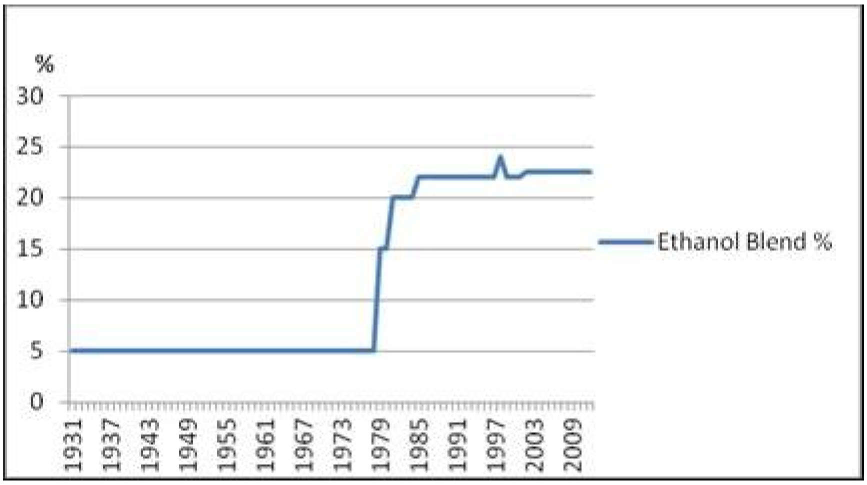
Phase 2: the Proalcool Programme, and first signs of a new path

By the time Petrobras was established in 1954, Brazil had accumulated 23 years of experience in using ethanol blended in petrol. Since its beginnings, the company has continuously used anhydrous ethanol in its operations, though in different proportions at different times.

The lack of infrastructure for ethanol blending, distribution, and sale at petrol stations is currently considered to be both a financial and technical barrier for ethanol implementation in countries other than Brazil. In the case of Petrobras, the investment in infrastructure for transporting fuel from ethanol refineries to storage terminals and in blending and distributing to petrol stations, together with the accumulated technical expertise and knowledge derived from blending activities, all date back to the formation of the company. Petrobras thus had first-generation ethanol interconnected with its fuel distribution infrastructure from its early years.

During the decade after 1964, Brazil’s domestic car production grew fourfold and by 1974 the country had 4 million cars and 1.4 million trucks and buses, and over 70 per cent of oil was imported (Sperling 1989). But oil prices quadrupled between 1973 and 1974 and as petroleum imports increased so did the country’s foreign debt, which rose from $6.2 billion in 1973 to nearly $80 billion in 1982. In response to this surge in oil prices, Brazil increased its use of biomass fuel, a proven blending petrol component which helped to reduce the cost of fuel imports.

Figure 1: Average Ethanol blend in Brazil



Source: Own elaboration with data from Petrobras and Dias Leite (2007)

Until 1975, anhydrous ethanol was used widely and blended at 5 per cent volume into petrol (see Figure 1). Domestic car production had increased, though not without major problems associated with the use of ethanol. Petrobras had a fuel distribution infrastructure designed to accommodate the particular fuel characteristics, and sugar cane suppliers were already full participants in the transport regime.

After the first oil shock in 1973 Brazil, already a major importer of crude oil which increased its foreign debt, now had to confront a sugar cane sector crisis that had resulted from the fall in sugar prices in the mid-1970s. In 1975 the Government embarked on a large-scale renewable energy programme that aimed to substitute petroleum supply with sugar cane alcohol. It set up the National Alcohol Programme: Proalcool.

This Programme set an initial target of producing and using approximately 3 billion litres of alcohol fuel by 1980, equivalent to 20 per cent of anticipated petrol demand, This was not only the largest renewable energy programme in the world, but also the largest state intervention designed to introduce the production of ethanol only-run cars. The Programme, as Moreira and Goldemberg (1999) state, forced Petrobras (at the time a state-owned company) to purchase a guaranteed amount of the alternative fuel. The promotion of cars designed to run on ethanol led to large subsidies; the government provided loans for such cars and sold hydrated ethanol at prices which at times were only 59 per cent of the price of petrol. Other incentives included owners of such vehicles paying 50 per cent less road tax and buyers being allowed 36 months of credit instead of the 12 allowed for buyers of conventional petrol cars.

With the Proalcool programme, a new transport fuel market was created. Sugar cane producers lobbied to secure subsidies, while, as Sperling states:

> … [Petrobras] the huge state petroleum monopoly (and one of the fifty largest corporations in the world at that time), lobbied to gain control of the entire programme and to protect its liquid fuels monopoly (Sperling, 1989, 77)

although it was not successful.

In its first phase (1975–9) the programme was designed to shift sugar cane production from sugar to alcohol and to increase the anhydrous blend to 20 per cent. The ethanol blend policy in the second phase continued (1980–94), but added ethanol-only powered cars[9] in 1980, after the initial 790 million gallons production plans had been met in 1979; the government then raised its ethanol production target to 2.8 billion gallons and set a goal of $5 billion to be invested in the following six years in fuel production and distribution facilities (Sperling 1989). From 1977 to 1979 the blend mix increased to 15 per cent and remained, on average, at that level (because of the Proalcool programme) until 1981 when it was raised to 20 per cent, since when the ethanol blending mix percentage has remained the minimum base for anhydrous implementation in Brazil. Since 1992, the ethanol blending percentage has varied between 20 per cent and 25 per cent as a proportion of ethanol supply.

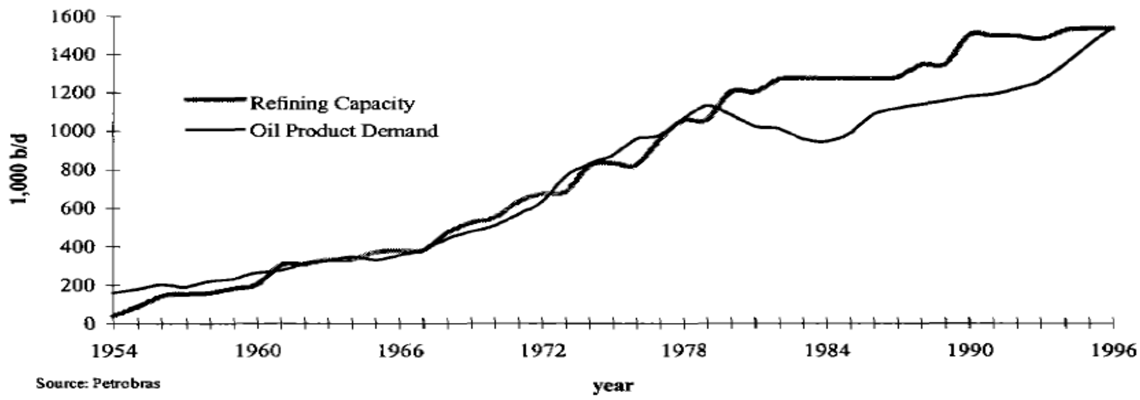
Petrobras was a monopolistic company from 1954 to 1997 when both its monopoly and full state ownership ended. The company, being the only incumbent oil firm during the implementation of the National Alcohol Programme, was therefore in charge of all technical modifications needed in the infrastructure for distributing and selling the alcohol fuel. For many years Petrobras opposed the Proalcool programme (Brilhante, 1997) and sought to increase refinery flexibility in the light of oil product demand reduction (Surrey, 1987) caused by an increasing share of hydrated ethanol sales. As Weiss (1990) notes, Petrobras was the immediate loser in the Proalcool Programme. The alcohol programme was a government initiative that determined the rate of adoption of anhydrous and hydrous ethanol, which set a base for the direction of innovation in the sugar cane industry. The

[9] The technology of these cars was developed at national research centres and used by the car manufacturing industry (Puppim de Oliveira, 2002).

increase in sales of hydrous ethanol, together with a higher anhydrous blend, occurred at the expense of petrol sales. Petrol had to be exported due to refinery limitations that could not allow major changes in the configuration of oil products being produced.

As can be seen in Figure 2 (below), Petrobras has increased its refining capacity since its formation in 1954; during the Proalcool Programme from the 1980s until 1996, however, the company had a surplus in operating refining capacity. The Proalcool programme also generated downstream losses for Petrobras, because it received a lower (fixed) price for its products than import parity prices for petrol.

Figure 2: Petrobras refining capacity 1954–1996



Source: Petrobras in Brandão (1998)

Petrobras, which operated in line with the general practice of other developing countries, invested in refineries to produce lighter distillates, notably petrol (Weiss, 1990) and in exploration activities. Offshore exploration activities were intensified in the 1981–92 period (Brandão, 1998) while the company was forced to distribute (to the Otto cycle engine car market) a competing product and a higher blend of ethanol into its petrol. Petrobras's investment followed a route towards self-sufficiency (Brandão, 1998), perhaps showing an upstream lock-in technological trajectory and practices for fossil-fuel production. This was despite growing sales of ethanol only-fuelled cars, which in 1986 reached nearly 90 per cent of total new vehicles sold in Brazil. The share of hydrated ethanol in the light vehicle market reached 40 per cent in the Proalcool phase. Petrobras was tied to its oil-based trajectory by government initiative and mandates, and these even generated losses for the oil company, as it reported in 1996 (Moreira and Goldemberg, 1999).

