Review of modelling approaches to the development of a ‘hydrogen economy’

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1 Introduction

The possible future development of a ‘hydrogen (H_2) economy’ has been subject to much speculation, discussion and analysis. As such energy systems do not yet exist, much of this analysis has been through scenarios exercises and/or quantification through the form of computer models, examining the ways in which hydrogen may develop as an energy vector.

These models have taken a variety of approach, often based on existing methods to modelling other aspects of the energy system, or indeed expanding such existing models to include hydrogen. There are number of challenges inherent to the development of a hydrogen economy that need to be represented within the modelling approach, in order that the analysis produced provides a reasonable analysis of the possible pathways for hydrogen development.

Section 2 discusses three of the main challenges in such modelling:

- competition for primary energy resources with other parts of the energy system;
- the inherently spatial nature of hydrogen infrastructure development;
- the level of technical detail required to appropriately represent the various hydrogen pathways.

It is noted that a number of additional factors may well be important in modelling any transition to a hydrogen economy including behavioural change and attitudes to risk, and institutional drivers at the regional or urban/rural level. Other working papers in the UKSHEC series investigate these issues (see for example Ricci, 2006; Hodson, and Marvin, 2005).

Sections 3 and 4 of this working paper then categorise a number of aspects of the approaches to hydrogen modelling, especially with regard to optimisation models versus those based on a scenario approach.

2 Challenges and methodologies in hydrogen modelling

2.1 Resource competition

A model that seeks to analyse the merits of different pathways for hydrogen supply will include a number of options that would depend on primary energy resources which could be used elsewhere in the energy system. Prime examples of this are the use of renewable electricity for hydrogen production via electrolysis vs. its direct use in the electricity system, and the reforming of natural gas or bio-methane into hydrogen vs. using that methane direct for residential heating.

Where no account is taken in the hydrogen modelling of these alternative uses of the primary energy resources, the results can be misleading. For example, as discussed by Eyre, Fergusson and Mills (2002), while renewable electrolysis could lead to a near-zero CO_2 footprint for hydrogen supply, in most situations it would actually lead to higher CO_2 emissions than using the same renewable electricity to displace fossil generation in the electricity system.

In addition to analysis of the impact of different pathways for hydrogen supply on the CO_2 emissions from the energy system as a whole, resource competition tend to provide an insight into future energy prices. In most developed countries, the price of energy in competitive energy markets is the product of demand and supply for that resource. Simple projections for the evolution of energy prices that do not include the impacts of resource competition on future demands are likely to diverge from actual prices more quickly than those that include such interactions.

2.2 The spatial dimension of hydrogen infrastructure development

Due to the difficulties and expense of distributing hydrogen, the development of H_2 infrastructure is, by necessity, likely to be highly geographically dependent. Variation in available resources, carbon sinks and density of demand in different locations (notably urban vs. rural) are likely to lead to infrastructures that differ in capacity, length, sectoral coverage, and the degree of centralisation[1].

A non-geographical model is intrinsically limited in representing these issues properly, although efforts can be made to 'guide' the model by use of bounds on energy chains and other constraints/assumptions. The issues faced in representing the modelled region's geography/demographics are essentially two-fold: representation of the use of local resources/sinks; and the degree of centralisation of the infrastructure. For a non-spatial model, the use of local resources (or CO_2 sinks) for H_2 production can be tackled 'offline' by bounding energy chains to supply no more than the proportion of demand is within a certain distance of these resources.

However, the degree of infrastructure centralisation is much more difficult to represent. The optimal solution to how centralised H_2 infrastructure should be is a trade-off between the economies of scale available in H_2 production and the costs of H_2 distribution. While the economies of scale for production are known, or can be estimated, costs of H_2 distribution – particularly for pipelines – are strongly dependent on the distribution distance and flow rate. Research by Yang and Ogden (2004) has shown that the least cost option depends on distance and capacity, as illustrated in Figure 1.

Figure 1 Least-cost H_2 distribution method as a function of distance and flow rate[2]

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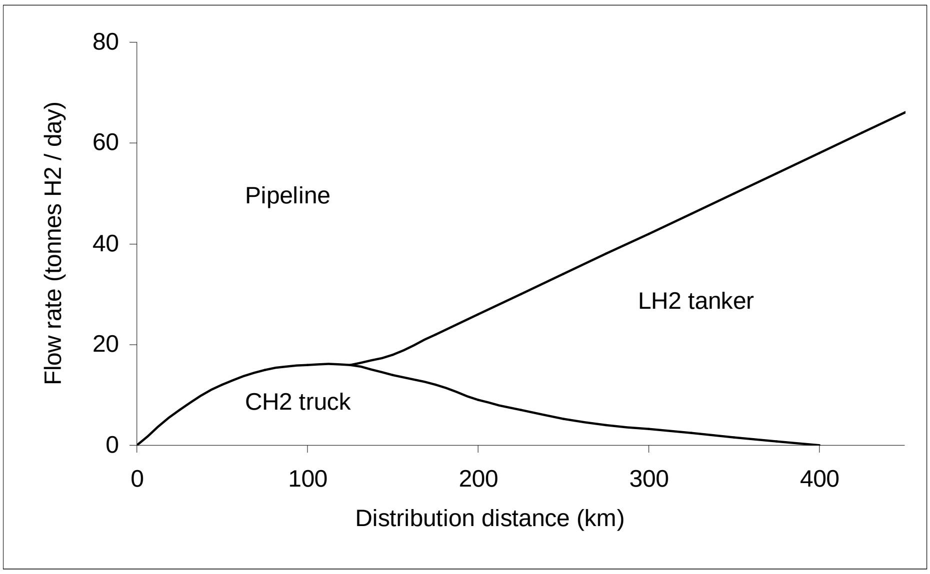
[1] For detailed discussion of this see Joan Ogden's work at Princeton and UC Davis, for example Ogden (1999)

[2] The exact trade-offs between the different distribution modes will depend on energy prices, changes in technology costs and other things such as policy interventions. However, while the 'switching points' may shift, the underlying relationships remain the same and the shapes on the graphs would be largely unchanged.



