CENTRE FOR RESEARCH IN ECONOMIC SOCIOLOGY AND INNOVATION
WORKING PAPER SERIES: ISSN 1759-2860





How innovation systems emerge to solve ecological problems: Biofuels in the United States and Brazil

CRESI WORKING PAPER NUMBER: 2010-03

Sally Gee*
Andrew McMeekin

Manchester Institute of Innovation Research, Manchester Business School,
Manchester, M13 9PL, UK.
Tel: +44 161 275 6859; Fax: +44 161 275 0923

*sally.gee@manchester.ac.uk

This paper has been submitted to Industry and Innovation and will be published in February 2011.

University of Essex

Abstract:

This paper discusses the re-emergence of biofuel innovation systems in the United States and Brazil. We argue that innovation systems emerge and evolve to solve a problem, and that the way the problem is framed and articulated has a significant impact on the direction and momentum of this evolution. Additionally, innovation sequences occur with a recurrent pattern of changing problems and innovative solutions. We consider the role of the State as a core actor in the mobilisation of innovation systems and discuss how specific institutional arrangements, political contexts and technological competencies influence how problems are framed. We find that role of the State varies across time as well as across different geographical regions. Finally, we suggest that as ecological problems intensify we might expect to see an increase in State intervention in innovation systems.

Keywords/tags:

biofuels, innovation systems, problem sequence, the State, Brazil, USA.

Citation:

Gee, S., and McMeekin, A., (2010) *How innovation systems emerge to solve ecological problems: Biofuels in the United States and Brazil*, Centre for Research in Economic Sociology and Innovation (CRESI) Working Paper 2010-03, University of Essex: Colchester

About CRESI:

Based in the UK's leading Sociology Department, the Centre for Research in Economic Sociology and Innovation (CRESI) is the first UK centre for research in economic sociology. With a clear focus on innovation, our research programmes highlight contemporary and historical processes of socio-economic transformation. You can read about our research and join our conversation.

Table of Contents

1 INTRODUCTION

In 2005, the United States (U.S.) and Brazil produced almost exactly the same volume of bioethanol for use as a transport fuel. The oil shocks of the early 1970s provided the impetus for both countries to embark on developing these new productive capabilities, but the paths that have been followed since the 1970s to achieve this historical moment of convergence could hardly have differed more. Since 2005, the volume of biofuel production has continued to increase significantly in the U.S., principally for domestic consumption, and has overtaken Brazilian supply capacity, which has continued to grow with a new orientation towards the creation of an international export market.

The purpose of this paper is to explore the contrasting biofuel innovation trajectories of the U.S. and Brazil. We discuss the emergence and evolution of innovation sequences in each country to explain differences in terms of the rate and direction of biofuel production capacity. That Brazil would choose sugar cane as its principal source of biomass, while the U.S. has chosen corn is perhaps obvious. That the bioethanol sectors of both countries originated at roughly the same time, just after the oil shock of 1973, also appears straightforward. But, why did the U.S. fall behind, while the Brazilian biofuel sector grew? Why, subsequently, did the U.S. embark on a rapid expansion initiative in the early 2000s? What were the respective roles of governments in each case and what novel modes of industrial organisation emerged? We answer these questions by suggesting that the innovation sequences in each country were oriented towards solving different types of problems. The relative political importance of energy security, economic growth opportunities and combating climate change as drivers of innovation has played a significant role in producing the observed variation. As such, a key concern in our analysis is to develop a stronger understanding of how political responses to different types of problem have been translated into specific policy instruments to stimulate the rate and direction of biofuel innovation. We also seek explanations for how the new biofuel industrial regimes in each country differ in terms of long standing institutional differences, perhaps most clearly in evidence when comparing the role of the state-owned oil company, Petrobras of Brazil, with its North American counterparts, as agents of innovation.

The paper is structured in the following way. In the next section, we introduce a framework for analysing the issues raised above, drawing on the concepts of innovation sequences and systems. The following two sections present our case studies of the U.S. and Brazilian experiences with biofuels. The final section presents our analysis and discussion.

2 SEQUENCES AND SYSTEMS OF INNOVATION

The concept of the innovation system is now widely used to explain interactions between technological change and economic development, especially amongst those with a preference for evolutionary explanations. In its recent incarnation, the approach was used to describe national specificities in institutional arrangements to explain variability in innovation performance across countries (Nelson, 1993; Freeman, 1995; Lundvall, 1992). Subsequent analysis has delineated the system by a particular technology (Carlsson, 1997; Jacobsson and Bergek, 2004; Hekkert *et al*, 2007) or a sector (Malerba, 2002). These alternative approaches differ according to whether national institutions, specific characteristics of technologies or economic specificities of particular sectors are considered the dominant logic underpinning the dynamics and evolution of the innovation system under investigation. Later work, especially Markard and Truffer (2008), usefully combine the approaches to suggest ways in which innovation dynamics can draw influence from all three spheres.

This later approach is consistent with other contributions that have explicitly argued against the imposition of *a priori* boundaries to the analysis of innovation systems, preferring to understand them as unfolding in scale and scope over time (Coombs *et al*, 2003). In other words, their geographical reach, sectoral orientation, and technological content evolve as part of the innovation process itself. Boundaries are a transient outcome of the process, always subject to potential revision. An approach that provides a useful development to the concept of innovation systems in this respect, is the idea that they are problem oriented (Metcalfe and

Ramlogan, 2008). Understanding innovation systems as problem orientated, (i.e. that they are formed to solve problems), provides dynamism and direction to the system: resources and capabilities are mobilised and coordinated in order to find a solution to the problem. Furthermore, since the problem is itself a moving target, the system evolves in response. In particular, a solution for one problem almost inevitably produces a new or modified problem and a renewed search for solutions. Thus innovation sequences occur with a recurrent pattern of changing problems and innovative solutions.

In this description of how innovation systems emerge and evolve to solve a problem (e.g. Metcalfe and Ramlogan, 2008), surprisingly little has been said about how problems are themselves constructed. Typically, it is implied that the problem is a functional one, associated with a fairly well described societal need. In the medical realm, for example, the problem sequences for cataracts (Metcalfe *et al*, 2005), coronary artery disease (Mina *et al*, 2007), or for HIV (Merito and Bonaccorsi, 2007) take the disease itself, in terms of its physiological symptoms and causes, as the problem to be solved. The solutions that are observed as the problem sequence unfolds are concerned with the 'physical technologies' of the respective therapies themselves and the 'social technologies' that account for how the new treatment is provisioned in the context of clinical practice (Nelson, 2005).

But the functional problems that innovation systems are mobilised to solve are interwoven with social, economic and political factors and these can play a significant role in how the innovation system is constructed. The history of the origins of electricity for widespread use, as recounted by Hughes (1983) illustrates the 'seamless web' of technical, economic and political factors that formed 'reverse salients' in the otherwise growing system and their associated 'critical problems' to be solved by engineers. A reverse salient is a term borrowed from the military, and refers to sections of the advancing front line which fall behind. Hughes chose this term, as opposed to bottleneck, for example, to emphasise the complexity framing a problem where individuals, groups, material forces and historical influences all play idiosyncratic causal roles. In his framework the articulation of a problem often defines its solution, reverse salients become defined as a series as critical problems, and innovative activity is directed towards solving these problems.

This elaboration of how to conceptualise the nature of problems that are to be solved is significant for the present analysis. As we shall see, the functional need that biofuels seek to attend to is concerned with the movement of people and goods, as an energy source for transportation. At this level, biofuels compete with other viable transportation technologies. But because the problem has been constructed in different ways in different places, we have identified significant variation in the constitution of the emergent innovation sequences. They all share the goal of seeking to provide an alternative to oil as a transport fuel, but differ in the interweaving of specific motivations and supplementary conditions for doing so.

