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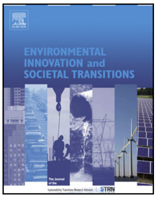

Pioneer countries in the transition to alternative transport fuels: Comparison of ethanol programmes and policies in Brazil, Malawi and Sweden

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ABSTRACT

Efforts to develop alternative transport fuels and vehicles are found in countries varying tremendously in their level of economic development. In this paper, we compare the alternative fuels transition, focusing on ethanol, in three countries: Brazil, Malawi and Sweden. Each can be described as a pioneer in developing the physical and institutional infrastructure and stimulating innovation towards alternative transport fuels. We assess the transition in these pioneer countries based on niche formation and interaction with regime and landscape levels. Particular reference is made to spatial and temporal path dependencies and to the significance of cross-scale and cross-sector effects that impact the innovation process. As other countries and regions develop programmes to address the twin challenges of energy security and climate change, they can benefit from a better understanding of linkages between techno-economic and socio-technical factors in transition paths of pioneer countries, across different scales and different stages of economic development.

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1. Introduction

The use of alternative transport fuels, particularly alcohol fuels, was widespread in Europe and the Americas before World War II but fell out of favour with the low oil prices of the 1950s and 1960s (Kovarik, 1998; Knothe, 2001). The oil price shocks of the 1970s spurred renewed interest in the U.S. and worldwide in stimulating a transition to alternative fuels. Some developing countries, Brazil foremost among them, recognised that biofuels could improve energy security, save foreign exchange and contribute to agricultural development. In addition to the U.S. and Brazil, several other countries committed themselves to biofuels (only alcohol fuels at that time), including Argentina, Costa Rica, Malawi, Swaziland, Sweden and Zimbabwe (Gowen, 1989).

Yet after a century of experimentation, alternative fuels provide less than 2% of global road transport fuels, and are heavily concentrated in just three regions—Brazil, the European Union (EU) and USA. Alternatives to liquid biofuels such as biogas, electric vehicles and fuel cell vehicles have barely moved beyond pilot stages. The transition away from fossil fuels has proven much more difficult in the transport sector than in other end-use sectors; oil dependency reveals the classic features of *path dependence* and technology *lock-in* that create barriers in the energy transition (Grübler, 2004).

More recently, a new tripartite rationale—energy security, climate change and rural development—has been driving biofuels programmes in developed and developing countries alike (Sorda et al., 2010). In addition to the EU, other regional bodies have been developing biofuels policies, such as the Southern African Development Community (SADC) and the Economic Community of West African States (ECOWAS) (Lerner et al., 2010; Jumbe and Madjera, 2012). Biofuels markets and policies have become a multi-scale phenomenon playing out at national, regional and global levels. Consequently, significant new interdependencies have arisen across these scales: the EU Renewable Energy Directive (EU-RED) in particular has had significant repercussions for global biofuels markets and policies (Johnson, 2011).

Only a few countries, however, have pursued consistent biofuels policies over several decades: Brazil, Malawi and Sweden are noteworthy for their efforts to maintain the newly established markets even after the oil price collapse of 1986. They are also noteworthy in terms of environmental impacts compared to the large biofuels programmes in the U.S. and Germany, where the key options (maize ethanol and rapeseed biodiesel, respectively) have poor energy balances and are not environmentally innovative. In contrast, sugarcane ethanol as used in Brazil and Malawi (and imported in significant amounts in Sweden) is noted in both EU and U.S. legislation as having the best energy and GHG balance among first generation biofuels (EC, 2009; US-EPA, 2010).

The environmental sustainability of different biofuels is not, however, the focus of this paper. Nor is the focus here on the overall sustainability transition in the transport sector, since this would require a much broader assessment covering both demand and supply sides and addressing systemic transitions (Geels, 2012). We are interested instead in analysing transition pathways across different levels of economic development for countries that engaged purposefully in stimulating the shift away from fossil fuels in the transport sector: How does the nature and scope of transition pathways vary with differing economic development realities and priorities? We therefore choose three countries—Brazil, Malawi and Sweden—spanning three different world regions and three different levels of economic development. Given that transition studies have been concentrated in a few European countries, this paper offers new geographical breadth. These countries have been regional "pioneers" or market leaders (global leader in the case of Brazil) in establishing ethanol as a transport fuel. The paper aims to place this role of market leader in a comparative developmental/institutional context in which temporal and geographical linkages are considered through a socio-technical lens.

The rationale and approach are outlined in the next section, followed by a review of fuel ethanol market development in the three countries and a comparison of key drivers, actors, policies/programmes, infrastructure requirements and institutional foundations. The paper draws on several different conceptual frameworks and thus none of these can be explored and/or applied on its own in great detail; the paper emphasises instead the overall biofuel-development pathways pursued by the three countries. The paper adds a socio-technical lens in analysing the evolution of the fuel-vehicle (and ethanol) systems so as to complement conventional analyses on techno-economic changes and/or political-economic drivers.

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2. Rationale, framework and approach

An historical analysis that crosses different regions places the transition to alternative fuels in its global market context while the national-level comparison considers how the transition process itself is influenced by economic development priorities. The rationale is three-fold. First, by considering the evolution over several decades—and at the same time choosing countries that are engaged in comparable pathways—we highlight the temporal dimensions of energy transitions across changing economic and political conditions. Second, our choice of three countries (Brazil, Malawi and Sweden) with quite different resource endowments and levels of economic development facilitates a comparative institutional assessment in the global transition away from fossil fuels and/or towards modern bioenergy (Silveira, 2005). Third, the comparison illustrates the increasing importance of spatial and economic linkages between technological systems and actors at national, regional and global levels and suggests a useful role for a socio-technical lens in analysing the shift to alternative fuels. Adding a spatial perspective recognises the multi-scalar nature of modern sustainability/energy transitions (Raven et al., 2012), which is especially relevant for bioenergy. It widens the geographical reach of transition studies, which have tended to focus on a few European countries (Coenen et al., 2012). In this section, different conceptual frameworks are briefly reviewed to structure and inform the choice of case studies, followed by an explication of the methods and approach.

2.1. Energy transitions and alternative pathways

Although the long-term viability of the fossil economy was questioned more frequently after the 1973 oil crisis, sustainability entered the policy debate mainly after the Brundtland report and the Rio Conference (WCED, 1987; UN/Rio, 1992). The increasing reliance on non-renewable resources in combination with a rapidly expanding global population in a changing climate has led to new perspectives on the role of energy in the economy. Non-renewable carbonaceous fuels will constrain economic growth and development unless the transition to renewable energy can be accelerated (Stern, 2006). Bioenergy has a special role in the transition as the stored (non-intermittent) form of solar energy and because of its flexibility in applications.

Energy transitions take place over many decades and involve a variety of symbiotic relationships across conversion technologies, fuels and end-user applications (Grübler, 2004). The historical transition towards large-scale fossil fuels, hydropower and nuclear power involved a long period of experimentation and learning with respect to appropriate scale and end-user needs (Wilson and Grübler, 2011). However, this techno-economic characterisation of energy transitions is less useful for bioenergy compared to other energy resources, since bioenergy crosses all energy carriers and varies in efficient scale and scope: Economies-of-scale are much more spatially and application-dependent compared to other energy classes (Hall, 1991). Technological clusters and networks of actors are even more important for bioenergy, due to the complexities of the biomass feedstock supply chain and associated infrastructures. A socio-technical perspective is thus quite useful in analysing bioenergy transitions.

Energy transitions are complicated by *path dependence*, which can lead to *lock-in* of sub-optimal technologies or systems. A new technology or system can grow quickly and gain significant market share, regardless of its superiority over alternatives arriving at a later stage (Arthur, 1989). The internal combustion engine itself is sometimes cited as an example, given the higher efficiency of other power trains (van den Bergh and Oosterhuis, 2008). Path dependencies in the fuel-vehicle system also arise from spatial clustering in socio-economic development (e.g. proximity to highways, parking, etc.) and the socio-cultural dependence associated with mobility. Path dependence also results in time lags as new actors engage in ongoing socio-technical struggles, such as biofuels actors dealing with well-established oil and auto industry actors (Gee and McMeekin, 2011).

The dominance of the internal combustion engine insures some role for biofuels in the near-term, at a minimum as bridge fuels while other infrastructures develop. The notion of "two-world technologies" becomes useful: biofuels extend the current system but can also facilitate eventual transition to fuel cells or electric vehicles, and even to greater public transit—by altering consumer choices between short and long-range transit (Meadowcroft, 2009; van den Bergh and Kemp, 2008).

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A similar perspective is that of hybridisation in which a technology/system niche expands through an existing regime rather than competing with it (Geels and Schot, 2007).

It is also important to recognise that a given pathway affects the innovation process via problem-solving and problem sequences, which arise as some problems are solved and new problems emerge (Metcalfe and Ramlogan, 2008; Gee and McMeekin, 2011). Actors face “reverse salients” along the innovation path that threaten collapse of the new technology/system, requiring adjustments and/or shifts in the path and the dominant actors (Hughes, 1983). A related idea is that of “path creation” in which initial conditions are constructed rather than given and a particular path constitutes a provisional stabilisation rather than a technological lock-in that will only respond to exogenous shocks (Garud et al., 2010). Similar to the innovation sequence perspective, under path creation actors are intimately involved in shaping expectations but are also behaving strategically and thus embedded in ongoing developments and not only reacting to external shocks.