Adapted from Yang & Ogden (2004)

Therefore, without geographical representation of demand and potential production sites, it is difficult to represent the distribution distances and flow rates with satisfactory accuracy. Approximations can be made using discrete infrastructure options or modelling transmission vs. distribution systems in a similar framework as natural gas networks. As such, increases in H_2 distribution costs with increasing centralisation are only roughly gauged and it is therefore difficult to identify the appropriate degree of centralisation, based on the aforementioned trade-off.

2.3 Level of technical detail

2.3.1 Temporal variations and the role of energy storage

Many models do not represent the temporal variations of energy supply and demand in sufficient detail to accurately analyse the potential role of energy storage technologies, of which hydrogen may be one. The ability to store energy is essential in any energy system, whether this is in the form of primary energy (coal, natural gas, biomass, hydro); indirect storage of electricity (batteries, pumped hydro, super-capacitors); or as hydrogen. In particular, storage of electricity to buffer variations in both supply and demand is essential, especially in a context of an increasing proportion of inflexible power generation (nuclear and renewables, except hydro).

Demand for storage services – both inflows and outflows – are a residual, dependent on the difference between demand and available supply at any given time. This makes the need for storage very sensitive to relatively small changes in demand and/or supply. Modelling of energy storage requirements and performance is therefore crucially dependent on the level of detail with which the variations of demand and supply are characterised, on both the seasonal and diurnal timescales.

2.3.2 Constraints on infrastructure operation

While many models use a relatively simple representation of the technologies that would be used in a hydrogen infrastructure, this can potentially miss important aspects of how these technologies can be operated. For example steam methane reformer (SMR) plants operate at high temperatures, and the time taken to cool and heat up properly means that a shut-down results in unavailability for 24 hours. They must also be operated at a minimum 30% of capacity to avoid significant damage to the reformer. As such, this 30% is effectively the minimum level of demand which should be in place before the SMR is installed.

Electrolysers also have operating constraints, such as a minimum load of around 25%, due to the danger of significant proportions of oxygen mixing with the hydrogen output stream at lower loads (Joffe, 2003). When operating on intermittent sources of electricity, this can potentially cause significant problems, potentially requiring buffering of the electricity supply with batteries. However, recent developments in PEM electrolysers are claimed to have solved the problem of operation on intermittent power supplies.

Models that ignore these constraints can potentially assume infrastructures that are technically unviable, or at least suboptimal.

2.3.3 Hydrogen demand technologies

Hydrogen based technologies, for both the transport and the power sectors (including micro-generation) are at an immature stage of technical development, when compared with current incumbent technologies. This is due firstly to technical parameters, including operation aspects of fuel cells of internal combustion engines as well as their integration with reformers, storage, liquefaction (as required), power electronics, heat exchangers, emissions control etc. These technical parameters have a major impact of efficiencies, availabilities, lifetime, range (for transport), power output, weight and size with resulting implications for the fixed and variable costs of operating these technologies. A second issue is the economic development of such immature technologies, which is partly related to engineering improvements but also to economies of scale, economies of learning in production and the development of niche markets (see Agnolucci and Ekins (2007) for further discussion). Models tend to deal with these future economics costs through technological vintages or learning curves (exogenous and endogenous).

2.4 Categorisation of modelling approaches

A variety of modelling approaches have been taken when looking at the development of hydrogen, often driven by a particular set of questions to be addressed. Almost inevitably, the choice of modelling framework will result in some question being answered well and others less well. There are three aspects to modelling of hydrogen that appear to characterise the modelling approach:

- **Optimisation vs. ‘scenario’-based models**: optimisation models generally provide a least-cost approach to modelling hydrogen development. Their results are ‘optimal’ in terms of the way the model is defined and the constraints within which it is allowed to reach its solution. However, such models can often produce results which, while being optimal in this sense, are felt to be unrealistic in the real world, due to constraints that are not – and sometimes cannot be – included in the model. ‘Scenario’-based models are therefore sometimes used to produce more ‘realistic’ stories to describe the development of hydrogen, although can give far less information on the relative economics of hydrogen energy supply and distribution.

- **Spatial vs. non-spatial models**: the importance of the spatial dimension of hydrogen infrastructure means that any model that tries to capture infrastructure development in any detail must either have a spatial element or a way or representing this aspect within the model. This latter approach will often have an ‘off-line’ assessment of possible infrastructures relating to different pathways for hydrogen development.

- **Internal resource competition vs. external methods**: models that narrowly look at the development of hydrogen can often miss aspects of its interaction with the wider energy system, especially with regard to the use of primary energy resources in different sectors. While competition for such resources can potentially be captured within projections for energy prices – the result of resource competition – this is an indirect method, making it less likely to properly capture this competition appropriately.

The following sections review approaches that have been taken to hydrogen modelling, grouped into optimisation and non-optimisation models. A particular focus of this review is how each of these models addresses the issues of resource competitions and the spatial development of hydrogen infrastructure.

3 Optimisation models

Optimisation models that have been applied to hydrogen infrastructure have taken a number of approaches. However, a fundamental aspect of each of these models is that the optimisation is based on life cycle cost minimisation. For some models, this covers the costs of the hydrogen technologies and energy costs, while other models including monetary valuations of other consequences of hydrogen infrastructure develop, such as CO_2 emissions and effect on driving time.