Furthermore, during the Proalcool programme, Petrobras developed an ethanol downstream infrastructure to cope with the 'new' hydrated fuel entering the system. It modified all its petrol stations, distribution channels, and transporting and storage terminals to allow for hydrated ethanol sales and petrol blends up to 20 per cent. Also, the upstream division of the company was constantly improved, as Petrobras invested heavily in exploration and production and in achieving proven oil reserves. Brazilian proven reserves grew from 1.5 billion boe in 1979 to 5.8 billion boe in 1996.

Phase 3: Flex-fuel cars, a breakthrough in the technological paradigm

In summary, the Proalcool Programme generated a number of changes in the system. First, the interrelated and interdependent fuel system infrastructure was modified and stretched. Before Proalcool, cars, fuel stations, and distribution infrastructure had a low blending percentage (5 per cent) without major modifications, but with the introduction of ethanol-only cars in 1979, the pattern of interrelation changed, petrol stations had to accommodate new hydrated ethanol pump stations. Although the fuel system at regime level changed as sugar cane producers became fuel producers, the oil company's technological development trajectory did not. The company opposed the shift towards ethanol implementation. A lock-in phenomenon was present; Petrobras kept on investing in exploration and production technology and although it changed part of its downstream infrastructure, the company was not involved in ethanol-producing activities. Major technological shifts and upgrades happened in the auto and sugar cane industries but not in the oil company. The continuous use of anhydrous ethanol since the early years eased the Government's decision to incorporate a larger share of anhydrous fuel in petrol, increasing the ethanol niche and forcing sugar cane producers to supply part of the fuel market, generating a regime shift. Finally, the Government's decision to implement Proalcool, following a national debt problem, enabled other actors in the regime to increase their participation; its authoritative mandates and targets generated a technological innovation breakthrough in the car industry which led to large-scale production of ethanol only-fuelled cars, speeding up substantially ethanol's rate of adoption.

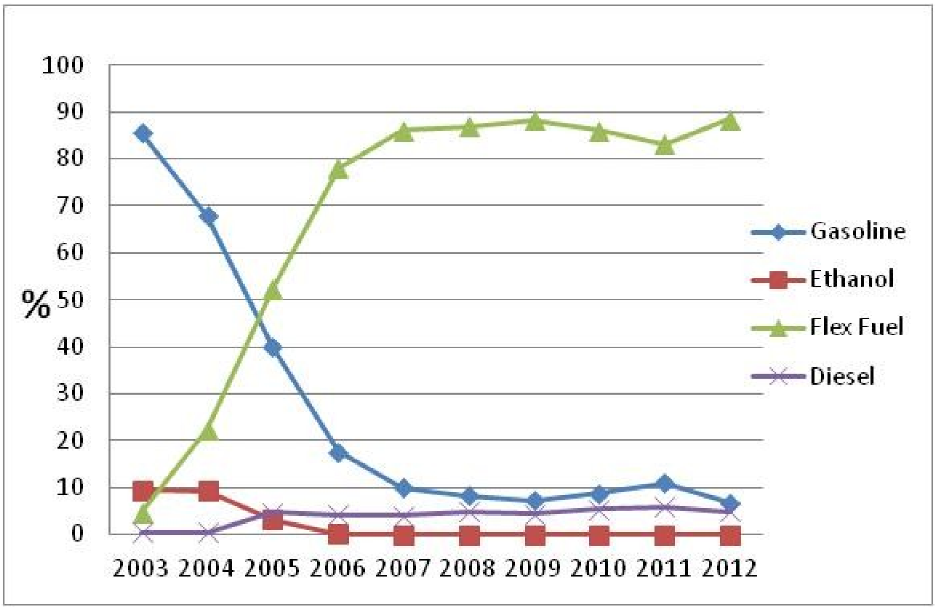
The transition of Petrobras

Although several car manufacturing companies (General Motors, Ford, Volkswagen) began to produce ethanol only-fuelled cars, in Brazil fuel shortages began to occur more frequently, as did technical car problems associated to cold starting and corrosion. Sugar prices increased and ethanol supply shortages worsened; consequently demand for this type of car evaporated. Sales of new ethanol cars dropped to 7 per cent in 1981, and by 1986 the Programme was no longer functioning. The higher alcohol blend in ethanol, however, remained (see Figure 1).

Until 1997, the government controlled ethanol prices by fixing a cap of 60 per cent of the petrol price at the pump (Almeida, Bomtempo, and de Souza e Silva, 2007); hence ethanol received a strong subsidy. In May 1997 the anhydrous ethanol market was liberalized and in February 1999 hydrous ethanol became liberalized in Brazil as well. Complete liberalization was in place by 2002 with the total liberalization of petrol, diesel, and LPG prices (Almeida, Bomtempo, and de Souza and Silva, 2007). Although the market had been liberalized, it was still dominated by petrol-only powered cars.

Flex-fuel cars became available in Brazil in 2003; this type of vehicle had a new engine that could run on any combination of fuels between hydrated alcohol and petrol. In 2003, only 2.6 per cent of new manufactured cars were of the flex-fuel type; by 2010, more than 80 per cent of all cars produced in Brazil were of the flex-fuel type (Anfavea, 2010). In a short period of time there was a rapid expansion of both production and sales of flex-fuel vehicles in Brazil (see Figure 3). The innovation that allows the car to run with any combination of the two fuels is conceived to be one of the major factors behind the expansion of hydrous ethanol production and sales from 2003 onwards. In 2010, the hydrated fuel was favoured by consumers and it took over 52 per cent of the fuel sales market. Moreover, it generated certainty that the alternative fuel was a real option for consumers. The technological breakthrough of the flex-fuel car enabled the growth of ethanol in this second stage of hydrous implementation – after Proalcool – increasing the share of ethanol as a fuel in the market and breaking the rigidity of a blend wall. The blend wall refers to the situation where the mandated amount of renewable fuels exceeds the ability of the vehicles and infrastructure to consume the renewable fuels; this is E25 or 25 per cent of anhydrous blend in petrol. This breakthrough unlocked the petrol car paradigm once more, creating a possible long-term transition in the fuels market.

Figure 3: Distribution of registered light vehicle fleet in Brazil (2003–12)



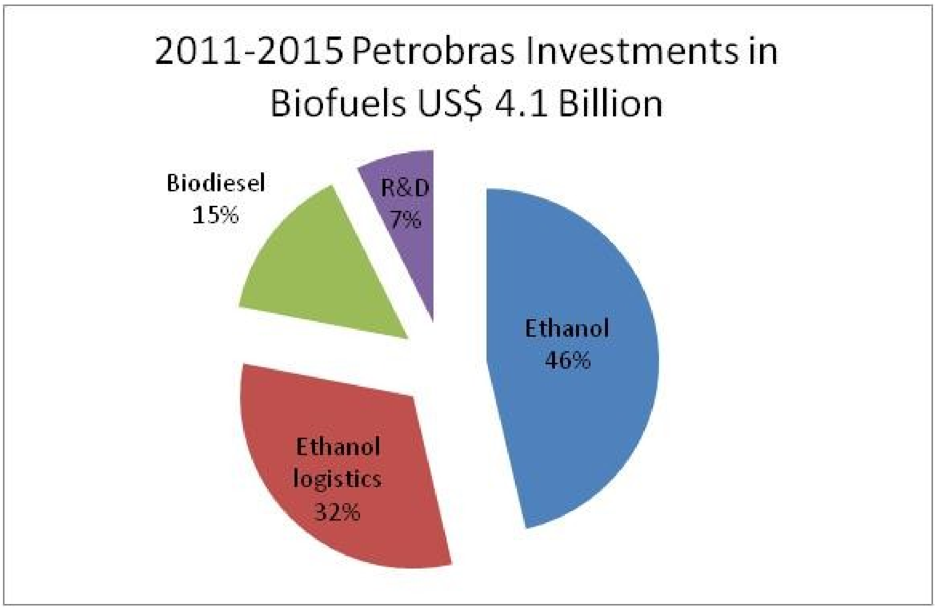
Source: Empresa de Pesquisa Energetica (EPE, 2012).

Prior to the 2003 introduction of the flex-fuel car market in Brazil, Petrobras had been the leading buyer and distributor of both hydrous and anhydrous ethanol in the Brazilian market through Petrobras BR Distribuidora, its distribution subsidiary. This situation continued after the introduction of the flex-fuel vehicle, as Petrobras BR had 40.6 per cent of total ethanol sales in 2010 while in the same year it had a leading 29.67 per cent for the total fuel petrol market. Despite its large share of the ethanol distribution market in Brazil, Petrobras did not produce conventional first-generation ethanol nor had the company dedicated R&D expenditure to developing second-generation ethanol or biofuels. Moreover, the company did not have a record of patenting activity on biofuels until later in the last decade (see Figure 8, Appendix).

Following the rapid development of the flex-fuel car in Brazil, the increased market share gained by hydrous ethanol, and the development of the green agenda, in 2008 Petrobras changed its strategy towards biofuels and created a Biofuel Business Subsidiary – Petrobras Biocombustível – within the company (company interview). This action, unprecedented in the history of the company, generated the first organizational change within Petrobras in response to the ethanol challenge. It follows other oil firms in a decreasing resistance towards ethanol, following a historic challenge (Carolan, 2010). Until 2011, Petrobras had not produced ethanol using conventional routes; in their 2009–13 Business Plan, however, the company announced its decision to invest US $1.5 billion in ethanol by establishing partnerships of its Biofuel Business Subsidiary with ethanol-producing firms. Moreover, the company announced an investment of $532 million[10] devoted to building new ethanol pipelines, in an attempt to create ethanol exporting (exclusively) infrastructure – a major infrastructure project for a competing non-fossil fuel product.

