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Title: How Should Barriers to Alternative Fuels and Vehicles be Classified and Potential Policies to Promote Innovative Technologies be Evaluated?

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Abstract: There appears to be increasing policy emphasis globally on developing innovative technologies and promoting incentives to support the take-up of alternative fuels and vehicles (AFVs) among consumers. The primary reason for this is that they potentially offer a pathway to reduce greenhouse gas (GHG) emissions and air pollution in the transport sector, without the need for contentious transport demand management measures such as road pricing or restrictive land use planning. However, despite the fact that AFVs are often seen as a panacea by policy-makers, there are a number of barriers to their widespread market penetration and diffusion. The objective of this paper is to present a framework, which can be modified and used by policy-makers to identify and qualitatively evaluate these barriers as well as potential policies that might be implemented to address these barriers. The paper concludes by assessing the strengths and weaknesses of applying this framework.

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Abstract

There appears to be increasing policy emphasis globally on developing innovative technologies and promoting incentives to support the take-up of alternative fuels and vehicles (AFVs) among consumers. The primary reason for this is that they potentially offer a pathway to reduce greenhouse gas (GHG) emissions and air pollution in the transport sector, without the need for contentious transport demand management measures such as road pricing or restrictive land use planning. However, despite the fact that AFVs are often seen as a panacea by policy-makers, there are a number of barriers to their widespread market penetration and diffusion. The objective of this paper is to present a framework, which can be modified and used by policy-makers to identify and qualitatively evaluate these barriers as well as potential policies that might be implemented to address these barriers. The paper concludes by assessing the strengths and weaknesses of applying this framework.

Key Words: Alternative fuels and vehicles, technological innovation, strategic niche management, learning-by-doing

1. Introduction

The objective of this paper is to present and apply a methodological framework, which can be used to identify and qualitatively evaluate barriers to the wide-scale deployment of alternative fuels and technologies, as well as potential policies and actions that may be implemented to overcome such barriers. This evaluation is used to illustrate how such a methodological framework can be adopted by policy-makers in order to assess and prioritise policy choices. The paper concludes by identifying the strengths and weaknesses of this methodological framework.

Alternative fuels and vehicles (AFVs) are increasingly favoured by policy-makers seeking to reduce greenhouse gas (GHG) emissions and air pollution in the transport sector (Lipman and Delucchi, 2006; Yeh, 2007). This is because they do not seek to reduce transport demand through contentious behavioural change measures such as carbon taxes, road pricing congestion charges or planning restrictions. In addition, they offer the potential for job creation, increased security of supply, for example in the case of domestic biofuel production, and economic growth.

There are a variety of alternative fuels and technological innovations, either currently on the market or at various stages of commercial feasibility. These range from alternative fuels such as biofuels, which are compatible with current internal combustion engines (ICEs), hybrids, which allow for the retention of the ICE fuelling infrastructure while incorporating fuel efficiency attributes, to more innovative alternatives such as pure electric vehicles. Common alternative fuels and powertrains include (IEA, 2003; Tzimas et al., 2004; Lipman and Delucchi, 2006; Yeh, 2007; Lantz et al., 2007; Hill et al., 2008; Nylund et al., 2008; Thomas, 2009; Offer et al., 2010):

1. Liquid biofuels derived from organic sources of material, including bioethanol, biodiesel, pure plant oil (PPO) and used cooking oil (UCO);
2. Biogas produced from the degradation of organic material from wastewater treatment plants, landfills, slurry pits or grass by anaerobic digestion;
3. Hybrid technology, including hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), which combine standard internal combustion engines (ICEs) running on petrol or diesel with an electric drivetrain motor;
4. Battery electric vehicles (BEVs), which are powered by electricity stored in batteries or an electric motor connected to a transmission;

5. Fuel cell electric vehicles (FCEVS), which use hydrogen as an energy source;
6. Liquid petroleum gas (LPG); and
7. Compressed natural gas (CNG).

Biofuels production has increased dramatically over the last decade or so. For example fuel ethanol output increased from 16.9 to 72 billion litres between 2000 and 2009 while biodiesel production increased from 0.8 to 14.7 billion litres (Sorda et al., 2010). The International Energy Agency (2011) projects that while biofuels only account for 2% of total global transport fuel by 2050 32% exajoules of biofuels will be used globally, providing 27% of world transport fuel. However, innovative technologies and fuels have yet to seriously penetrate the mainstream market. For example, in the United States, there were approximately 826,000 alternative fuelled vehicles in use in 2009, of which about 500,000 were flexi-fuel vehicles (FFVs) operating on ethanol (E85)[1]. This compares to a total fleet in the US in 2009 of 254.2mn vehicles[2]. Globally, there are about 1 billion vehicles in use, with projections expected to reach 2 billion by 2030 (Sperling and Gordon, 2009). However, at present there are only about 70 million AFVs in use.

There are various economic, technological and institutional reasons why AFVs have not yet attained greater market penetration or which might constrain future diffusion. This paper seeks to identify and categorize these barriers and presents a framework for doing so. It also identifies and evaluates potential policies to address these barriers. Previous studies that were identified in this paper have not attempted to identify and evaluate both the barriers to AFVs as well as potential policies and measures that could be used to incentivise their uptake within a general framework.

Byrne and Polonsky (2001) examined the role of different stakeholder groups, including national and regional government, the corporate sector, collaborators, competitors, activist groups and consumers, and the interaction with different impediments or barriers. The primary barriers that were identified were regulatory, financial resources, lack of consumer demand, the limited availability of AFVs, fuel delivery outlets and maintenance services and adverse perceptions of vehicle characteristics such as performance, safety and image. It was

[1] http://www.eia.gov/renewable/alternative_transport_vehicles/pdf/attf_V1.pdf
[2] http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html

concluded that adoption of AFVs was likely to be incremental. Romm (2006) identified six major barriers to AFV success, including: (a) high initial capital cost; (b) issues with on-board fuel storage and limited range; (c) safety and liability concerns; (d) high fuelling cost; (e) limited availability of fuelling options; and (f) improvements in competition from conventional vehicles. However, this analysis did not evaluate these barriers or suggest individual policies that could be implemented to address them.

Struben and Sterman (2008) examined barriers to the the diffusion of alternative vehicles by way of a formal dynamic innovation-diffusion model, which looked at the impact of driving experience, 'word of mouth' and marketing. It was concluded that marketing programs and subsidies must remain in place for a sufficiently long period to allow for diffusion to become self-sustaining. Foxon and Pearson (2008) examined the barriers to the general diffusion of cleaner technologies and sustainable innovation and identified failures in infrastructure provision, transition failures, lock-in failures and institutional failures as the primary barriers. They suggested capitalising on 'windows of opportunity' and promoting a diversity of options to overcome technical and institutional 'lock-in'.

Other analyses have looked at more specific technologies or jurisdictions. For example, Steenberghen and López (2008) focussed on the barriers to the implementation of natural gas, LPG, hydrogen and biofuels in Europe and concluded that a combination of direct policies and clear Government leadership is required to improve the attractiveness of innovative technologies for consumers. Zhao and Melaina (2006) focussed on the main barriers to hydrogen-based transportation in China and compared lessons learned with the United States in order to provide insights into appropriate strategies for developing hydrogen infrastructure in China.

Ahman (2006) examined the history of electric vehicle (EV) programmes in Japan and the role of Government policy in promoting innovative programmes. It was concluded that 'picking winners' by policy-makers is not an ideal strategy and flexibility, adaptability and cooperation in terms of technical choice are necessary. Sovacool and Hirsh (2009) looked at the specific socio-technical obstacles and barriers to PHEVs and a vehicle-to-grid transition (V2G), which they regard as a necessary precursor to the adoption of PHEVs. It was concluded that impediments such as social or cultural values and political interests may be just as important as technical barriers.