3.1 The MARKAL modelling framework

The MARKAL (MARKet ALlocation) modelling framework is a highly used optimization framework with over 30 years development through the International Energy Agency’s ETSAP network and around 100 active teams in over 30 countries. MARKAL is a data-driven, technology-rich energy systems economic optimisation modelling framework. It encompasses the entire energy system, from the resource base to end-use sectors, with a wide variety of technologies and options for conversion and distribution in between. It is an optimisation model that minimises the overall costs of the energy system, given the demands, available resources, technologies and constraints. The model is driven by subsectoral energy service demands, e.g. the demand for lighting, space heating or bus-kilometres. By representing demand for energy services rather than energy itself, the model can substitute end-use technologies. This enables the model to meet the service demand with a technology that consumes less energy (e.g. a low-energy light bulb or a fuel cell bus).

To construct a country or regional model, the specific characteristics of that energy system are mapped into the model including a highly detailed and validated set of resource, process, conversion and end-use technologies, disaggregated energy demands, and constraints based on physical, regulatory and policy factors. The model is exactly calibrated to actual resources supplies, energy consumption, electricity output and installed technology capacity in the base year (generally 2000), and then evolves in 5-year time steps through to the model horizon, in a consistent and powerful ‘what-if’ framework.

MARKAL is a ‘bottom-up’ modelling framework, which means that its results are driven by the detail of the available resources, service demands and technologies. As such, it is necessary to have a model that is rich in technology detail, both on economic and technical characteristics (e.g., investment costs, efficiency etc). Different approaches to the representation of hydrogen within the MARKAL modelling framework are discussed below. These issues are explored in more detail in UKSHEC Working Paper 28 (Joffe et al, 2007).

3.1.1 Strengths and weaknesses

One of the major strengths of MARKAL is that it represents the entire energy system and the entire energy chains from primary energy resource to energy service demand. This allows the model to choose *combinations* of primary energy resources and technologies in minimising the cost of meeting energy service demands within the specified constraints. Hence it can identify synergies between measures on the demand and supply sides, as well as the infrastructures that connects them.

This, in turn, allows competition in areas of the energy system not captured by more specific models that focus only on part of the system. For instance, competition could be for finite primary energy resources between different energy carriers, e.g. electricity and hydrogen, which might be used for differing end uses, such as domestic energy vs. transport.

Imposition of a CO_2 emissions (or other policy) constraints add an extra dimension to this competition, as it enables the optimisation of the energy system for cost-effective emissions reduction. The use of resources is then driven not only by cost, but also by the efficiency of whole energy chain and consequent emissions per unit of energy service. This enables the best use to be identified for low-carbon energy sources in reducing CO_2 emissions, e.g. renewable electricity being used directly as electricity or natural gas used in for combined heat and power (CHP).

One of difficulties of representing infrastructure in linear programming (LP) models such as MARKAL has been that discrete, large investments can be difficult to represent properly. This is because the model will try to build a fraction of such investments, e.g. half a nuclear plant or 10% of a ‘fat’ hydrogen pipeline. This has been addressed within MARKAL by the introduction of a ‘lumpy investment’ option which only allows whole numbers of certain large scale investments to occur. The use of this feature turns MARKAL into a mixed-integer linear program.[3]

The fact that MARKAL is a model of the entire energy system means that it is inevitably less detailed than models specifically designed only to look at one part of the system. This is a consequence of the integrated energy system approach and it therefore becomes important to understand and minimise the extent to which its simplifications impact on the model results. These include are two key areas which are important for representation of hydrogen within the energy system:

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[3] A range of further MARKAL variants address additional methodological issues, including a Macro component (via non-linear programming) to investigate macro-economic implications, elastic demands to endogenous behavioural change, stochastic approaches for characterizing uncertainty and goal programming and other near optimal solutions.

- **Energy storage** – standard MARKAL uses 2 time-slices in each of 3 seasons, combined with a peaking requirement to represent typical peak, shoulder and base-load demand periods in the electricity sector. However, this resolution may not provide sufficient detail to represent potential imbalances in energy supply and demand within each entire day of the year. Increasing the resolution with which electricity demand and available capacity are characterised would improve the MARKAL model's representation of the demand for storage services, and therefore the need for storage technologies in the electricity system. Furthermore, the possibility to use hydrogen to store energy offers the option either to re-generate electricity or to use this hydrogen in the transport sector.

- **Spatial representation –** as a non-geographical model, MARKAL is inherently limited in directly representing the spatial aspects of the energy system, such as the locations of resources and demands, as well as the infrastructure required to link the two. There are approximations to representing many types of infrastructures within a model such as MARKAL, although this is potentially more complex for hydrogen as a completely new infrastructure would be required.

A number of approaches have been taken for the treatment of hydrogen distribution within MARKAL modelling and these are described in the following sections.

3.1.2 The US Environmental Protection Agency (US EPA) MARKAL model

Rather than allowing a choice of distribution options, the US EPA MARKAL model assigns it a distribution method to each scale of H_2 production technology. The H_2 production-distribution combination is then the infrastructure required to supply delivered hydrogen for use, e.g. at a fuelling station.

The US EPA approach has different distribution infrastructures, corresponding to their different scales of H_2 production: Central Station, Midsize and Distributed. The distributed scale H_2 production requires no distribution infrastructure, while each of the other two scales had their own corresponding H_2 distribution infrastructure. These infrastructures were based on analysis based on National Research Council et al (2004). These distribution options were generic and applied across the entire US.

The options in the model have been constructed to form complete 'production plus delivery' infrastructures, each of which would supply hydrogen all the way to the end user. For the large-scale production facilities, pipeline distribution is assumed, while the mid-size production is combined with H_2 liquefaction and distribution by road. The decentralised production option requires no distribution infrastructure.

As such, each of the options is equivalent from the end users perspective and the option selected by the model is therefore simply a function of the size and growth rate of demand. The model uses the lumpy investment option to ensure that only whole numbers of each option can be selected. Only transport related hydrogen applications are considered in the US EPA model

The US EPA MARKAL model uses an limited subset of 'aggregated' representation of H_2 infrastructure. However this ensures options for 'delivered' hydrogen compete on a level playing field, and that only plausible solutions for H_2 infrastructure development are considered.