2.2. Lead markets

Stricter environmental regulations can encourage eco-efficiency and innovation as early movers seek competitive advantage (Porter and van der Linde, 1995; Beise and Rennings, 2005). Eco-innovation strategies have consequently been based on the idea that governments can act as political entrepreneurs in introducing environmental technologies and creating a “lead market” that spreads to other countries (Cleff and Rennings, 2012). *Pioneer* countries play an important role by establishing lead markets for environmentally innovative technologies and thereby demonstrating their compatibility with economic competitiveness (Huber, 2008). The president of the European Commission, Barroso (2008) has stated that EU leadership on renewable energy technologies will improve competitiveness and maintain the “first-mover advantage.” An oft-cited example is Denmark’s investment in wind power, which allowed its manufacturers to maintain a leading position as the global market expanded (Kamp, 2007; Brandt and Svendsen, 2006).

The lead market concept arose in part from the notion of first mover advantage at the firm level that occurs when a firm gains information and experience that facilitate strategic competitive advantage (Lieberman and Montgomery, 1988). Whereas a firm has to internalise the risks, governments can spread the risk across all taxpayers. Another distinction is that in the case of global sustainability transitions, a gradual loss of market leader advantage is often desirable, since it can facilitate diffusion to other regions. In the case of fuel-vehicle system innovations, empirical evidence suggests that market leader advantages require that performance improvements accompany environmental benefits (Beise and Rennings, 2005; Geels, 2012). In this paper we are not concerned with first mover advantage at firm level but instead with lead markets arising at national level.

In the case of alternative fuels and/or bio-based fuels, lead markets should be considered in relation to *implementation and deployment* of the fuel-vehicle systems rather than technology development. The location of feedstock sources is flexible, since the raw bio-based materials are widely available although nevertheless spatially dependent. The example of Sweden is noted in this respect, since it has been highly innovative in alternative fuels market development even though it has generally imported a majority of the ethanol used (Chen and Johnson, 2008; Sandén and Hillman, 2011). Nor is the location of production of the various technologies (e.g. engines, distilleries) of high relevance, since these are dictated by economies-of-scale in a global economy. Lead markets here can thus be viewed as those that have implemented alternative fuel-vehicle systems in an innovative and more sustainable manner.

2.3. Strategic niche management and multi-level perspective

Path dependence relegates changes to the margins of the dominant system, further locking in the associated infrastructure, in this case the fossil fuel-vehicle system. In order to stimulate broader introduction of new technologies, markets or management processes, a “niche” can be created and protected in its early stages through coordinated policies and institutions. Thus, *Strategic niche management* (SNM) has been proposed, involving: “the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation" (Kemp et al., 1998). SNM attempts to integrate the interests and perspectives of stakeholders in a broader platform for interaction rather than previous technology-push approaches (Schot and Geels, 2008). The unpredictability of technological trajectories underlines the importance of niches in articulating demand and promoting learning (Rip and Kemp, 1998).

Three elements have been emphasised in SNM: shaping expectations, network building and learning processes. Learning processes allow for feedback, which also requires measuring, monitoring and reporting (van der Laak et al., 2007). Expectations are important for consumer acceptance of alternative fuels, since reliability and performance are key concerns for car owners. Expectations are quite important on the feedstock supply side in the case of biofuels, especially in developing countries where biofuels offer a new rural livelihood. A highly promoted biofuel in Africa has been jatropha; experience in countries like Tanzania illustrates the difficulties of creating a critical mass of growers (van Eijck and Romijn, 2008). Network building is complicated by the fact that some of the required actors have strong vested interests in the dominant (fossil) system and therefore it is necessary to include newer actors to help overcome that inertia (van der Laak et al., 2007).

The recognition that niche experiments cannot transform markets without the presence of broader interactions at higher governance levels contributed to the development of the multi-level perspective (MLP) on technological transitions (Geels, 2002). Niches can be supported during their formative phases, while incumbent and dominant social groups affect the linkages that contribute to wider diffusion of technologies (Geels and Schot, 2007). The role of organisational structures and behaviour affect innovation and are characterised by social-technological co-evolution (van den Bergh and Bruinsma, 2008). A multi-level socio-technical perspective on energy transitions fits well with the multi-scale nature of biomass resources. Spatial constraints along with the greater complexity of organisational structures favour local biomass resources in some applications but physical and economic factors favour international trade in other applications.

The policy and regulatory *landscape* is defined by key driving forces that establish the overall framework in which policy-makers and private actors set priorities. The energy and transport actors translate these priorities into policies, programmes and demonstration projects and collectively define the *regime* that governs technology implementation. Technological or market *niches* serve to introduce the new technology/system in a structured and/or protected manner. The driving forces lead to varying degrees of policy emphasis according to fluctuation in exogenous variables (e.g. oil prices, perceived climate impacts). The actors involved in the energy-transport regime cross multiple resource sectors (agriculture, forestry, etc.) and economic interests or industries (oil, autos, farmers, etc.).

Cross-sector interactions (energy–agriculture–transport–environment) complicate the transition process and create a larger set of stakeholders compared to other energy sources. Niches might be defined in terms of a technology (e.g. flex-fuel vehicles) or an alternative end-use application (e.g. cooking). Niches may be linked in socio-economic and political terms to the energy, transport, agriculture and environmental regimes, which in turn are impacted by the policy landscape. Other applications, technologies and markets may offer complementary, supplementary or competing options. Competing technologies may be spatially disconnected, e.g. biogas vehicles may dominate in a different region, whereas complementary technologies may in fact be co-located (e.g. heat and power). The MLP and SNM help to structure the comparison in the three country case studies, although it is important to note that the MLP and SNM complement the overall conceptual approach here rather than being the primary organising framework for the comparison.

2.4. Spatial dependence and differentiation

The MLP and to some extent the literature on Technological Innovation Systems (TIS) have been criticised for paying scant attention to the geography of transitions (Coenen et al., 2012; Truffer and Coenen, 2012). The effect of this exclusion can be to relegate spatial aspects to an exogenous element in transition analysis. A related concern is the tendency for both the MLP and the TIS to be applied at national level, even though there are multi-scalar developments that appear to play a significant role in niche development and transitions (Raven et al., 2012). Cross-scale effects are important for biofuels, due to the fact that local economies for biomass feedstock may differ significantly from the national and regional economies associated with end-user markets. Socio-technical factors arise as these markets are emerging due to the strong expectations of key actors in the supply chain for secure biomass supply and infrastructure.

Spatial dependence has been observed in the overall orientation of key actors, based on the geography of energy resources. An interesting example is found in comparing biofuels market development in Sweden and the Netherlands. As a neutral country with no fossil resources that is also somewhat geographically isolated, alternative transport fuels in Sweden have been accorded a high priority among both public and private actors (Ulmanen et al., 2009). Interest was lower and progress slower in the Netherlands, which has its own fossil resources (natural gas) and is also a major energy trading hub within Europe. There has been no strong energy-transport network of actors in Netherlands as there has been in Sweden (Lovio and Kivimaa, 2012).

This type of spatial interdependence can also be associated with renewable energy technology diffusion more generally, due to the interplay between market segments, transactions and user profiles (Jacobsson and Johnson, 2000; Dewald and Truffer, 2012). Sub-national divergence in innovation pathways may exhibit spatial dependencies that affect technology system development and deployment (Raven et al., 2012). Regional differences within Brazil and Sweden have affected the pace and nature of technology diffusion (Compeán and Polenske, 2011; Sandén and Hillman, 2011). Cross-scale connections between national and regional levels can be significant, for which EU renewable energy legislation serves as a prominent example (EC, 2009; Johnson, 2011). An integrated market such as the EU thus takes on new spatial dependencies that directly affect the actor networks as well as the physical infrastructure for alternative fuels.

2.5. Approach and methods

In this paper, we use these conceptual frameworks in analysing alternative transport transition pathways in the three countries, focusing especially on fuel ethanol programmes and policies. The moderately long timeframe of the analysis—covering almost four decades, in combination with the considerable geographical spread—spanning three regions/continents—places some special requirements on the approach. We have drawn on a wide range of published literature in developing the conceptual framework and shaping the country analyses, which have also been informed by the authors' experience in both professional and research capacities. Each of the authors has more than fifteen years of experience with biofuels in the three regions. The approach taken here thus draws on interactions over many years with a wide variety of both public and private sector actors involved in all the links of the biofuels chains. Interviews, discussions and seminars with key actors therefore provided "deep background" for the research and have facilitated insights not easily accessible through published literature.

3. Fuel ethanol programmes and policies of pioneer countries

Ethanol has emerged in the past decade as the most significant among the various alternative fuels or fuel-vehicle systems that have entered the market (Sorda et al., 2010; Hira, 2010; Lamers et al., 2011). In addition to Brazil, global biofuels market expansion is attributed to EU and U.S. biofuel mandates (EC, 2009; US-EPA, 2010). The fuel ethanol market has also been analysed as a strategic investment for Least Developed Countries (LDCs) in relation to energy security and climate mitigation (Pacini and Batidzirai, 2012; Batidzirai and Johnson, 2012). More than twenty-five countries have legislation related to blending of ethanol and/or biodiesel (Sorda et al., 2010). We do not evaluate the global market in this paper, but focus instead on the three pioneer countries, which effectively provided country-wide demonstrations that have influenced regional and global markets and policies. Consequently, the case studies—from three regions and three levels of economic development—form a useful lens on the evolution of the global transition to alternative fuels.