[10] This investment is equivalent to about a fifth of the Petrobras five year investment plan in pipelines for oil and oil products (Petrobras business plans 2009–2013).

Figure 4: Petrobras biofuels Investments



Source: Own elaboration with data from Petrobras 2011–15 Business Plan.

Petrobras moves into ethanol upstream activities

In their 2011–15 Business Plan the company announced a record $4.1 billion in investments in biofuels. Together, investment in ethanol and related projects thus accounted for nearly 80 per cent of total biofuel planned investment (see Figure 4). For the first time, after a long history of ethanol implementation, and after having lost over half its market share in the light vehicle fuel market in 2009 (due to a substantial take-up of flex-fuel cars, and because the price of hydrated ethanol remained about 70 per cent that of petrol – ethanol has 30 per cent less energy density than petrol), Petrobras shifted its strategy to acquire shares in ethanol-producing factories. In the budget given to its recently created Petrobras Biofuels Subsidiary (Petrobras Biocombustível), the company announced its participation in nine distillation plants, which allowed them to take 4 per cent of the ethanol market share in 2012 (see Table 2). Petrobras expects to expand its production capacity to 5 600 million litres to reach a 12 per cent market share in 2015.

Table 2: Petrobras ethanol production

Year	Number of Plants	Production capacity (Million litres)	Market share in Brazil
Before 2006	Nil	Nil	Nil
2012	9	893	4%
2015	9	5600*	12%*

Source: Petrobras (2012). Note: (*) estimated by Petrobras.

In addition to its acquisition of ethanol units in production, the company increased its R&D expenditure for biofuels with a total of US$0.3 billion in their 2011–15 Business Plan. The increase means that biofuels now represent 7 per cent of the company's total R&D, up from 5 per cent in their previous Business Plan for 2006–10 (see Table 3).

Table 3: Petrobras R&D

Petrobras R&D	2006–10 US$ millions	2011–15 US$ millions
Biofuels R&D	32	300
Average per year	8	75
Share of total R&D	5%	7%

Source: Petrobras Business Plans

It is relevant to mention that the Brazilian company is planning to invest in a specific ethanol pipeline infrastructure, as noted above. This investment represents approximately 32 per cent of the total Petrobras biofuel expenditure.

In summary, from 2005 onwards, Petrobras shifted its strategy towards ethanol production, starting with a new organizational structure that gave their biofuel subsidiary a position in the company; the shift also involved providing R&D resources to this subsidiary to search for and develop new advanced, or second-generation, biofuels. In addition, it announced plans to provide financial resources to build an ethanol pipeline, in conjunction with other companies, in Brazil. Hence a new sociotechnical trajectory is being followed in the company, one that takes into account the substantial changes and participation of other producing actors – such as the sugar cane sector in the fuel transport regime in Brazil. The drivers for this major shift in Petrobras strategy are related to the commercial availability and success of the flex-fuel car, which allowed an expansion of biofuel production and consumption, alongside further loss of market share for conventional petrol fuel in Brazil.

Brazil and Petrobras

There are four main actors that influence the motor fuel production system of Petrobras: the oil company, the Brazilian government, the sugar cane sector, and the automobile industry. Throughout 81 years of history in using ethanol as part of the system, these main actors have modified and influenced the proportion of ethanol used. The case study shows that the ethanol path, which started after the 1931 decree through a minor implementation, could deviate from the lock-in characteristic of the system. The Proalcool programme was the first large-scale programme for hydrous ethanol in the world. This government policy, largely supported by sugar cane producers, was implemented in the 1970s and allowed a great deal of experimentation in the use of ethanol as a substitute fuel and a higher blend (increased from 5 to 20 per cent). It can be argued, however, that, at least in fuel transport and distribution, the oil company had already followed a 'large-scale ethanol-blending route' that had developed within the natural trajectory of the oil company through time. It is argued that Petrobras has, since its beginnings, furnished vast technological, financial, and human resources and expertise to a fuel which is an alternative to its core oil-based products. This has created a powerful inertia – based on a network of actors, policies, technological knowledge, and consumer awareness of ethanol-blended petrol – that restrains Brazil from reverting to petrol only. It was not until flex-fuel cars entered the market in 2003, however, that ethanol became the dominant fuel in the Brazilian vehicle market. This dual development influenced a modification in the firm's R&D activities and investment decisions towards a search to produce both first- and second-generation biofuel possibilities.

In that way, Petrobras has followed a similar path to other oil firms. It may be that the level and volume of ethanol used by the company through time, both as a wholesaler and a distributer, did not have a decisive influence on the upstream (production) area of the company, making it difficult to unlock itself from a path-dependent trajectory based on oil feedstock. Moreover, this case study shows that external factors – such as sustained government policies and innovations in sectors directly connected or interdependent in the lock-in system – may, in the long term, influence others players in the system, in this case, Petrobras. The influence and modifications that might follow form part of a transition and possible regime shift. A summary of elements influencing Petrobras's first- and second-generation ethanol implementation can be seen in Table 4.

Table 4: Petrobras: first and second generation ethanol implementation

PETROBRAS	First Generation	Second Generation
Driver for implementation	External /Gov Mandate. Development of Flexfuel car	Internal . Environment/Business Opportunity
To what extent, ethanol implementation	Expansion in Downstream . World leaders, direction to larger implementation.	Demonstration stage/Behind peers
Technological Shift/Trajectory	"End of pipe" implementation . **Base for Lockin first gen trajectory.**	Two patents related to Renewable /both to Biodiesel.
Technical Interrelatedness	Adjustments implemented until (Blend wall) for Anhydrous.	Similar to established infrastructure, however some other molecules Butanol (eg) compatible.

Source: Own elaboration

5. The Case of BP: A newcomer but a quick adapter

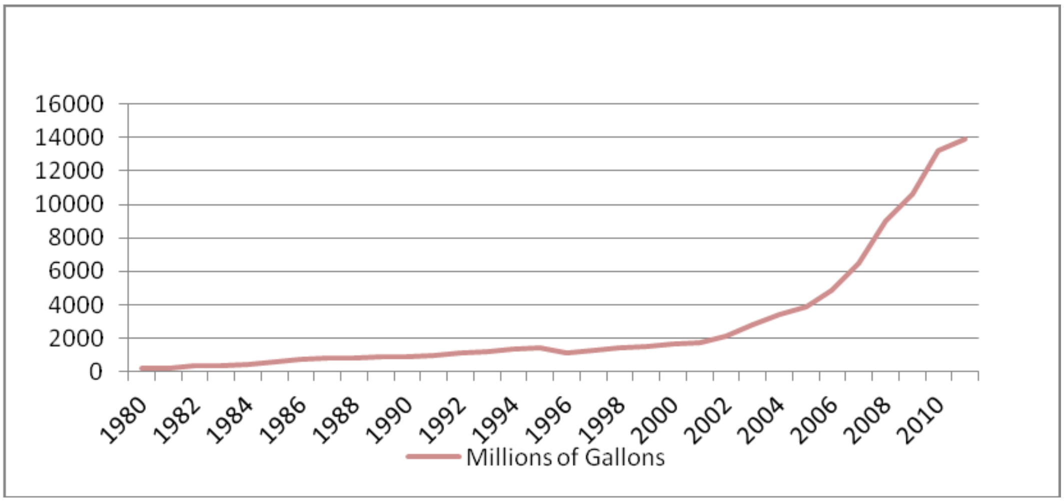
Unlike Petrobras, BP is a relatively new player in the biofuels market. Also unlike Petrobras, it has faced much less stringent mandatory requirements for ethanol implementation. The use of biofuels has probably had some effect on its technological path, and this effect could vary depending on the extent and rate of ethanol implementation, leading possibly to a new direction in BP’s trajectory, perhaps unlocking or decreasing the firm’s path dependence. Furthermore, given the differences in initial conditions, the trajectory adopted by BP is likely to have different features from that of Petrobras. These are the issues which will be explored in this section.

Regulatory changes in USA and EU

BP is a multinational company that has its largest downstream presence in the USA and the UK. It therefore has to comply with biofuel mandates in these countries, as well as the EU policies on biofuels in the case of the UK. Distribution, trading, and operating activities in these biofuel markets have been growing substantially since 2002, in response to the establishment of biofuel blending mandates for the US market. In the EU, the use of biofuels has increased more than ten-fold since 2000, although growth slowed substantially after 2011.

As ethanol blending mandates became generalized across the states of the USA from 2003, the production and consumption of biofuels increased substantially (see Figure 5).