There are some similarities between the approach that we are proposing and the multilevel perspective for understanding technological transitions (Geels, 2002, Kemp, 1994). In that framework, the landscape represents the rather inert and slow changing macro-institutional arrangements that constrain or facilitate changes in a technological regime (which is itself also constituted by institutional factors, this time at the meso-level). For our current purposes, changes in the relative importance of different political drivers for biofuel innovation would presumably be constitutive of landscape dynamics. Correspondingly, we might also assume that major regional differences in the political negotiation and prioritisation of societal problems to be addressed by innovation policy suggest multiple co-existing regime changes affected by significantly different landscape dynamics. In our language, the emergence of multiple and different innovation sequences reflects significant differences in the definition of the problems that they are seeking to solve. This, in turn, suggests that an important component of the analysis is the need to account for the different roles that the State has as a core actor in the mobilisation of innovation systems.

Therefore, the final strand of our analytical approach focuses on the respective roles of public and private actors in emergent innovation systems and on the market and non-market forms of coordination that account for how knowledge and resources are exchanged within the system. We are suggesting a form of analysis that goes beyond the focus on how government policy facilitates the functions of innovation systems (Hekkert *et al*, 2007) or influences the performance of private innovation actors by establishing the appropriate incentive structures. To do this, we follow contributions which have described varieties of capitalist political economy (for example, Hall and Soskice, 2001). We adopt a view that innovation is a multimodal economic process, involving the coordinated action of public and private actors in market and non-market modes of interaction (Harvey *et al*, 2002; Harvey and McMeekin, 2007). In this approach, the focus is on comparative and historical variation. The varieties of capitalism, that are manifestly different in Brazil and the U.S., play a key role in explaining the institutional and organisational arrangements constructing the problem and subsequently generating solutions.

To summarise, the approach that we are developing to analyse and compare the unfolding biofuel innovation sequences in the U.S. and Brazil foregrounds the following considerations:

1. Innovation systems emerge and evolve in relation to the changing nature of the problem that they have been mobilised to solve;
2. Innovation systems are characterised by interactions between States and private enterprise in market and non-market modes of economic governance.

In adopting this type of approach we will try to make sense of the contrasting institutional arrangements in Brazil and the U.S. for incentivising, structuring and organising innovation and the importance of path dependencies relating to pre-existing organisational capabilities. We believe that this approach will be particularly useful for explaining differences in *how* the roughly similar volumes of bio-ethanol in 2005 were produced in significantly different institutional and organisational terms and *why* this came about as a result of the respective innovation systems being oriented towards different problem specifications.

2.1 Sequences and Systems of Biofuel Innovation

Before describing in detail the emergence of biofuel innovation systems in Brazil and the U.S., it is worth signalling a couple of issues that perhaps mark out this technological transition as quite atypical. It is not, as has been the case in many historical examples, an example of a new technological regime that from its inception commanded an *obvious* performance advantage over the incumbent regime. Furthermore, the account of how (physical) technologies provoke change in institutional arrangements (social technologies) requires some careful consideration in this situation where the foundational technological capabilities have been in existence for well over one hundred years. We argue that the framing of politically important problems has been fundamental to the resurrection of dormant biofuel capabilities, and discuss how the interpretation and articulation of problems has varied across place and over time. Then, with the contrasting problem specifications of different regions and times established, we can analyse how they have shaped and been shaped by their associated emergent technological, organisational and institutional configurations.

3 METHODOLOGY

The country specific case studies reported in this paper are part of a broader project; 'The transition to a sustainable bioeconomy: innovation and expectations' comparing emerging bioeconomies in Europe, the USA and Brazil. As part of an extensive primary research programme we conducted semi-structured interviews during 2008 and early 2009 with key industrial and academic players in the U.S. and Brazil. In Brazil (19 interviews), we conducted interviews in Rio de Janeiro (Petrobras, university, government officials), Campinas (sugarcane biotechnology companies, scientists), and Piracicaba (biorefinery, bioethanol companies, scientists). In North America (14 interviews), we conducted interviews in Ottawa (cellulosic ethanol producer), Chicago and the mid-West (bioethanol producers, major agricultural firms, scientists), and the East coast (cellulosic ethanol producers). Prior, and parallel, to the interview stage, we undertook qualitative institutional analysis and extensive secondary data analysis drawing on multiple sources of information, ranging from academic literature and government and industry association reports, to annual reports, press releases and newspaper coverage. We have triangulated the empirical data and present it as chronological narratives of the emerging and developing biofuel innovation systems of the U.S. and Brazil respectively.

4 THE UNITED STATES AND BIOETHANOL

The history of ethanol as a transportation fuel in the U.S. dates back over 100 years to the era of automobile design and mass production; Henry Ford built his first car (the quadricycle) to run on pure ethanol and the Model T was a flexible fuel vehicle (Keeney, 2009; Solomon *et al*, 2007). Petrol became the dominant fuel in the 1920s, primarily because of the relatively low price of oil due to plentiful supplies, alcohol taxes and feedstock prices (Dimitri and Effland, 2007). Ethanol produced from corn was added to petrol to increase octane levels and to supplement supplies during the depression and both world wars. As the price of oil reduced again at the end of the Second World War, ethanol use dramatically declined and, from the late 1940s until the late 1970s, there was virtually no commercial fuel ethanol available anywhere in the U.S.