3.1. Market leader par excellence: the Brazilian experience

The story of ethanol in Brazil is among the best-known—and the most successful—of all renewable energy programmes in the world. The Brazilian story is unique in terms of the "innovation journey" that has resulted in the replacement of more than 50% of petrol for Otto cycle (fuel ignition) vehicles. It is neither feasible nor necessary here to recount the details of Brazil's ProAlcool programme and subsequent market development, which are well-documented elsewhere (Moreira and Goldemberg, 1999; Goldemberg, 2007). We focus instead on a few key elements to facilitate the country comparisons and illustrate the role of pioneer countries. A brief summary of the programme and the market restructuring of the 1980s and 1990s is followed below by a section on flex-fuel vehicles, which provided the key innovation driving the recent rapid ethanol market expansion.

3.1.1. Brazilian National Alcohol Programme

A key issue in Brazil's agricultural development in the early 1970s was the volatility in sugar prices, which made it difficult for producers to recoup recent modernisation investments. At the same time, high oil prices after 1973 constrained economic growth and created major trade deficits. A number of programmes were initiated to reduce oil import dependence: nuclear, vegetable oils (ProOleo) and ProAlcool (Rosillo-Calle and Cortez, 1998). The ProAlcool programme for ethanol was initiated in November 1975, with three main objectives (GoB, 1975):

(i) reduce national dependence on oil imports;
(ii) promote technical and industrial development through ethanol fuel production; and
(iii) strengthen the sugarcane and sugar sectors.

The original legislation and research were aimed at two crops: sugarcane and cassava (manioc). In terms of social development, cassava—the crop of poor farmers—was preferable to large-scale sugarcane. In commercial terms, it soon became clear that sugarcane was far superior and consequently there was little further experimentation with cassava. Furthermore, the stabilising effect on sugar producers' incomes from having two major commercial products became a key rationale (Moreira and Goldemberg, 1999). The emphasis on sugarcane was a clear choice in favour of rapid market development over the redistributive effects that might have been realised with cassava (Saint, 1982). This choice also facilitated the clustering of innovation around São Paulo that ultimately left Northeast Brazil behind in technical terms (Compeán and Polenske, 2011). The shift in the locus of development also revealed significant spatial dependencies in the evolution of the sugar–ethanol innovation system: the network of private actors that later came to dominate that system became more and more concentrated around São Paulo (Furtado et al., 2011).

ProAlcool was comprehensive in addressing industrial development, financing, infrastructure, and agricultural research within one broad programme. A special challenge in the early years was establishing the transport and distribution infrastructure, which required close collaboration with the state-owned oil company, Petrobras. Pipelines were alternately used for oil and ethanol to supply São Paulo, requiring innovative methods to avoid corrosion and undesired mixing (Demetrius, 1990). In a vast country such as Brazil, it was necessary to adopt a phased approach to ethanol blending: gradually increasing mandates were established in the sugar centres of São Paulo and the Northeast, followed by introduction in other major urban areas.

The initial target of 3.5 billion litres for 1980 was achieved by 1982. The production of neat (ethanol) vehicles in Brazil facilitated the creation of a market for hydrous (95%) ethanol, which lowers the cost by avoiding dehydration technology. The automobile manufacturers signed an agreement in 1979 with the government to produce ethanol-only vehicles, which were also prioritised for government fleets (Demetrius, 1990). The second oil crisis led to a long-term government policy aim to replace all gasoline with ethanol (Cordonnier, 2008). At the same time, the mandate for blending secured the near-term market for anhydrous (99%) ethanol. The *coordinated* approach taken in Brazil can be contrasted with the *regulated* approach adopted for ethanol in the USA around the same time (Gee and McMeekin, 2011). By careful coordination of supply and demand, the market penetration in Brazil quickly surpassed the USA, whose fuel ethanol market did not develop in earnest until two decades later.

3.1.2. Market restructuring

The ethanol market initially grew quickly but the collapse in oil prices in 1986 posed considerable challenges and producers were forced to respond to the changing economics. During the period from 1987 to 1990, the average ethanol production cost declined at more than double the rate experienced in the previous ten years (Moreira and Goldemberg, 1999). Yeast recovery, water recycling, and improvements in energy economy were among the highly innovative measures taken on the industrial side. Another important development in the Brazilian sugar–ethanol complex, which began in earnest in the early 1990s, was the leadership role played by the private sector in pushing the sugarcane innovation system forward at a time when government support was weakening due to financial and institutional pressures (Furtado et al., 2011). Private sector actors took over major roles in agricultural research as well as the more traditional roles in industrial production and distribution. The major role played by the private sector in agriculture was unusual for a developing country and provided the competitive edge that made Brazil a world leader in sugar and ethanol markets (Furtado et al., 2011).

Government continued to play its role in terms of prices, infrastructure and regulations. However, the recovery of world sugar prices in the 1990s presented additional policy challenges as the regulated price of ethanol was too low compared to production cost, thus encouraging producers to shift towards sugar and away from ethanol. Brazil became the world's main importer of alcohol fuels for several years, including even methanol since there was insufficient ethanol available on global markets (Moreira and Goldemberg, 1999). The sale of ethanol cars plummeted, not only due to fuel price differentials, but also in response to a reduction of taxes on gasoline cars. Consumer confidence was affected by a series of government policy reversals in taxation and regulations (Rosillo-Calle and Cortez, 1998). Price deregulation was initiated in the 1990s to wean ethanol and sugar producers off guaranteed prices. A producer cartel was temporarily able to manipulate prices, which increased at a faster rate than petroleum prices, and additional measures were needed to restore competitiveness (Hira and de Oliveira, 2009). These new challenges—organisational and economic as well as technical—might be described as "reverse salients" that were holding back the ethanol market expansion (Gee and McMeekin, 2011; Hughes, 1983).

3.1.3. Technological innovation: flex-fuel vehicles

The low and/or stable oil prices of the late 1980s and 1990s contributed to what appeared to be a plateau in the Brazilian fuel ethanol market. The mandated blend created a market floor, but without any prospect of significant expansion, the previous dynamism in the sector seemed unlikely to return. Without dedicated ethanol vehicles, the only possibility for any major market expansion was to devise ways to increase the share beyond the 25% maximum. The development of electronic fuel injection systems in the 1970s paved the way for using different mixtures of ethanol and gasoline, but the appropriate combination of hardware and control software to allow a variable mixture would take many years to develop. The hardware sensor developed by Bosch was rejected by automakers and the software-based solution developed by Magneti Marelli was the first to be adopted in Brazil and was able to gain half the market share in the early years (Yu et al., 2010).

The launch of flex-fuel technology during 2003–2004 was a game-changing solution and marks another successful phase in the problem-innovation sequence (Gee and McMeekin, 2011). It virtually eliminated the issue of consumer confidence, as car owners would henceforth have flexibility in choice of fuel. As the sixth largest automobile manufacturing country in the world, Brazil's automobile manufacturers provided the major testing ground for investing in the new flex-fuel technology. At the same time, the long experience with ethanol in Brazil and the maturity of its supply and end-use infrastructure facilitated rapid consumer uptake of the new flex-fuel vehicles (FFVs), which now account for over 90% of new car sales in Brazil (ANFAVEA, 2011). The popularity of FFVs resulted in the consumption of ethanol exceeding gasoline in Brazil as of 2009. There are still some regional and seasonal differences in prices and availability and car ownership is affected somewhat by income constraints (GAIN, 2011).

3.2. Regional innovator: bioethanol in Malawi

Malawi is a small country in southern Africa that depends heavily on subsistence agriculture, with an estimated per capita income of 800 USD/year and a population of 15 million. It is among the most densely populated of the Least Developed Countries (LDCs) in sub-Saharan Africa, and faces increasing pressure on biomass resources due to the overwhelming dependence on biomass and especially fuelwood, which accounts for nearly 90% of its primary energy needs (Juma, 2007; Johnson and Jumbe, 2013). Although Malawi has some coal, it depends entirely on imported petroleum products. It was among several African countries that developed ethanol programmes in the 1970s for reasons similar to those of Brazil. However, Malawi is the only one that has been blending ethanol continuously since its start (in 1982). In this section, we review the evolution of the programme and identify some noteworthy features.

3.2.1. *Establishing domestic ethanol production*

High oil prices are especially serious for a landlocked oil-importing country such as Malawi, affecting the prices of all imported goods and the costs of getting their own products to export markets. Transport costs in Malawi account for an estimated 14% of total product costs, compared to the world average of 6% (UNCTAD, 2011). Malawi's single-party political structure made it possible to quickly translate energy security concerns into tangible results through a new ethanol blending programme. The country's first ethanol plant, ETHCO Ltd. (Ethanol company of Malawi), opened in 1982 and has operated continuously, with annual production of fuel-grade ethanol ranging from 10 to 20 million litres (Chanje, 1999). The plant uses sugarcane molasses from the neighbouring Dwangwa sugar factory as feedstock. Since irrigation water is available from Lake Malawi, production was not susceptible to climate-induced interruptions such as that which affected Triangle Ltd. in neighbouring Zimbabwe (ESMAP, 2005).