Hoekman (2009) examined the main factors involved in the commercialisation of biofuels, with a specific focus on the US market, and concluded that, for biofuels to become successful on a large scale, they would need to be cost-effective along the entire supply chain. Coelho (2005) looked specifically at the trade barriers to biofuels and how biofuels production might be limited by World Trade Organisation (WTO) provisions. Lantz et al. (2007) looked at the potential for expansion of biogas in Sweden and found that biogas systems are affected by a number of different incentives and barriers, including energy, waste treatment and agricultural policies. This paper aims to build on this literature by identifying and evaluating barriers and policy measures for all categories of AFVs without limiting the evaluation to a particular national system boundary or technology.

2. Methodology

Banister (2005) suggests that barriers to sustainable transport can be divided into seven main categories, including:

1. Financial barriers, which include additional costs to consumers, capital and operating costs for investors and resource constraints on public finances;
2. Technical or commercial barriers, which might limit market availability and commercial feasibility;
3. Institutional and administrative barriers;
4. Public acceptability;
5. Legal or regulatory barriers;
6. Policy failures and unintended outcomes; and
7. Physical barriers.

This paper seeks to apply this methodology to the evaluation of AFVs by identifying barriers and classifying them according to the categories above. This categorisation can be used to broadly identify what the main barriers are.

2.1. Evaluation of Barriers

The main barriers that were identified are evaluated under a number of headings, including:

(a) Timeline, e.g. short-term, medium-term, long-term. In this case, short-term is defined as 1-2 years; medium-term is 2-5 years and long-term is 5-10 years. This relates to the potential timeframe within which the particular barrier could be overcome or at least significantly mitigated through appropriate policy actions.

(b) Level of subsidiarity, e.g. international, federal or supranational (for example the European Union or United States), national, regional, local or municipal authority, etc. This step involves identifying the appropriate vertical administrative levels for policy implementation.

(c) Type of policy measure required, e.g. fiscal incentives or taxes; regulatory such as statute or mandate; technical improvements; institutional; education and awareness campaigns.

(d) Actor, e.g. Government, transport operators, State agencies, local authorities, general public, industry, etc. This step involves identifying the appropriate institutional actors and stakeholders, which are likely to take the relevant action.

(e) National relevance. This relates to measures that can be dealt with by Government or local authorities or which policy-makers have autonomy over to make decisions and is expressed as a simple binary yes/no.

(f) Significance, e.g. highly significant, quite significant, low significance and not significant. Significance will be evaluated according to whether the particular barrier is likely to be an obstacle to delivering sustainable transport, depending on the particular type of action. Because there is no common parameter, this is by nature a subjective evaluation.

It is suggested that this typology allows policy-makers to decide which barriers should be tackled initially and provides a framework for concerted action over a long-term period. The timeframe typology used for both barriers and recommended policy actions is indicative only and is confined to a ten-year framework, notwithstanding that some barriers will require concerted action over a longer framework and that some policies, while introduced in the short- or medium-term may have longer-term residual effects. Figure 1 shows how barriers are prioritised. Thus, priorities would be those barriers, which can be dealt with in the short-term by policy-makers in national Government or local authorities, which are relevant and which are highly significant.

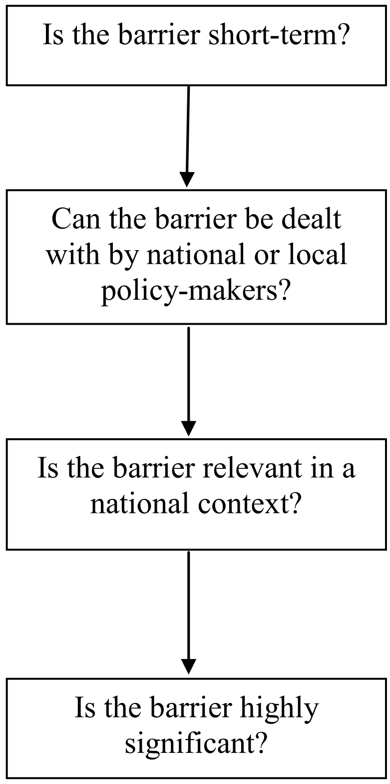

Figure 1: Classification of Barrier Priorities

2.2. Evaluation of Policy Priorities

In order to qualitatively analyse individual policies, measures and actions and to develop an impact matrix, a number of criteria were selected. These criteria were selected on the basis that they were most determinative of the potential effect of a policy measure and cover the broad spectrum of sustainability appraisal by measuring the economic, social and environmental effects of an action as well as the administrative timeline within which to implement it. More inclusive or participatory methods could be used to modify the criteria as part of future work and increase the transparency and robustness of the methodology (Kowalski et al., 2009; Garmendia and Stagl, 2010).

The criteria that were used in this appraisal include:

1. Type of policy measure required, e.g. fiscal, technical, regulatory, guidelines, education and awareness.
2. Timeline, e.g. short-term, medium-term, long-term. In this case, short-term is defined as 1-2 years; medium-term is 2-5 years and long-term is 5-10 years. This relates to the potential timeframe within which the particular policy action could be taken.

3. Net additional cost to consumer. This is classified using an increase in cost/reduction in cost/neutral (no effect).
4. Net additional cost to public finances (which includes central Government and local and municipal authorities). This is classified using a high/medium/low/neutral (no effect) ranking, although some policy options will be classified on the basis of 'net gain in revenue', 'reduction in revenue' or 'reduction in cost', where appropriate.
5. Modal shift. This is classified using a high/medium/low/neutral (no effect) ranking. Low implies a modal shift from private car use to public transport, walking or cycling of less than 5% from a business as usual scenario. The 'medium' ranking indicates a modal shift of between 5% and 15% and the 'high' ranking indicates a modal shift in excess of 15%. The 'neutral' classification indicates that it will be unlikely that there will be any modal shift.
6. Reduction in GHG emissions. This is classified using a high/medium/low/neutral (no effect) ranking.
7. Impact on rural communities. This is classified on the basis of positive impact/negative impact/neutral (no effect). In essence, this is included for the purpose of comparative analysis but each action is assigned a 'neutral ranking' although fuel cost savings may have a beneficial impact for long-distance commuters and rural dwellers. This may have an unintended effect of leading to longer vehicle kilometres travelled.
8. Impact on lower socio-economic groups. This is classified on the basis of positive impact/negative impact/neutral (no effect).

The criteria of modal shift and impact on rural communities are included for the sake of holistic evaluation and for ease of comparison with travel demand management measures, although these will *de facto* be neutral throughout the evaluation. In terms of potential policy instruments, measures such as education programmes, awareness campaigns or the introduction of technical guidelines might be relatively easy to implement, whereas fiscal or regulatory measures may require more complex institutional machinery and attract a certain level of public opprobrium and commercial or administrative resistance. However, the outcome of fiscal or regulatory measures is easier to predict compared with 'soft measures' such as education, training and awareness.

3. Evaluation of Barriers to Alternative Fuels and Technologies

3.1. Financial Barriers

Financial barriers can include additional increased costs for consumers, initial and operating costs for investors as well as Government fiscal support such as subsidies, excise relief and direct grants. These are somewhat interdependent as direct Government support may subsidise the cost of production and/or the cost of purchase. However, production costs may be difficult to manage in a globalised inter-connected production system.