3.1.3 The ECN MARKAL model

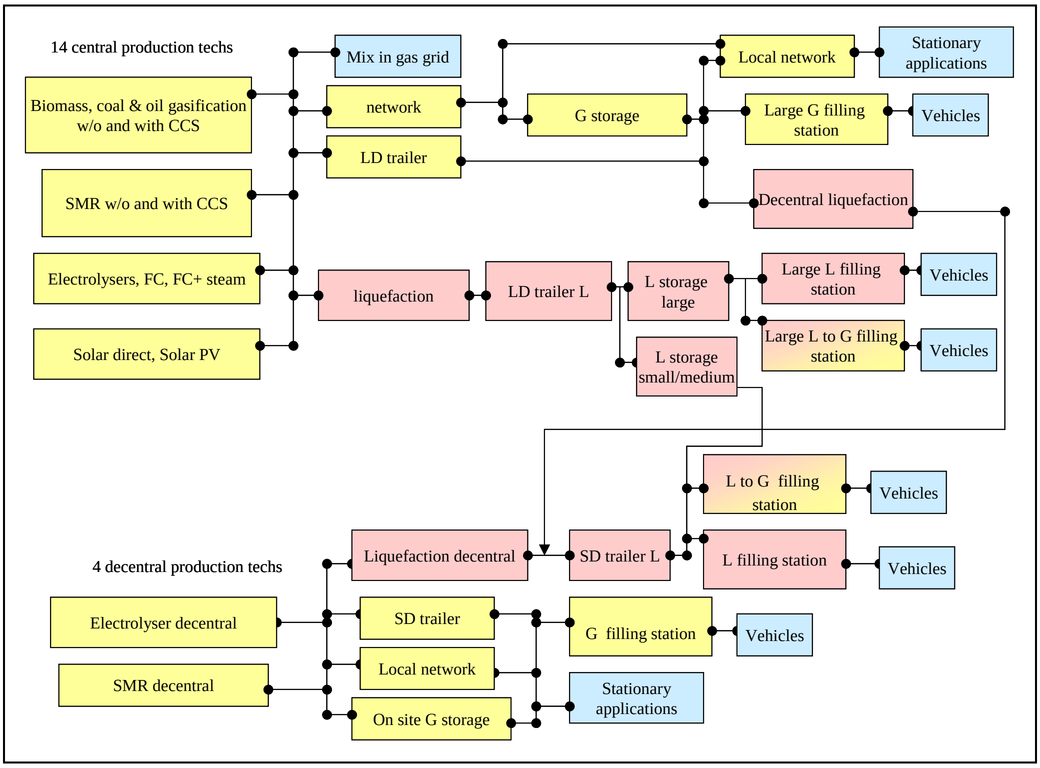
The ECN MARKAL model is being used as part of the EC HyWays project to develop a roadmap for hydrogen and fuel cells in the European Union, as well as another EU project titled Cascade Mints. The modelling of hydrogen using MARKAL is an extension of ECN's existing MARKAL model for Western Europe, incorporating a greater level of detail and sophistication than the previous characterisation (Martinus et al, 2005).

As detailed in Figure 2, the ECN model has very considerable detail on hydrogen production (both centralized and decentralized), using electrolysis, steam methane reforming and gasification of coal or biomass. Major storage and transportation options include:

- distribution by road in compressed or liquid form;
- development of a dedicated H_2 pipeline distribution network; or
- mixing H_2 with natural gas in the existing pipeline system.

Finally a full set of end-use technologies are depicted in the transport, buildings and industrial sectors.

Figure 2 Summary depiction of ECN MARKAL hydrogen chains



Adapted from Martinus et al (2005)

As discussed in section 2.2, the least-cost method of distributing pure hydrogen depends both on the flow rate and the distribution distance and representation of pipeline distribution is difficult in an optimization framework. This issue of distances is handled by drawing a distinction between the local hydrogen 'distribution' pipeline systems and longer distance 'transmission' pipelines, in a similar way to the treatment of natural gas pipeline infrastructure, and by using the ‘lumpy investment’ MARKAL feature for different capacities of pipeline to be specified but only of each built. This allows a description of how incremental unit cost of energy transmission capacity falls substantially with increasing diameter, and therefore capacity (Yang & Ogden, 2004).

The ECN MARKAL model allows the model the flexibility to choose appropriate combinations of H_2 production and distribution technologies. However, while this flexibility allows a large number of plausible solutions for H_2 infrastructure development, it also allows some implausible solutions as well.

3.1.4 The UK MARKAL model

The UK MARKAL model as been extensively updated by the Policy Studies Institute on behalf of the UK Energy Research Centre (UKERC). The UK MARKAL model represents centralized hydrogen production via coal, biomass and waste gasification, electrolysis, and steam methane reforming. With the addition of liquid hydrogen imports, these options are distributed via gaseous hydrogen by road (tube trailers), gaseous hydrogen by dedicated pipeline or liquefied hydrogen by road. Transmission and distribution is split out allowing different transport modes and micro-generation to face different distribution costs based on Yang and Ogden (2004). Through the use of the electricity and natural gas distribution networks, small scale hydrogen production competes with large scale H_2 provision, to flow to hydrogen end-use technologies by transport mode (fuel cell and ICE vehicles) as well as micro-generation by sector and hydrogen storage options. This detailed approach to hydrogen energy pathways results in a similar approach to the ECN model.

Similarly to other energy system optimization model the UK MARKAL model is limited in its temporal detail for energy storage, and spatial details for infrastructure development. However, under an ongoing project funded by the UK Department for Transport, this approach is being changed, to incorporate improved representation of temporal and spatial aspects (Strachan et al, 2007). The spatial aspect of H_2 infrastructure is being addressed by soft-linking to a GIS-based spatial model of H_2 infrastructure development for the UK. Linking an energy system model to a GIS framework has been in discussion at ETSAP and other energy modelling forum, with Biberacher (2006) giving one example of a methodology to undertake this.

