Tyndall°Centre
for Climate Change Research

The hydrogen energy economy: its long-term role in greenhouse gas reduction

Geoff Dutton, Abigail Bristow, Matthew Page,
Charlotte Kelly, Jim Watson and Alison Tetteh

January 2005

Tyndall Centre for Climate Change Research Technical Report 18

The Hydrogen energy economy: its long term role in greenhouse gas reduction

Geoff Dutton

Energy Research Unit (ERU)
CCLRC Rutherford Appleton Laboratory
Chilton, Didcot, Oxon.,
OX11 0QX
Tel: 01235 445823
Fax: 01235 446863
Email: a.g.dutton@rl.ac.uk

Abigail Bristow, Matthew Page, Charlotte Kelly

Institute for Transport Studies (ITS)
University of Leeds, Leeds, LS2 9JT
Tel: 0113 343 5325
Fax: 0113 343 5334
Email: A.L.Bristow@its.leeds.ac.uk
M.Page@its.leeds.ac.uk
C.E.Kelly@its.leeds.ac.uk

Jim Watson, Alison Tetteh

SPRU – Science and Technology Policy Research
University of Sussex, Falmer, East Sussex, BN1 9RF
Tel. 01273 873539 Fax. 01273 685865
Email: w.j.watson@sussex.ac.uk

Tyndall Centre Technical Report No. 18
January 2005

This is the final report from Tyndall research project IT1.26 (The Hydrogen energy economy: its long term role in greenhouse gas reduction).

Part 1: Overview of project work and outcomes

Part 2: Technical report

Appendices and references

Part 1: Overview of project work and outcomes

Abstract

The potential contribution and viability of the hydrogen energy economy towards reducing UK carbon dioxide emissions in the time horizon to 2050 has been assessed using a quantitative model of the UK energy system in the context of a set of diverse socio-economic scenarios. It is argued that different sets of prevailing circumstances are likely to result in very different opportunities for hydrogen and hence very different transition pathways and ultimate penetration levels. For example, within a global market-based economy with low emphasis on environmental issues, hydrogen is likely to appear only in niche markets (such as portable power supplies and custom-built vehicles), whereas, in an economy with high emphasis on environmental factors, hydrogen could well displace petroleum as the transport fuel of choice.

However, among the many diverse hydrogen production, storage, and distribution fuel chains, not all would make a positive impact towards reducing carbon dioxide emissions. Notwithstanding certain technical problems, the decision on whether to strategically encourage a transition to the hydrogen economy and the ultimate environmental benefits of such a transformation will depend on the outcome of a number of important political and social decisions. These include the acceptability of large scale carbon dioxide sequestration (hydrogen derived from fossil fuels), decisions about land-use (hydrogen from biomass), a possible doubling (or more) of the current electricity production capacity with a high penetration of renewable electricity (hydrogen from electrolysis of water), and/or the public acceptability of a large scale nuclear renaissance (hydrogen from electrolysis of water or from thermo-chemical cycles).

Any rapid transition (say, over 25 to 40 years) to a fully developed hydrogen economy would require a contribution from at least some and possibly all of these sources. Such a transition could result in a marked decrease in carbon dioxide emissions over the long term, but might even result in increased emissions within the shorter term (due to the initial use of hydrogen derived from fossil fuels without carbon dioxide sequestration or from the bulk grid electricity supply resulting in increased load factors and lifetimes of old fossil-fired power plant to meet the increased overall demand).

Conclusions

This project has explored a set of alternative energy scenarios for the UK in 2050, with a particular focus on the possible role for hydrogen within each and development of the associated transition pathways. These scenarios range from a *World Markets* scenario in which there are no explicit drivers for hydrogen to a *Global Sustainability* scenario in which hydrogen becomes a central component of the UK energy system.

The results of the scenario exercise include storylines of the likely development of hydrogen technologies and infrastructure together with quantitative indicators of the contribution to UK energy demand. The detailed storylines and quantitative pathways from the current energy system to the alternatives for 2050 have been developed using linked transport and energy models. These pathways have been evaluated from technical, environmental and economic perspectives with the help of a stakeholder workshop.