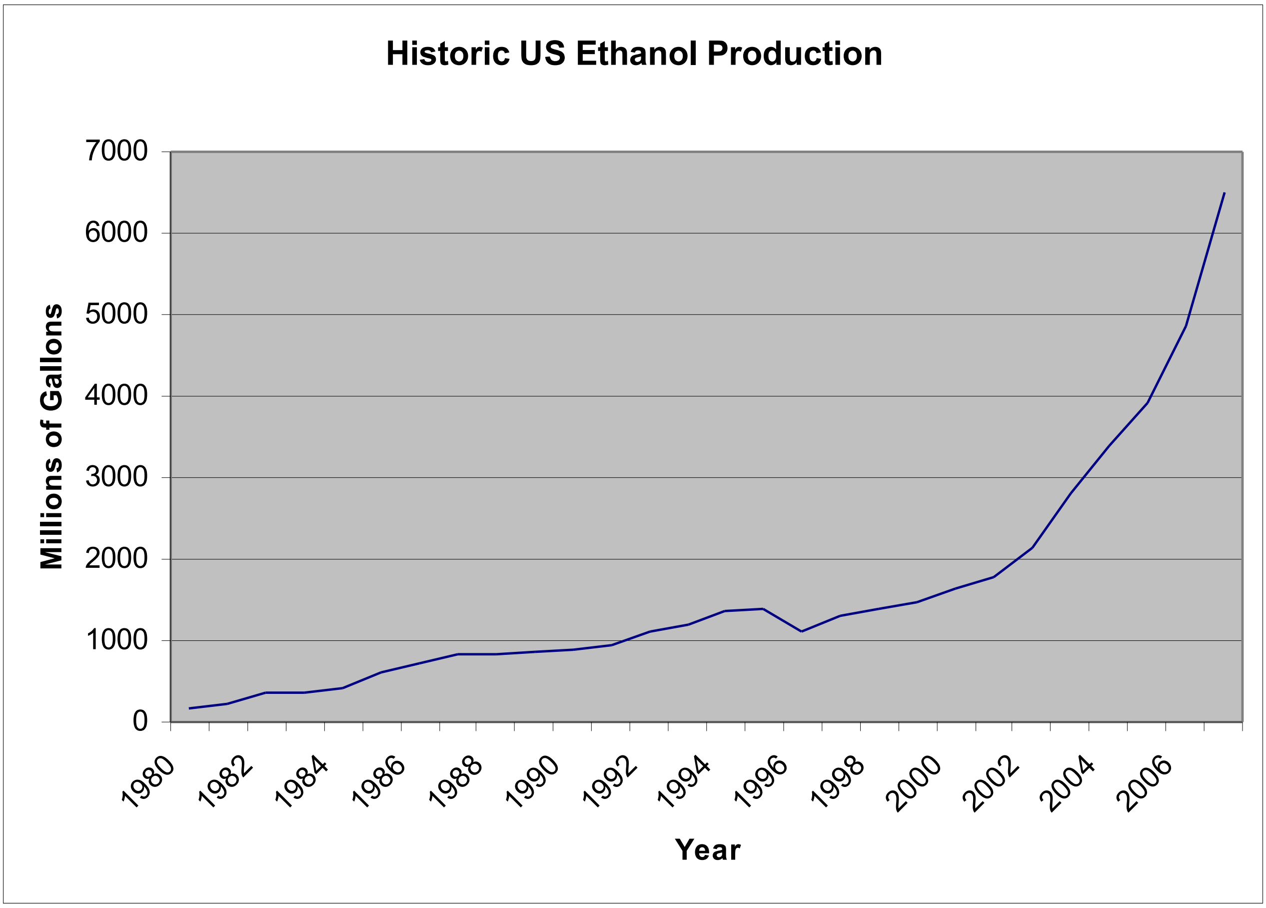

Figure 1: Historical US Ethanol Production – created from data provided by the Renewable Fuels Association, 2008

The late 1970s / early 1980s marks the beginning of the modern ethanol industry. The empirical data is presented in three phases corresponding with the significant changes in production shown in Figure 1. The first phase explores the emergence and steady expansion of the modern U.S. bioethanol industry (1978 -2000). The second phase discusses the factors instrumental in the rapid expansion of the industry (2000 – 2005). Finally, we discuss what new trends are emerging in the US biofuels industry (2005 onwards).

4.1 Emergence and steady expansion (1978-2000)

The re-emergence of the U.S. ethanol industry in the late 1970s was stimulated by the changing international economic and political landscape. Historical interest in ethanol as a transportation fuel corresponds with periods of war and fluctuating supplies of oil (NSEA, 2009). This relationship between domestic and energy security was emphasised by a number of high profile events in the 1970s; the first of which was the Arab Oil Embargo (1973). The embargo lasted a year and quadrupled the price of oil, exposing the vulnerability of western economies to interruptions of supply. Energy security became a political problem and the US government responded with a variety of initiatives intended to stimulate domestic energy production.

Levels of State intervention increased after the 1979 OPEC oil crisis, the Iranian hostage crisis and the U.S. grain embargo of the Soviet Union (The Ethanol Fact Book, 2007). The heightening of Government response mirrored the levels of economic vulnerability perceived in the U.S. and interventions were designed to stimulate existing (albeit dormant) domestic capabilities in ethanol production. Legislative action (e.g. The Energy Security Act, 1980) was fundamental to the emergence of this new ethanol industry and interventions took a variety of forms ranging from excise tax credits for biofuel producers and blenders, research funds to stimulate the development of domestic capacity and barriers on imports. Ethanol friendly policies and bills during the 1970s and 1980s were strongly supported by the farm and corn lobbies. Subsidies for consumption in this first phase were minor and mainly provided by government procurement programmes (Koplow, 2006).

The political articulation of the energy security problem, as well as the defined solution, was demonstrated when President Carter asked the CEO of ADM, a large agricultural processing firm, to convert a new alcoholic drink plant into a synfuel plant[1]. ADM went on to expand their construction of new ethanol plants (ADM, 2009) and by the end of the 1980s ADM accounted for 80% of total US ethanol production capacity (Financial Times, 2008). Clearly the emerging institutional configurations were influenced by existing capabilities. The large agricultural processors were well positioned in terms of access to feedstock, distribution networks and capital equipment to respond to the energy problem articulated by the Government. By 2000, ADM was still the largest US producers accounting for 40% of total capacity this. The other large producers at the time were Minnesota Corn Processors 7%, Cargill 6% and Williams Energy 5%. 42% of total US ethanol production capacity was highly fragmented amongst small companies with less than 100mgy[2] capacity[3]. The prominence of small producers was facilitated by the relatively large scale of agricultural farms in the US and the formation of farmer cooperatives, relatively cheap ethanol production techniques and federal incentives to support small producers.

4.2 Rapid expansion (2000-2005)

The rapid expansion of the US ethanol industry was triggered by the specification of a new ecological problem for the biofuel innovation system to solve. The 1999 decision in California to ban the fuel additive methyl tertiary butyl ether (MTBE) addressed concerns about groundwater contamination (DOE, 2009; Solomon *et al*, 2007). In 2000, the Environment Protection Agency recommended that MTBE should be phased out nationally and in 2004 California, New York and Connecticut switched from MTBE to ethanol. This created an immediate market for ethanol in a relatively short time. This initial rise in demand (and the development of the modern dry mill) had two main outcomes on the supply side. Firstly, it gave a boost to the rural economy. Secondly, a new type of organisation (dedicated biofuel firms) entered the market between 2000 and 2003; for example VeraSun and Aventine. These firms focused on producing 'first generation'[4] bioethanol from corn and played a pivotal role in

---

[1] ADM were the main manufacturer of high-fructose corn syrup (HFCS) and ethanol is another product of the corn wet milling process. An aggressive lobbying effort was undertaken by ADM who were seeking additional markets for the products of their mills (Keeney, 2009). This activity preceeded the intervention by President Carter

[2] Million Gallons per Year (mgy)

[3] These figures are calculated from Renewable Fuels Association data.

[4] Discussions of biofuel technologies are typically framed in terms of generations. This can lead to some confusion, since it fails to differentiate between the different phases of biofuel production and end product (NFCC, 2007) and poses the problem of how to establish the dividing lines between 2ndm 3rd and 4th generations. A better framework is one that distinguishes between innovation in feedstocks, processing and the end product on the one hand and between technologies as commercialised, prototype (i.e. field trials or demonstration plants) or laboratory status on the other (McMeekin *et al*, 2010). In this paper, and in relation to the U.S., we refer to bioethanol production from corn by fermentation as first generation. By second generation we mean the production of lignocellulosic inputs by thermochemical or fermentation processes, possibly relying on biotechnology. We do not discuss other types of biofuel, e.g. biodiesel, in this papers as the primary focus by the US Government has been on bioethanol and

'scaling-up' the US's bioethanol capacity, exiting the market as the focus shifted to cellulosic ethanol.

In addition to this discrete environmental issue, concerns about energy security continued to be an important driver of the US ethanol industry. The US trade deficit in crude oil rose from $27 billion in 1987 to $100 billion in 2002 and in 2001 the cost of maintaining a military presence in the Middle East exceeded $50 billion per year (The Ethanol Factbook, 2007). The location of reserves in unstable, and often unfriendly, regions was a huge political and economic issue in the U.S.. The Twin Tower bombings in September 2001 (9/11) and the resulting 'War on Terror' further increased concerns about US dependence on imported crude oil. The political and economic importance of the energy security issue, combined with environmental concerns, is demonstrated by the increasing number of new incentives and laws passed each year in the US. These increased from 31 in 2003 to 101 in 2007 (Financial Times, 2008). There are too many to review here, suffice to say these laws continued the trends outlined in phase 1 (tax incentives, tariffs, grants and loans) and increased in intensity. The 2000 Biomasss R&D Act (Biomass R&D, 2009) marked a change in government intervention, and signalled renewed support of R&D activity. This act instructed the DOE and the USDA to integrate their biomass R&D and initiated a program to develop technologies and feedstocks for bio-based fuels. The resulting Biomass R&D Initiative signalled a period of increased Government investment.