Figure 5: Expansion of US ethanol production 1980–2011 (millions of gallons)



Source: Own elaboration with data from the US Energy Information Administration

In contrast to Brazilian sugar cane ethanol, US ethanol production is mainly derived from corn. In 2011, the US total production of ethanol amounted to 13 900 million gallons, a nearly eight-fold increase since 2001. The total US production of ethanol in 2011 represented approximately 10 per cent that of petrol, up from approximately 1 per cent in 2001 (EIA 2012). Ethanol can be found in about 96 per cent of all petrol sold (RFA, 2013) in the USA. It is estimated that in 2012 ethanol displaced 462 million barrels of imported crude oil. The USA became the largest biofuel consumer market for ethanol followed by Brazil. The production and use of biofuels in the USA was predominantly driven by the public policies promoting biofuels policies that were in place: the first US Renewable Fuel Standard (RFS) in 2005 and the second RFS2 enacted in 2007. The first standard required 7.5 billion gallons of ethanol to be blended in petrol by 2012, while RFS2 distinguished between conventional and advanced biofuels (those that generated 50 per cent lower greenhouse gas emissions), and set a goal of 15.2 billion gallons of renewable fuel to be blended into petrol, up to

13.2 billion gallons of which should be from conventional biofuels, 2 billion gallons from advanced biofuels, with 100 million gallons from cellulosic biofuel. The latter target, however, was not met, as there was no production from cellulosic biofuel to contribute to the target. In 2013, the EPA, reduced the target for cellulosic biofuel use in 2013 to 6 million gallons, significantly lower than its previous target.

The US Environmental Protection Agency (EPA) approved E10, a blend of 10 per cent ethanol and 90 per cent petrol by volume, as the maximum ethanol blend in most of the vehicle fleet until 2011, when the EPA approved an increased blend of 15 per cent of ethanol in all light duty vehicles made on or after 2001. The US government decided to reverse the maximum ethanol blend to 10 per cent in 2013. A small amount of E85 is sold in the USA for vehicles specially manufactured for a maximum blend of 85 per cent ethanol and 15 per cent petrol.

Oil companies operating in the US market faced a loss of 10 per cent of petrol market share in volume terms due to a decade of ethanol implementation. BP has been selling biofuels in the USA for more than 25 years and currently holds around 10 per cent of the global biofuel market. In the USA, the company is one of the top sellers of ethanol-based fuels.

In the UK, blending of biofuels with petrol or diesel is mandated by legislation. The EU CEN Fuel Standards set the maximum limit of biofuel concentration that can be blended with petrol – currently 5 per cent by volume or E5 and 7 per cent biodiesel (B7) by volume. Both oil companies and vehicle manufacturers, as well as biofuel producers, have come to an agreement on these biofuel standards.[11] The EU blend wall of 5 per cent maximum ethanol blending percentage is the lowest of the three major consuming regions: the USA has E10 (or 10 per cent ethanol blend) and Brazil has 20–25 per cent blend.

In October 2007, the UK Parliament approved the Renewable Transport Fuel Obligation (RTFO) that came into force on 15 April 2008. The RTFO mandates that all petrol bought must contain a 2.5 per cent biofuel component, rising to 5 per cent in 2010 and 10 per cent in 2020. These figures aimed to bring the UK into line with European Union (EU) Renewable Energy directive targets, set in 2005, that promote the use of biofuels for transport. After a revision in 2009, following the Gallagher Review of Biofuels in 2008 which recommended a slower rate of increase in biofuel blending content, new limits were announced and the limit was fixed at 3.25 per cent for April 2009/10; 3.5 per cent for 2010/11; 4 per cent for 2011/12; 4.5 per cent for 2012/13 and 5 per cent for 2013/14.

The UK Department for Transport reported in 2012 that six billion litres of renewable transport fuel have been supplied since the introduction of the RTFO. For 2011/12 there was a shortfall of the amount required by the mandate, as only 1.6 billion litres of renewable fuel were supplied, representing 3.6 per cent of total road transport fuel, falling short of the 4 per cent mandate for this period. Only 12 per cent of the feedstock is supplied domestically, while bioethanol was mainly sourced from the USA (reaching 69 per cent of ethanol supplied). Overall, about a third of biofuels consumed in the EU are imported.

[11] The standard for Bioethanol is EN 15376. The standard for biodiesel is EN 14214.

After a proposal by the European Commission was presented in May 2013 to reduce the proportion of conventional biofuels used in the transport sector, the EU Parliament decided to cap the contribution of first-generation, or conventional, biofuels at 6 per cent compared to Europe's renewable energy target of 10 per cent by 2020. The aim of this was to encourage the production and development of second-generation and advanced biofuels in the fuel road transport mix.

In 2013, both the EU and the USA suspended the potential increase of the biofuel mandate requiring the blending of conventional biofuels, thus halting the rise in the current maximum blending limit (blend wall). The intention of this suspension was to encourage a larger production of advanced biofuels, although this technology had not reached large-scale commercialization. Brazil, on the other hand does not have any legislation in place to promote the production and use of second-generation and advanced biofuels.

BP shift from MTBE to ethanol, 1980s–2003

BP faced an ethanol mandates regulation in two of its largest markets, the USA and the EU. The increase in consumption of ethanol – substituting it for MTBE and other ethers from 2003 – made the firm shift its buyer–blender–distributor position from 2005 onwards.

During the mid-1970s and the early 1980s, crude oil prices were at record highs and, in combination with changes in the availability of high-quality oil, refining firms were forced to transform their operations. In the early 1980s, refineries were built to refine low-sulphur high-quality crude, but these were forced to turn to supplies of less expensive, heavier crudes, while still being required to produce the high-quality products that the market was demanding, and that met tougher environmental regulations (Chen 2005); this made refining operations more complex and in need of substantial investment.

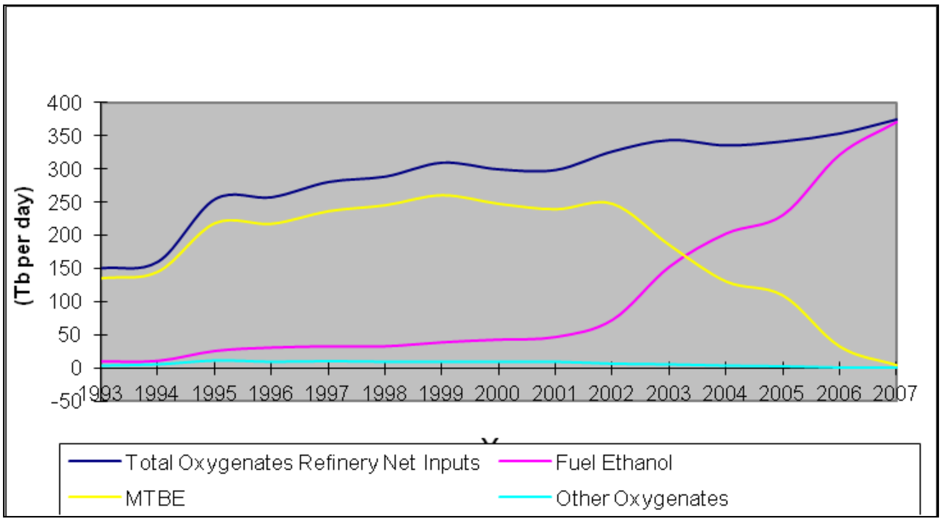
From that period, for example, tougher environmental regulations were put in place by the USA. There were new specifications for petrol, which resulted in a push towards new or revamped refining processes such as alkylation and etherification (of alcohols to form fuel additives) together with hydro treating. As Bel and Bourgeois (2003) describe it, ethers (MTBE, TAME, ETBE) became the class which had the highest number of innovations being put forward in the refining industry for the 1988–98 period. Environmental standards for petrol were strengthened, passing from 300 parts per million (ppm) sulphur content in 2003 for the USA and 150 ppm in Europe to 30 ppm in the USA in 2006 and 15 ppm in Europe (Valero, 2002).

From the 1990s onwards, business as usual for oil refineries meant refining a heavier crude oil while complying with industry standards, and for that purpose MTBE was widely used as an oxygenate. This helped the resulting fuel to reach a higher octane number and enabled it to burn more cleanly than using lead additives. In the USA, many refineries built MTBE plants in their refining facilities, using it to blend with conventional or reformulated petrol. Blending operations in refineries could be continuous or batch-wise runs and could use different ethers or a mixture of ethers and alcohols (MTBE, ETBE, ethanol, methanol, etc.), each mixture or blending component resulting in a different octane number and vapour pressure. Such a process is not straightforward, because when trying to control the blending for a certain specification or quality, another measured variable might jump out of range. Refineries around the world use different ethers. In the USA, MTBE was the most commonly used (11 per cent of the total volume of ethers) while in Brazil ethanol was used as the main blending component.

Each country/region has its own specifications that allow or ban the use of each ether or blending oxygenate and prescribe the tolerance levels required in order to meet the standards for petrol sold in the market. Within each region, companies are limited by the ways in which they can operate in the market. For each market or region, an oil company may have one or more refinery, pipeline infrastructure, or a nearby harbour which could allow them to import or move their products from one terminal to another.

Until ethanol became widely used in the USA from 2004, MTBE was the common oxygenate, and methanol seemed to be the most promising substitute for petrol. Nonetheless, as years passed, the methanol possibility became more difficult due to problems of material compatibility in the petrol distribution system, as well as public relations setbacks in the 1980s (Sperling 1989); a subsequent ban on MTBE increased ethanol demand to levels of 10 per cent mix with petrol (see Figure 6 below for the data of US refinery oxygenate net inputs 1993–2007).