The key findings are that:

- In a *Global Sustainability* type of world a high utilisation of hydrogen could be achieved within the context of a predominantly low carbon transport fleet over a timescale of 50 years (with large scale hydrogen vehicle introductions in the bus and light goods vehicle fleets by 2010 and in the car fleet by 2016, followed by annual new buy growth rates of 30%), but, in the absence of major hydrogen production technology innovations, would need to be supported by concurrent investment in additional renewable energy (or nuclear) capacity if the anticipated carbon dioxide emissions savings are to be achieved.
- While hydrogen introduction into the transport sector may be driven by automobile manufacturers, the benefits of reduced carbon dioxide emissions are unlikely be realised without appropriate political backing for low-carbon hydrogen production routes. In the *World Markets* and *Provincial Enterprise* type worlds, where community values are of low priority, the hydrogen production routes of choice remained largely fossil-fuel-based with little reduction (and even increases) of carbon dioxide emissions.
- The UK Government's target of 60% carbon dioxide emissions reductions by 2050 are unlikely to be achieved without substantial changes in the transport sector; a shift to hydrogen as the major transport energy carrier could make the difference, but only in a world where environmental protection underpins cultural and political philosophy.

Objectives

The principal objective of the project was to establish the benefits (and potential limitations) of a hydrogen-based fuel economy and the technical advances which may be required to realise it. The project has addressed a series of important technical issues, including:

- production of estimates for the improvements in emissions of greenhouse gases (and improvement in urban air quality) at selected penetrations of the hydrogen energy economy within the context of the socio-economic scenario set,
- identification of the likely transition pathways for integrating hydrogen into the energy mix,
- assessment of the implications for capital investment and hence the long term economic viability of the hydrogen economy,
- definition of the stepping-stones (both technical and political/infrastructural) towards fuel cell vehicles fuelled by hydrogen,
- consideration of the environmental impact of large scale hydrogen use.

Work undertaken

The project was divided into two phases.

In phase I, a technology review (Dutton, 2002) was carried out and used to inform two further reports: one on the lessons to be learned from historic development of large technical systems (Watson, 2002) and the other on the likely role of hydrogen in powering transport (Pridmore and Bristow, 2002).

In phase II, a quantitative model (*THESIS*) of the UK energy system was developed to model consumer demand in the 4 major end-use sectors (Domestic, Industry, Service and other commerce, Transport) and the associated primary fuel demand and carbon dioxide emission profile. *THESIS* includes detailed sub-models of the electricity production stock and the Transport vehicle population. The model was used to anticipate the changes in demand and energy supply system to 2050 under the various scenarios without hydrogen. A set of sub-models for hydrogen production, storage, and distribution were then introduced and results obtained for the modified scenarios including various levels of hydrogen penetration.

Results

Phase I of the project resulted in the publication of 3 working papers (Dutton, 2002; Watson, 2002; Pridmore and Bristow, 2002), available from the Tyndall Centre Internet site. These papers and the plans for phase II of the project were presented to a group of stakeholders at a meeting held at CCLRC Rutherford Appleton Laboratory on 13 March 2002.

Phase II of the project resulted in the development of the Tyndall Hydrogen Economy Scenario Investigation Suite (*THESIS*) (Dutton et al., 2003; Dutton, et al., 2004). Detailed transition scenarios to a hydrogen economy were developed against the framework of the SPRU/Foresight contextual futures scenarios and quantitative analysis carried out of the implications for vehicle populations, hydrogen production and storage capacity, electric power plant installation, and other infrastructure. The results not only indicate the scale of development required to implement the hydrogen economy, but also help to quantify the assumptions implicit in the broader energy scenarios for 2050, developed by the Cabinet Office (Performance & Innovation Unit, 2002 and Energy Review Advisory Group, 2001a and 2001b) prior to the UK Energy White Paper published in February 2003. The preliminary results of the Phase II modelling were presented to a further group of stakeholders at a meeting hosted by SPRU on 28 April 2004 and the feedback from that meeting used to refine the results before writing this final report.