4.3 Continued expansion and the new technological frontier (2005 onwards)

In 2005 the Energy Policy Act (EPA) was passed. This is the most significant legislation affecting the demand side. The EPA established the Renewable Fuels Standard (RFS) which mandated the annual use of 7.5 billion gallons per year of renewable fuels in the U.S. fuel supply by the year 2012. The EPA was motivated by energy security concerns but shaped by competing concerns about environmental quality and economic growth. Proposals to allow oil and gas production in the Arctic National Wildlife Refuge (ANWR) were blocked but so were proposals to restrict greenhouse gas (GHG) emissions and increase car fuel economy standards (Holt and Glover, 2006, p10). The Energy Independence and Security Act (EISA) in 2007, or the President's "Twenty in Ten" challenge, built on the EPA and called for a 20 percent reduction in oil use by 2010. The EISA increased the mandated minimum level of use of renewable fuels in the RFS from 5.4 billion gallons in 2005 to 9.0 billion gallons per year in 2008, further increasing to 36 billion gallons per year in 2022. The 2007 Act also requires the increased use of "advanced" biofuels (e.g. cellulosic ethanol and biomass-based biodiesel) with 21 billion gallons of the mandated 36 billion gallons of renewable fuel required to come from advanced biofuels by 2022. These Acts secured a market for the ethanol industry and clearly provided a strategic research direction. Energy security remained the primary problem as demonstrated by the two controversial provisions that were *not* included in the enacted law; the Renewable Energy Portfolio Standard (RPS) and the repeal of tax subsidies for oil and gas (Sissine, 2007). The formulation of these acts demonstrates how the government has responded to a reverse salient and the related critical problems, and in doing so has structured a technological space for the discovery of solutions. The reverse salient in question involved both environmental and social concerns, specifically around climate change mitigation and the use of food commodities for fuel production. This became most prominent in the public and political responses in 2008 when the Searchinger *et al* (2008) article on indirect land use change (ILUC) raised concerns about the environmental impact of biofuel production, particularly first generation corn-to-ethanol. This article was preceded by corn price spikes and food vs. fuel concerns. In 2006, the price of corn was below $3.00/bushel, by 2008 the corn price was averaging $5.50/bushel (Keeney, 2009). This clearly has an impact on the price of bioethanol too[5]. Although environmental and climate change concerns have shaped policy (see CAST, 2006), for example the EISA requires that biofuels achieve a 20% reduction in GHGs, the primary political debate at the time of these legislative changes revolved around

lignocellulosics.

[5] The vulnerability of corn supply is shown on Graph A where the dip in ethanol production (1995-1996) is the result of a poor corn crop and the doubling of prices.

energy security and the production capacity potential of the existing corn-ethanol regime. The increasing political importance of the energy security problem is demonstrated by a move away from traditional supply side interventions to a more directive (and systemic) policy approach to guarantee a market for advanced biofuels. The rapidly expanding biofuel system seeking to solve the energy security problem suddenly faced the reverse salients of how the system impacted on climate change and food shortages. Developing a way to use agricultural residues and other waste streams emerged as the critical problem to be solved, relieving pressures on further land use change and competition between fuel and food.

The rapid expansion period of 'scaling-up' industrial capacity for first generation biofuels overlaps with a period of increased R&D in advanced biofuels, initially marked by the 2000 Biomass R&D Act. Cellulosic ethanol was identified as the most viable, and quick, solution to the energy security problem and R&D in this area has been strongly promoted by government policy (Herrera, 2006). Cellulosic ethanol could also potentially resolve emerging concerns about negative environmental impacts from biofuel production (Eggert, 2007) and food vs fuel competition. The Biomass R&D Initiative promoted the development of cellulosic ethanol capabilities and innovative activity was directed towards two major reverse salients; 1) developing better feedstocks (by genetically altering seeds) and 2) more efficient conversion processes (using biotechnology to create enzymes able to break down lignin efficiently). The Biomass Program outlines a number of explicit strategies for achieving a commercially viable cellulosic ethanol industry, including promoting collaborative R&D in feedstock and conversion technologies, supporting public-private partnerships to demonstrate large scale integrated biomass systems, and supporting activities to accelerate commercialisation.

State intervention has had a significant influence on the biofuels innovation system in the U.S. R&D support, combined with a guaranteed market, has facilitated public science activity and stimulated significant changes in industrial structure. For example, there has been a variety of new entrants into the biofuels industry. Firstly, agricultural-biotechnology companies, such as Monsanto, Syngenta and DuPont; Secondly, biotechnology-biofuels companies, such as Verenium, Coskata and Iogen; and thirdly, the oil companies, such as Conoco-Phillips, Shell and Chevron. All have collaborative relationships with industry and academia. Both the existing agricultural-processors and the newly entered agricultural-biotechnology firms have an interest in feedstocks and processing, and are actively collaborating in both areas. Mergers and collaborations with the biotech-biofuels firms tend to focus on combining complementary capabilities in biotech enzymes and cellulosic ethanol technologies with the intention of creating vertically integrated cellulosic ethanol companies.

5 BRAZIL AND BIOETHANOL

The pre-1970s historical development of the Brazilian ethanol industry shares many similarities with the emergence of the US industry. Ethanol was considered a suitable fuel for vehicles from the turn of the twentieth century, dropping out of favour in the 1920s as the price of oil declined yet receiving significant state attention in the 1930s as the price of oil increased again (Nunberg, 1986). However oil prices began to drop again after the Second World War and by the 1970s ethanol production was minimal. The 1970s marks the beginning of the modern Brazilian ethanol industry.

The empirical data is presented in three phases corresponding with the significant changes in production shown in Figure 2. During the first phase, in contrast to the U.S., ethanol production increased rapidly from 1976 to 1985. During the second phase, between 1985-1997, we see a similar period of slow growth followed by a sharp drop in production levels until 2000. The third phase after 2003 is one of continued rapid expansion, and by 2005 Brazilian and US levels of ethanol production converge over the 15,000 million gallons mark.

5.1 Emergence and rapid expansion (1975–1985)

The re-emergence of the Brazilian ethanol industry in the 1970s was stimulated by the changing international economic and political landscape, and shaped by the existing domestic situation. In 1973, Brazil was importing four-fifths of its oil (Winfield, 2008) and the oil shocks discussed in the U.S. case study had significant implications for Brazil. In addition to general economic dependence on oil, the newly industrialising, militarily run, country had a growing car production industry (central to Brazil's economic growth) and increasing levels of car ownership. The military government were highly motivated to maintain economic and political stability and responded to rising oil prices by investing in domestic production and increasing foreign debt. At the same time the Brazilian economy was experiencing a sugar export crisis due to the low world sugar price. The use of sugarcane as a feedstock was fundamental to the particular trajectory followed by the ethanol industry in Brazil. The importance of sugarcane to Brazil as an agricultural commodity has shaped sugar policy throughout the century. For example, during the 1960's the government invested in modernising the domestic sugar industry to compete in world markets, doubling the capacity of the sector during the early 1970s (Lehtonen, 2007). This contributed to Brazils sugar processing capacity, which was necessary for the emergence of the domestic biofuel industry. In the early 1970s the burgeoning domestic production capacity, the weakness of the world sugar market, the accelerating economic crisis, and the growing emphasis on alcohol as a petroleum substitute, were the main factors influencing the emergence of the Brazilian ethanol industry (Nunberg, 1986). Domestic economic concerns, existing industrial capacity, new economic opportunities and a powerful sugarcane lobby (Nass *et al*, 2007) were significant factors influencing the political framing and articulation of industrial and energy problems. These issues converged into a 'bioethanol produced from sugar cane' solution.