Figure 6: US Refinery and blender oxygenate net inputs 1993–2007 (thousand barrels per day)



Source: US Energy Information Administration

As can be seen from Figure 6, it was not until 2003 that ethanol became widely used as an oxygenate in the USA. This occurred when several states banned MTBE due to water contamination concerns, together with the perceived potential for increased liability exposure due to the elimination of the oxygen content requirement for reformulated petrol, as mentioned in the Energy Policy Act 2005 (EIA 2006). California was one of the first to ban MTBE and to introduce stricter regulations for petrol production, forcing oil refineries to comply by January 2004 with full substitution of MTBE with ethanol. All refiners had to present their plans to incorporate the changes in their terminals and operations. This sudden change had several impacts for refiners, such as: net loss of petrol production capacity, a tight ethanol market, and short-term limitation in ethanol production and transportation capacity(EIA 2006).

Refiners face several difficulties in production, distribution, and petrol storage when shifting from MTBE to ethanol. Ethanol-blended petrol cannot be mixed with pure petrol, and unlike MTBE, ethanol blend must be stored and transported separately from the mixture until it is added in the last step of the supply.

Since ethanol is mainly produced in separate facilities of oil refinery units, often in remote locations far from end-users, fuel distribution becomes an important factor of the production chain and could add to the cost of using an alternative fuel. Fuel distribution systems in major markets such as the USA operate through pipelines, which allow lower transportation costs and greater efficiency. The fuel transportation system is privatized and represents large investments with significant sunk costs. Transportation costs for fuels that cannot be transported through the pipeline system are normally higher than pipeline costs. Ethanol cannot normally be transported by pipeline due to its water affinity.

BP has been an active ethanol distributor and blender since 2004, when the USA introduced its first biofuel mandate. Although the USA has a longer history with ethanol blending than any EU country, the share of biofuels in the fuel pool was not significant until the country banned MTBE and started to substitute ethanol for it from 2003.

During the period from 1980 to 2003, BP implemented changes in its operations to accommodate ethanol. It became an active distributor of ethanol and started its first stage of ethanol-related investments. The main changes were technical and logistical, and it shifted its refinery operations to comply with the new fuel standards. BP, however, did not adjust its pipelines to use ethanol, it only made technical and logistical changes.

In this first period, small and incremental changes took place in ethanol implementation; it was the start of the 'ethanol trajectory' by BP into large-scale operation. Interdependence and interrelatedness system factors, however, were present in this first stage; fuel infrastructure did not undergo major changes, transportation of fuel remains within a pipeline system, whereas only blending, storage, and additional truck transportation had to be modified in order to comply with the biofuel blending mandate in the USA. The company did not shift its R&D programme or production systems at this stage, remaining locked-in its oil-based trajectory. As will be seen in the following section, BP developed several strategies towards advanced biofuels.

Despite the fact that changes in downstream were not severe but merely incremental, the increase of ethanol consumption and blending mandate in the USA, together with increasing concerns on climate change impacts and greenhouse gas emissions, did motivate a shift in expectations among BP directors about the future of the fuel business. Thus, the firm started to investigate whether the historic paradigm of the liquid-fuelled combustion engine was under some kind of a challenge (company interview). A future fuels team was formed in the company in 2004/5 comprising four senior officers, in order to look for a strategy for the next 20–30 years of BP fuels (company interview) as two drivers clearly emerged: one being climate change and the other, energy security. As a company interviewee stated:

> There was a paradigm shift in terms of influencing policy for sure, of the last 20 years and prior to 2000 the policy driver in the fuels space was local air quality, reducing NO_x, emissions in OECD markets where we operate, and consequently on the fuels, to be able to reduce those regulated emissions and changes of policy drivers to enable to support the various engine technologies required for manufacturers to meet those regulations.

At this stage, the company did not elaborate a strategy towards biofuel growth, it complied by meeting the required regulations, but it represented the beginning of a biofuel expansion in the market.

New expectations among company managers about the future of ethanol and its regulation were shaping BP decisions on key issues of their involvement in alternative energy as well as on the challenges and responses needed in their major downstream market, the USA.

2000–2013, BP's upstream strategy shift

Despite a substantial increase in the production of first-generation biofuel in the last decade, it has stalled since 2010. The same has happened to E85 and flex-fuel vehicle market penetration. Moreover, the US Energy Information Administration estimates that:

> … both ethanol blending into gasoline and E85 consumption are essentially flat from 2011 through 2040 as a result of declining gasoline consumption and a limited penetration of FF Vs, (flex-fuel vehicles). (EIA 2013 p80)

Facing this future scenario, and a lack of progress in the production of second-generation biofuels, first-generation ethanol producers, interested in a larger market share, have sought to increase the current blending mandate from 10 per cent to 15 per cent, as has recently happened with EPA in the USA. The enhancement of blending, however, would create additional problems to car makers and fuel providers. In fact, the industry has raised concerns in relation to the problems associated with larger blending proportions, and has warned of ethanol blending hitting a 'blend wall' in the status quo road transport system. (The blend wall is the percentage limit up to which biofuels can be blended in petrol without affecting the car.)

Even if first-generation biofuel lobbyists manage to secure and implement a larger mix of ethanol into petrol, it would be reaching or nearly reaching a definite stall due to current vehicle fleet characteristics.

Currently, ethanol in the USA is being transported mainly by rail; it was not until 2009 that one pipeline company started to transport ethanol on its multi-purpose pipeline, although it required certain adaptations (EIA 2012). Pipelines are the most efficient way to transport ethanol, but the current infrastructure does not allow ethanol to be distributed this way due to its water affinity and potential corrosion.

E10 can be sold at any petrol station but the higher permitted ethanol blends (E15 and E85), can only be sold in upgraded stations with purpose-built storage tanks.

In the USA, ethanol consumption has grown in the past decade, despite the incompatibility of ethanol with either the country's currently most efficient transportation method or with its filling stations. This shows how the blending mandate can overcome technical difficulties and result in more efficient established practices.

Furthermore, it has been the case that incumbent regime actors, such as BP, have started to deviate from their ethanol buyer–blender only activities and have realized investments into the ethanol niche, developing a strategy that has increased its participation, and further development of the niche, by investing in R&D as well as becoming interested in new forms of advanced biofuels (those that are not derived from grains or conventional sources). BP's biofuel initiatives have been mainly run through its BP Alternative Division.

After their initiative in the solar business – BP Solar International subsidiary – BP launched BP Alternative Energy in 2005 (hydrogen, solar, and wind power generation) to develop other energy sources and renewables.

BP Alternative Energy comprised BP's low-carbon businesses and future growth options outside oil and gas. These were biofuels, wind, and solar, along with demonstration projects and technology related to carbon capture and storage. In April 2013, however, BP announced plans to divest from their wind business following a prior exit from their solar activities in 2011, to focus exclusively on biofuels for both the production of first-generation fuels and the development of advanced biofuels. BP Alternative Energy has projects to the value of $8 billion by 2015 (BP, 2012a) and the firm claims to have committed $1.5 billion to biofuels operations and research since 2006. Since 2006, BP has announced investments in production facilities in Europe, Brazil, and the USA. BP Alternative Energy is investing $8 billion in the growth market of biofuels, while undertaking the long-term measure of building carbon capture and storage and clean technology projects. Investments of $5 billion have already been made.

In 2006, BP created the BP Ventures team with the aim of investing in high-potential disruptive innovations that are aligned to the company's core business activities. The portfolio of this team's investments amounted to $120 million in 2010. The BP Ventures team partners with early stage businesses; it incubates R&D from universities and uses company resources to help develop those technologies. The Ventures team acts as the corporate venture capital arm of BP Alternative Energy. The team invests in: clean-tech funds, biotech, carbon offsetting, solar, energy efficiency, and storage. An example of the type of investment undertaken by the Venture team is a project associated with REAC Fuel, a Swedish firm developing a new method for converting biomass to fuel.

In August 2009, BP and Martek Biosciences Corporation signed a joint development agreement to work on microbial oils for biofuel applications; this technology offers an alternative to current processes for producing biodiesels from vegetable oils. BP agreed to contribute up to $10 million. Martek will perform the biotechnology research and development associated with this initial phase, whilst BP will contribute to its integration in the value chain.

In 2007 BP took an initial 50 per cent stake in a Brazilian sugar cane ethanol venture, Tropical BioEnergia SA. With this joint venture the oil company announced it was investing $1 billion to build two sugar cane ethanol refineries in the state of Goias. The first refinery started operations in 2008. In March 2011, BP announced the acquisition of majority control (83 per cent) of the Brazilian ethanol sugar cane producer Companhia Nacional de Acucar e Alcool (CNAA). With this investment, BP expected to increase its overall production capacity to 1.4 billion litres of ethanol equivalent annually. Because of this $680 million agreement, BP became the operator of two producing ethanol refineries, located in the states of Goias and Minas Gerais. A third ethanol mill is under construction in Minas Gerais. BP estimates that 2500 people work in these mills, equivalent to 3 per cent of its 2012 total labour force. At full capacity, each mill will produce 480 million litres of ethanol equivalent per year by crushing an expected 15 million tonnes of sugar cane. Each mill could also export 340 GWh to the grid.

In 2011, BP purchased the remaining shares of Tropical BioEnergia and completed the 100 per cent acquisition of CNAA to gain full control of the three ethanol production mills in Brazil.

In December 2012, BP announced a $350 million investment in its fully owned Tropical Bionergia to increase its production by building a new ethanol mill, doubling its production capacity by producing 450 million litres of ethanol equivalent per year. The plant is expected to be at full capacity by the end of 2014. The new refinery will be established in Goias state along with most of BP's refineries. The investment is estimated to create 7650 direct and indirect jobs.