However, the company has faced difficulties in reliable supply of feedstock (molasses). ETHCO is owned separately from the adjacent Dwangwa sugar factory, resulting in the need for price negotiations and creating uncertainties (Chanje, 1999). This factor along with spare plant capacity and the desire to maintain blending targets, prompted ETHCO to secure additional sugarcane molasses supply (as much as 40%) from the Sucoma sugar factory, located several hundred kilometres to the south. Ironically, use of diesel trucks to transport molasses from Sucoma reduced the otherwise positive environmental and economic benefits of ethanol substitution for gasoline (ESMAP, 2005).

A new distillery was opened in 2004, achieving cost savings by avoiding molasses shipment. However, the new plant was also encouraged by the Department of Energy for energy security reasons and to facilitate the broader reach of the ethanol market nationally (GoM, 2004). The new factory has been upgraded with modern molecular sieve technology for dehydration, which is also planned for the ETHCO plant. Although it has higher upfront capital cost compared to the traditional azeotropic distillation process, the molecular sieve technology prevents chemicals from coming into contact with the ethanol, improving the company's market prospects for potable ethanol due to high purity standards (Leal, 2012; CARD, 2012). Molecular sieves also have better energy economy and have the additional advantage of achieving higher dehydration levels, resulting in extra dry ethanol (99.95% purity) that is more suitable for fuel blending (Leal, 2012).

3.2.2. *Ethanol fuel blending in Malawi*

Public–private partnerships and market coordination (for blending, distribution, transportation, etc.) facilitated the implementation of the Malawi programme, and in fact there was no mandatory blend during the first two decades. In order to create an incentive for oil companies and fuel distributors, the price of ethanol has always been pegged slightly lower than the cost of imported gasoline (GoM, 2009). As a result, there has been a changing gap between fuel ethanol price and production cost, enabling profits to be made depending on oil prices and ethanol blending volumes. In the early years (before 1986 oil price collapse) high blends above 20% were sometimes used, and there were some performance and reliability issues with older vehicles (Chanje, 1999).

The oil price collapse in 1986 and the lower oil prices of the 1990s led to market adjustments. The ethanol producer (ETHCO) entered the other end-use markets for ethanol, namely industrial, pharmaceutical and potable ethanol. These markets obtain higher prices than fuel ethanol and offer a means of diversification in final products. With growing demand and decreased supply due to the competing markets for ethanol, the level of blending decreased in the ensuing years, averaging closer to 10% rather than 20% (Chanje, 1999). ETHCO had actually exhibited a clear preference to discontinue the blending programme due to low profitability, but was pressured by the government to maintain the commitment with the rationale of energy security (CARD, 2012).

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A number of changes ensued with the higher oil prices of the 2000s. The available domestic supply expanded with the opening of the second distillery in 2004. At the same time, health and environmental concerns began to enter the rationale. Unleaded fuel was introduced in Malawi and thus ethanol gained a new role in replacing lead as an anti-knock agent. A mandatory minimum blend of 10% was introduced through legislation enacted in 2004 (GoM, 2004). Regulations to enforce the required blend were finally implemented in 2008–2009 by the Malawi Energy Regulatory Agency (MERA, 2009). The energy security issue seems omnipresent in the form of highly disruptive physical shortages as well as financial constraints; the first author of this paper observed long queues at filling stations during a visit to Malawi in October 2012, with some stations completely out of petrol and diesel. The economic and political pressure to expand ethanol blending has led to renewed government commitments to do so (Johnson and Jumbe, 2013).

In recent years, the political approach to biofuels has matured significantly. A Stakeholders workshop was held in November 2008 and a Biofuels Advisory Council was created (Wambua, 2011). A non-profit organisation, the Biofuels Association of Malawi, was formed in 2009, with an initial focus on oil-based crops for biodiesel, particularly jatropha. The emphasis is understandable since the ethanol industry is well-established and operates at a larger scale; however, there could be benefits for small sugarcane growers (CARD, 2012). Technical standards have been developed for ethanol and biodiesel through the Malawi Bureau of Standards, which is funded through fuel levies on energy products (MERA, 2009). The technical standards will improve reliability in domestic markets, facilitate trade and help to set standards elsewhere in Africa.

3.2.3. Multiple products and applications

An innovative technical feature of the first distillery was the integrated design, which included facilities for multiple processes and products. Stillage waste (vinasse) from ethanol production was to be turned into biogas, using an anaerobic digester funded by the Dutch government. At the time, biogas from vinasse was not a well-proven technology in comparison to the well-known procedures for running an ethanol distillery. A lack of training and standardised operations resulted in the biogas plant being shut down without ever having operated for more than a few days at a time (Chanje, 1999). Interestingly, the same type of project is now being investigated as a CDM project in Malawi and other countries; significant emissions savings are possible by producing biogas and avoiding open discharge ponds that release methane (Khatiwada and Silveira, 2011).

Another by-product is the provision to farmers of fertilisers derived from the vinasse effluent from ethanol distilleries. The vinasse continues to present a disposal problem, as its volume is quite large, more than ten times the amount of ethanol produced; in the past, it was often simply dumped on nearby (dirt) roads as a type of inexpensive paving material (Cornland et al., 2001). The development of the fertiliser programme has helped with the disposal problem while also providing a value-added product to nearby small farmers (ETHCO, 2010).

An alternative application that has recently been explored is the use of ethanol for cooking. Malawi has experienced an accelerating rate of deforestation, which is exacerbated by the high population density and the 95% of households that rely on wood and charcoal (GoM, 2009). Tests have been conducted on several stove designs, with good results in terms of performance (Robinson, 2006). However, there seems to be resistance on a social and cultural basis to cook without wood or charcoal. This significant socio-cultural component provides an illustration of the potential value of taking a socio-technical perspective in efforts to stimulate innovations in this market segment.

3.3. Multiple paths to alternative fuels: the case of Sweden

The story of alternative fuels in Sweden began in earnest after the first oil crisis in 1973, at which time Sweden had become heavily dependent on imported oil, not only for transport, but also for industrial cogeneration, petrochemicals, power generation and household heating. In fact, only about 20% of oil was used in the transport sector whereas today it is the opposite, with more than 80% of oil being used for transport (SEA, 2011). The development of alternative fuels has undertaken a rather winding road since that time, first emphasising methanol, and later focusing on biogas, ethanol

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and electric vehicles in varying proportions. In this section, we consider the significance of some key elements of the programmes and relevant policies.

3.3.1. From methanol to ethanol

The Swedish alternative fuels programme in the 1970s emphasised methanol, based on the recommendations of a working group that created Svensk Metanolutveckling AB (SMAB), which was owned in part by Volvo and the government. Methanol received more than 75% of research and development funding for alternative fuels in the ensuing years, while SMAB was later reconstructed as a technical consulting group (Sandén and Jonasson, 2005). During the following decade, various implementation schemes were considered for blending methanol (M15 and M20) as well as M100 in fleet vehicles. Support for methanol waned due to the lack of economically viable domestic production along with the oil price collapse of 1986.

Ethanol as a fuel was promoted by farmers and their interest groups in the late 1970s, and new connections developed with agro-industrial players in Sweden and abroad. A new fermentation technology (Biostil) was developed by the Swedish company Alfa Laval, who participated in a demonstration project (Sandén and Jonasson, 2005). The political sentiment against nuclear power in Sweden benefitted biomass R&D in both the heat and power and transport sectors. Ethanol was allocated more than one-third of alternative fuel R&D during 1993–1997 while biogas received a somewhat greater share.

In the initial years when methanol was favoured, the fossil fuel route was envisioned while research on gasification of wood and peat was expected to eventually provide renewable feedstocks. The lack of progress on methanol contributed to the ideas for producing ethanol from wheat, with the idea of later switching to cellulosic ethanol production. Farmers and their allies were successful in bringing the wheat ethanol programme to the fore, and a pilot plant run by Agroetanol AB opened in 2001 using a special tax exemption that was eventually approved at EU level (Sandebring, 2004).

There has long been an assumption in Swedish energy/transport policy that lignocellulosic conversion was necessary for the long-term viability of an ethanol fuel market. Strong domestic political support along with interest from the EU research directorate and international investors contributed to the inauguration of a pilot plant in Örnsköldsvik in 2004 and detailed studies such as the NILE project (NILE, 2010). However, the pilot plant has closed due to completion of the pilot testing phase and lack of sufficient funds for a commercial-scale plant (SEKAB, 2011).

3.3.2. Fleet vehicles and market development

Starting in the 1980s, a research, development and testing programme was initiated under which bus engines were re-designed to run on ethanol by SCANIA. The first ethanol bus was introduced in 1985 and by 1996 there were 300 ethanol buses operating in Sweden, covering about 6% of the total fleet. By 2010, there were over 600 ethanol buses in Sweden, including 400 in Stockholm (Miljöförvaltningen, 2010). The third generation design of SCANIA ethanol buses has been introduced in recent years, for which GHG savings have been estimated at 90% (SCANIA, 2010). There are also a number of trucks running on ethanol in modified engines. These large-scale demonstrations with fleet vehicles served to promote and spread experience with the new fuel among customers, distributors and other actors across a number of regions and municipalities.