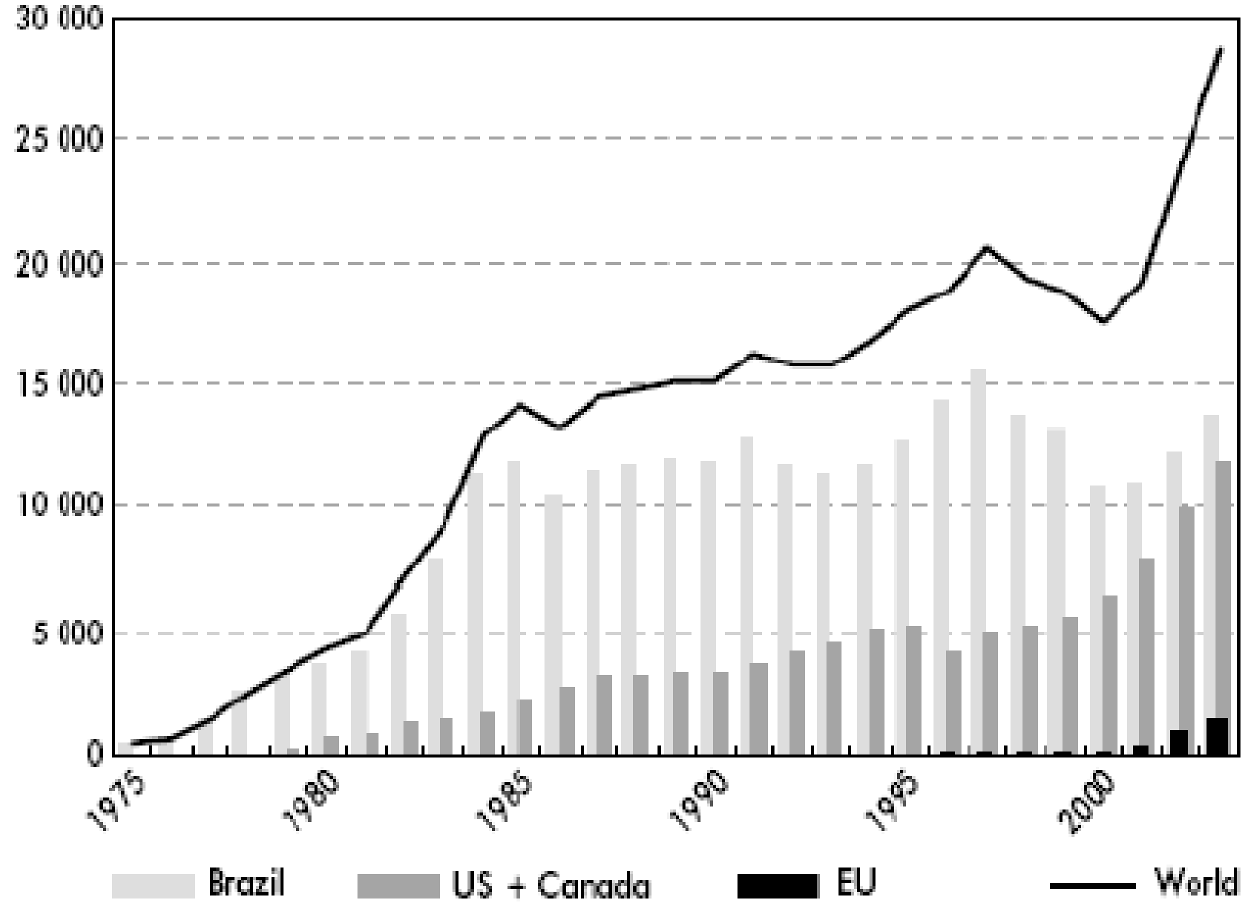

Figure 2: World and Regional Ethanol Production 1975-2003 (millions of gallons) – sourced from Vessia (2006)

The articulation of this solution by the Brazilian government was embodied by the establishment of the Proalcool Program in 1975. This programme was designed to promote national growth, reduce regional disparities, and address energy dependency issues by coordinating the domestic production *and* consumption of ethanol. The Proalcool Program can be split into two phases; Phase 1 (1975-1979) and Phase 2 (1979-1985). In the first phase the program concentrated on producing anhydrous alcohol for blending with petrol. A 20% ethanol: 80% petrol target ratio was set as this was possible with the existing stock of cars.

Petrobras, the state-owned oil company, was mandated to purchase a guaranteed amount of ethanol from producers, then blend and distribute the petrol-ethanol mix. This level of intervention by the State was enabled by the pre-existing economic structure, including State ownership of Petrobras, and the concentration and centralisation of the sugarcane industry under the Instituto de Azucar e Alcool (IAA). The State in Brazil directly intervened in the emergence of the innovation system around the articulated problem, and was a core actor in the mobilisation of the system. Emphasis was placed on increasing agricultural production, and modernising and constructing production plants. The government operated a credits scheme for distillery construction and by 1979 there were 104 ethanol distilleries in operation. The price received by ethanol producers was also set close to the average costs of production, thus insulating producers from market fluctuations. In addition, the IAA implemented a national agricultural research programme to promote the development of new sugarcane varieties. This research accelerated the improvement in sugar cane yields by approximately 10 tonnes per hectare; to 60.5 tonnes in 1982.

The second oil crisis in 1979 stimulated expansion of the Proalcool program. The blending of anhydrous ethanol with petrol had been so successful that maximum capacity was restricted by engine design, sugar and ethanol supplies. Phase 2 of the program coordinated the production of hydrous alcohol for use in engines designed to run on pure ethanol. Initial efforts to develop a dedicated engine capable of running on pure ethanol were State controlled and conducted at the Centro de Tecnologia Aeronautica (CTA) in Sao Paulo (Goldemberg, 2008). The State persuaded multinational car producers located in Brazil to commercialise this technology and invest in developing their production capacity. The involvement of the car industry was essential for the continuation of the programme and the government signed contracts with Fiat, VW, Mercedes-Benz, GM and Toyota to produce 250,000 cars by 1980 and 350,000 by 1982 (Sandalow, 2006). The State simultaneously stimulated consumption by providing tax incentives for the purchase of cars run on hydrous ethanol and mandating that all government vehicles were ethanol fuelled. Further incentives were created in the early 1980s when the Brazilian government capped the pump price of hydrous alcohol at 64.5% of the petrol price. Consumers responded by purchasing large numbers of ethanol powered vehicles and in the mid 1980's pure ethanol vehicles accounted for 80 percent of all new cars sold (Ueki, 2007). At the point of purchase by the consumer, the relative price of bioethanol has remained below petrol throughout the period and for most of the 2000s (De Almeida *et al*, 2007).

5.2 Industry stagnation (1985-2002)

This phase of rapid growth is followed by a phase of stability, or stagnation. In 1985-86 there was a sharp drop in the international price of oil which coincided with economic depression and the transition to a civilian government. Production subsidies for the ethanol sector were withdrawn from 1986 (Lehtonen, 2007). Consumption subsidies were maintained in order to minimise the risk of defaults on existing public loans. Supplies of ethanol were interrupted in 1988 when an increase in the world sugar price motivated many sugar producers to divert their crops to the world market. This resulted in a domestic fuel crisis and the abandonment of pure-ethanol engine vehicles by car producers and consumers. Ethanol producers responded to the economic depression, reduction in demand and fall in world oil prices by reducing R&D budgets.