Relevance to Tyndall Centre research strategy and overall objectives

There have been many published studies of the hydrogen economy, but few have been carried out in the context of global warming and the need to reduce carbon emissions and none have addressed the specific energy mix in the UK. A major shortcoming of many existing, more general studies is that they have tended to treat electricity supply and transport end-use separately, which leaves a gap in the logic if the transport fuel is to be produced using electrical power, thereby requiring a large increase in capacity. An exception to this trend was the study by Eyre, Fergusson, & Mills (2002) for the Department for Transport, which compared hydrogen and biofuels as alternative transport fuels and did include an assessment of their extended impact on the overall energy system. The current project, conducted independently, has produced detailed projections of the carbon dioxide emissions implications of several different realisations of the hydrogen economy. These projections, together with the associated estimates of hydrogen and electrical power plant capacity, represent essential information in determining the contribution of the hydrogen economy to delivering a low carbon energy system, making the results highly relevant to the goals of Theme 2 of the Tyndall Centre. The study goes beyond that of Eyre et al. (2002) in that end-use applications of hydrogen are considered in all sectors and the aggregated impact on the electricity and gas supply systems quantified; however, the conclusions of the two studies are in broad agreement.

Potential for further work

The *THESIS* model developed within this project could be used to further test the robustness of policy strategies with respect to hydrogen (or other alternative fuels) in realising carbon dioxide emissions reductions. For example, one of the possible limiting factors in the widespread deployment of fuel cells is the availability of platinum for use as a catalyst in membranes.

Although other authors (see, for example, AEA Technology, 2002) argue that this will not be a problem, there will need to be a major increase in mining capacity, which clearly will not take place until there is more certainty about the end-use market, and this will almost certainly restrict the achievable growth rate for the industry. The *THESIS* model is able to evaluate the effect of different growth rates in hydrogen fuel cell vehicles and hence to estimate the associated rise in demand for platinum. Future work could investigate whether these rises could be supported within the necessary time-frames and to examine other possible restrictions due to material scarcity (for example, in hydrogen storage materials, electrolyser membranes, etc.), market growth rates, or technological developments in delivering energy efficiency.

The *THESIS* model could be easily adapted to other problems involving coupling between the Transport sector and the rest of the energy supply system, for example, comparing the use of biomass for biofuel production, or as a feedstock for electricity production (or, in carbon dioxide emission terms, as an industrial feedstock for a currently "dirty" process), or, indeed, for other industrial or agricultural processes with known or suspected carbon dioxide impacts.

The model would benefit from an improved model of Combined Heat & Power (CHP) penetration within the Domestic, Industry, and Service sectors. Development within this area was hindered by the lack of good data on actual heat demand (as opposed to electricity and gas/coal consumption) broken down by building type and annual energy demand profile.

Communication highlights

Phase I of the project produced three Tyndall Centre working papers, which were presented to a Stakeholders' Workshop at CCLRC Rutherford Appleton Laboratory on 13 March 2002 and subsequently published via the Tyndall Centre web-site:

> Dutton, A.G. (2002), **Hydrogen Energy Technology**, Tyndall Centre Working Paper No.17, April 2002: http://www.tyndall.ac.uk/publications/working_papers/wp17.pdf
>
> Pridmore A and Bristow A (2002), **The role of Hydrogen in Powering Transport**, Tyndall Working Paper 19, April 2002: http://www.tyndall.ac.uk/publications/working_papers/wp19.pdf
>
> Watson, J (2002), **The Development of Large Technical Systems: Implications for Hydrogen**, Tyndall Centre Working Paper No.18 , April 2002: http://www.tyndall.ac.uk/publications/working_papers/wp18.pdf

During phase II an additional working paper was produced relating to hydrogen future scenarios:

> Watson J, Tetteh A, Dutton, G, Bristow A, Kelly C, Page M (2004), **UK Hydrogen Futures to 2050,** Tyndall Centre Working Paper No. 46, February 2004, available from: http://www.tyndall.ac.uk/publications/working_papers/wp46.pdf

and a paper was written and presented at the 1st European Hydrogen Energy Conference in Grenoble in September 2003:

> Dutton, A.G., Watson, J., Bristow, A., Page, M., Pridmore, A. (2003), **Integrating hydrogen into the UK energy economy**, 1st European Hydrogen Energy Conference (EHEC), Grenoble, France, 2-5 September 2003

An additional presentation on hydrogen and its implications for wind energy development was made at the British Wind Energy Association Conference in Brighton in October 2002 and subsequently published as a paper:

Dutton, A.G. (2003), **The hydrogen economy and carbon abatement – implications and challenges for wind energy**, Wind Engineering, Vol. 27, No.4, p. 239-256, 2003

A final Stakeholders' Workshop for the project was held at SPRU on 28 April 2004, where preliminary results from the scenario pathways modelling were presented. It is intended to write one or more future papers to more widely disseminate the research findings from the project.

