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The feasibility of distributed hydrogen production from renewable energy sources and the financial contribution from UK motorists on environmental grounds

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ABSTRACT

Decarbonisation of the transport sector in the UK would serve to meet climate change obligations through greenhouse gas reductions, reduced pollution levels and an improvement of energy security through a reduced dependency on imported crude oil and refined fuels. Hydrogen fuel cell vehicles have the potential to fulfil these aims, more so when the hydrogen used to power them is produced from renewable energy sources. The electrolytic production of hydrogen at the point of sale eliminates the need for hydrogen distribution costs and promotes sustainability but the business case is dependent upon the production of hydrogen at an acceptable cost to the public. This study calculates the hydrogen production cost using varying capacity hybrid wind/solar PV systems and associated hydrogen generation, storage and dispensing technologies in supplying a scenario population exposed to average UK weather conditions. It examines if the environmental benefits are evident through the UK car-owning public's willingness to pay for a cleaner transportation fuel. Whilst the respondents' concerns for the environment are strong, a high degree of sensitivity over fuel pricing remains. In spite of this, the projected demand for hydrogen fuel cell vehicles through to 2030 and the use of renewable energy tariffs shows that certain configurations of hydrogen production infrastructure are still financially viable. The possibility exists for the application of fuel taxation whilst still maintaining price parity with conventional hydrocarbon fuels.

1. Introduction

Hydrogen is the simplest and most abundant chemical element in existence. It is the power source of stars and here on our Earth it forms a component of chemical compounds which humankind has been able to harness as fuels. Organic compounds make up traditional fossil fuels and one hydrogen-containing inorganic compound, water, can be utilised as a source of hydrogen which in itself offers huge potential for use as a transportation fuel.

A transition to hydrogen fuel offers a number of societal benefits which include a greater degree of energy security, a reduction in pollution levels and a drop in greenhouse gas emissions (Hoffmann, 2012). Addressing each issue in turn, the successful propagation of hydrogen as a transportation fuel would result in a reduced dependency on crude oil for the production of petrol and diesel fuels, a large proportion of which is located in politically sensitive regions of the world, subjecting it to price volatility and resulting in economic and political pressures at home. Used in its cleanest form the only by-product of hydrogen when used in transportation is water, following its reaction with oxygen and resulting energy release. This means exhaust pipe pollutants CO_2, NO_x and SO_x, typically associated with combustion engine (CE) vehicles have the potential to be eliminated, leading to a reduction of inner-city pollution levels. The degree of pollution is however dependent upon the means by which hydrogen fuel is consumed. Direct combustion in a manner similar to petrol and diesel engines still produces NO_x compounds due to the high temperatures involved (Sørensen, 2012). Hydrogen fuel cell vehicles (HFCVs), using hydrogen to produce electricity and power a vehicle battery, emit only water as the by-product thereby reducing overall inner-city NO_x levels. Thirdly, on a global scale, a lower level of greenhouse gas (GHG) emissions is possible when compared to using conventional hydrocarbon fuels in transportation. The degree of reduction is dependent upon the method of hydrogen generation employed as some production processes generate GHGs as by-products thereby offsetting some of

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the gains through its use. The UK Government, through enacting the Climate Change Act, has committed to reducing the level of CO_2 emissions to 80% lower than the 1990 levels by 2050 (Great Britain, *Climate Change Act 2008*) and hydrogen could play a key role in achieving this target. In this context, Spataru et al. (2015) utilised 48% of non-commercial vehicles in the UK being hydrogen fuelled as a means of achieving this target.

Like gasoline, hydrogen is not a primary energy source i.e. it must be created before it can be used, unlike other sources of energy such as coal and natural gas. Hydrogen and gasoline are therefore commonly referred to as energy carriers. Described by Bartels, Pate and Olson (2010) the current main industrial-scale methods of producing hydrogen are either by the steam reforming of methane (SMR) or the gasification of coal, both of which emit CO_2. A third method, the electrolysis of water, accounts for 4% of hydrogen production (Ngoh and Njomo, 2012). The electrolytic generation method involves using electricity to split water into hydrogen and oxygen in an electrolysis cell. Reactions occur at both the positive and negative electrodes when a potential difference is applied. At the positive electrode oxygen is liberated and at the negative electrode hydrogen is formed (Sørensen, 2012).

Whilst the actual production process of hydrogen through electrolysis produces no GHG emissions, the means by which the generation of the required electricity occurred will have an influence on the overall environmental impact. Electricity generation from fossil fuels produces GHGs whereas generation from renewable energy sources (RES) offers perhaps the best means of environmentally sustainable hydrogen production with no GHG emissions from direct operation.