This model will represent plausible spatial infrastructures, corresponding to the locations of different options, especially with regard to resources, and the distribution options appropriate to differing scales of hydrogen production. Connecting MARKAL to a spatial model of infrastructure development will produce results that combine the strengths of both approaches: an integrated energy system model that incorporates a geographical representation of how energy infrastructure develops. This change in approach brings the model’s representation of hydrogen closer to the US EPA approach of specifying distribution infrastructures ‘off-line’. However, unlike the US EPA model, the infrastructures in the UK GIS-MARKAL modelling framework will have the potential to be geographically-specific, rather than simply depending on the scale of production. It will have the capability to represent any number of H_2 infrastructures, based on the actual geography of the UK and the locations of primary energy resources, carbon sinks, existing energy infrastructure and likely H_2 demand.

Additionally, under this project, the resolution with which both demand and supply are captured will be substantially improved by further work to extend the number of time-slices available to the model from the current seven to around thirty (both diurnal and seasonal) to better match actual UK demand profiles maximum. This will enable the model to better capture the need for flexible plant and energy storage services, especially related to peak demands.

3.2 Spatial hydrogen infrastructure optimisation models

Models developed to 'optimise' the development of hydrogen supply infrastructures tend to incorporate a spatial dimension to the representation of demand and the supply infrastructure. However, to date at least, they have not internalised any aspect of resource competition within the optimisation[4], relying instead on projections of future energy prices. Such an internalisation would require a sufficient representation of the rest of the energy system to capture the effects on the entire system of the choice of hydrogen supply pathways.

3.2.1 The *bpIC-H2* model

The *bpIC-H2* model by Hugo et al (2005) developed by BP Gas Power & Renewables and the Centre for Process Systems Engineering at Imperial College London is a good example of this approach to hydrogen infrastructure optimisation. A mixed-integer linear programming (MILP) model, it contains a representation of a wide range of hydrogen technologies.

Importantly, it also incorporates spatial representation of sites of hydrogen demand – with evolving demand over a time horizon of 20 years or more – and potential production. This aspects enable it to dynamically optimise hydrogen infrastructure development, including the trade-offs between centralised vs. decentralised infrastructures. However, its representation of the spatial aspects of the issue is limited to these specified sites of hydrogen demand and a number of specified potential hydrogen production sites

As well as the costs associated with hydrogen infrastructures, this model also tracks CO_2 emissions during the optimisation. As with MARKAL, a constraint can be imposed on the maximum CO_2 emissions allowed during a given run. This functionality enabled Hugo et al to present the curve in Figure 3, which shows the trade-off between hydrogen supply infrastructure costs and CO_2 emissions, over a range of allowed CO_2 emissions. The solutions on this curve represent only a subset of the possible hydrogen infrastructures; many other infrastructures are possible but are not least-cost under the CO_2 constraint imposed, i.e. they are somewhere below this curve.

However, while the trade-off between cost and CO_2 emissions is important for consideration of hydrogen infrastructures, the model's optimisation algorithm does not include resource competition with other sectors. This means that careful interpretation of its results is needed to identify the infrastructures that would result in cost-effective CO_2 emissions reduction within the energy system as a whole.

Furthermore, while the model contains sufficient representation of hydrogen technologies to include both the associated costs and CO_2 emissions, it is essentially a high-level tool. It does not include constraints on the operation of the technologies,

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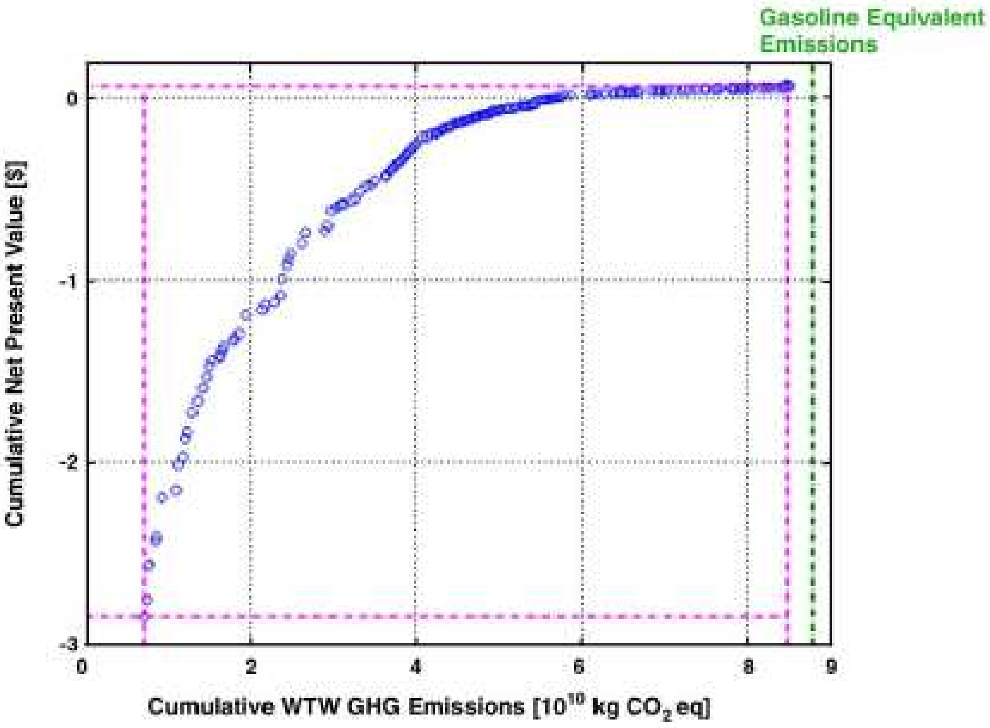
[4] Other energy system interactions are also not included (e.g., demand vs. supply side efficiency improvements)

nor does it have any representation of the variability of resources on a seasonal or within-day basis.