For the passenger car market, the classic chicken and egg problem arises: no one will buy the cars unless there are filling stations to provide the new fuels, but fuel distributors cannot justify the additional cost with so few customers. Cooperation between the oil distributor OKQ8 and the Swedish Ethanol Fuel Foundation (SSEU) addressed the issue in the early 1990s. A number of filling stations were established as demonstration sites and flex-fuel vehicles (FFVs) were imported from the USA for pilot testing. In 1996, OKQ8 and SSEU joined an environmental train tour around Sweden, which was organised by the Natural Step Foundation, offering a challenge to local authorities and companies: OKQ8 would put up an ethanol filling station if they would purchase at least ten FFVs (Sandén and Jonasson, 2005). A little over a year later, there were 30 pumps and 300 FFVs in various locations around the country. Municipal procurement programmes in the ensuing years together with tax incentives resulted in purchases of several thousand FFVs by 2004–2005. The most active among municipal players is Stockholm city, which launched its Clean Vehicles Programme in 1994; by 2009, 40% of newly registered vehicles met the environmental standards and more than half of these were ethanol FFVs (Miljöförvaltningen, 2010).

3.3.3. Multiple pathways and local initiatives

Although the initial phase emphasised one option (methanol) and a second phase embraced ethanol, later phases embraced multiple options to avoid closing off pathways needing time to mature (Sandén and Jonasson, 2005). Ethanol first entered the picture through a repositioning, in which it was lumped together with methanol as "alcohol fuels": legislation and policy were developed through the Motor Alcohol Committee (MAC, 1986). This shift signalled a transition phase away from the single pathway approach. Along the same lines, the SSEU was renamed the Bioalcohol Fuels Foundation (BAFF). Use of the term "alcohol fuels" also illustrates how social discourse affects technical adoption: the inclusion of ethanol already in the early 1980s (when methanol was the sole priority) gave it a foot in the door that its supporters could later build on (Ulmanen et al., 2009).

Biogas and hybrid/electric vehicles started to enter the picture in the late 1980s. The rise of biogas illustrates how multiple factors must intersect to overcome the network externalities of competitors (i.e. biogas requires separate infrastructure). One was the link to compressed natural gas in vehicles coupled with plans for natural gas imports. Another factor was increasing interest from municipalities in alternative fuels as a way to reduce air pollution and improve waste disposal (Sandén and Jonasson, 2005). Yet another factor was that the number of actors involved was relatively small with the focus on bus fleets and since local wastes were controlled by municipalities. Biogas offered a quadruple win that made it politically popular: waste disposal, reduction of local air pollutants, replacing non-renewable imported fuels and GHG reduction.

The development of multiple pathways benefited from regional diversity in combination with the active role of municipalities and national investment. Availability of natural gas in western Sweden facilitated introduction of compressed natural gas buses—and by extension—biogas buses. The Local Investment Programme established in 1998 provided 250 million SEK to municipalities for clean energy and transport projects (Rehnlund et al., 2004). The environmental vehicles (mijöfordon) programme established in 2006 provided tax exemptions and incentives (such as free parking) for "environmental cars." Efficient and/or smaller diesel vehicles were included in the definition, which drew criticism from environmental groups (Gröna Bilister, 2012).

3.3.4. A biofuels market leader

After Sweden joined the EU in 1995, its alternative fuels market had to be harmonised with EU policies, which affected the eligibility of financial incentives and initially constrained Swedish biofuels development. EU payments for agricultural surpluses reduced the incentives for domestic production, while at the same time the tax exemption for the wheat-ethanol plant had to be negotiated with the EU (Sandebring, 2004). Initial advantages for Sweden were few, due to stable oil prices in the late 1990s and the EU funding focus on biomass for heat and power rather than transport. At the same time, the European-wide social networking and funding that comes with EU membership enhanced the stature of the Swedish programme considerably. Stockholm city's Clean Vehicles initiative coordinator, Gustav Landahl, noted that his agency's expanded role came about "almost by chance" due to a meeting in Brussels that led to the groundbreaking ZEUS project (Zero and Low Vehicle Emissions in Urban Society) in 1996 (Miljöförvaltningen, 2010).

As EU renewable energy policies began to emerge, Sweden's early efforts began to pay off: it was one of just two countries to meet the Biofuels Directive target of 2% in 2005 (EC, 2011). The number of FFVs and ethanol fuelling stations increased rapidly between 2002 and 2005, even though the EU targets were voluntary (Nykvist and Whitmarsh, 2008). Sweden was also involved in many EU-funded alternative transport programmes; it was well-poised to play a leading role since so many Swedish actors had acquired experience not only in RD&D side, but also with implementation and policy aspects—which were relatively unexplored in other EU member states. The city of Stockholm provided a leadership role in the global diffusion of ethanol vehicles through the EU-funded BEST project during 2006–2009, involving the expansion of vehicles and infrastructure in 8 cities in Europe, China and Brazil (BEST, 2011).

When biofuels returned to global agendas with a vengeance in 2007–2008, Sweden was well-poised to integrate its programme with the EU agenda and take a leadership role, in spite of its modest size among EU Member States. Sweden gained headlines in 2006 when its “Commission on oil dependency” (Kommissionen mot oljeberoendet) stated the goal of being oil-independent by 2020, although the goal was not fully clarified (Regeringskansliet, 2006; Chen and Johnson, 2008). Sweden has already met the 2020 EU-RED requirement of 10% renewable energy in transport, although this is due to double-counting provisions in the EU-RED for biofuels made from wastes (EC, 2009). Analysis suggests that rather stringent measures on both the supply and demand side would be required to achieve total oil import independence, with (second generation) ethanol playing a significant role (Lindfeldt et al., 2010).

3.4. Comparison

In spite of the significant differences in resource endowments, there are many similarities in the transition pathways and the respective roles of the three countries as pioneers or market leaders. A breakdown of key characteristics and examples is summarised in Table 1; the early phase corresponds roughly to the late 1970s and most of the 1980s, whereas the later phase refers mainly to the period starting in the late 1990s. The era of low and/or stable oil prices of the late 1980s until the late 1990s might be considered as a middle era when change was slower and thus is not included in the table. The “landscape” factors related to international trade are quite different in the three cases: whereas Brazil has global market power in resources (sugarcane), end-use products (ethanol) and end-use devices (vehicles), Sweden has much less market influence and Malawi as an LDC has very little. However, Sweden and Malawi do have some influence with respect to regional policies. The goal of energy security was common across all three countries and still remains prominent, while Sweden as a major environmental actor has since emphasised climate change and “oil independence.” New actors entered in the later phases in all cases, and the comparison is interesting between Brazil and Malawi, which both became more democratic; farmers, civil society and other groups gained a greater voice. Financial incentives have been applied to vehicles in Brazil and Sweden, and to fuels in all three, while various types of R&D support have been important in Brazil and Sweden. As a direct result of the ethanol programme, Brazil has introduced advanced methods in the agricultural sector such as agro-ecological zoning that have wide applicability (Strappason et al., 2012) whereas agricultural spin-offs have been more limited in the case of Malawi and Sweden.

On the industrial and infrastructure side of the equation, there are some clear differences. Fuel blending was practiced in Malawi without a mandate, whereas Brazil implemented fuel blending through regulatory requirements and Sweden later followed EU targets. Brazil with its large market initially aimed for ethanol-only vehicles, which eventually set the stage for flex-fuel vehicles (FFVs) (Yu et al., 2010). The market for FFVs was incentivised through the environmental vehicles programme in Sweden, while Malawi has only begun to experiment with FFVs. A key difference in terms of competing options is that Sweden promoted clean vehicles, regardless of fuel, whereas Brazil and Malawi focused only on ethanol. Unlike the EU market, in Brazil biodiesel is aimed mainly at heavy duty vehicles (e.g. trucks, buses) since diesel cars are uncommon. The dynamics behind these differences and similarities are analysed further in the Discussion section below.

4. Discussion

In this section, we draw on the three case studies to identify five dynamics or lessons that are relevant to the nature and/or significance of the innovations achieved in the alternative fuels transition: niche development, variety creation and compatibility, social/organisational network evolution, cross-scale and cross-sector effects and the duration and timing of the transition. Reference is made to experiences in each of the three countries in relation to key elements from the conceptual framework (given in bold) as summarised in Table 2.

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Table 1
Comparison of key characteristics of ethanol and alternative transport fuels programmes/policies in Brazil, Malawi and Sweden.