The widespread use of hydrogen as a vehicle fuel currently requires significant supply chain development due to the virtual absence of HFCVs from the UK's road network. Whilst commercial scale hydrogen production already exists, the development of the distribution network to the point of sale is dependent upon the sale of hydrogen vehicles leading to what Kriston, Szabó and Inzelt (2010) term a "chicken and egg problem". Addressing this issue, the UK industry and government formed a coalition to produce a roadmap for the introduction of HFCVs on the UK's roads. It proposed siting the initial filling stations in major cities and connecting roads in the early years through to full population coverage by 2030 (UKH2Mobility, 2013). One means of assisting this in the short-term until the larger scale infrastructure is developed could involve producing hydrogen from locally distributed electrolysers within the towns and cities. The principle materials and utilities, water and electricity, already being widely distributed. Such an approach would contribute to regional sustainability. From a business perspective, the competitive strategy of distributed hydrogen production using RES could be argued as providing a source of hydrogen fuel with the lowest direct carbon footprint possible (albeit at possibly a higher cost than other means of hydrogen production) and from a supply chain design perspective, this research would seek to answer the question of whether the distributed production of hydrogen by RES has the potential to be a viable future supply chain configuration for the UK, subject to local variations in RES availability and whether the environmental benefits offered are acceptable to the UK public by means of a willingness to pay (WTP) a price premium for hydrogen fuel over conventional petrol and diesel fuels.

Insights into the viability of such a supply configuration could be gained by examining environmental and government fiscal policy towards the taxation of hydrogen fuel and whether a subsidy would be required for hydrogen produced from RES to be competitive with conventional hydrocarbon fuels. Specifically: –

Table 1
Abbreviations.

Abbreviations	
CE	Combustion Engine
CRF	Capital Recovery Factor
FiT	Feed-in Tariff
GHG	Greenhouse Gases
HFCV	Hydrogen Fuel Cell Vehicle
LCE	Levelised Cost of Electricity
LPG	Liquefied Petroleum Gas
O&M	Operations & Maintenance
PV	Photovoltaic
RES	Renewable Energy Sources
SMR	Steam Reforming of Methane
VAT	Value Added Tax
WTP	Willingness To Pay

1) Is the importance of environmental concerns reflected in the WTP amount?
2) The determination of a possible taxation level on hydrogen fuel.

The objective of the research is therefore to investigate the extent to which the UK public is prepared to pay for a product that offers greater environmental sustainability.

2. Literature review

Despite the hydrogen supply chain lacking in current physical infrastructure much academic research has already been performed pertaining to future supply chain design in order to meet the market demand for HFCVs (Table 1). A key requirement for the successful transition to hydrogen as a large-scale vehicle fuel is being able to successfully match the emerging hydrogen demand with emerging infrastructure (Melendez & Milbrandt, 2008). This is commonly achieved through the use of mathematical modelling techniques to determine optimal supply chain configurations to meet service requirements at the lowest cost performed on different spatial scales of hydrogen infrastructure. Winskel et al. (2009) in utilising the Markal linear programming model to show the prospects for hydrogen as a future vehicle fuel for buses and cars in the UK running through to the year 2050 and basing the modelling on vehicle lifetime, energy efficiency and capital and maintenance costs with assumptions made for how these costs may change in future. Vehicle penetration levels form the output from the model and so the likely requirements of an aggregated national vehicle hydrogen demand can be made. Modelling performed at a regional level has been used to determine the optimal layout of hydrogen production, storage and transportation infrastructure with which to meet the national hydrogen requirement at the lowest cost. Almansoori and Shah (2006) have performed a number of studies on hydrogen infrastructure applied against Great Britain. Their initial model being further developed and subsequently refined and expanded in later papers. Almansoori and Shah (2006) first presented a single framework for the production, storage and distribution of hydrogen and developed a supply chain based on optimised infrastructure and operational costs. Being a snapshot model of an established hydrogen market it does not consider the development of the infrastructure over time as the number of HFCVs increases. This initial model was refined further in Almansoori and Shah (2009) to include the availability of hydrogen feedstock materials and the scale of the hydrogen production and storage facilities brought about by modelling the infrastructure over five time periods from 2005 to 2034 ranging from 5% market share in the first period to 100% in the fifth. Almansoori and Shah (2012) in their latest research introduced a further spatial scale to their model giving consideration to filling stations within a particular geographic area in terms of number, operating cost and the