Financial barriers for consumers include: (a) the cost of vehicle purchase; (b) vehicle operating costs; (c) additional fuel costs; (d) maintenance costs; and (e) possible vehicle modification costs, for example in the case of converting vehicles to run on biofuel blends. Innovative technologies carry a price premium, particularly in the short-run, due to a lack of critical mass, low economies of scale and complex fuel storage requirements, in the case of hydrogen vehicles. Gaines and Cuenca (2001) project, however, that cost reductions might be expected in the longer-term as a result of material substitution, economies of scale in production, design improvements, and/or development of new material supplies.

Notwithstanding that, however, even in the long-run and with larger production tranches, the price of EVs is likely to be significantly higher than conventional vehicles due to the costs of the lithium ion battery packs. Delucchi and Lipman (2001) noted that most studies suggest that BEV purchase costs are expected to remain higher than conventional vehicle costs, even accounting for lifecycle costs, although these studies differ depending on assumptions regarding the types of vehicles, range, energy efficiency and the life and cost of the battery. From a social equity perspective, there appears to be a positive relationship between income and hybrid adoption, which suggests that financial incentives may disproportionately benefit and effectively create a subsidy for higher income consumers. In addition, lower income consumers may be less able to afford the higher up-front premium and are more likely to discount future fuel cost savings (Diamond, 2009).

In general, most consumers will only opt for alternative fuels if they are price competitive with mineral fossil fuels and environmental considerations tend to be overshadowed by price and availability (Bomb et al., 2007). However, energy-efficient AFVs such as HEVs and BEVs may have lower operating costs than standard internal combustion engine vehicles

(ICEVs) (Johansson and Ahman, 2002). Furthermore, AFVs with lower emissions will have reduced external social costs, which possibly justify Government intervention by way of subsidies in order to internalise the benefits of these positive externalities (Lipman and Delucchi, 2006).

However, consumers generally fail to factor in or discount fuel cost savings over the lifetime of the vehicle and tend not to prioritise fuel economy as a factor when purchasing a fuel-efficient vehicle or else opt for a fuel-efficient vehicle for symbolic rather than economic reasons (Turrentine and Kurani, 2007). The payback period for EVs depends on the annual mileage driven, the length of vehicle ownership, fuel and electricity costs as well as tax relief or exemptions. Consumer choices may also be adversely affected by price volatility or fluctuations in the price of fossil fuels.

Alternative fuels such as biofuels may also have a higher production cost, particularly in the initial stages, due to lower economies of scale (Ralston and Nigro, 2011). This largely depends on the source, biofuel feedstock, scale of production, conversion and refining process, level of Government subsidies and excise relief, transportation costs and use of by-products or waste materials. Ryan et al. (2006) compared the cost of various bioethanol and biodiesel fuels and found that the only biofuel that was cheaper than the equivalent fossil fuel in the European Union at that time was bioethanol from Brazilian sugarcane, although biodiesel from used oil and fat was only marginally more expensive. Demirbas (2009) concluded that the cost of feedstock is the major component of the overall cost of biofuels. Bomb et al. (2007) point out that the main barrier to biofuels in the UK is production cost and suggest that this is not adequately compensated for via excise relief.

Some AFVs, for example flexi-fuelled vehicles (FFVs), may require costly modification. However, this depends on the type of biofuel used. For example, low biodiesel blends up to 15-20% and 5% bioethanol (E5) can be used in ICEs in blended form and are generally granted a warranty by the manufacturer, compared with 100% vegetable oils (B100) or 85% ethanol blends (E85), which may require engine modification or retrofitting.

AFVs may also require maintenance costs (Potoglou and Kanaroglou, 2007). Biofuel blends above 20% (B20) can cause maintenance problems over the long-run as a result of corrosion, microbial growth and deposits in the fuel injection system (Shahid and Jamal, 2008). EVs can require filter changes and have short battery lifetimes, which mean that batteries need to be replaced. Initial and replacement battery costs are a significant component of the total lifecycle cost of BEVs (Delucchi and Lipman, 2001).

Potential investors may also face considerable capital and operating costs. Capital and operating costs include those associated with storage capacity, handling equipment for alternative fuels, developing service stations of various types and sizes, retrofitting refuelling infrastructure, investment in distribution systems and fuel cell propulsion systems, for example in the case of hydrogen. Production and manufacturing costs vary, depending on the material, assembly, delivery and advertising costs (Ogden et al., 2004). It is estimated that the cost of converting a current filling station to dispense 50,000 gallons of gasoline equivalent per month is \$1.4 million in the case of hydrogen, \$0.9 million for CNG and \$0.6 million for LNG. The cost for methanol, ethanol, DME and LPG is reported to be about \$200,000 while, in the case of biodiesel, conversion will not imply any cost (Agnolucci, 2007).

Returns for investors may be affected by large sunk investments in conventional technologies and infrastructure and limited profitability of operating refuelling stations (Kemp et al., 1998). As a result of unprofitable infrastructure and fuel retail, investors may be reluctant to enter the market or may exit an unprofitable market (Flynn, 2002). Investors may also be reluctant to enter the market due to the uncertainty surrounding biofuel demand. This, together with the fact that other crops can give a higher return, means that land owners may be reluctant to cultivate dedicated energy crops due to the long-term commitment involved Hammond et al. (2008).

Carriquiry et al. (2011) project that, although second-generation biofuels could significantly contribute to the future energy supply mix, cost is a major barrier to increasing commercial production in the near to medium term. Depending on various factors, the cost of second-generation (cellulosic) ethanol can be two to three times as high as the current price of gasoline on an energy equivalent basis. The cost of biodiesel produced from microalgae, a prospective feedstock, is many times higher than the current price of diesel.

Public finance resources can be used to subsidise the production of AFVs, for example by taking into account reductions in external or social costs which are not currently internalised in market transactions, thus increasing their commercial feasibility. However, Governments and policy-makers may be reluctant to directly subsidise production costs and grant excise relief, particularly in the infant industry phase and/or where projections of demand are uncertain, and may be unwilling to commit the funds to sponsor research and development (R&D) in nascent technologies (Bomb et al., 2007; Goldemberg et al., 2008; Hammond et al., 2008; Hira and de Oliveira, 2009). There are a number of reasons for this, including, *inter alia*: (a) limited national resources, particularly during periods of economic uncertainty or austerity; (b) reticence among policy-makers to seek 'first mover' advantage, who instead prefer to adopt a 'wait and see' approach; (c) insufficient research capacity at corporate and/or academic level; (d) uncertain international policy outlook, which permeates down to national level; and (e) lack of political or policy leadership.

3.2. Technical Barriers and Market Availability

Technical barriers can occur at the corporate or systemic level and can be classified broadly as: (a) technological barriers; (b) infrastructure barriers; and (c) uncertain raw material availability. Technological barriers relate to commercially feasibility and impact on whether a potentially innovative technology can develop from an academic or industrial prototype to full mass-scale production or whether it is more limited in its scope, for example to particular technology niches, markets or scale.

In particular, it should be noted that while some alternative fuels such low-blend biofuels can be used with current internal combustion engines (ICEs), alternative powertrains such as BEVs require a technological shift away from the standard ICE and towards an innovative technology (with associated infrastructure). As a result, liquid blended biofuels are 'technologically-compatible' with the incumbent vehicle market and refuelling infrastructure and can be mandated at supplier-level without any discernible consumer disruption, which offers a considerable advantage.