Phase	Brazil		Malawi		Sweden	
	Early	Later	Early	Later	Early	Later
Motivation and drivers	• Foreign exchange • Energy security	• Economic Development • Environmental Sustainability	• Foreign exchange • Energy security	• Energy access • Low-carbon development	• Oil prices • Energy security • Air quality	• Climate change • Oil in dependence
Key actors	• State Oil company • Sugar companies	• Automobile manufacturers • Engine designers • Farmers' Unions • NGOs	• Oil distributors • Sugar companies • Distillery owners	• Local officials • Village heads	• National agencies • Engine designers • Researchers	• Regional agencies • Research groups • Consultants • Farmer groups
Financial and regulatory incentives	• R&D support • Producer subsidies • Vehicle subsidies • Mandated blend	• Agricultural R&D • Mandated blend	• Lower Price for ethanol • Tax reductions	• R&D support • Blend depots • Fuel levies to develop standards • Mandated blend	• R&D support • Energy taxes	• Carbon tax • Environmental vehicles incentives • EU targets
Agricultural and resource development	• Specialised varieties of sugarcane • Cassava experiments	• Agro-ecological zoning • Mechanised harvesting	• Use of surplus molasses	• Provision of fertilisers	• Use of black liquor/cellulosic feedstock	• Ethanol from wheat and wood • Multi-product systems
Technical/vehicle innovations	• Engine modification • Neat ethanol vehicles	• Flex-fuel vehicles	• Experiments with different blends • Engine modification	• Testing flex-fuel vehicles • Technical standards	• Ethanol-adapted bus engine • Truck engines	• Adoption and import of flex-fuel vehicles • New ethanol bus engine
Innovation in production, end-use or delivery	• Continuous fermentation	• Recycling of water, yeasts • Molecular sieves	• Integrated biorefinery complex	• Molecular sieves • Ethanol for cookstoves	• Trade and product distribution systems	• Pilot plant for lignocellulosic ethanol
Infrastructure changes	• Ethanol storage • Filling stations	• Adapt pipelines to ethanol • Port facilities for export	• Blending depots	• Multiple distilleries and transport systems	• Fleet vehicles • Filling stations	• Regional expansion • Construction of biorefineries
Associated or complementary products/markets	• Sugar • Use of by-products	• Bagasse cogeneration • Bio-plastics	• Biogas production • Carbonation	• Potable ethanol • Industrial ethanol • Cooking	• Pulp and paper	• Animal feeds • Chemicals
Competing or supplementary options	• Pure ethanol engines • Fleet vehicles	• Biodiesel programme • Bagasse cogeneration	• Alternative uses for molasses	• Jatropha growing • Diesel and paraffin replacement	• Methanol • Biogas	• Electric vehicles • Hydrogen • Biogas • Diesel

Table 2
Key dynamics regarding ethanol and alternative transport fuels programmes/policies in Brazil, Malawi and Sweden.

Key dynamics	Brazil	Malawi	Sweden
Niche development	• Early ethanol vehicle niche **competes** with dominant fossil **regime**. • Government procurement of ethanol vehicles **shaped expectations** for growing market • Introduction of FFVs allows **co-existence** with dominant **regime**	• Market too small for fuel-vehicle niches; technical production niches allowed economic/product **complementarity**. • **Network** of public and private actors was initiated. • Malawi's role as a regional **market leader** encouraged pilots for FFVs.	• Climate complications **reduced confidence** in ethanol-only cars. • **Spatial dependence** exhibited by fleet vehicle approach, due to energy security concerns in urban areas. • FFVs allowed **social learning** promoted by Stockholm city.
Variety creation and compatibility	• Authoritarian political **landscape** facilitates focus on ethanol only. • After democratisation, **landscape** pressures for social compatibility of biofuels • Infrastructure compatibility with **dominant regime** facilitated through state oil company	• Authoritarian political **Landscape** facilitates focus on ethanol only. • After democratisation, new biofuels options emerge • **Spatial** compactness and low demand ease infrastructure changes in the transition	• Multiple options avoid **lock-in** but slow down overall transition. • **Spatial differentiation** emerged as different fuels emphasised in Stockholm vs. western Sweden • Technology neutrality benefits **dominant regime** (via "clean" diesel vehicles).
Social/organisational network evolution	• Negotiation with auto companies promoted **co-existence**. • **Landscape** factors (energy security) placed pressure on state oil company. • **Purposive** nature of transition led to **social learning** as private sector took over from government and Brazil emerged as world **market leader**. • **Spatial effects** in alliances between private sector actors.	• **Spatial** factor (landlocked area) created **landscape** pressures on auto and oil industry actors (economic + energy security). • Regional exposure due to Malawi's role as a regional **market leader**. • Private sector actors engaged by policymakers through establishment of an alternative energy-transport **regime.**	• Local governments created **landscape** pressures on auto and oil companies. • Alternative **regime** energised agricultural sector. • Alliances cultivated between municipalities, fuel distributors, automakers via **social learning**. • **Market leader** role allows strong EU engagement and leadership. • **Reverse salients** as **social learning** creates opposition.
Cross-scale and cross-sector effects	• Shifting locus of sugarcane **regime** to São Paulo created **spatial dichotomy** in national development policies. • Sugar/ethanol market **spatial dependency** led to deregulatory pressure, setting stage for long-term ethanol market stability. • Investment in agro-industry co-products development facilitated by **market leader** status.	• Regional African efforts draw on Malawi **pioneering** experiences. • Technological innovation was stimulated for co-products due to **spatial** linkages. • Private sector develops non-fuel ethanol markets, placing pressure on fuel ethanol **regime**. • Return of **landscape** pressures (energy security) leads to formal government blending regulations.	• Local energy/transport **regime actors** pushed national government to take more action. • Swedish **pioneering** role led to actions at EU level. • New agricultural products (e.g. animal feed) led to stronger **spatial** market synergies. • Growing EU diesel car market negatively affected ethanol focus after Sweden joined EU.

Table 2 (*Continued*)

Key dynamics	Brazil	Malawi	Sweden
Timing and duration	• Private sector took over after democratisation, when ethanol regime threatened by new **landscape** pressures. • **Landscape** factors (low oil prices) challenged early success. • Timing for ethanol vehicle introduction during period of economic growth facilitated successful **path creation**. • Current **dual regime** is stable, contingent on **landscape** factors (mainly sugar and oil prices).	• Even after democratisation, strong government role needed to maintain blending due to private sector's alternative **niche** markets. • **Landscape** factors (low oil prices) challenged early successes. • Timing at stage of low auto use and early economic development level simplified **path creation**. • Structural factors push expansion but **spatial factors** contribute to lack of internal market competition.	• Early **Niche** experiments led to eventual role as **market leader**. • Mature level of car ownership and high reliability of public transit complicated **path creation** for alternative fuels. • Deliberative and inclusive nature of Swedish political **landscape** slowed down transition. • Future of ethanol **regime** now unclear due to **reverse salients** in EU market due to fuel/food and climate concerns.

Note: Keywords related to the conceptual framework are given in bold.

4.1. Niche development

Technological niches are distinct from market niches, as the latter tend to be aimed at extracting price premiums rather than achieving market transformations. However, this distinction becomes blurred in the case of alternative fuels, since the relevant focus is on the fuel-vehicle system. Furthermore, innovation in one or even two of the key sectors (agriculture, energy, transport) does not guarantee that the fuel-vehicle system will evolve in the same direction. Hence niche development is connected to the notion of innovation in implementation and deployment (Section 2.3). Brazil and Sweden actively promoted various fuel-vehicle niches, while Malawi's small market constrained use of fuel-vehicle niches, although fuel production niches were pursued in upgrading factories to allow multiple products (Section 3.2.1). Three types of niches are especially relevant for ethanol and/or alternative fuel-vehicle systems: dedicated vehicles/markets, fleet applications, and hybrid/flexible engines.

Dedicated ethanol vehicles (E100 or E85) build the market more quickly and can take advantage of the higher compression (octane) obtained using ethanol. In Brazil, the government's promotion of ethanol vehicles was initially aimed at replacing all gasoline consumption. The eventual failure of ethanol-only vehicles was due to landscape pressures in the form of low oil prices and ineffective policy coordination after democratisation (Hira and de Oliveira, 2009). The use of E85 in earlier FFVs in Sweden was promoted using U.S. FFV imports, but this niche market did not develop significantly and the key actors shifted the focus to heavy-duty vehicles. For passenger cars, technical complications in colder climates required a supplementary gasoline tank and complicated the ethanol-only engines in Sweden and even in some colder areas of Brazil (Moreira and Goldemberg, 1999).

Fleet applications allow technical and market experimentation, while avoiding the negative publicity that can occur in the general market. Fleet applications also help in determining which actors are prepared to champion the new fuel/vehicle and push for further adoption. In Brazil, ethanol-only vehicles were included in government fleet procurements. Public vehicle fleets are too small in Malawi but experimentation is underway (Wambua, 2011). In Sweden, fleet applications were based on ethanol engines for heavy duty vehicles (buses and trucks) that were promoted for energy security reasons—to insure that buses and trucks could run in the event of a shortage (MAC, 1986). This type of niche derives from Northern European style urban planning, which relies heavily on mass transit. Surprisingly, despite wide use of buses in urban areas and for regional traffic in Brazil, introduction of ethanol engines in Brazilian bus fleets was only considered much later (BEST, 2011).