Part 2: Technical report

1 Introduction

The term *hydrogen economy* was first used during the energy crises of the 1970s to describe a national (or international) energy infrastructure based on hydrogen produced from non-fossil primary energy sources. Within this concept, hydrogen is regarded as a suitable storage and transmission vector for energy from renewable or nuclear power systems, allowing the generator or utility increased flexibility in responding to fluctuations in wind or solar input or consumer demand, on a short term (minutes/hours) or seasonal basis. Hydrogen can be stored and transported in pressure vessels or transmitted by pipeline to the point of end-use. It is a versatile fuel, which can easily be substituted for traditional fuels, whether for stationary or transport applications, resulting in improved efficiency and negligible pollution at the point of use.

The principal drivers behind the current interest in the hydrogen economy are:

- oil and gas resource depletion,
- global warming,
- urban air quality,
- security of energy supply,
- lack of suitable large scale electricity storage media.

Considering the current need to develop responses to human-induced climate change, a fully developed *hydrogen economy* has the potential to drastically reduce emissions of carbon dioxide within the electrical power, transport, and low grade heat supply sectors. However, the energy path from solar, wind, and other renewable generators, through hydrogen production via electrolysis and widespread storage and distribution, to end-use in cars, aeroplanes, and domestic and business premises is complex and currently very expensive. Intermediate paths, employing hydrogen derived from fossil fuel sources, are already used to produce merchant hydrogen for industrial uses and are likely to be more economic (subject to fluctuations in fossil fuel price) in the short to medium term. Most, but not all, of these fossil fuel based paths will require potentially expensive carbon dioxide sequestration, if they are to contribute to the reduction of greenhouse gases.

The extent to which hydrogen might be necessary to support increased penetrations of (intermittent) renewable electricity remains a point of contention. It has been argued that wind electricity could expand to an overall national penetration level of at least 20% without requiring any need for hydrogen (or other large scale) storage (see Wu et al. 2004 and Milborrow 2001[1]). However, the position may be different *locally* at the end of long distribution lines or in already “weak” grids, where there may be a potential role for hydrogen to support renewable electricity development in lieu of major grid reinforcement. At the same time, if hydrogen was becoming established as a major transport (and possibly domestic) fuel in the area, its potential to support smoothing of the demand profile may become economically supportable.

Section 2 of this technical report reviews the main technologies for hydrogen production, storage and distribution, and end-use. Section 3 then introduces the concepts of scenario-building and

1 Milborrow 2001 estimates that additional plant of the order of about 5% of the installed wind plant capacity would be needed to support a wind power penetration level of 20% on the UK grid

develops targets for possible hydrogen futures within the context of a widely used set of contextual futures (the SPRU-Foresight scenario set). The Tyndall Hydrogen Economy Scenario Investigation Suite (THESIS) is then described in Section 4 – including particular detail about the Transport sector sub-model (section 4.2), the electrical power network (section 4.3), and the hydrogen technology components (section 4.4) – and used to develop hydrogen transition pathways within the context of the previously described scenario set in Section 5. These transition pathways are described in some detail, in terms of the overall energy requirements, the electric and hydrogen plant installations, and the potential contribution to carbon dioxide emissions reductions, and then subjected to a brief sensitivity analysis (section 5.2). Finally, the output from a stakeholders' workshop where the preliminary findings of the project were presented and discussed can be found in Section 6 and the overall conclusions from the project in Section 7.

2 Hydrogen technology

2.1 Hydrogen properties and safety

Hydrogen is an *energy vector*, not a primary fuel. It does not exist in pure molecular form naturally on Earth (although hydrogen atoms are estimated to comprise 0.14% by weight of the earth's crust), but must be produced from other sources.