In October 2012, BP and the Dutch chemicals company DSM established a joint venture agreement for the development of new technology for the conversion of sugars into renewable diesel, extending the relationship with Martek Bioscience Corporation.

Through a joint-venture agreement with DuPont and AB sugars, BP has announced a new ethanol plant in Hull, UK. The plant, inaugurated in 2013, is expected to produce 420 million litres of ethanol, equivalent to supplying about a third of the UK's renewable fuels obligation.

In summary, from 2003 onwards, BP has modified its strategy towards ethanol production. BP's path has been evolving in line with the growth of first-generation ethanol in the USA and the EU, after policies were in place to reduce greenhouse gas emissions and tackle climate change. Despite BP not having downstream operations in Brazil, the company has created an investment portfolio that has provided it with larger scale sugar cane ethanol production facilities. It started an acquisition strategy for producing first-generation ethanol, following a company stance on biofuels use. The company announced (BP 2011) that they would only produce affordable, low-carbon, sustainable, and scalable biofuels.

After 2008, the company created a Biofuel Business Unit – the new biofuel segment of the Alternative Energy Division – which in 2013 became the main recipient of investment resources within the division. The company's involvement in second-generation operations and other advanced biofuels is presented in the Appendix.

Assessment of BP and biofuel

The relatively short history of BP in the biofuel market reveals some interesting lessons. Technological interrelatedness and interdependence (a downstream regime) in the fuel transport system may become a barrier for incompatible fuels; these barriers are embedded and may limit the adoption of new technologies if they are not compatible with existing practices and infrastructure. The sustained characteristic of the blending mandate, however, forced companies to adapt current infrastructure to accommodate the new fuel, despite its being inefficient at current levels of production.

There has been technological development but it has been driven by a powerful lock-in effect that guides the search and innovation process, which consequently follows a particular trajectory. Nonetheless, BP has been able to react swiftly to a 10 per cent loss in petrol volume, by developing investments in the ethanol niche. Moreover, although the technological paradigm appears to be unchanged, the direction of the company's technological trajectory has started to move, as a result of focusing its alternative energy activities on advanced biofuels research and development,

By establishing ethanol blending mandates aimed at addressing concerns on energy security and reducing greenhouse gas emissions, governments are supporting niches that destabilize current regimes more generally, and are helping to develop them by strategically managing their mandates and targets. In the case of BP, its strategies and trajectories have co-evolved by being directly affected through both market share and through the ethanol niche as a solution to demands for lower emissions.

Although government policies are exogenous drivers of biofuel development, the take up of flex-fuel vehicles, even in the EU and the USA, has not yet been sufficient to provoke any substantial breakthrough, and indeed the take up of such vehicles has been relatively low.

6. Concluding remarks

The cases in this paper have shown under what conditions of biofuel implementation the oil firms (PB and BP) have started to modify their strategy towards biofuels and to what extent they have started to invest in this alternative energy option. As predicted by theory, it is clear that external stimulus was required to affect a path-dependent system. In addition, 'technological interdependence' is a strong barrier that can be overcome with the flex-fuel car; the blend-wall limit, however, (20–25 per cent in Brazil and 10–15 per cent in the USA) imposes constraints if there is not a substantial take-up of flex-fuel cars. Also, while there have been some similarities, Petrobras and BP have adopted different strategies to address biofuel mandates and expansion.

The two companies exhibit several important differences and similarities. External drivers were a determining factor for both in pursuing the ethanol route. The use of government mandates allowed the ethanol niche producers to form part of the regime's fuel production transport system, forcing established firms such as Petrobras and BP to adopt the new fuel and overcome both the technical difficulties and the problems associated with the incompatibility of established distribution and storage practice.

In both cases, the established oil firms' inertia initially prevented them from investing in renewable fuel; as time passed, however, and mandates were sustained and in some cases intensified, both firms suffered from losses in market share which prompted biofuel investments in first-generation biofuels, in which they became relevant players. BP was faster than Petrobras in increasing its share of biofuels in the fuel mix, but both firms have started to invest in the production of conventional biofuels. In 2006 Brazil announced expenditures on research and development for the commercialization of second-generation and advanced biofuels.

One clear difference between the two firms, however, is that, until a technological breakthrough in the automobile sector spurred the expansion of hydrated ethanol towards the market, Petrobras generated only internal organizational change. In the case of BP, although flex-fuel cars are available in both the US and EU markets, this was not a relevant factor in incorporating a Biofuel Business Unit. The flex-fuel car, representing no more than 5 per cent of all cars in the USA and 0.1 per cent in the EU in 2013, has not caused a substantial increase in the consumption of neat or hydrated biofuels in the EU [12] or USA. This is a major difference between the oil firms studied. The successful development of the flex-fuel car in Brazil has prompted an exponential increase of biofuel production and consumption. It has contributed to a market majority take over from petrol to ethanol in Brazil, affecting Petrobras's downstream profitability.

The scope of biofuel policies also shows substantial differences between the two cases. Brazil has adopted far-reaching policies regarding the use of ethanol, a situation that no other country has sought to imitate. The incorporation of large scale-ethanol into the national fuel production system was an ambitious system-changing policy that has permitted major changes in the country. The sustained ethanol mandate from 1931 onwards, despite the bust years of the Proalcool programme, maintained the ethanol trajectory that was further expanded with the flex-fuel car innovation. BP has faced a less stringent regulatory environment both in the USA and the EU, with blending mandates reaching no more than 15 per cent as recently as 2013 in the USA.

[12] In 2010, only 13,000 flex-fuel vehicles (including alcohol) were registered in the EU out of 238.8 million cars in stock (EU Statistical Pocket Book).

As can be seen in the Appendix, both companies are involved in the development of second-generation biofuels. In fact, both companies shifted their R&D strategy and created their Biofuels Division after 2005. These decisions preceded their decision to enter the upstream biofuel producing market. In fact, the vast majority of their biofuel production is located in Brazil. Despite the fact that Petrobras has had a longer history with ethanol implementation, including hydrated ethanol in large scale, BP has been more active in pursuing the advanced biofuel route, and it reacted faster than the Brazilian company to a loss of petrol market share. This in part is due to its flexibility and history of investing in alternative energy, away from its core activities. BP's direction of technological progress towards biofuels was also driven by the RFS2 US policy.

Both companies have started a shift in their technological paradigm by investing in R&D, developing an acquisition strategy with ethanol producing firms, and creating a division for biofuels within the company. Although, there are contextual country factors to take into account, it is clear that Petrobras went through an ambitious restructuring because of the Proalcool programme; this included changing its refining output configuration and, more importantly, a condition to develop a strategy for increasing its exploration and production activities. The high cost of the Proalcool programme was in part charged to Petrobras, which at that time was fully state-owned. BP invested in biofuel operations after a displacement of 10 per cent of the gasoline market in the USA and the expectation of other mandates in markets where it operates. It would, however, be difficult to see further investment being developed if the returns on investments were not generated accordingly.

There are differences in the drivers causing the change in the regimes and generating a transition towards ethanol as an alternative fuel, and indeed the drivers in Brazil have not always been the same. Each of the different stages throughout the history of Petrobras has shown different motivations or reasons for using ethanol. During those years, however, sugar cane producers have led, jointly with government, the introduction and predominance of ethanol in the Brazilian fuel transport market. On the other hand Petrobras, from the beginning, opposed the idea of using ethanol as widely as was put forward in the Proalcool Programme but was never able to stop it. The company today, however, faces a different scenario (Brazil is now self-sufficient in oil and has a petrol surplus) and pressures associated with environmental issues have made it take action towards promoting ethanol expansion. The Brazilian case shows a range of different drivers for ethanol implementation throughout its history, and it can be said that Petrobras now faces a whole new set of conditions, including the recent flex-fuel car technology. The motor industry holds one of the keys to boosting ethanol expansion in the world. But Brazil, the EU, and the USA face different drivers triggering change. The motives for promoting and implementing biofuel policies in the USA and the EU are more concerned with the question of reducing greenhouse gas emissions than with agribusiness lobbying groups. This is reflected in the amendments to their biofuel policies that have resulted in legislation that encourages further development and commercialization of second-generation or advanced biofuel.

Finally, if mandates are sustained, as they have been in Brazil, the USA, and the EU, it is probable that we will start to see an increasing number of energy firms participating in this market, with biofuels generating larger market share losses by petrol producers. The use of biofuels in oil firms is now embedded in the fuel technological system, generating a lock-in for downstream operations in such markets. As can be seen in the Petrobras case, however, a full transition will not happen if flex-fuel cars do not become dominant. The flex-fuel car is one of the keys to unlocking the system, as can be seen in the Brazilian experience.

Appendix: Oil firms and second generation biofuels

Research and Development (R&D)

Technological change in oil firms has been studied through different lenses, although upstream activities such as exploration and production (Voola, 2006; Acha, 2002; Finch, 2002) have received greater attention than downstream ones (Chen, 2002; 2005). Technological change is often measured by oil firms' investment in total R&D, or by their R&D intensity and patenting activity. R&D expenditure is used as a proxy for the technological effort of a firm, but it only reflects part of the effort devoted to technological development and investment (Pavitt 1984). R&D intensity (R&D expenditure as a share of total revenues), is therefore a measure that corrects for the size of the firm.