Graph B shows an initial drop in ethanol production followed by fluctuating levels between 1998-2002. Since the creation of the Proalcool Program, the prices of fuel, and the prices received by ethanol producers, have been set by the Brazilian government. Prior to 1985, the price was set to correspond with the cost of production. After 1985, this price was set below the average cost of production in an attempt by the federal government to control inflation (Goldemberg *et al*, 2004). Consumption subsidies for the ethanol sector ended in 1997 as part of the liberalisation program. This had an immediate impact on production levels which generally dropped as subsidies were withdrawn, prices fluctuated and stocks of ethanol declined. Minimum blending policies and import tariffs were maintained ensuring that ethanol retained a market and the focus in the sector shifted to R&D.

5.3 Rapid re-expansion (2003 onwards)

The relatively low, but stable, level of Brazilian ethanol production ensured by mandatory 20% ethanol-petrol blending, maintained the ethanol industry through a period of reduced government support and adverse economic conditions. However, in 2003 domestic ethanol production began to rapidly increase. The renewed interest in ethanol as a transportation fuel was the result of a number of inter-related social, political and economic factors. The US had begun investing heavily in ethanol production and global economic growth increased the demand for oil, pushing the price of oil up from 2003. World wide consensus to reduce greenhouse gas (GHG) emissions and dependence on Middle East oil imports led many countries to explore biofuels as one technological solution. This created a potential export market for Brazilian ethanol. The Brazilian government framed the global climate change problem as an economic opportunity. In 2007 the Government explicitly aspired to substitute 10 percent of the global use of petrol with Brazilian ethanol exports within 2 decades (Lehtonen, 2007). In 2008, Brazilian ethanol accounted for over half of all ethanol exported worldwide and the ethanol program in Brazil had replaced approximately 1.5% petrol consumed worldwide by 2008 (Goldemberg, 2008).

The introduction of the flexible fuel vehicle (FFV) to Brazil was fundamental to the expansion of the ethanol industry. In 2001 the Brazilian government agreed to offer the preferential tax rate applied to pure ethanol cars to flex-fuel vehicles (Lehtonen, 2007). Ford launched their prototype in 2002 and VW entered the market in 2003. Graph C shows how successful the penetration of the FFV is in Brazil. At the beginning of 2006 approximately 75% of new cars manufactured in Brazil were FFVs (Moreira, 2006; Marris, 2006).

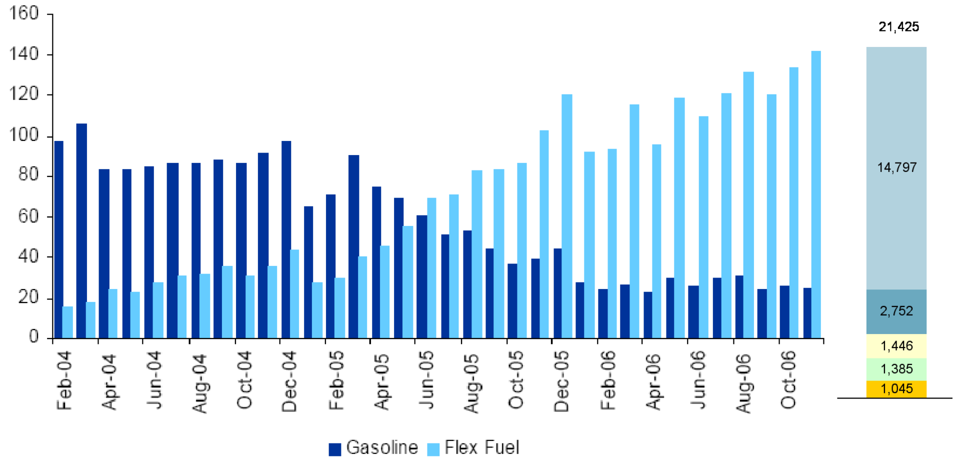

Figure 3: Evolution of the production of light vehicles (thousands) and the Total Brazilian Fleet (2007) – sourced from Romanelli (2008)

The FFV is capable of running on pure petrol, pure ethanol or any blend between. This increased the substitutability between the fuels for consumers (Hira and de Oliveira, 2009) and the substitutability between sugar and ethanol markets for producers. The resultant increase in the domestic market for bioethanol enabled by the success of the FFV has resulted in conflicts between domestic and export use. The government recently enacted legislation lowering the required percentage of ethanol in petrol blends from 25-20 percent to ensure that both domestic demand and export opportunities can be met. This further demonstrates the dominance of the economic development problem over that of climate change.

New reverse salients have emerged and been articulated as critical problems as the system has evolved. In addition to infrastructure constraints to international distribution (an issue addressed by the State and key firms such as Petrobas), the vision of Brazil as a major exporter demands a major increase in the volume of bioethanol produced. This reverse salient has been articulated as a series of critical problems related to increasing sugar cane yields and improving processing capabilities. Research based on traditional methods has been complimented by biotechnology approaches. Quite speculative genomic science initiated in

2000 (Harvey and McMeekin, 2005) has created the possibility for new transgenic sugarcane varieties. This has seen the emergence of new domestic biotechnology firms spun-out of the government research programmes, for example Allelyx in plant genomics and Canavialis in sugar cane breeding. Sugarcane refining productivity has increased dramatically over the past decades and Dedini, the dominant equipment provider in this sector, has occupied a central position in the sugar refining innovation trajectory. Dedini have developed a process enabling the production of bioethanol from bagasse and straw[6] with the aim of doubling refining productivity. A commercial demonstration plant, capable of producing 5,000 litres per day, has been in operation since 2003, through a joint venture between Dedini, COPERSUCAR (the cooperative of sugar growers) and FAPESP, the Sao Paulo State government research funder. During the 30 year period since ProAlcool ethanol production has multiplied by 30, yield per hectare has increased by 60% and production costs have declined by 75% (Nass *et al*, 2007). As in the US case we see how the innovation system involves the coordinated action of public and private actors in market and non-market modes of interaction.

6 DISCUSSION AND CONCLUSIONS

A central issue addressed in this paper is the framing and articulation of 'problems' by the State, and the subsequent mechanisms employed to incentivise system emergence to address these problems. Understanding innovation systems as problem orientated provides dynamism and direction to the system. The system is understood as goal seeking, evolving towards articulated objectives. However, as previously emphasised, surprisingly little has been said about how problems themselves are constructed. The biofuel industries of the U.S. and Brazil re-emerged during the 1970's in response to strategic interventions by their national governments intended to mobilise innovation systems around a specific problem. The case studies clearly demonstrate how global events, such as the oil shocks of the 1970s, can be framed in different ways, and that this framing is dependent on multiple technical, economic and political factors.

In order to develop our understanding of how innovation systems emerge and evolve, we draw on Hughes (1983) concept of the reverse salient. This refers to the complex of economic, social, political and technological factors, which at a given point in time inhibit further growth of the system. The reverse salient is resolved into a technical problem that can be addressed by the innovation system. When there is a failure to solve a major problem in the old system, a new system or new subsystem emerges. In the U.S. the reliance on Middle Eastern oil was perceived as a major problem with the oil system stimulating the emergence of a new domestic liquid fuel system. As oil prices reduced and supplies stabilised, political interest declined, and ethanol production capacity experienced marginal growth. In comparison, the international oil price shocks threatened economic growth and political stability in Brazil. The military-run, newly industrialising country had a growing car manufacturing industry and increasing levels of car ownership. Simultaneously, Brazils sugar industry was experiencing an export crisis. The sugar and car industries were of strategic importance to the wider Brazilian economy, complete with powerful lobbies. Economic stability was critical to maintaining the political regime. Developing cane-to-ethanol capacity provided another market for the powerful sugar industry, fuel for increased domestic car ownership, which in turn facilitated growth of the domestic car manufacturing industry and reduced dependence on imported oil.