Hydrogen has more energy per unit mass than any other fuel and it avoids or substantially reduces CO_2 and other emissions at the point of use (which both serve to make it attractive for transport applications). However, in this context, hydrogen's main drawback is that of low density and consequent low volumetric heat content (approximately 25% that of natural gas at the same temperature and pressure). This makes the on-board storage of sufficient hydrogen to maintain current expectations of vehicle range a major technical problem.

Hydrogen can be produced, stored, and used in many diverse ways, but the ultimate energy paths can be complex and the most commonly suggested fuel cycles (usually involving electrolysis) are expensive, by comparison with existing fossil fuel prices. It is interesting that some of the less talked about production routes (from fossil fuels) are relatively inexpensive and the perceived environmental problems (continued need for extensive carbon dioxide sequestration) may be soluble. The basic properties of hydrogen are tabulated in Appendix 2 and compared with the equivalent data for petrol and natural gas.

Hydrogen is safer than commonly held perceptions might suggest. Leaks are difficult to detect because the gas is colourless and odourless, but it mixes much faster with air than either methane or petrol vapour (see high diffusion coefficient) which makes accidents in the open air less critical. In confined spaces, there are potential problems, which should be addressed by the provision of suitable vents. Hydrogen has a much wider explosive range in air (13%-59%) than methane (6.3%-14%), but the latter is explosive at lower concentrations. There is a factor 10 difference in minimum ignition energy between hydrogen and either methane or petrol, but this is of little significance when it is considered that even the spark from a static electric discharge has sufficient energy to ignite natural gas. In all other respects, hydrogen is broadly similar to the fuels it might replace.

2.2 Hydrogen production

Currently hydrogen is used almost exclusively as an industrial chemical, within which capacity it is applied to a wide variety of uses, including ammonia production (for fertiliser manufacture), refinery use for desulphurisation and other processes, and methanol production. The annual world production is around 500 billion Nm^3 (Gregoire-Padro, 2001).

The bulk of hydrogen (almost 50%) is produced by steam methane reforming (SMR), which is the most economical (large scale) route; partial oxidation of hydrocarbon fuels can be competitive where a cheap source of oxygen is available.

The major hydrogen production technologies considered within the hydrogen scenarios and transition pathways were:

(i) Steam methane reforming (SMR): natural gas is pre-heated and purified and then reacted with steam in the presence of an active nickel catalyst to produce hydrogen and carbon monoxide; the carbon monoxide is further reacted with water in the “shift” reaction to produce additional hydrogen; the hydrogen gas produced requires additional purification before use in low temperature fuel cells or in solid state storage devices; process efficiency 65%-75%,

(ii) Partial oxidation of hydrocarbons (POX): viable with any fossil fuel); process efficiency 50%,

(iii) Integrated gasification combined cycle (IGCC): a coal gasifier converts pulverised coal into a synthesis gas (mixture of H_2 and CO) by adding steam and oxygen; the resulting Syngas is cleaned of impurities and used to produce energy in a gas turbine; expected thermal efficiency improvements of 10% over conventional coal-fired steam turbine,

(iv) Electrolysis: water is split into hydrogen and oxygen by the application of electricity (and hence the extent of carbon dioxide production depends on the source of electricity generation).

Other less well developed hydrogen production technologies include:

(i) Pyrolysis: thermal decomposition of hydrocarbons in the absence of oxygen,

(ii) Photoelectrolysis: splitting of water directly into hydrogen and oxygen using sunlight as the only energy input,

(iii) Biological: photosynthesis or fermentation processes,

(iv) Thermo-chemical cycles (e.g. sulphur-iodine process) as the basis for solar-thermal or nuclear thermal hydrogen production systems.

2.3 Hydrogen storage & distribution

To achieve a fully functioning hydrogen economy, hydrogen will need to be stored on a wide range of scales. Large, centralised storage would be required if hydrogen is produced in large plants for wider distribution; longer term or seasonal storage would be required in systems relying on large penetrations of renewable energy; comparatively small scale storage is required on board vehicles, possibly in homes, and for portable devices.

Long term storage is feasible in **underground caverns** (depleted gas wells, salt caverns, etc.).