Figure 3 Optimal trade-off curve between cost and CO_2 produced by the bpIC-H2 model



Source: Hugo et al (2005)

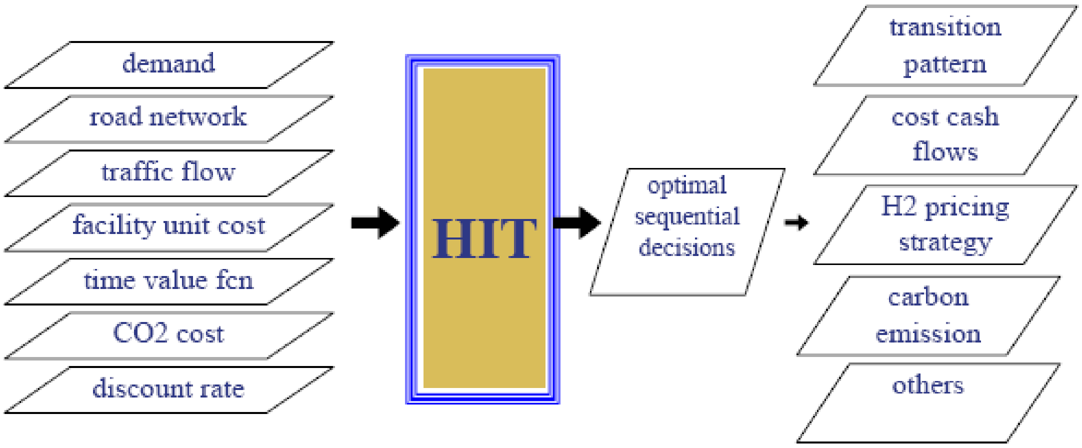
3.2.2 The Hydrogen Infrastructure Transition (HIT) model

The Hydrogen Infrastructure Transition (HIT) model developed at the University of California, Davis is another spatial optimisation model, this time based on a dynamic programming (DP) approach (Lin et al, 2006). HIT has a much greater representation of spatial information than the *bpIC-H2* model, including road networks and traffic flows, as well as hydrogen demand distribution. A schematic of the HIT model is presented in Figure 4.

The HIT model is used to determine the ‘optimal’ decisions for the development of hydrogen infrastructure. These decisions are then used for further calculations and analysis, based on engineering economics.

The HIT model is the only model reviewed here that considers the optimal build-up of refuelling facilities over time, for a given exogenous-determined build-up of hydrogen penetration from private vehicles. In order to do this, it trades off the coverage of fuelling stations and the driving time required to get to the nearest station. The driving time is calculated using spatial information about the road network and its associated traffic flows, and a monetary value is attached to this driving time so that it can be included in the optimisation model. This element of the model is based on the work of Nicholas et al (2004).

Figure 4 Schematic of the UC Davis Hydrogen Infrastructure Transitions model



Source: Lin et al (2006)

HIT also tracks CO_2 emissions, but rather than this mainly being used at the constraint level, as per the use of the *bpIC-H2* and MARKAL models, a monetary value is attached to the CO_2 emissions. This is in the form of a uniform ‘carbon tax’, rather than a damage costs, due to the lack of data availability for damage costs associated with climate change in particular regions.

The model is purely focused on hydrogen infrastructure and therefore does not include any explicit aspect of resource competition; energy prices are an exogenous input. While designed generically, for potential widespread applicability, the HIT model has been applied as a case study to the city of Beijing, in Lin et al (2006).

3.2.3 Other spatial optimisation models of hydrogen infrastructure

Other spatial optimisation modelling of hydrogen infrastructure development has been undertaken at Imperial College London by Martin and Rahal, as part of the European HyWays project, and by Stamatina-Parissis. Whereas the modelling by Hugo had been a generic approach that was not specifically applied to any particular country or region, Martin and Rahal’s model was run for a number of European member states: France, Germany, Greece, Italy, the Netherlands and Norway. Stamatina-Parissis’s modelling work has focussed on the optimisation of renewable hydrogen supply to urban centres in the UK (Stamatina-Parissis et al, 2005).

4 ‘Scenario’-based models

While scenario-based models depart from the above focus on ‘optimality’, they attempt to model the consequences and implications of multiple plausible storylines, or scenarios. The move away from a modelling sense of optimality enables these scenarios to include ‘soft’ drivers and constraints that are difficult to model, and therefore to include in an optimisation. By externalising the decision-making aspect of the development of the system in question, such drivers and constraints can be included more fully. The role of the model is then to calculate the implications of such scenarios; in the case of hydrogen scenario models, these implications normally focus on the hydrogen infrastructure and energy system costs, as well as CO_2 and other pollutant emissions.

4.1 Tyndall Hydrogen Energy Scenario Investigation Suite (THESIS)

The Tyndall Hydrogen Energy Scenario Investigation Suite (THESIS) is the tool that was used by the Tyndall Centre for Climate Change Research to assess the long-term role of hydrogen energy economy in greenhouse gas reduction in the UK to 2050 (Dutton et al, 2005). The model was used to estimate the reduction in greenhouse gas and other pollutant emissions and the implications for capital investment of a number of transition pathways and end-states for the hydrogen economy.

The model does not explicitly calculate the costs of a hydrogen economy, but instead examines the implications for the energy system – and, consequently, CO_2 emissions – of using hydrogen in four end-use sectors: Transport, Domestic, Industry, and Service / other commerce. Its structure is illustrated in Figure 5. One of the main strengths of this model is its ability to examine potential interactions between the transport sector and the electricity sector.