However, all of the AFVs highlighted above face technological barriers to some extent. For example, the high viscosity of biofuels, particularly at low temperatures, may affect performance. Use of unmodified vegetable oil may lead to engine problems such as coking, increase in tank sediments and deposits and should only be used after proper filtration, removal of contaminants, degumming and dewaxing. In addition, engine thermal efficiency may be diminished, leading to a perception of inferior performance associated with vehicles operating on biofuels (Agarwal, 2007).

LPG and CNG technology is constrained by natural gas supply, distribution and safety concerns, barriers to entry, lack of available upstream facilities and competition with natural gas infrastructure (Reuster and Neumann, 2008). CNG vehicles require a greater amount of space for fuel storage than conventional vehicles. Gas companies also differ as to whether gas should be supplied in compressed or uncompressed form. Hydrogen vehicles or FCEVs offer lower volumetric energy and well-to-tank efficiency compared to BEVs due to the energy required for compression or liquefaction and may lead to losses in storage and transmission (Ahman, 2001; Campanari et al., 2009). Thus, achieving the range of a conventional gasoline vehicle with a pure FCEV requires a bulkier hydrogen tank than the equivalent gasoline tank (Offer et al., 2010). In addition, colder climates can affect their performance (Haraldsson et al., 2005).

Ralston and Nigro (2011) have identified a number of technical barriers to PHEVs, which have a broader application to EVs, including: (a) specific energy density of the standard lithium ion battery, which is in the order of 1% that of gasoline; (b) variable battery charging time and length of charging, e.g. in order to fully charge a BEV overnight (when the majority of charging is expected to take place), many BEV owners would need to install a Level 2 charger in their homes, which requires a system upgrade, as 240-volt outlets are not common in most household garages; (c) uncertain battery lifespan and durability, which depends on charge rates, depth of discharge swings and temperature; (d) technical difficulties integrating with the national grid; and (e) home charging and the provision of charging cables from the mains may not be practical in apartment blocks or terraced houses with limited off-street parking.

Currently, the most developed near-term technologies are HEVs, which have reached a certain critical mass on the market, with the notable success of the Toyota Prius, followed by BEVs. First-generation biofuels, in both pure and blended form, have also attained a critical level of visibility and awareness, as a result of Government support in the form of direct excise relief, subsidies, indirect tax relief, e.g. capital allowances, and obligatory percentage or volumetric bending mandates (Sorda et al., 2010). Second and third-generation biofuels are not yet fully commercially feasible on a global scale (Bacovsky, 2010; Carriquiry et al., 2011). However, they are expected to come on the market as enzymatic technologies develop, sustainability requirements become more stringent and fossil fuel prices increase.

Sims et al. (2010) suggest, however, that second generation biofuels will continue to face major constraints to overall commercial deployment due to the logistics of providing a competitive and perennial supply of biomass feedstock to a commercial-scale plant as well as improving the performance of the conversion process. As a result, third-generation biofuels cultivated from arable biomass may ultimately be the best long-term option (Singh et al., 2011).

Hydrogen fuel cell electric vehicles (FCEVs) are not yet widely available on the market beyond limited niche applications and demonstration programmes and commercial availability is not expected to happen before 2020 due to technological bottlenecks such as storage, material availability, durability and high costs (Frenette and Forthoffer, 2009). However, technical advancements in recent years, e.g. the proton exchange membrane (PEM) fuel cell, have made FCEVs more competitive.

The primary technical barriers limit, along with other impediments, the commercial availability of AFVs, which may be considered as a consumer-level barrier. Indeed, the lack of quality and reliable AFVs at the retail phase is one of the major barriers to their adoption, as low visibility and limited public awareness hinder demand. Thus, AFVs may simply not be available on the market or may not be attractive to consumers, in the absence of positive incentives, for example due to perceptions about performance, image and functionality.

For example, pure BEVs are generally limited to passenger cars and small vans due to the size and weight of the batteries required to power the electric motor, which leads to relatively low energy density (Offer et al., 2010). EVs in general are perceived as not having sufficient driving range and owners can experience 'range anxiety', where they may feel 'stranded' if refuelling facilities are not available. The distance that a BEV can be driven before it needs recharging depends on the type and number of batteries installed and can range from 30 to 120 miles. PHEVs overcome this 'range anxiety' to some extent, as they are capable of running fully on gasoline when the battery becomes discharged (Benecchi et al., 2010). For this reason, they are potentially a more popular choice among consumers, who rank the insufficient battery range of BEVs as the number one reason to choose a PHEV over a BEV (Ralston and Nigro, 2011).

Furthermore, current fuelling and charging infrastructure is generally inadequate outside of limited urban locations and potential consumers may be dissuaded if adequate nationwide refueling facilities are not available or charging facilities are not available along major urban arterial routes, particularly owners of BEVs and flex-fuel or bi-fuel vehicles. Indeed, the adoption of AFVs is dependent on refueling availability and consumers will not purchase vehicles that they cannot refuel. This limited availability of refuelling and charging infrastructure may also lead to a perception that AFVs are unsuitable for longer journeys, particularly where vehicles have limited driving range before charging is required (Melaina and Bremson, 2008; Melaina et al., 2008).

For example, in 2005, the number of alternative refuelling stations in the US totalled approximately 5,000, with 63% LPG stations, 16% natural gas, 12% electric and 4% ethanol. This compares to approximately 160,000–170,000 conventional gasoline refuelling stations. Owners of AFVs, therefore, are often faced with inconvenient local refuelling and limited driving ranges for long-distance trips (EERE, 2005). It is estimated that there are about 1,000 natural gas refuelling stations in EU, of which some are public, but the majority are reserved for private use of captive fleets. This number is less than 1% of the total number of refuelling stations for conventional fuels (at present close to 113,000) (Tzimas et al., 2004). This dynamic is likely to alter as LPG and natural gas vehicles are overtaken by EVs and, ultimately, FCEVs.

The lack of adequate and reliable refuelling and charging facilities is compounded by the ‘chicken and egg’ conundrum, that is the anomalous situation where customers are reluctant to purchase AFVs unless refuelling infrastructure is available, manufacturers will not produce vehicles that people will not buy and fuel, vehicle providers will not invest in infrastructure for vehicles that do not exist and where there is no critical level of demand and consumers cannot purchase vehicles that are not available (Winebrake and Farrell, 1997; Jensen and Ross, 2000; Flynn, 2002). Romm (2006) argues this remains the most intractable barrier to the development of AFVs.

In addition, industrial economies have become ‘locked-in’ to fossil fuel energy systems through a process of technological and institutional co-evolution driven by path dependence since the major discoveries of fossil fuels (Unruh, 2000; Van Bree et al., 2010). This institutional lock-in is due to significant increasing returns to the adoption of incumbent energy technologies as a result of economies of scale and learning effects (Carillo-Hermosilla, 2006). Indeed, the entire refuelling infrastructure and auto manufacturing system dedicated to gasoline vehicles has dominated the industry for nearly a century (Zhao and Melaina, 2006).

There are also specific significant infrastructural challenges associated with hydrogen and FCEVs, such as adjusting to infrastructural change, carrying hydrogen storage on-board, on-board reforming of a hydrogen carrier such as methanol and petrol as well as safety issues. The introduction of hydrogen may require a new dedicated pipeline transportation and distribution infrastructure and it is anticipated that hydrogen use will be predominantly in densely populated urban areas initially before gradually expanding into rural areas.