According to the EU R&D scoreboard 2012, the oil and gas industry has an R&D intensity of 0.3 per cent and is classified as a low R&D intensity sector in comparison with other industries such as food and drug retailers, transportation, mining, construction, and industrial metals. R&D intensity in pharmaceuticals and biotechnology is 15.1 per cent, health care 5.9 per cent, and technology hardware and software above 5 per cent, although it is generally less than 1 per cent in other sectors. While oil and gas companies are labelled as 'low R&D intensive' they have been reported as the sector with the highest growth of sales for 2011 (23.4 per cent). Sales values, however, are arbitrary as they mostly depend on oil prices, which can vary by a factor of two or more within a short period of time. R&D figures need to be interpreted with caution, since different companies may use different definitions of R&D in their reporting. Within the oil and gas sector, the super majors (Shell, Exxon, and BP) are among the top ten in R&D expenditure, as shown in Table 5. The average R&D expenditure by the top ten companies is €826.88 million and R&D intensity is 0.67 per cent. Private oil companies spend an average of €685.7 million on R&D expenditure and R&D intensity is 0.28 per cent.[13]

[13] Creusen and Minne (2000) argue that state oil companies have done little research on new and environmentally friendly energy technologies as their share of R&D and patenting activities in this type of technologies is relatively low.

Table 5: Oil and Gas companies R&D expenditure and R&D intensity 2011

Company	R&D million euros	R&D intensity (%)
1. PetroChina	1622	0.7
2. Petrobras	1149.6	1.1
3. Royal Dutch Shell	869.5	0.2
4. Schlumberger*	829.3	2.7
5. Exxon Mobil	806.9	0.2
6. Total	776.0	0.5
7. Gazprom	643.0	0.6
8. China Petroleum and Chemicals	596.4	0.2
9. BP	491.5	0.2
10. Chevron	484.6	0.3

* Oil equipment, services & Distribution Company.

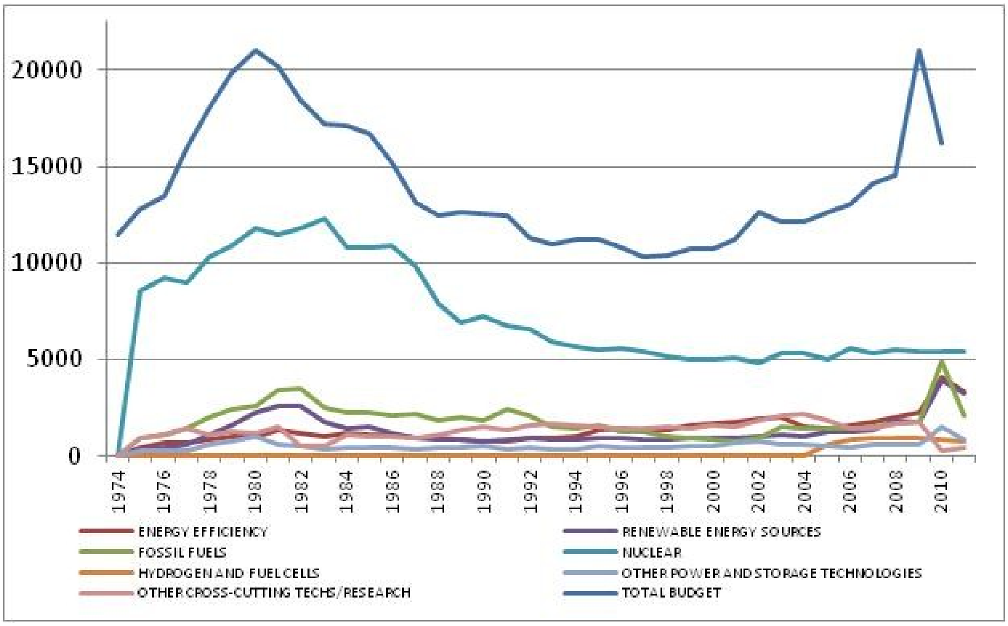
Source: EU R&D Scoreboard 2012

Companies also benefit from alliances with universities and research institutions. In fact, major oil companies and leading service suppliers are the main performers and funders of research and engineering development upstream (Acha, 2002). They access technologies and markets through strategies that include mergers, acquisitions, and joint ventures. They distinguish themselves, however, for their growing orientation towards environmental and climate change issues. Link (1996) states that petroleum companies, along with chemical firms, are the most active members of research joint ventures (RJV), principally those concerned with environmental R&D.

R&D in biofuels

Second-generation biofuels are described as: biofuels produced from feedstock of ligno-cellulosic materials that include straw, bagasse, forest residues, and purpose-grown energy crops (International Energy Agency, 2008). The activities related to second-generation biofuels are R&D-based, and for ethanol production are mostly a form of biotechnology process. With few exceptions, such as the Shell Solar Energy programme and BP's solar adventure (BP 1998), oil companies have historically done little research on new and environmentally friendly energy technologies (Creusen and Minne 2000).

Figure 7: Total Research and Development investment by type of energy (1974–2010) in US millions (2010 US dollars)



Source: data from the International Energy Agency 2012

This follows a general trend of energy companies' research and development investment associated with renewable sources, as can be seen in Figure 7. However, this figure also shows that in the late 1970s both nuclear and renewable energy had a substantial share of R&D expenditure, in part due to record high oil prices for those years. From that period until the late 1990s, however, there was a decrease in overall R&D investment. Expenditure shifted radically upwards by the end of the last decade, in part pushed by an interest in renewable energy technologies. A similar trend is shown when analysing patent activity in biofuel technology, with some initial development in the 1970s followed by a long 30 year period of stagnation in patent records, which only recovered in the past decade (see Figure 8 below).

Oil companies have adjusted their research stream to incorporate biofuels (Carolan 2010). There have been partnerships of oil firms with biotech companies and research centres in universities to develop second-generation biofuels. BP, for example, has announced joint venture activities with DuPont and a collaborative research programme with US universities (BP, 2012b). Petrobras has also developed partnerships; its Research Centre, CENPES, has been developing second-generation biofuels since 2008. This activity has not, however, been translated into holding ethanol-related patents in the UPSTO or EPO databases, although it owns two patents related to biodiesel. In recent years Shell has divested from other renewable technologies – such as wind, solar, and hydro power – while increasing its activities in biofuels. There has also been an increase in patent activity by oil firms in ethanol and other biofuels (Hu and Phillips, 2011). Oil firms do not usually report figures for their R&D activities in biofuels; however some firms have produced figures for their involvement in this field or as part of relevant joint ventures. BP states that since 2006, it has committed more than $1.5 billion to existing operations and research and development capability in Europe, Brazil, and the USA – seldom in partnership with other institutions and businesses – to develop the technology, feedstock, and processes required to produce advanced biofuels.

With respect to second-generation biofuels, BP has a $500 million 10-year programme with the University of California for research on biofuels, as well as developed partnerships with DuPont for making butanol, a different biofuel molecule. The company continues to test this fuel as it argues that it has a higher density, is less volatile and corrosive than ethanol, and can be transported through pipelines because it doesn't pick up water (unlike ethanol) and because ethanol plants may be converted to biobutanol plants. The company created the subsidiary BP Biofuels in 2006 as part of their Alternative Energy division.

According to the Shell Sustainability Report 2011, Shell invested $1.1 billion dollars in R&D during that year. Shell predicted, in 2012, that biofuels would contribute 9 per cent of the global transport fuel mix by 2030, up from 3 per cent in 2011. The company states that it has become one of the world's largest biofuels distributors, blending around 7.4 billion litres of biofuels in its petrol and diesel in 2011. In 2012, its R&D expenses were $1314 million, compared with $1125 million in 2011 and $1019 million in 2010. In August 2012, however, Shell terminated its collaborative research agreement with Codexis Inc., a $400 million investment project to develop biofuels made from cellulosic sources. Shell moved into the production of biofuels in 2011 for the first time, through a joint venture with COSAN (a Brazilian company); they set up Raízen, in which Shell has a 50 per cent share.

Petrobras reported an investment of $54 million in biofuels R&D during 2012.[14] The Brazilian energy company has an overall budget of $3.5 billion dollars for their biofuel subsidiary, Petrobras Biocombustiveis, in their 2010/14 Business Plan, which includes $350 million for second-generation R&D. Although the company had the second-largest R&D expenditure among top oil firms (Table 5), it does not hold a dominant position in the research and development of second-generation biofuels nor in biofuel patent records.

Biofuel patents

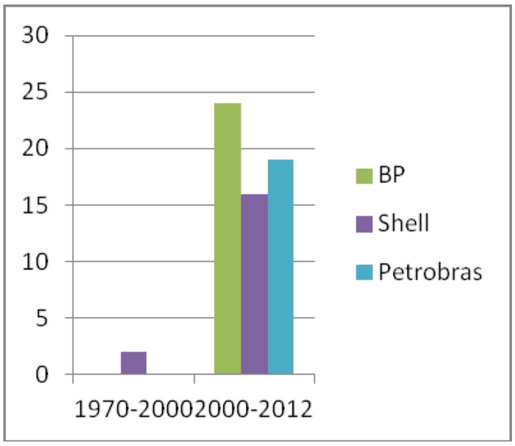
There have been some studies regarding the emergence of biofuel patents. Ethanol patents were studied by Hu and Phillips (2011), who considered patents a useful measure for innovation and technological trajectories in regimes. The majority of innovative activities in biofuels are from the private sector. Karmarkar-Deshmukh and Pray (2008), when researching USPTO data, found that the highest share of bioethanol patents are held by biotechnology companies, accounting for nearly 90 per cent of all bioethanol patents, followed by oil firms (8 per cent), and agro industry companies (2 per cent).