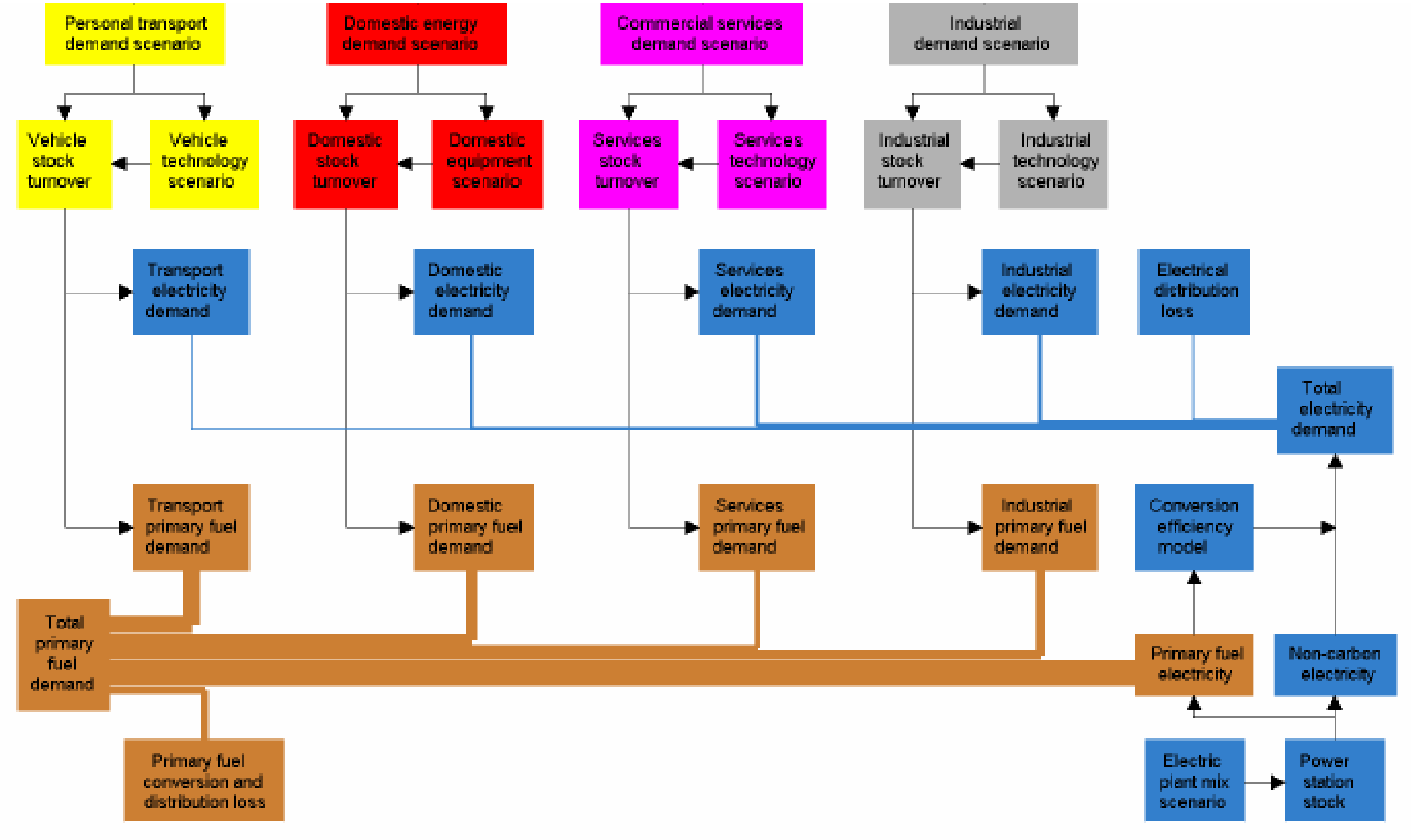
In order to look at the effects of hydrogen use on the power system, THESIS includes a detailed sub-model of the electricity production stock to 2050. This allows the implications of competition for primary energy resources, e.g. the use of renewable electricity for hydrogen production vs. direct use in the power system, to be integral to the model's results. This capability to analyse the implications of primary energy resource competition is one of the model's key strengths.

Depending on the fuel demands that result from different scenarios for end-use demand and supply options, the model will decide whether or not to add further electricity generation and/or hydrogen production capacity in each time period. New capacity for hydrogen and electricity is introduced according to technology profiles specific to each scenario. The model also tracks vehicle populations, again according to the scenario's end-use transport demands and the penetration of hydrogen into different transport modes.

Before examining scenarios for hydrogen development, a 'non-hydrogen' baseline was established. THESIS was then used as a tool to examine four socio-economic scenarios for the transition to a hydrogen economy, each involving differing hydrogen supply pathways and end-uses. The model was used to demonstrate the changes in these energy flows, as well as the stocks of electricity generation and hydrogen production capacities that would result from each of these scenarios, and the implications for greenhouse gas emissions.

While THESIS is not an economic model, the outputs of the model include the implications for investment in new hydrogen and electricity capacity and could therefore be translated into capital and energy costs. However, the primary focus of this modelling work was to analyse and understand the implications for CO_2 emissions of different ways in which a hydrogen economy could develop.

Figure 5 Schematic of the THESIS model



Source: Dutton et al (2005)

4.2 Hydrogen Infrastructure Techno-Economic Spatial (HITES) model

The HITES model was developed at Imperial College London as part of a 3-year project on the development of hydrogen infrastructure for vehicles in London. Initially developed as a technical and emissions model, it later incorporated a cost database that allows it to analyse the costs of different infrastructures, based on scenarios for technology costs, energy prices and land costs. While it was developed to be applicable as a generic model, its application thus far has been to London (Joffe et al, 2003).

HITES is a scenario model that combines scenarios and assumptions about demand growth, geographical areas of demand, approach to infrastructure development, choice of technologies, availability of feedstock and energy prices. It explicitly incorporates a representation of the spatial development of H_2 infrastructure, including calculation of distribution distances and their effects on the costs of H_2 distribution, pressure gradients within pipelines and diesel consumption for road distribution.