Hydrogen can be produced from a variety of primary energy feedstocks and distributed in a variety of forms using different technologies. Gaseous hydrogen, for example, can be distributed in dedicated pipelines over a long distance, while liquefied hydrogen can be transported in tankers by rail, ship or road. Unlike most other fuel infrastructures, hydrogen can be produced either centrally or distributed (Li et al., 2008). Mercuri et al. (2002) suggest that the most economic hydrogen supply is on-site steam reforming although electrolysis and delivery of liquid hydrogen may offer additional flexibility in the early stages of infrastructural development.

The long-term global availability of source materials such as lithium may prove to be a limiting factor for the development of EV batteries. In addition, there are constraints on the availability of platinum group metals for fuel cell vehicles (Tonn and Das, 2002). Biofuel feedstock availability can also be limited and lead to uncertainty among producers and investors (Hammond et al., 2008). Finally, natural gas may face the same long-term resource constraints as crude oil

3.3. Institutional and Administrative Barriers

Institutional resistance may be prevalent among vehicle manufacturers and/or importers, fuel retailers, policy-makers, the media and the advertising industry. The main institutional barriers associated with AFVs include the historical aversion to new or innovative technologies and resistance to change from stakeholders who have sunk costs into the existing infrastructure (Jaccard, 2005; Sperling and Yeh, 2010). As a result, stakeholders may be reluctant to invest in the infrastructure required to support a nascent technology, particularly in the early stages where demand is not yet realised and projections are uncertain.

This exacerbates the ‘chicken and egg’ conundrum intrinsic in the transformation of the energy system, which calls for a staged and inherently slower approach (Melaina and Bremson, 2008; Struben and Sterman, 2008). Dougherty et al. (2009), in evaluating the barriers to a large-scale transition to hydrogen in the US, argue that the inertia of existing energy infrastructure and the large amount of investment in conventional energy resources continue to slow the transition towards less polluting energy sources.

In addition, investors may be reluctant to make what can be expensive and risky investments in the absence of clear policy signals, political attention, media interest and market demand from consumers. The introduction of new fuels is an infrequent, uncertain and slow process, largely due to the time required for diffusion between policy development and technological change, particularly where energy technologies are long-lived and capital intensive, thus leading to path dependence in the incumbent techno-institutional complex. In addition, there is inherent lock-in by existing technologies and institutional infrastructure. Indeed, petroleum-based fuels dominate, despite the policy focus and investments made in developing innovative technologies, because of their basic physical characteristics and high energy densities (Unruh, 2002; Romm, 2006; Agnolucci, 2007).

Unruh (2002) suggests that ‘carbon lock-in’, which is where fossil fuels are embedded in the dominant institutional infrastructure, constrains policy actions and, as a result, policy-makers should create flexible policy regimes that allow for future evolution. The introduction of innovative fuels and technologies is an infrequent, uncertain and slow process, largely due to the difficulties associated with major changes in the social and economic systems in which new technologies are always embedded (Kemp, 1994).

Hillman and Sandén (2008) argue that new technologies are plagued by uncertainty, incompatibility and a lack of advocates. Cowan and Hulten (1996) suggest that overcoming existing lock-in requires the occurrence of a number of 'extraordinary events', namely: (a) a crisis in the technology involved, (b) regulatory drivers, (c) technological breakthroughs, (d) changes in taste and consumer preferences, (e) the evolution of niche markets, and (f) scientific results.

3.4. Public Acceptability

Public acceptability of AFVs depends on a number of factors: (a) they should offer similar or superior functional attributes to existing fuels and technologies; (b) sufficient infrastructure must be in place to avoid or limit range anxiety and support maintenance, charging and refueling; (c) they should not be prohibitively expensive so that they are beyond the purchasing reach of the average consumer; (d) they should not lead to public concerns about flammability or safety; (e) they should not lead to (unintended) social, economic or environmental impacts; and (f) they should be perceived in favorable image terms.

First, innovative fuels and technologies may not be available on the market in designs that are attractive to the consumer at large or may be unsuitable for particular purposes. This is particularly prevalent with regards to EVs, where consumers have concerns about 'range anxiety' and vehicles are perceived to be unsuitable for longer journeys, daily long-distance commuting and/or larger families. Consumers generally require comparable or superior performance with conventional vehicles and might have particular perceptions about reliability, performance and comfort. This can lead to inertia and scepticism among the general public or certain population cohorts due to conservative attitudes, low level of public visibility and cultural values, coupled with a lack of awareness of the incentives and benefits. As a result, certain types and models may be publicly identified with a particular demographic and/or income bracket and, as a result, are seen as a niche or peripheral product. This may require industry and stakeholders to inform and educate as well as 'selling the benefits' through awareness campaigns (Banister, 2008).

Secondly, there may be a lack of available qualified technicians and spare parts in the event of mechanical failure, which can reduce consumer confidence, although this can be overcome by maintaining a minimum storage buffer of key equipment and developing a network of competency. In addition, there may be excessive mark-up of parts by conversion dealers, exaggerated claims of environmental and economic benefits and poor design of promotional programmes (Flynn, 2002). Thirdly, consumers will be reluctant to purchase new vehicles or fuels at the pump if they carry a price premium and are significantly more expensive than their petrol or diesel equivalent.

Fourthly, there may be public safety concerns about flammability and explosion hazards, in particular with hydrogen vehicles and natural gas vehicles (NGVs), where fuels are stored at high pressure (Paltrineiri et al., 2009). However, this can be overcome by increasing awareness and knowledge through awareness campaigns or specialised training, for example in the case of public transport operators, as well as vigilant and robust safety systems (O'Garra et al., 2005; Van der Straten et al., 2007).

Fifthly, certain fuels and technologies may result in a public backlash, if their ancillary or downstream impacts are not managed. For example, policies to support and incentivize ethanol production included 'perverse' subsidies, which resulted in competition for land and indirect land use change (ILUC) from forested land and wetlands to arable land. Other potential environmental impacts may include adverse impacts on biodiversity and sensitive ecosystems, deforestation, soil degradation or erosion, water appropriation, groundwater contamination and habitat fragmentation. Social impacts can include poor working conditions in biofuel-producing countries as well as spikes in food and commodity prices, which severely impact on the most vulnerable (Charles et al., 2007; Hammond et al., 2008; Nylund et al., 2008; Escobar et al., 2009; Lam et al., 2009; Rathmann et al., 2009).

3.5. Regulatory or Legal Barriers

Regulatory or legal barriers can include: (a) regulatory gaps; (b) trade barriers; (c) potential legal challenges; and (d) planning restrictions. First, regulatory gaps can occur where there is a lack of government regulation and incentives and where the regulatory landscape operates in a policy vacuum. Alternatively, there may be inconsistent or weak policy signals, which hinder investor confidence and consumer demand. Inadequate incentives and policy signals can lead to market failures, which hinder the diffusion of cleaner technologies (Montalvo, 2008).

Secondly, direct excise relief to indigenous biofuel producers and preferential treatment for domestic production may violate World Trade Organisation (WTO) rules, and in particular, the Technical Barriers to Trade Agreement (TBTA), which governs the international trade of goods and regulates the use of protective subsidies in order to reduce or eliminate their distorting effects, retain market access for foreign suppliers and protect trade liberalisation. This regulatory ambiguity is compounded by the lack of a specific classification system for biofuels (Harmer, 2009; Payne, 2009; Switzer and McMahon, 2010).

Thirdly, the development of AFVs and associated infrastructure may be hindered by the lack of common or harmonised safety certification or quality standards. Finally, charging points for EVs at residential or commercial developments may need planning permission or exemptions (Byrne and Polonsky, 2001; Steenberghen and López, 2008).

