STATE-OF-THE-ART MODELLING OF HYDROGEN INFRASTRUCTURE DEVELOPMENT FOR THE UK:
Geographical, temporal and technological optimisation modelling

Final Report on Modelling Methodology and Modelling Outputs
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Executive Summary

Overview and key modelling goals

Hydrogen (H$_2$) infrastructures and technologies offer the possibility of radical and deep cuts in carbon dioxide (CO$_2$) emissions in the long-term, notably in the transport sector. However, the long-term role of any new H$_2$ infrastructure in a future decarbonised UK energy system is highly uncertain. Two key considerations are the distribution of hydrogen (spatial aspects), and its potential role in energy storage (temporal aspects).

Firstly, understanding spatial considerations is important as H$_2$ has no existing transmission infrastructure and is expected to develop initially in local/regional clusters. Secondly, understanding temporal aspects is important considering the potential requirement to store significant amounts of H$_2$, especially if it were required to meet both transportation demands and provide a balancing mechanism in electricity provision.

This final report presents key findings from an innovative research project under the DfT Horizons programme to quantify a range of long-run scenarios of H$_2$ infrastructure development under deep CO$_2$ constraints, and compare the results of introducing spatial and temporal detail. These analytical extensions were anchored in the UK MARKAL energy systems model to provide a consistent framework to account for multiple interactions between a future H$_2$ economy and different resources, energy carriers and sectoral demands.

Modelling methodology

Two extended MARKAL models were constructed to investigate spatial and temporal drivers of H$_2$ infrastructure development. Computational constraints means that the two models were not linked. The spatial MARKAL model was constructed with a Geographical Information Systems (GIS) based interface of plausible gaseous and liquid H$_2$ infrastructures and delivery systems. The temporal MARKAL model was constructed with substantially enhanced representation of energy service demands, resources, and power sector operation to better model daily load duration curves as well as explicit consideration of the role of H$_2$ and other energy storage options.
A hydrogen expert stakeholder workshop (held at DfT on January 8th 2007), was instrumental in defining the drivers (and hence model parameters) of H₂ infrastructures. This led the development of both the spatial and temporal model extensions.

The spatial model used GIS analysis of population and economic drivers, to define 12 demand regions (9 key urban areas, and 3 aggregated areas). Energy service demand and technology data for hydrogen and other transport pathways was then disaggregated to these regions. Similarly, 6 UK H₂ supply points were defined based on GIS analysis of UK energy resources, sites for carbon capture and sequestration (CCS), and liquid H₂ and LNG terminals. H₂ infrastructures options for combinations of transport and stationary applications were then mapped onto the supply-demand regions. Future H₂ infrastructures (liquid delivery by tankers, gaseous pipeline networks, and small scale production) were modelled using discrete or integer investments to recognize the minimum operational size for economic H₂ infrastructure components as these are sequentially built up in the coming decades.

The temporal model's diurnal and seasonal detail was extended to address issues of approximating the electric load demand, and to allow both energy service demands and renewable energy resources to be disaggregated based on availability. Explicit demand side (plug-in hybrid vehicles, night storage heaters) and supply side (pumped hydro, and hydrogen) storage technologies were parameterised and incorporated into the revised model.

**Modelling scenarios**

An exploratory set of long-run UK energy scenarios were run for the spatial and temporal models based on back-casting scenarios focusing on a -60% reduction in UK CO₂ emissions (C60). These were broadly consistent with the general equilibrium MARKAL-Macro assumption sets generated for the 2007 UK Energy White Paper, but this new MARKAL model variant is not directly comparable to the EWP analysis. In particular, this analysis entails the full representation of air transport by including international aviation in an attempt to analyze possible H₂ deployments at airports. Hence, the results from this work should not be viewed in relative terms to these previous policy relevant analysis, but rather in a ‘what if’ framework to see how H₂ infrastructure might develop when the UK’s geography is taken into account under various scenarios.
Spatial model extension results

The spatial model entails additional discounted cumulative costs (compared to a geographically averaged approach) of £14.6 from 2000-2050 (equating to an 18.4% increase). This additional cost translates into a marginal price rise from £170/tCO$_2$ to £219/tCO$_2$. Hence, it is interesting that H$_2$ infrastructure costs rise compared to previous standard estimates of H$_2$ costs. This finding indicates that when the UK's topology and settlement patterns are taken into account, actual transmission distances (and hence costs) are significantly higher than an averaged approach. However in the non-spatial model, imposing a CO$_2$ constraint entails less H$_2$ due to resource constraints on zero-carbon production. The reverse is true under a spatial model. Higher H$_2$ costs entail less H$_2$ in the base case but increased H$_2$ due to the potential for geographically matching supply and demand. The share of H$_2$ in transport energy rises from 12% in the base case to 36% in the C60 case.

An intuitive matching of H$_2$ supply points with demand regions is found. Crucially, in all H$_2$ delivery modes, the model seeks to cluster demands if possible in order to benefit from economies of scale in supply and distribution. Furthermore, increased use of H$_2$ in the DfT spatial model entails radical changes in other sectors, notably the electricity network, as they compete for resources (and in C60 scenarios for CCS capacity).

Focusing on H$_2$ pathways, in the C60 case, a major expansion occurs as in addition to buses and HGV vehicles the urban car fleet is serviced with H$_2$. In most runs, imported liquid H$_2$ and a liquid H$_2$ distribution mechanism is preferred. Pipelines are restricted to niche applications at ~10% of H$_2$ supply. The minor use of pipelines reflects the long construction lead times and resultant early under-utilised capacity.