The biofuels system in Brazil emerged to solve a problem of economic and political stability that could not be solved by the existing oil system at that time. In comparison, the biofuels industry in the U.S. emerged to solve a problem of energy security, but the oil price hikes of the 1970s were temporary and the energy security problem reduced in importance. Without continued political support and interest from the strong agricultural lobby the biofuels industry did not re-emerge as rapidly as in Brazil. The relative importance of the unresolved major problem influenced the momentum of system emergence.

In both cases the evolution of problems, or problem sequences, provides direction and momentum to the emerging innovation system. Innovative activity is concentrated around

[6] The DHR (Dedini rapid hydrolysis) process converts cellulosic matter into sugars, which can be fermented and distilled to produce bioethanol.

reverse salients which become defined as a series of critical problems. Once critical problems are solved the system boundaries evolve (or advance) and other reverse salients emerge. For example, the successful scaling-up of biofuels production capacity in the U.S. altered the problem space. Concerns about the environmental impact of biofuels (especially GHG emissions from ILUC) coincided with corn price spikes and debates about the production capacity potential of the existing corn-ethanol regime. These concerns combined to form a reverse salient limiting further system development. The framing and articulation of the problem changed as the system evolved, new knowledge came to light and the problem was renegotiated. The US government responded by incentivising and mandating cellulosic ethanol production and subsequent innovative activity was directed towards this goal. Inherently, in a dynamic and complex system, problems can never be fully resolved, partial solutions to problems change the problem space resulting in altered understanding of their nature. Thus reverse salients, and their related critical problems, change and influence how the system evolves, the rate of its expansion and how it is constituted.

The Brazilian sugarcane-to-ethanol production regime is characterised as highly productive and efficient, and no reverse salient emerged in the same way. Indeed, such has been the momentum of the Brazilian biofuel system that it is re-directed away from economic stability towards further expansion beyond its initial national boundary through the development of export markets. A potential export market for Brazilian biofuels was created by the US focus on energy security and investments in domestic ethanol production, as well as the global intention to reduce GHG emissions. The export opportunity was coherent with the original economic development agenda and enabled by the demand driven capacity stimulated by the introduction of domestic flexible-fuel vehicles. Changing market conditions provided an opportunity for expansion and an altered understanding of the problem stimulated further efforts to increase the volume of bioethanol produced for export. Innovative activity directed at solving this reverse salient has been concentrated on major innovations in agriculture and refining technologies. In Brazil, new knowledge, especially speculative genomic science, has presented novel opportunities for solving these critical problems.

The framing and articulation of problems occurs within a context of relative institutional stability and the specific modes of economic governance instituted in different regions. In Brazil, prior to 1985, the governing military regime directly intervened in both the supply and demand sides of the biofuels industry. The Proalcool programme provided a comprehensive, system-wide, set of policies to induce growth. Petrobras, the state controlled oil company, was a major coordinating firm, despite initial resistance. In comparison to the direct command and control approach of Brazil, market-based instruments were employed initially in the U.S. with policies based on market failure justifications, e.g. R&D tax incentives and tariffs. The Renewable Fuels Standard in 2005 introduced demand side mandates and signified a change of style in intervention reflecting the increased strategic importance given to the energy security problem. The oil firms, and dedicated biofuel firms, only entered the system to find substitutes for MTBE and in response to blending mandates. The more direct (and system orientated) style of State intervention that arose in the US demonstrates a move away from the 'liberal market' orthodoxy. This is particularly interesting as the U.S. is regarded as the archetypal example of a successful liberal innovative economy. This rhetoric is clearly different from the reality.

Dominant physical and social technologies create institutional lock-in, or path dependency. In Hughes language, momentum provided inertia to the older well established system. In the first two phases in Brazil and the U.S. there was little tension between the incumbent firms in the oil industry and the slowly emerging biofuels trajectory. The oil companies in the U.S. have been relatively inactive. In Brazil the initial resistance of Petrobras was overcome by direct government ownership. Due to high levels of mandatory blending the oil firm and the emergent biofuel system have co-existed in an almost symbiotic relationship. During the third phase there have been increasing tensions between the old and new systems in Brazil *and* the U.S.. Petrobras, already with significant biofuels capability in-house, created a fully owned subsidiary. In the U.S. oil firms have begun constructing networks around themselves involving public science institutes and dedicated biotech-biofuel firms in order to develop in-house capacity. The momentum or inertia in the incumbent system stifled the emergence of a new competing innovation system. Government intervention, in response to a major problem in the old system, has been a central driver of the new innovation systems in both countries.

The emergence of the biofuels industries in the U.S. and Brazil are probably the most prominent recent examples of governments intervening to 'solve' large scale political and ecological problems. The State has clearly played a crucial coordinating role in both innovation systems, though the style and level of intervention has varied spatially and temporally. In both countries the emergence of a biofuel industry was primarily motivated by energy security and economic growth rather than environmental concerns, which have tended to shape the formulation of solutions rather than the framing of problems. However, climate change mitigation is a problem of unparalleled scale, associated with significant market failure. Any solutions will require the development of innovative capacity and corresponding shifts in industrial organisation. As industry has little or no incentive to self organise this necessitates a strong coordinating role for government. In light of this, as ecological problems intensify we might expect to see an increase in state intervention in innovation systems.

7 REFERENCES

ADM (2009) corporate timeline accessed at: http://www.admworld.com/naen/about/TimeLine_history.html

Biomass R&D (2009) The official interagency *Biomass Research & Development Initiative* website, accessed at: http://www.brdisolutions.com/default.aspx

CAST (2006) Convergence of Agriculture and Energy: Implications for Research and Policy, *The Council for Agricultural and Science Technology (CAST) Commentary*, QTA2006-3, November.

Carlsson, B. (ed.) (1997) *Technological Systems and Industrial Dynamics*, Boston, Kluwer Academic

Coombs, R., Harvey, M. Tether, B.S. (2003) Analysing distribution processes of provision and innovation, *Industrial and Corporate Change*, 12, 5, p1051-1081.

De Almeida, E.F., Bomtempo, J.V., De Souza e Silva, C.M. (2007) The performance of Brazilian Biofuels: an economic, environmental and social analysis, *FURJ Working Paper*, 5.

Dimitri, C. and Effland, A. (2007) Fueling the Automobile: An Economic Exploration of Early Adoption of Gasoline over Ethanol, *Journal of Agricultural & Food Industrial Organization*, Vol. 5, Article 11.

Eggert, A. (2007) Transportation Biofuels in the USA – Preliminary Innovation Systems Analysis, Institute of Transportation Studies, UC Davis, Research Report, UCD-ITS-RR-07-10, accessed at: http://pubs.its.ucdavis.edu/publication_detail.php?id=1089

DOE, 2009. The United States Department of Energy Biomass Program, information accessed at: http://www1.eere.energy.gov/biomass/pdfs/biomass_program_mypp.pdf

Financial Times (2008) Interactive Feature: Ethanol boom and bust, October 21, accessed at: http://www.ft.com/cms/s/0/6ed47d6e-9f7a-11dd-a3fa-000077b07658,dwp_uuid=ca98ca88-6456-11dd-af61-0000779fd18c.html

Freeman, C (1995) The National System of Innovation in Historical Perspective, *Cambridge Journal of Economics*, No19, p 5-24;

Geels, F. (2002), *Understanding the dynamics of technological transitions*, Enschede-Twente University Press;

Goldemberg, J. (2008) The Brazilian biofuels industry, *Biotechnology for Biofuels*, 1:6.