3.6. Policy Failures and Unintended Outcomes

Unintended economic, social or environmental impacts can occur with policy implementation, which may result in policies being abandoned or modified following a public and media backlash. For example, biofuel mandates and subsidies introduced in the US following the Energy Policy Act of 2005 and in the EU with Directive 2003/30/EC ("the Biofuels Directive") gave rise to a media furore following reports of food price rises, which led to the so-called 'tortilla riots' in Mexico (McMichael, 2009). Indeed, Ziegler (2007), the UN special rapporteur on the right to food, called biofuels a "crime against humanity" and asked for a five-year moratorium on the practice of using food crops for fuel. In addition, there were a number of studies around the same time that reported that biofuel production actually resulted in a net increase in GHG emissions, depending on the nature of feedstocks and the way they are processed and distributed (Birur et al., 2007; Searchinger, 2008).

Policy failures can also occur with policy and programme design, e.g. fleet refuelling facilities may not be located in convenient locations, while government subsidies and excise relief schemes may fail to achieve sufficient progress towards targets or on a satisfactory cost-effectiveness basis. Programme design has sometimes placed the focus on the acquisition of AFVs rather than use. For example, vehicle conversion or purchase may be undertaken to avail of preferential tax treatment, e.g. taxation relief for FFVs.

Furthermore, isolated demonstration projects may not necessarily lead to widespread deployment or spur the necessary technological innovation. This is exacerbated by an absence of programme support by key stakeholders such as local retailers. Instead of focusing on reducing costs and meeting customer needs, government-funded demonstration projects often focus on public relations and overtly political objectives.

3.7. Physical Barriers

Physical barriers to AFV production generally relate to restrictions on the availability of material inputs and this may ultimately be a critical constraint to the global production of, for example, electric vehicles, which may require the extraction of rare earth metals and platinum group metals as battery materials (Ball and Wietschel, 2009). Furthermore biofuels production requires sufficient land, water inputs and climatic conditions (Hammond et al., 2008; Yang et al., 2009). As a result of increased biofuel production, there is increased demand for arable land, which has resulted in the conversion of forest to cropland and indirect land use change (ILUC) (Timilsina and Shresta, 2011; Harvey and Pilgrim, 2011). An additional specific physical barrier for EVs is the provision of charging points at locations where parking is restricted, e.g. apartment blocks, terraced houses, or where there is no on-site parking.

3.8. Comparative Evaluation

Table 1 provides an overview of the barriers to AFVs that were identified above. The evaluation was conducted by the authors by reference to empirical studies but is inherently subjective. Future work could strengthen the analysis by adopting a participatory stakeholder approach or selecting a number of jurisdictions as case-studies. All of the barriers that were identified as short-term barriers were judged to be either ‘not significant’ or of ‘low significance’. The exception was lack of awareness of alternative fuels and technologies, which was judged to be ‘quite significant’. However, this could be addressed through education and awareness, targeted advertising and marketing and further research.

Medium-term barriers that were identified as ‘highly significant’ include:

1. The availability of alternative fuels and technologies for sale.
2. The perception that EVs are unsuitable for longer journeys due to limited driving range, particularly where nationwide refuelling or charging infrastructure does not exist.

3. Lack of home or on-street charging points for EVs as well as the technical challenges associated with developing home charging points.

Long-term barriers that were identified as ‘highly significant’ include:

1. Uncertainty about biofuel feedstock or EV battery raw material availability.
2. Infrastructural challenges associated with developing infrastructure where demand does not yet exist.
3. Inherent lock-in and path dependence, i.e. where existing infrastructure prevents innovation in developing alternative fuels and technologies.

Table 1 illustrates that the most significant barriers are related to the category of technical barriers, commercial feasibility and market availability, which are driven to some extent by cost and in turn impact on institutional resistance and public acceptability. In addition, it can be seen that these might be difficult to tackle at an autonomous national or local level by policy-makers and might be more relevant at an international or industrial level. The most policy-relevant barriers, which are regarded as ‘highly significant’, include the availability of alternative fuels and technologies and home or on-street charging in the medium-term and the lack of nationwide charging and refuelling infrastructure in the long-term. In particular, charging and refuelling infrastructure must be sufficiently convenient to alleviate consumer concerns about ‘range anxiety’ and fuelling options.

Table 1: Evaluation of Barriers to Alternative Fuels and Technologies

Barrier	Timeline	Level of Subsidiarity	Type of Policy Measure	Institutional Actor	Relevance	Significance
Financial barriers						
Cost of alternative fuel	Medium-term	National	Fiscal	Government	Yes	Quite significant
Cost of vehicle modification	Short-term	National/local	Fiscal	Government/industry	Yes	Not significant
Maintenance costs	Medium-term	Local	Technical/fiscal	Industry/transport operators	No	Low significance
Vehicle price	Medium-term	National	Fiscal	Government/industry	Yes	Quite significant
Low price of fossil fuel	Medium-term	National	Fiscal	Government	Yes	Quite significant
Cost of storage capacity and stations	Long-term	Local	Technical/fiscal	Industry	No	Quite significant
Cost of infrastructure	Long-term	National/local	Fiscal	Government/industry	Yes	Quite significant
Production costs	Medium-term	International/national	Fiscal/technical	Government/industry	Yes	Quite significant
Costs of fuel delivery	Medium-term	International/national	Fiscal/technical	Government/industry	Yes	Quite significant
Sunk investments in existing infrastructure	Long-term	International/national	Fiscal	Industry	No	Quite significant
Inadequate subsidies or excise relief	Medium-term	National	Fiscal	Government	Yes	Low significance
Training costs for transport operators	Short-term	National	Fiscal	Transport operators	Yes	Not significant
Technical barriers and market availability						
Availability of alternative fuels and vehicles	Medium-term	International/national	Regulatory/fiscal	Government/industry	Yes	Highly significant
Unsuitability of existing infrastructure	Long-term	N/A	N/A	Industry	No	Quite significant

Table 1: Evaluation of Barriers to Alternative Fuels and Technologies (Cont.)

Barrier	Timeline	Level of Subsidiarity	Type of Policy Measure	Institutional Actor	Relevance	Significance
Limited driving range, e.g. for electric vehicles	Medium-term	International	Technical	Industry	No	Highly significant
Inadequate marketing and promotion	Medium-term	National	Education and awareness	Government/industry	Yes	Low significance
Uncertainty about feedstock or raw material availability	Long-term	International	N/A	Industry	No	Highly significant
Home or on-street charging	Medium-term	Local	Technical	Government/industry	Yes	Highly significant
Infrastructural challenges, i.e. ‘chicken and egg’ scenario	Long-term	Local	Technical/institutional	Government/industry	Yes	Highly significant
Availability of qualified technicians	Short-term	Local	Technical	Industry	No	Not significant
Institutional and administrative barriers						
Inherent lock-in and path dependence	Long-term	National/local	Institutional/technical	Industry	No	Highly significant
Stakeholder resistance	Long-term	National	Institutional	Industry	No	Quite significant
Delays in fleet turnover	Medium-term	Local	Fiscal	Government/industry	Yes	Low significance
Public acceptability						
Inertia and scepticism among public	Medium-term	Local	Technical/education and awareness	Government/industry	Yes	Quite significant
Low level of visibility	Medium-term	Local	Regulatory/fiscal	Government/transport operators	Yes	Quite significant
Unsuitability for long journeys	Medium-term	International	Technical	Industry	No	Highly significant

Table 1: Evaluation of Barriers to Alternative Fuels and Technologies (Cont.)