Given that H$_2$ imports are cost optimal under these model assumptions, a sensitivity run with only domestically sourced H$_2$ showed an additional cumulative cost of £6.1 and a very different supply-demand hydrogen configuration. Without H$_2$ imports, significantly less H$_2$ is used as part of a CO$_2$ reduction strategy (down from 652 PJ to 197 PJ) illustrating that personal car transport does not switch to H$_2$ vehicles by 2050. With no imported H$_2$, and CCS capacity still being used by the power sector, Scottish renewables now provide more than 50% of UK H$_2$ demand in 2040 and by 2050 this rate increases to 85%. Liquid H$_2$ delivery from Scotland stretches from South Scotland down to the Midlands.

Finally a set of sensitivity runs illustrate how the model reacts when additional constraints are placed on the system. Meeting a -80% CO$_2$ reduction scenarios entails a severe convexity in
costs with CO₂ marginal prices rising to £500/TCO₂. This expensive marginal prices reflects that now 54% of all transport demand is based on H₂ (now including H₂ for international aircraft). Imported H₂ and demand clustering for economies of production remain important.

**Temporal model extension results**

The temporal model extension paints a complex picture of future hydrogen pathways, and specifically for the potentially important role of energy storage. A range of parametric model runs (under both base and -60% CO₂ constraints), investigated the role of demand-side storage (plug-in hybrid vehicles and night storage heaters) and supply-side storage (pumped hydro and hydrogen).

It is clear that electricity storage is important as a power system balancing mechanism. On average, the system chooses about 7 - 10% of electricity demand as storage. Demand side storage is preferred, partly due to their lower operational costs. Hydrogen storage is greatly preferred to be used in the transport sector rather than buffer the electricity network.

Storage has a profound effect on the electricity sector which is driven by both generation and capacity requirements. Additional storage allows base-load plant to be better utilized (up to 80% under the base case and 65% under the CO₂ constrained case). The inclusion of plug-in hybrid vehicles results in night-time electricity loads being highest as large volumes of power are delivered to charge these vehicles.

Generally the transport (car) fleet moves to a significant share of plug-in hybrid vehicles, both because they act as a cost effective demand side storage option, and due to their efficiency advantages versus conventional IC engines or hybrid vehicles. Overall the transport sector under a CO₂ constrained scenario realises a 35-40% H₂ share, in the bus, HGV and car sectors. This H₂ is sourced from coal supplemented by electrolysis in the base runs, while coal CCS and increasing imports of H₂ are preferred in the CO₂ case. If plug-in hybrids are restricted and there is less demand for power, more CCS capacity is freed up for H₂ production.

**Key conclusions and future work**

While UK Government policy on future technology options in transport has regularly referred to the introduction of H₂ from low-carbon sources, there has not been a explicit vision of how
an infrastructure for H₂ production and distribution could develop. Exploratory modelling under spatial and temporal extensions to the UK MARKAL model, illustrate a range of key findings for the role of hydrogen in -60% UK reduction in CO₂ emissions:

- the importance of matching H₂ supply points and demand regions
- the strong preference for a small number of large-scale H₂ supply centres serving a network of multiple transport mode and regional demands
- the economic competitiveness of large-scale imported H₂
- under security of supply concerns, the potential role of Scottish renewable sourced H₂
- the preferred route of liquid H₂ distribution
- the interplays between different demand and supply side electricity storage options (notably plug-in hybrid vehicles).

Last, the combined results of these model runs encourage us therefore to think creatively about the ways in which the often hitherto unconnected power and transport sectors could by policy measures be joined up in order to make more efficient use of scarce energy resources, or new infrastructures.

Future spatial modelling work will focus on alternate supply-demand configurations, and detailed ‘what-if’ analysis to ascertain the tipping points between resource options, and transport modal take-up of H₂ and use of alternate infrastructures. Future temporal modelling work will seek to incorporate a dedicated power sector sub-module with period-to-period storage to allow investigation of H₂ storage and intermittency.

Acknowledgement

A number of recent policy relevant analyses (by researchers at PSI, Kings College London, and AEA Energy and Environment), on long-term deep (-60%) CO₂ reductions have been conducted with variants of the UK MARKAL model. These have included:

- Underpinning research using the MARKAL and MARKAL-Macro (M-M) variant models for DBERR and DEFRA for the Energy White Paper (see http://www.dti.gov.uk/energy/whitepaper/page39534.html)
• Additional work for DEFRA using the M-M model on more stringent (up to -80%) CO₂ reductions (see http://www.defra.gov.uk/environment/climatechange/research/index.htm#markal)

• Research using the M-M model for IPPR and WWF on more stringent (up to -80%) CO₂ reductions (see http://www.ippr.org.uk/publicationsandreports/publication.asp?id=572)

• Research undertaken for UKERC using the M-M model on international drivers on long-term UK CO₂ reductions

• This research project for DfT Horizons using a new MARKAL GIS model, investigating spatial and temporal aspects of hydrogen infrastructures

A critical point is that these are different models with some individual assumptions changed and hence they are NOT intended to be comparable. The DfT Horizons assumptions (bar the hydrogen-specific spatial and temporal assumptions) were made coherent to the earlier work for IPPR and WWF. However the great majority of assumptions are also consistent with the DEFRA work and earlier DBERR work underpinning the Energy White Paper.