Flexible fuel vehicles (FFVs) have clearly been the game-changer, particularly in Brazil and Sweden where the end-use infrastructure was well-developed. By allowing any mixture of ethanol and gasoline, consumer confidence was enhanced while also facilitating a more seamless infrastructure transition from gasoline to ethanol. The FFVs thereby "unhitched" the ethanol market somewhat from political decisions and "hitched" it more closely to international markets, especially sugar and oil prices. In Brazil, the transition was even more rapid than expected, with over 90% of vehicle sales now FFVs. In Sweden, the market response has been reasonably good, but the government policy of technology neutrality in classifying vehicles as "environmental" has ironically shifted the majority market share (as of 2011) to fossil diesel cars (Gröna Bilister, 2012). Malawi has been experimenting with FFVs since 2007 on a pilot basis (ETHCO, 2010).

4.2. Variety creation and compatibility

As discussed in Section 2.1, attempts to consciously stimulate new fuels/vehicles must invariably contend with the question of whether an inferior option might be prematurely adopted as the front runner, gain market share and eventually become entrenched or locked in. A related issue is how to insure compatibility with long-term transport infrastructures that are envisioned as desirable or likely, such as hydrogen infrastructure and fuel cell vehicles. Such issues entered the debate in Sweden at an early stage, as is fitting for a social democracy that emphasises bringing all sides to the table. The mix of options that received funding and support included not only the various biofuels (methanol, ethanol, biogas, RME and others) but also electric and fuel cell vehicles along with hybrid options of various types. Compatibility with a future hydrogen economy also became a selling point in the debates among interest groups in the 1990s (Sandén and Jonasson, 2005; Jönsson, 2006). The end result was the creation of a variety of options as the basis for experimentation and learning.

In stark contrast to Sweden, the developments in Brazil and Malawi resulted in rapid convergence on ethanol. Both Brazil and Malawi had authoritarian governments at the time they started their programmes; there was little democratic political pressure to engage in wide consultations or create linkages with civil society groups. Brazil and Malawi were thus able to fairly quickly replace 5–25% of gasoline with ethanol, whereas it took Sweden more than thirty years to reach a 5% share for ALL alternative fuels. The quick start in Brazil had a strong economic rationale due to the well-established sugar industry, but it was clearly not sufficient to guarantee success, which came only after the more coherent Brazilian programme of the 1990s by which time democratic rule was well-established. A more inclusive biofuels programme with extensive stakeholder involvement has now been established in both Brazil and Malawi, especially in their socially oriented biodiesel programmes (Hall et al., 2009; Wambua, 2011). The political popularity of the Malawian ethanol programme led to consistent support from the government, as championed through the Malawian Department of Energy (Mhango, 2011).

In Sweden, the market structure and consumer response reveals greater risk aversion to ethanol as a long-term solution compared to Brazil, with consumers exhibiting greater price sensitivity (Pacini and Silveira, 2011). At the macro-level, Sweden as a rich country seems to more easily absorb higher oil prices: the Swedish experimentation with different alternative fuels revealed mush less sense of urgency compared to Brazil and Malawi. The Swedish approach is a hybrid—seeking compatibility through an emphasis on alcohol fuels, but maintaining variety creation through investment in biogas, electric vehicles and hydrogen/fuel cells. However recent incentives, such as "green vehicle" premiums/rebates, favoured options that are compatible with existing infrastructure: diesel and flex-fuel vehicles have overwhelmingly dominated sales under these premiums (Gröna Bilister, 2012). Partly in response to criticism over the fact that "clean" diesel vehicles received 60% of "environmental" rebates in 2011, the government allocated 200 million SEK for so-called "super eco-car premiums" starting in 2012 to vehicles emitting less than 50 g CO_2/km (Regeringskansliet, 2011).

The infrastructure issue in Malawi illustrates one advantage of being at an earlier stage of development. There are relatively few personal vehicles and relatively few filling stations. Only a small number of blending depots were required, in which gasoline and ethanol are blended before arriving at the filling stations all over the country (ETHCO, 2010). The blending approach used in Malawi served as a demonstration for other countries in southern Africa (Johnson and Matsika, 2006).

Infrastructure compatibility in Brazil represented a considerable challenge, considering the vast size and diversity of the country. Early involvement of the state oil company Petrobras guaranteed proper fuel distribution while agreements with automobile manufacturers helped establish a rapid pace for the transition (Cordonnier, 2008). The government's heavy hand and the oil price issue resulted in little political opposition. Again it is interesting to contrast the case of an authoritarian regime with a social democratic regime (Sweden). The infrastructure changes needed in Sweden had to be carefully coordinated from the ground up, such as by convincing municipalities to offer incentives or by alliances between fuel distributors and supporters.

4.3. Network evolution

A key aspect in the evolution of actor networks is found in the changing role of the big industrial players—oil and automobile industries—within a modified energy/transport regime that puts their product or market at risk. Brazilian government pressure placed on oil and auto companies resulted in a "purposive" transition in which the authoritarian regime wielded political power that would be impossible today (Lehtonen, 2011). Such pressure could also be coordinated with state-owned Petrobras to provide infrastructure. Negotiations with the government pushed the automobile manufacturers' towards ethanol-only vehicles, and demand was created through public procurement (Cordonnier, 2008). The traditional reluctance of oil companies has re-emerged in recent years, while non-profit organisations expressed concern about the impacts of biofuels on food security, again illustrating problem sequences in the innovation process (discussed in Section 2.1) due to "reverse salients" (Gee and McMeekin, 2011; Hughes, 1983). Some of these actors specifically aimed to discredit the perceived sustainability of the new path (ethanol) and destabilise its supporting networks (Pilgrim and Harvey, 2010; Garud et al., 2010).

In the case of Malawi, the government had limited market power and could offer oil distributors additional margins by increasing the blend (Chanje, 1999). The persistent high cost of ethanol in Malawi is due in part to the difficulty of stimulating competition in a small LDC (Mhango, 2011). In Sweden, the auto manufacturers and oil companies resisted change until a specific opportunity presented itself in the form of the Scania ethanol bus programme. In this case, the most effective pressure on oil and auto companies came not from the national government, but from the municipalities, with some cooperation from oil distributors, based on sustainability strategies in response to Agenda 21 (Sandén and Jonasson, 2005).

Another long term network effect is associated with how new constellations of actors—farmers, NGOs, technical consultants, entrepreneurs and others—became integrated into the overall network and began to exert influence. It is interesting to note which country's alternative fuels programme seemed to be most influenced by farmers—not Malawi or Brazil, where farmers make up a large share of the workforce—but Sweden, where farmers make up an extremely small but politically powerful group. However, the ethanol programme in Brazil contributed to overall agricultural modernisation in São Paulo, and greater political freedom later facilitated wider participation. In both Brazil and Malawi, farmers and NGOs have subsequently influenced the direction of their respective biodiesel programmes (Wambua, 2011; Hall et al., 2009).

The influence of the new networks extends far beyond their own countries: ethanol, sugar and bioenergy consultants from Brazil are in high demand all over the world (Goldemberg et al., 2004). Independent consultants from Sweden have worked extensively abroad, providing a mobile form of institutional memory (Sandén and Jonasson, 2005). The city of Stockholm led a number of EU-financed clean vehicles projects and networking through EU-financed projects became an important element of international alternative fuels programmes (BEST, 2011; Miljöförvaltningen, 2010). Analogous developments are found in Malawi, which has become a regional example for southern African countries (SADC, 2006). The technical expertise in Malawi is highly valued; ethanol companies elsewhere in Africa have tried to recruit Malawian staff (ETHCO, 2012). The Malawian example illustrated that poorer countries can mobilise their own biofuels actor networks and do not need to wait for global agreements or foreign support (Batidzirai and Johnson, 2012). The role of transnational networks is an important area for future transition research as it connects spatial characteristics to niche development and transition pathways (Raven et al., 2012).

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4.4. Cross-level and cross-sector linkages

The technological and market niches that developed for alternative fuels—mainly ethanol in the three cases analysed here—are linked to developments at regime or sector level (especially energy, transport, agriculture) as well as to global markets and institutions. The relation to agriculture, rural development and climate adds dimensions that were previously missing in the fossil-based energy/transport regimes of the post-WWII oil economy. Consequently, new actors have emerged in developed and developing countries alike and are increasingly crossing the boundaries from local to national to global. These new actors have influenced the international debate, which has in turn enabled them to enhance their public visibility (Pilgrim and Harvey, 2010).

In all three countries, high oil prices and the political instability of oil-exporting countries were key elements at landscape/policy level in the early years. The Brazilian programme suffered a severe setback with the low oil prices of the late 1980s, while the Malawi programme was scaled back from 20% to 10% blending. The small Malawian market meant that private sector producers had to find alternatives, which they did, through the potable and industrial ethanol markets. The influence of the Malawian Department of Energy thus became important in maintaining the blending commitment amidst such internally competing markets in combination with lower oil prices (CARD, 2012; Mhango, 2011). Sweden's leadership role on environmental issues allowed other concerns to enter the policy void created by low oil prices: air quality and later climate change became major driving forces. Nevertheless, lower oil prices affected the pace of alternative fuels development, since other measures could address air quality, such as end-of-pipe controls and fuel quality adjustments (Sandén and Jonasson, 2005).