Barrier	Timeline	Level of Subsidiarity	Type of Policy Measure	Institutional Actor	Relevance	Significance
Lack of awareness	Short-term	National	Education and awareness	Government/industry	Yes	Low significance
Perceived reduction in comfort and safety	Medium-term	International	Technical	Industry	No	Quite significant
Excessive mark-up and exaggerated benefits	Short-term	Local	Regulatory	Government/industry	Yes	Not significant
Concerns about environmental impacts of biofuels	Long-term	International/national	Regulatory/technical	Government/industry	Yes	Quite significant
Regulatory and legal barriers						
Lack of consistent regulatory standards	Medium-term	International/national	Regulatory	EU/Government	Yes	Low significance
Inconsistent or weak policy signals	Long-term	International/national	Regulatory/fiscal	EU/Government	Yes	Low significance
Limited excise relief for domestic biofuel producers	Medium-term	National	Regulatory/fiscal	Government	Yes	Quite significant
Planning permission for charging points	Short-term	Local	Regulatory	Government/local authorities	Yes	Low significance
Physical barriers						
Availability of feedstocks and land for biofuel production	Long-term	International/national	N/A	N/A	No	Low significance

4. Evaluation of Policies to Promote Alternative Fuels and Technologies

Policies and measures, which may incentivise the market introduction of AFVs, can be classified as the following:

1. Regulatory or 'technology-forcing' instruments, e.g. renewable fuel mandates, low-carbon fuel standards and vehicle emission standards;
2. Economic instruments, such as subsidies, excise relief, capital grants, tax incentives and discounted loans;
3. Procurement instruments, such as mandatory green public procurement, for example postal delivery vehicles, mass transit, taxi fleets;
4. Collaborative instruments, such as network management, voluntary stakeholder agreements, public-private partnerships; and
5. Communication and diffusion instruments, such as vehicle buyers' guides, vehicle labelling, education and awareness campaigns, training programmes and media publicity.

Table 2 shows an evaluation of potential policies to promote AFVs. It is suggested that short-term priority could be given to free parking for a limited period of time, which might help to encourage the uptake of AFVs at medium-cost to local authorities, although it is recommended that this is time-limited. This might be necessary in order to develop a baseline level of visibility in the community and is not expected to deliver significant GHG emission reductions. Tax incentives such as vehicle taxation relief, tax-holidays, subsidies, rebates and fuel excise could deliver medium GHG reductions but at a significant cost if these were to be sustained over a longer period.

The other short-term measures that were identified all yield a low reduction in GHG emissions at low cost, with the exception of staggered payment schemes and discounted loans, which would carry no additional cost to the Exchequer as these are private sector initiatives. Scenario planning and stakeholder partnerships with vehicle manufacturers, importers and operators may be necessary to adequately prepare a transition strategy. This could include visioning exercises, roadmaps and backcasting, which can be used to anticipate drivers and challenges and show how market potential can be developed (Van Mierlo et al., 2006; Yeh, 2007; Hillman and Sandén, 2008; Nylund et al., 2008; Seymour et al., 2008).

McDowall and Eames (2006) used scenarios and other foresight methods to sketch out a transition to a hydrogen economy and predicted that rapid transitions to hydrogen energy would only occur under conditions of strong government support or as a result of major discontinuities in societal values, coupled with ‘game changing’ technological breakthroughs. Scenario planning can also be used to develop a coherent national transition strategy, which anticipates where investments should be made and where incentives should be targeted.

Medium-term measures that were identified include policies aimed at supporting nascent technologies and building a critical mass from an initial low baseline. It is essential that refuelling infrastructure is developed, e.g. by encouraging investor companies to construct and operate fuelling stations, through strategic planning and investment, setting standards for fuelling stations and ensuring the early profitability of fuelling stations. Industry stakeholders should also engage in risk management, e.g. by developing a thorough plan for spare part availability through risk analysis and contingency plans, maintaining a minimum storage buffer of key equipment for maintenance, enhancing technical capacity, ensuring competent aftermarket conversions by suppliers, targeting a wide range of stakeholders and avoiding exaggerated claims and optimistic projections.

Market advertising measures might include marketing, awareness campaigns, vehicle buyers’ guides, vehicle labeling, training, sales of used converted vehicles at public auction, advice to fleet managers on greening their fleets and promotional programmes to achieve visibility and ‘set an example’ or act as a ‘pioneer’ (AEA, 2007). This could also involve, for example, setting a target that a certain percentage of car-related advertising in showrooms and in the national media should be related to AFVs in stock.

Policy-makers can also create appropriate market signals through emissions regulations, renewable fuel mandates, low-carbon fuel standards and restrictive low emission zones. Other measures that might be considered include mandatory targets in public sector fleet procurement and allowing AFVs access to high occupancy vehicle (HOV) or bus lanes. Policy-makers should also work with industry partners to develop consistent codes and standards for production, distribution, storage and use and to develop demonstration programmes through green procurement to increase awareness (Farrell et al., 2003;

Potoglou and Kanaroglou, 2007; Haller et al., 2007; Van der Laak et al., 2007; Van Dokkum and Dasinger, 2008; Ball and Wietschel, 2009; Dougherty et al., 2009).

Sovacool (2009) argues that all modes of transport require policy support by Government initially. Some of the successful large-scale introductions of AFVs have not been backed by any 'introduction strategy' but have been supported by favourable framework conditions and programme support, including the engagement of key stakeholders such as national governments; local and regional authorities; the fuel industry; vehicle manufacturers; producers of batteries and operators of charging stations; non-governmental organisations (NGOs); vehicle users, e.g. fleet owners or vehicle user associations; and the media.

Policy-makers should also focus on 'technological learning' or 'learning-by-doing', which can lead to substantial cost reductions and result in 'early mover advantage' (Schwoon, 2008). This promotes the diffusion of new technologies through a virtuous circle in which experience drives down the cost of the new technology and opens up larger markets, which in turn encourages further investment and yields greater experience. The coevolution of technological innovation and consumer behavioural change will depend on positive feedback from 'early movers' as well as the attainment of a critical visible mass, market pull and technological and knowledge spillovers within industry and among consumers (Struben and Sterman, 2008; Zhang et al., 2011).

Public policy should adopt an assertive role in attempting to effect a generational paradigm shift towards a low-carbon vehicle fleet and fuel mix. In the short- to medium-term, this may involve targeting niche markets such as public transport, airports or university campuses allows innovation and competition to weed out lower-performance technologies before risking broader disruptions, creates a critical level of visibility and awareness and allows the 'lead adopters' who have a high willingness to pay for the new technology to be identified (Nesbitt and Sperling, 1998).

Strategic niche management can be used to create pilot and demonstration programmes where innovative technologies and concepts are tested in order to learn about their positive attributes and allow for wider diffusion (Raven, 2007). However, Zhao and Melaina (2006) looked at experiences with AFV programmes in both the US and China and concluded that niche markets can provide a good start for AFVs, but do not necessarily lead to expansion into mainstream consumer markets.

Thus, a longer-term transformational framework of transition management will also be required, where policy-makers aim to initiate structural change and regularly re-orient and adjust goals through ‘reflexive’ or ‘adaptive governance’ in order to align short-term conflicts with longer-term ambition and create the conditions for co-evolutionary social, technological and environmental change (Rotmans et al., 2001; Kemp and Rotmans, 2004).