Oil companies had almost non-existent activity related to patents in biofuels during the last three decades of the twentieth century, then later amended that position to achieve a comparatively small participation in overall biofuel patenting activity. Oil firms, developing a new strategy towards the technological development of second-generation biofuels, began to hold patents on these technologies, mainly from 2000 onwards. Moreover, as shown in Figure 8, the number of biofuels patents has been historically low, particularly when compared to the number of patents in the core activities of firms in the energy sector. For the 1997–8 period Creusen and Minne (2000) found that Exxon had 364 patents, Shell 263, while BP held 97 patents in their core activities. By contrast, taken together, all major oil companies held only one patent for renewable technology (it related to hydropower technology).

There has been a broadly even development in patents between technologies for biodiesel and cellulosic bioethanol (Figure 9). Historically, the EPO has recorded 6023 biodiesel patents and 4854 cellulosic bioethanol patents. However, during the last three years there has been a decrease in biofuel patents, in part explained by a decrease in R&D investment after the financial crisis.

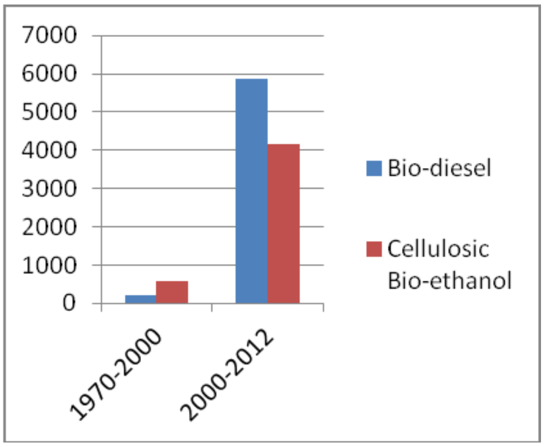
As seen in Figure 8, BP, Shell, and Petrobras have the largest share of patents in biofuels among oil firms. Their position, however, has not been homogeneous with respect to the type of technology developed, as BP is the only company that has more patents in cellulosic bioethanol than in biodiesel.

Figure 8: Biofuels patents by oil firms



30 years vs. 12 years

Figure 9: Biofuel patents by type

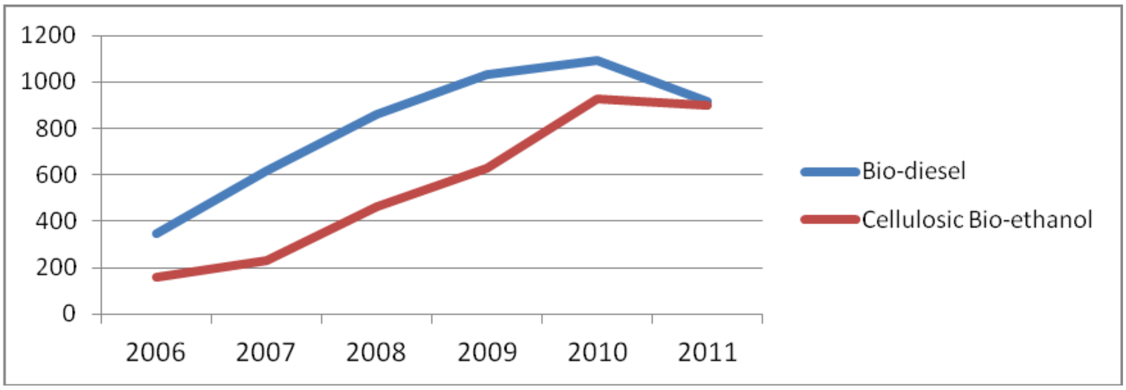


30 years vs. 12 years

Source: Own elaboration with data from Espacenet

During the 1970s biofuel patents were slightly oriented toward bioethanol in contrast to biodiesel technology. As interest in biofuel patenting activity grew in the 2000/12 period, however, biodiesel patents regained interest as shown in Figure 9. For the 2006/12 period, the number of patents for both biofuel technologies was practically even (Figure 10).

Figure 10: Biofuel patents by type, 2006/11.



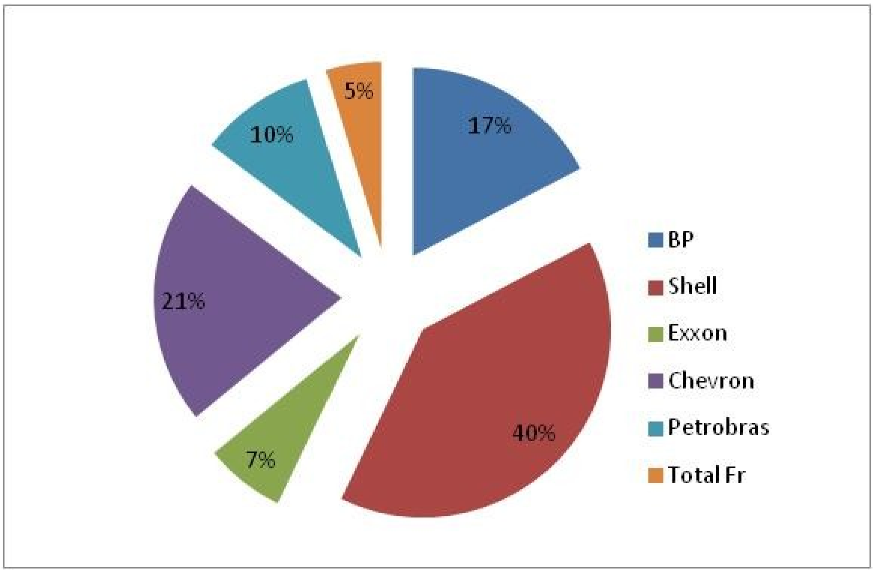
Source: Own elaboration with data from Espacenet

Note: EPO Classification Y02E50/10 for biofuels, Y02E50/13 for biodiesel and Y02E50/16 for cellulosic bioethanol.

Figure 10 shows the increase in patents for both cellulosic bioethanol and biodiesel – almost as equal shares. Not all major oil firms, however, have been developing a patenting strategy. This can be seen in Figure 11, where Shell is shown to have the largest share of alternative non-fossil fuel patents, followed by Chevron and BP.

Although biofuel patents by oil firms have growth since 2006, BP holds more cellulosic bioethanol patents than any other oil firm (see Figure 12). Oil firm patents in biodiesel are distributed more evenly, with Petrobras, Shell, and Exxon leading in this respect.

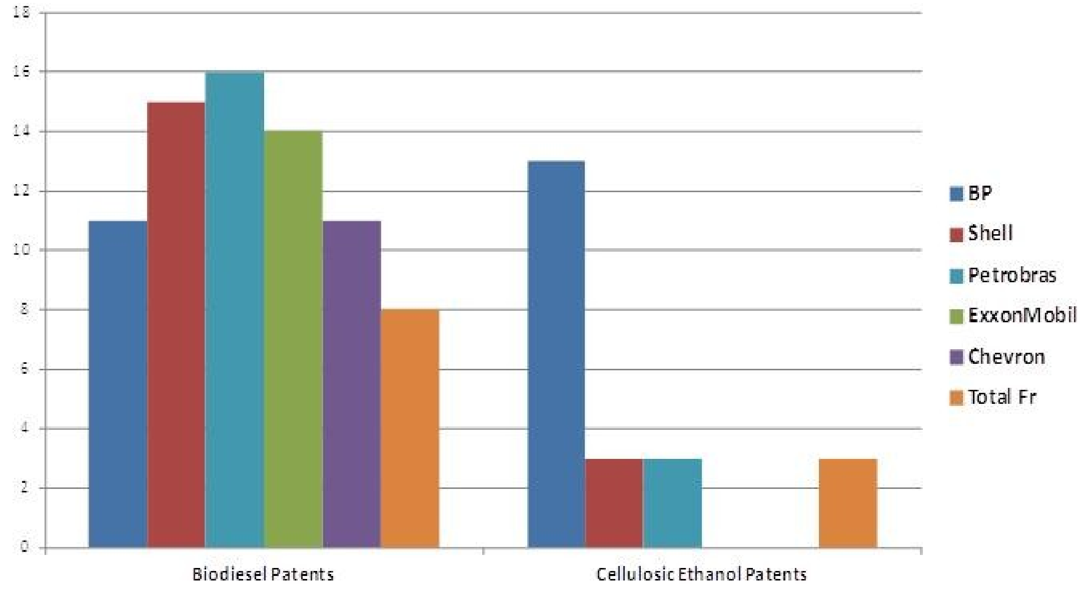
Figure 11: Patents in alternative fuels (non-fossil) by oil firms



Source: Own elaboration with data from Espacenet (Historic)

Note: EPO Classification Y02E50/10 for biofuels, Y02E50/13 for biodiesel and Y02E50/16 for cellulosic bioethanol.

Figure 12: Oil firm patents by type of biofuel



Source: Own elaboration with data from Espacenet.

Classification for non-fossil fuel technologies. Until 12/08/2012.
Note: EPO Classification Y02E50/10 for Biofuels, Y02E50/13 for Biodiesel and Y02E50/16 for cellulosic bioethanol.

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