The technical simulation part of the model incorporates a detailed characterisation of the technologies and simulates the operation of specified infrastructures, analysing their performance and identifying potential areas for refinement, such as storage capacities and compression requirements. All of the economic parameters, such as technology costs, energy prices and land costs are exogenously specified.

There are many potential constraints on infrastructure development in an urban setting. Scenarios for infrastructure development have therefore been built ‘by hand’, including knowledge of the ‘soft’ constraints on infrastructure development and economics of H_2 distribution and refined using the results of the technical simulation.

This modelling approach has the advantage of incorporating a spatial representation of H_2 infrastructure as an integral part of the modelling work. The scenarios for infrastructure development, while not being cost-optimal in the sense of having been produced by a cost-optimisation model, have been developed with cost minimising and feasibility in mind. However, the model focuses only on one part of the energy system – the development of hydrogen infrastructure – and its energy price scenarios are exogenous inputs, rather than deriving from competition for energy resources.

5 Conclusions

A variety of modelling approaches have been taken to the question of how a hydrogen economy could – or should – develop. It is clear from this review that, while a number of models do many things well, each approach has its own advantages and disadvantages. These include the inclusion of energy system and wider economic interactions, a focus on spatial aspects of hydrogen infrastructure development, and the use of optimal vs. scenario solutions.

A model is a methodological tool to systematically provide insights into transitions to a hydrogen energy system. It is vital to understand the limitations, as well as the strengths, of each modelling approach, and to carry out extensive sensitivity and uncertainty analysis. That way, the correct model can be chosen to answer a particular set of questions regarding the development of a hydrogen economy.

6 References

Agnolucci P. and Ekins P. (2007) *Technological transitions and strategic niche management: the case of the hydrogen economy*, International Journal of Environmental Technology and Management, forthcoming.

Biberacher, M (2006), *Fusion in the global energy system – GIS and TIMES*, Final Report, CIEMAT, Madrid, available at http://www.etsap.org/documentation.asp

Dutton, G., A. Bristow, M. Page, C. Kelly, J. Watson and A. Tetteh (2005). *The hydrogen energy economy: its long-term role in greenhouse gas reduction*. Tyndall Centre for Climate Change Research. Available from: http://www.tyndall.ac.uk/research/theme2/final_reports/it1_26.pdf

Eyre, N., Fergusson, M., Mills, R. (2002), *Fuelling road transport: implications for energy policy*, Energy Saving Trust, Institute for European Environmental Policy & the National Society for Clean Air and Environmental Protection, November 2002

Hugo, A., P. Rutter, S. Pistikopoulos, A. Amorelli and G. Zoia (2005). *Hydrogen infrastructure strategic planning using multi-objective optimization*. International Journal of Hydrogen Energy 30(15). http://dx.doi.org/10.1016/j.ijhydene.2005.04.017

Hodson, M., and Marvin, S., (2005), *Emerging UK Hydrogen Economies: Policy/Urban and Regional Infrastructure 'Drivers'*, UKSHEC Social Science Working Paper No. 7, SURF Centre, University of Salford.

Joffe, D., D. Hart, and A. Bauen (2003), *Modelling of Hydrogen Infrastructure for Vehicle Refuelling in London*. Journal of Power Sources, 2003(131): p. 13-22. http://dx.doi.org/10.1016/j.jpowsour.2003.11.076

Joffe, D., N. Strachan and N. Balta-Ozkan (2007), *Representation of Hydrogen in the UK, US and Netherlands MARKAL Energy Systems Models*. Policy Studies Institute, UKSHEC Social Science Working Paper No. 28.

Lin, Z., J. Ogden, Y. Fan, D. Sperling (2006), *The Hydrogen Infrastructure Transition Model (HIT) & Its Application in Optimizing a 50-year Hydrogen Infrastructure for Urban Beijing*. University of California, Davis. UCD-ITS-RR-06-05. http://repositories.cdlib.org/itsdavis/UCD-ITS-RR-06-05/

Martinus, G., K. Smekens, H. Rösler (2005). *Modelling the transition towards a hydrogen economy*, presented at the 2005 British Institute of Energy Economics conference. http://www.biee.org/downloads/oxford05/Martinus_Smekens_Rosler.pdf

National Research Council, National Academy of Engineering, Committee on Alternatives and Strategies for Future Hydrogen Production and Use (2004), *The* H_2 *Economy: Opportunities, Costs, Barriers, and R&D Needs*. http://www.nap.edu/catalog/10922.html

Nicholas, M., S. Handy and D. Sperling (2004). *Siting and Network Analysis Methods for Hydrogen Stations Using Geographical Information Systems*. Transportation Research Record 2004: pp. 126-134.

Ogden, J. (1999). *Prospects for Building a Hydrogen Energy Infrastructure*. Annual Review of Energy and the Environment 24: pp.227-279.

Ricci M. (2006) *Exploring public attitudes towards hydrogen energy: conceptual and methodological challenges*, UKSHEC Social Science Working Paper No. 13, ISCPR, University of Salford.

Stamatina-Parissis, O., D. Joffe, D. Hart and A. Bauen (2005). *Renewable Hydrogen Supply Options for London*, Imperial College London. Presented at the 2005 European Hydrogen Energy Conference, Zaragoza, Spain.

Strachan, N., K. McGeevor, N. Hughes, R. Kannan and D. Joffe (2007) *State-of-the-art modelling of hydrogen infrastructure development for the UK: Geographical, temporal and technological optimisation modelling*, 1st Interim Report to the Department of Transport on Data and Scenario Specification.

Yang, C. and J. Ogden (2004), *Defining low-cost hydrogen pathway strategies to meet an evolving hydrogen demand*, presented at the 2004 US NHA conference.