The relation to the agricultural regime clearly went through a transformation in all three countries. Agricultural actors gained influence in Sweden and Malawi through the technical and market niches established for ethanol, but also due to the wider recognition that domestic biomass resources had an important role in future energy shifts. The purposeful shifting of the agro-industrial sugar complex in Brazil to São Paulo from the Northeast was aimed at achieving a radical re-organisation of the industry into a sugar–ethanol complex (Compeán and Polenske, 2011; Furtado et al., 2011). This shift was politically significant enough that it led to new policies to address fundamental economic inequities in the two regions (Lehtonen, 2011; Compeán and Polenske, 2011; Furtado et al., 2011). The oligopolistic sugar–ethanol regime centred in São Paulo also created political pressures to take a more socially conscious route in designing the Brazilian biodiesel programme (Hall et al., 2009).

Cross-sector linkages also enter through the existence of multiple (energy and non-energy) co-products, thus exploiting *economies of scope* as well as *economies of scale*. Experimentation with different combinations of sugar cane juice and molasses allowed technical-economic optimisation between sugar and ethanol outputs (Macedo, 2005). At the same time, these physical linkages came into play with the price liberalisation of the 1990s: ethanol suppliers could decrease production in response to relative price changes, i.e. by diverting potential ethanol feedstock into sugar production. Consequently, the economic flexibility that helped build up the programme in the 1980s became a liability in the 1990s when shortfalls resulted in significant ethanol imports and the government opted not to intervene (Hira and de Oliveira, 2009).

Other important co-products include cogeneration, animal feeds and fertilisers. Even when co-products do not initially result in new markets, they can leverage financing, reduce environmental burdens and cultivate local benefits. Bagasse cogeneration in Brazil offers a co-benefit that is well-represented among CDM projects (UNEP/Risoe, 2011). Co-products can provide value even if they are never formally commercialised: in Malawi, the provision of fertilisers to local farmers at no cost brings good will towards the private sector (ETHCO, 2010). In Sweden, animal feeds are a co-product from wheat ethanol production, and serve to offset the environmental/climate burden of imported soya, thereby reducing GHG emissions (Börjesson, 2009). Other non-energy co-products can offer additional economic incentives to producers: examples include the provision of carbonation for soft drinks in Malawi's distilleries (Chanje, 1999) or the production of bioplastics from sugarcane by-products in Brazil (Leal, 2012). These co-products provide stabilising factors for the ethanol regime through economic flexibility while also creating new actor networks that gain an interest in the success of the new regime.

4.5. Duration and timing of transitions

Sweden has been engaged in this path as long as Brazil, but has achieved only 8% replacement of oil in transport, compared to more than 25% in Brazil (or more than 50% if only gasoline is counted) and 10–20% in Malawi. Although Sweden has been a leader in this area, early efforts focused on research whereas implementation was not well-addressed until the late 1980s. The deliberative nature of Swedish social democracy and later, accommodation to the EU agenda, may have drawn out the transition process. The timing of policy changes in relation to the phase of economic development is important: the emergence of a middle class in Brazil brought a tremendous increase in personal automobile ownership and provided the engine of growth to support the expanding market niche for ethanol in the 1970s (Lehtonen, 2011). The authoritarian regimes in Malawi and Brazil at their respective stages of development could kick-start their ethanol programmes in a manner that is not possible in Europe, due to political plurality as well as economic maturity. It can also be observed that even in a wealthy and environmentally advanced country like Sweden, the more “radical” and costlier supply—side innovations such as electric vehicles and fuel cell vehicles have been marginalised to those that fit better with the fossil fuel regime—biofuels and biogas (Nyqvist and Whitmarsh, 2008). An interesting question for future research is thus whether radical innovation in energy/transport transitions is less feasible in mature economies.

Consequently, the dominant energy/transport regime remains fairly intact in all three countries. Indeed, the key economic-political advantage of ethanol is the capacity to co-evolve alongside minor changes in existing infrastructure and institutions, somewhat analogous to the two-world solutions discussed by Meadowcroft (2009). Thus all three countries have gone down the path of co-existence rather than radical transformation and it can be argued that it was the only feasible path given overwhelming oil dominance and its lock-in effects. However, the Brazilian market is still expanding due to the popularity of FFVs whereas a plateau may have been reached in Sweden and to some extent in Malawi. The weaker political agenda in Sweden is due to greater dependence on EU policies, stable world oil prices and pressing issues such as the financial crisis, which together have prevented “oil independence” from being fully incorporated into energy/transport planning (Lindfeldt et al., 2010; Johnson, 2011).

Although Sweden placed special emphasis on ethanol, it is nevertheless a leader in terms of exploring and supporting multiple alternative fuels/vehicles pathways. However, since it started its transition at a much more advanced stage of development, the economic urgency was lower compared to Brazil and Malawi. Furthermore, biofuels in Sweden—as well as in the EU and some other OECD countries—has entered a state of limbo, contingent on advances in the commercial feasibility of second generation ethanol, which would undoubtedly lead to more enthusiasm from industrial actors. The lack of competitive domestic ethanol production has in some respects become an Achilles heel in the Swedish programme. Policy leadership grounded in improved competitiveness is important for the next wave of biofuels expansion and consequently a deeper analysis on the political economy of past and future trajectories poses a useful topic for future research.

It is interesting to note the relative independence and strongly national character of the trajectories in the three countries, which originated in the energy security reasoning of the 1970s. Market developments and actor networks have become less isolated since that time, due to increasing globalisation and also the increasingly transnational character of the actor networks (as discussed in Section 4.3). It should nevertheless be recognised that in spite of globalisation the unique role of *pioneer countries* at early stages of experimentation and market development suggests that national-level policies and programmes remain crucial for the innovation process (Huber, 2008). This is especially true for new fuel-vehicle systems given the omnipresence of energy security concerns.

5. Conclusions

Each of the three countries—Brazil, Malawi and Sweden—can be regarded as a *pioneer* with respect to alternative fuels in their respective regions, and each one ascribed a special role for fuel ethanol, although the Swedish approach was more pluralistic. Developing countries as diverse in size and resources as Brazil and Malawi have moved fairly quickly on the path to alternative fuels, albeit

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focusing on biofuels and strongly kick-starting ethanol, due to their natural resources base and for the sake of compatibility and cost. Sweden and other EU countries—with greater infrastructure and vested interests across many different agricultural, energy and industrial actors—are moving much more slowly. We find little evidence to support expectations of a fast (i.e. one or two decades) transition to alternative transport fuels in the EU, whereas oil-importing developing countries have a better chance due to stronger incentives and lower path dependence. Regardless of the speed of such transitions, these three pioneer countries have demonstrated innovative deployment of niches for fuel-vehicle systems, while also establishing well-functioning actor networks to integrate sector objectives and thereby lay the foundation for a sustainable transport transition regardless of the eventual role of specific fuels and technology platforms.

It is interesting to note that the three market developments were hardly linked to each other at all: each country had a strong national focus grounded mainly in energy security concerns. The public interest rationale was later supplemented with co-benefits, especially air quality, climate mitigation and rural/agricultural development. This period of isolation in the evolution of alternative fuels programmes—and the strong national focus that it engendered—has been waning somewhat in the face of growing international trade and the integration of transport and communication systems. The strong economic influence even of the global market leader (Brazil) is tempered somewhat by influential international actor networks that arose in part due to these three market leaders and those that followed in each region. Consequently the socio-technical dimensions of the transition to alternative fuels have advanced considerably, with each of these countries initiating new hubs for expertise and networking and putting greater pressure on the dominant fossil-based regime.

The spatial linkages in this transition have also become more pronounced over time, revealing a sub-national dichotomy in the largest country (Brazil), geo-political pressures in the northernmost country (Sweden) and facilitating greater geographical breadth in the network of actors in the case of Malawi. Nevertheless, in spite of multi-scalar effects and transnational actor networks, the role of pioneer countries and the associated national-level innovation policies and programmes remain highly significant precisely due to path dependencies in early stages and the complexities of new path creation. Furthermore, the comparison here reveals the strong linkage between alternative transport fuel transitions and overall economic development priorities: such alignment was decisive in all three countries in spite of the wide differences in the levels of economic development.

In all three pioneer countries the interplay of a coordinated network of public and private actors was crucial. In the case of Brazil, although the initial strong framework was established through an authoritarian government that pursued its goals unilaterally, serious landscape pressures led to concerted action by the new network of private actors, which is widely credited with preventing the collapse of the Brazilian ethanol market. Government actors were quite strong in Sweden, especially at local or municipal level, but the ultimate success of the two crucial niche developments—ethanol buses and flex-fuel vehicles—relied on alliances with key private sector actors in vehicle technology development and fuel distribution. In Malawi, fuel and auto companies were brought into the discussion and private actors have managed the sugar/ethanol operations to high international standards, while at the same time an increasingly open dialogue with government has been accompanied by public pressure when needed.

The experiences of the three pioneer countries provides evidence that strong national policies, when accompanied by the nurturing of a broad public–private alliance of actors, can play a decisive role and accomplish alternative fuel transitions at different stages of economic development. Although fuel ethanol is only one element in the complex and multi-faceted transition to sustainable transport and mobility, it is arguably one of the few segments where tangible progress has been made, and thus offers a valuable historical record that can inform the design of energy, transport and mobility policies and programmes.

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