Goldemberg, J., Coelho, S. T., Nastari, P. M. And Lucon, O. (2004) Ethanol learning curve – the Brazilian experience, *Biomass and Bioenergy* 26, p301-304.

Hall, P.A. and Soskice, D.W. (2001) *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, Oxford University Press, USA.

Harvey, M. and McMeekin, A. (2005) Brazilian Genomics and Bioinformatics: instituting new innovation pathways in a global context." *Economy and Society* 34(3) (2005): 634-658.

Harvey, M. and McMeekin, A. (2007) *Public or Private Economies of Knowledge? Turbulence in the Biological Sciences*, Edward Elgar, Cheltenham, UK.

Harvey, M, Quilley, S., and Beynon, H. (2002) *Exploring the Tomato: Transformations in Nature, Economy and Society*, Edward Elgar, Cheltenham, UK.

Herrera, S. (2006) Bonkers about biofuels, *Nature Biotechnology*, 24, p755-760.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S. and Smits, R.E.H.M. (2007*)* Functions of Innovation Systems: A new approach for analysing technological change, *Technological Forecasting and Social Change*, 74, 4, p.413-432.

Hira, A. and de Oliveira, L.G. (2009) No substitute for oil? How Brazil developed its ethanol industry, *Energy Policy*, 37, p2450-2456.

Holt, M. and Glover, C. (2006) Energy Policy Act of 2005: Summary and Analysis of Enacted Provisions, *Congressional Research Service report for Congress*, Order code RL33302, March 8: assessed from http://ncseonline.org/NLE/CRSreports/06Apr/RL33302.pdf

Hughes, T.P. (1983) *Networks of Power; Electrification in Western Society 1880-1930*, John Hopkins University Press, Baltimore and London.

Jacobsson, S. and Bergek, A. (2004) Transforming the energy sector: the evolution of technological systems in renewable energy technology, *Industrial and Corporate Change*, 13, 5, p.815–849.

Keeney, D. (2009) Ethanol USA, Viewpoint, *Environmental Science and Technology*, Vol. 43, No.1, p.8-11.

Kemp, R. (1994), Technology and the transition to environmental sustainability. The problem of technological regime shifts., *Futures*, 26, 1023-1046.

Koplow, D. (2006) Biofuels – at what cost? Government support for ethanol and biodiesel in the United States: 2007 update, Earth Track report prepared for The Global Subsidies Initiative (GSI) of the International Institute for Sustainable Development (IISD), Geneva, Switzerland, accessed at: http://www.earthtrack.net/earthtrack/library/BiofuelsUSupdate2007.pdf

Lehtonen, M. (2007) Biofuel transitions and global governance: lessons from Brazil, conference paper, *Amsterdam*: accessed at: http://www.2007amsterdamconference.org/Downloads/AC2007_Lehtonen.pdf

Lundvall, B.A. (1992) *National Systems of Innovation: Towards a theory of innovation and interactive learning,* Pinter Publishers.

Malerba, F. (2002) Sectoral systems of innovation and production, *Research Policy*, 31, 2, p247-264.

Markard, J. and Truffer, B. (2008) Technological innovation systems and the multi-level perspective: Towards an integrated framework, Research Policy, 37, 4, p596-615.

Marris, E. (2006) Drink the best and drive the rest, *Nature,* 444, p670-672.

McMeekin, A., Gee., S., Harvey, M., Nugroho, Y., Pilgrim, S and Upham, P. (2010) European Biofuels to 2020 and beyond, Final Project Report, The Sustainable Consumption Institute, Manchester, June, accessed at: http://www.sci.manchester.ac.uk/medialibrary/foresight_of_biofuels_final_project_report.pdf The Executive Summary can be accessed at: http://www.sci.manchester.ac.uk/medialibrary/foresight_of_biofuels_exec_summary.pdf

Merito M.and Bonaccorsi A. (2007) Co-evolution of physical and social technologies in clinical practice. The case of HIV treatments, *Research Policy*, 36,7, p1070-1087.

Metcalfe, J.S., James, A., Mina, A. (2005) Emergent innovation systems and the delivery of clinical services: The case of intra-ocular lenses, *Research Policy*, 34, 9, p1283-1304.

Metcalfe, J.S. and Ramlogan, R. (2008) Innovation systems and the competitive process in developing economies, *The Quarterly Review of Economics and Finance*, 48, 2, p 433-446

Mina, A., Ramlogan R., Tampubolon, G. and Metcalfe J. S. (2007) Mapping Evolutionary Trajectories: Applications to the Growth and Transformation of Medical Knowledge, *Research Policy* 36, 5, p789-806.

Moreira, J.R. (2006) Brazil's experience with bioenergy, in P Hazell and R. K. Tachuari (eds) Bioenergy and Agriculture: Promises and Challenges, Focus 14, *International Food Policy Research Institute*, Washington DC

Nass, L.L., Pereira, A.A. and Ellis, D, (2007) Biofuels in Brazil: An Overview, *Crop Science*, Vol.47, p2228-2237.

Nelson, R. (1993) *National Innovation Systems*, Oxford University Press, New York and Oxford.

Nelson, R. (2005) *Technology, Institutions and Economic Growth*, Cambridge, MA and London, UK.

NFCC (2007) NNFCC Position Paper: Biorefineries, January.

Northeast Sustainable Energy Association (2009), Ethanol Factsheet, accessed at: http://www.nesea.org/greencarclub/factsheets_ethanol.pdf

Nunberg, B. (1986) Structural Change and State Policy: The Politics of Sugar in Brazil since 1964, *Latin American Research Review*, 21:2, p53.

Renewable Fuels Association, (2008). Historical US Fuel Ethanol Production, accessed at: http://www.ethanolrfa.org/pages/statistics

Romanelli, T (2008) Ethanol and sustainability issues – the case of Brazil, presented to Mark Harvey and Andy McMeekin, ESALQ, Piracicaba, 7 July.

Sandalow, D. (2006) Ethanol: Lessons for Brazil: A High Growth Strategy for Ethanol, Aspen Institute.

Searchinger, T., Heimlich, R., Houghton, R.A. Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T. (2008) Use of US Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change, *Science*, Vol. 319, p1238-1240.

Sissine, F. (2007) Energy Independence and Security Act of 2007: a Summary of Major Provisions, *Congressional Research Service report for Congress*, Order code RL34294, December 21, accessed at: http://energy.senate.gov/public/_files/RL342941.pdf

Solomon, B.D., Barnes, J.R. and Halvorsen, K.E. (2007) Grain and cellulosic ethanol: History, economics and energy policy, *Biomass and Bioenergy*, 31, p416-425.

The Ethanol Fact Book (2007), published by the *Clean Fuels Development Coalition* (CFDC) assessed at: http://www.ethanolacrossamerica.net/pdfs/2007EthanolFactBook.pdf

Ueki, Y. (2007) Industrial Development and the Innovation System of the Ethanol Sector in Brazil, Discussion Paper 109, *Institute of Developing Economies*, Japan, accessed at: http://ir.ide.go.jp/dspace/bitstream/2344/588/3/ARRIDE_Discussion_No.109_ueki.pdf

Winfield, E. (2008) Ethanol in Brazil, *The University of Iowa Center for International Finance and Development,* Briefing Paper, accessed at: http://www.uiowa.edu/ifdebook/briefings/pdf/Ethanol_in_Brazil.pdf

Vessia O. (2006) Biomass and Biofuels, online publication for the *Zero Emissions Resource Organisation*, accessed at: http://www.zero.no/transport/biodrivstoff/hva-er-biodrivstoff/biomass-and-biofuels/?searchterm=biofuels