In the long-term, it is essential that new technological clusters receive continued and sustained research and development (R&D) investments in order to improve performance, identify the potential spill-overs of technological innovation and strengthen ‘path dependence’ (Farrell et al., 2003; Kim et al., 2004; Zhao and Melaina, 2006; Van Mierlo et al., 2006). However, this would involve considerable expenditure and policy-makers would need to consider: (a) whether a competitive advantage could be gained at national level; (b) what positive spill-over effects might occur; (c) whether it may be preferable to adopt a ‘wait and see’ approach and piggyback on international developments; (d) whether risk and opportunity could be shared with industry and/or academic ventures; and (e) whether the resources are available to sponsor the R&D required.

Other long-term measures might include forced early retirement of older vehicles through mandatory scrappage schemes and possibly mandatory AFV import targets for vehicle manufacturers. Both of these measures might result in a medium reduction in GHG emissions but could increase cost to the consumer, while mandatory import targets would be potentially contentious from an industry perspective.

Table 2: Evaluation of Policies to Promote Alternative Fuels and Technologies

Policy Action	Type of Policy Measure	Timeline	Cost to Consumer	Cost to Exchequer	Modal Shift	Reduction in GHG Emissions	Impact on Rural Communities	Impact on Lower Socio-economic Groups
Tax incentives	Fiscal	Short-term	Reduction in cost	High	Neutral	Medium	Neutral	Positive
Staggered payment schemes	Fiscal (might include discounted loans)	Short-term	Reduction in cost	Neutral	Neutral	Low	Neutral	Positive
Free parking	Fiscal	Short-term	Reduction in cost	Medium (cost to local authorities)	Neutral	Low	Neutral	Positive
Refuelling infrastructure	Technical	Medium-term	Neutral	Neutral	Neutral	Medium	Neutral	Neutral
Research and development	Technical	Long-term	Neutral	High	Neutral	Medium	Neutral	Neutral
Risk management	Technical	Medium-term	Neutral	Neutral	Neutral	Low	Neutral	Neutral
Scenario planning	Technical/administrative	Short-term	Neutral	Low	Neutral	Low	Neutral	Neutral
Emissions regulations	Regulatory	Medium-term	Increase in cost	Low	Neutral	Medium	Neutral	Negative
Restricted HGV access	Regulatory	Medium-term	Neutral	Low	Neutral	Low	Neutral	Neutral

Table 2: Evaluation of Policies to Promote Alternative Fuels and Technologies (Cont.)

Policy Action	Type of Policy Measure	Timeline	Cost to Consumer	Cost to Exchequer	Modal Shift	Reduction in GHG Emissions	Impact on Rural Communities	Impact on Lower Socio-economic Groups
Setting mandatory import targets	Regulatory	Long-term	Increase in cost	Neutral	Neutral	Medium	Neutral	Negative
Mandatory use in public sector fleet	Regulatory	Medium-term	Increase in cost	Medium	Neutral	Low	Neutral	Negative
Forced early retirement of older vehicles	Regulatory	Long-term	Increase in cost	Low	Neutral	Medium	Neutral	Negative
Bus lane access	Regulatory	Medium-term	Neutral	Low	Neutral	Low	Neutral	Neutral
Consistent codes and standards	Regulatory/ Technical	Medium-term	Neutral	Low	Neutral	Low	Neutral	Neutral
Stakeholder partnerships	Institutional	Short-term	Neutral	Low	Neutral	Low	Neutral	Neutral
Market advertising	Education and awareness	Medium-term	Neutral	Medium	Neutral	Medium	Neutral	Neutral
Eco-labelling of vehicles	Education and awareness	Short-term	Neutral	Low	Neutral	Low	Neutral	Neutral
Demonstration programmes	Education and awareness	Medium-term	Neutral	Medium	Neutral	Low	Neutral	Neutral
Targeting niche markets	Education and awareness	Medium-term	Neutral	Medium	Neutral	Low	Neutral	Neutral

4. Discussion and Conclusions

A range of alternatives to the dominant fossil fuel infrastructure currently exist or are close to commercialization. However, all potential alternatives have some inherent technical limitations at present or are not yet cost-competitive (Ball and Wietschel, 2009). As a result, fossil fuels are expected to be the leading energy source in the transport sector for the foreseeable future, primarily because of their dominant status, their particular chemical and physical properties, which enable convenient distribution and storage, and their compatibility with the internal combustion engine (Farrell et al., 2003; Zhao and Melaina, 2006; Nylund et al., 2008).

Alternative fuels only seem to be viable on the mass market if the price of oil remains high for a sustained period of time to allow time for innovative technologies to build a critical mass and attain a critical level of market visibility (Delucchi and Lipman, 2006; Zhao and Melaina, 2006). However, Leiby and Rubin (2004) found that, in the absence of any new and substantial policy initiatives, it may be difficult for AFVs to gain a foothold in the market. Notwithstanding that, in a market economy where vehicle manufacturers, fuel suppliers, and consumers all make independent decisions, the efficacy of government policies to reduce dependence on fossil fuels is highly dependent on the world price of petroleum.

Ball and Wietschel (2009) have argued that there seems to be a 'technology race' between BEVs and the FCEV. While the challenges for batteries are technical and economic in nature, there are cost and safety considerations for fuel cells. Nevertheless, there is unlikely to be a 'silver bullet' in the coming decades and the transport sector is likely to demonstrate a much more diversified portfolio of fuels in the future. Notwithstanding that, policy-makers should endeavour to remain 'technology-agnostic' and introduce standards or taxation measures that do not incentivise any particular fuel or technology but set the appropriate conditions for consumers and investors.

Table 1 indicates that the main barriers to AFVs are related to technical limitations, commercial feasibility and market availability. These are driven to some extent by higher production costs and in turn impact on institutional resistance and public acceptability. The most policy-relevant barriers, which are regarded as 'highly significant', include the availability of alternative fuels and technologies and home or on-street charging in the medium-term. The lack of nationwide charging and refuelling infrastructure is the major barrier in the long-term.

A range of policies and measures were evaluated, as can be seen in Table 2. It was concluded that developing refuelling infrastructure, supported by tax incentives and awareness campaigns, should be prioritised in the short- to medium-term. Longer-term policies and measures that were identified and which could be highly effective include forced retirement of vehicles that do not adhere to specific fuel economy and emission standards and mandatory import targets, although these could result in additional costs for consumers and the domestic vehicle industry, as well as limit consumer choice.

Policy-makers have a range of options and should consider the following: (i) develop a transition strategy and engage in scenario planning on a cooperative basis with industry stakeholders; (ii) identify potential 'lead adopters' and develop a strategy for strategic niche management; (iii) develop stakeholder partnerships with industry and consumer groups; (iv) promote the adoption of a new socio-technological regime through awareness campaigns and education programmes; (v) change the taxation structure by taxing negative externalities such as GHG emissions and creating positive incentives through excise relief and subsidies; and (vi) ensure a consistent mix of policy and regulatory signals, which offer long-term certainty.

It is concluded that the evaluation framework used in this paper could serve as a useful template for the identification and evaluation of barrier and policy priorities and could be modified depending on the system and/or geographical boundary. In addition, it can be adapted and used by policy-makers in order to guide policy priorities and develop national AFV policy strategies or local action plans for strategic niche management. It is sufficiently flexible to be modified for particular jurisdictions, depending on particular consumer choices, policy preferences and the stage of technological innovation. Furthermore, it is suitable for national or cross-country evaluation as particular barriers, policy measures and technologies might be more or less suitable, depending on the jurisdiction. However, as a qualitative tool, it is vulnerable to subjective evaluation and should be supported by empirical analysis, where possible. In addition, this framework should be applied at the particular level of interest and the evaluation should not be construed as universal as it may depend on particular system factors.

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