For shorter intervals, hydrogen is commonly stored as a **compressed gas** in conventional steel cylinders (usually 200 bar / 50 litres) or, on a larger scale, in spherical pressure vessels, or is **liquefied** and placed in cryogenic dewar vessels.

Current developments utilise composite (typically aluminium liner strengthened with glass or carbon fibre reinforcement) cylinders up to 300 bar and developments are underway to produce tanks capable of holding hydrogen at 700 bar. Apart from cost and serious concerns over the safety of installing such high pressure tanks in cars, higher pressure requires increased energy for compression and (thermodynamic) problems in achieving fast fill times.

The energy required for liquefaction can be as high as 35% of the energy contained in the stored hydrogen, although research is underway that aims to reduce this to below 20%.

Research and development is underway to develop **solid-state** hydrogen storage devices utilising **metal hydrides** or **carbon-based** powders. The challenge is to develop a suitably lightweight store that can achieve at least 7 wt.% of hydrogen, with fast recharge kinetics and a low (< 100 ^{o}C) desorption temperature.

Hydrogen is conventionally distributed in gaseous form in cylinders or large tanks, or in liquid form by tanker or occasionally pipeline. Future applications may include storage and transport as a solid metal hydride. The optimum method depends on quantity delivered and distance transported.

A large scale hydrogen pipeline distribution infrastructure is conceivable, but would be expensive. There are significant technical problems (arising from embrittlement of metals and the use of certain kinds of plastic pipe) related to the use of the existing natural gas pipeline network (although it is considered feasible to dilute the natural gas supply by up to 10% by volume with hydrogen). However, a complete changeover to pure hydrogen distribution is probably logistically impractical since some consumers would still require natural gas during any changeover period.

Alternatively, some researchers have suggested that local production of hydrogen − by very small scale steam methane reforming or electrolysis of water − may be more economically feasible.

2.4 Hydrogen end-use technology

Hydrogen is a good fuel for internal combustion (IC) engines and can improve efficiency by around 20% compared to the use of gasoline. Although still limited by the Carnot efficiency, this is comparable with the efficiencies achieved in practice with the current generation of PEM fuel cells. Although NO_x emissions are produced, they can be limited to an order of magnitude less than from a petrol engine.

Hydrogen use in turbines and jet engines is similar to use of conventional jet fuel. There are some avoided problems from sediment and corrosion and considerably lower pollutant levels. Overall efficiency improvements are likely due to the capacity to increase gas inlet temperatures beyond the current limit of 800 ^{o}C.

A *fuel cell* utilises a chemical process to convert hydrogen (or a hydrogen-rich fuel) into electrical energy and heat. It can do so at high efficiency (not subject to limitations of the Carnot cycle), producing a non-fluctuating, DC power output. Most fuel cells (notably PEMs) have high power densities (i.e. high power output per unit weight, volume, or area). Different types of fuel cell are distinguished by their different electrolytes and the different temperatures reached during operation (Larminie & Dicks 2000).

Fuel cells display high efficiency across most of their output power range. This means that, whereas the internal combustion engine has a point of maximum operating efficiency (usually at high revolutions with large fall-off at low revolutions), the fuel cell has a very flat characteristic and is generally more efficient at fractions of its rated power. As a consequence, the fuel cell will show even larger advantages over an IC engine during a drive cycle compared to continuous output tests.

3 Socio-economic scenarios

Scenarios represent logical and consistent "storylines" about the future. These storylines can be applied at a number of different levels from sub-national to global. In the present instance, they are used as a tool for exploring future drivers and inhibitors for the use of hydrogen in the UK. The scenario construction assumes that the whole world is subject to the forces described within them. This is no more or less realistic than the assumption that any one country will conform strictly to any one scenario over time. The scenarios represent pictures of the future in "possibility space", representing a range of credible future states of the world. The world will not in practice conform to any one scenario even over a short time period. However by systematically imagining a range of possible future states, the robustness of particular policies or technologies currently under consideration can be examined.

This section summarises the results of a scenario development exercise carried out within the Tyndall Hydrogen project. Four major scenarios were developed for 2050 as a result of two in-depth discussion meetings by the project team held in late 2002 and early 2003. They were refined further during 2003 to reflect the needs of the overall hydrogen introduction model and transport sub-model being developed for the project.

The scenarios build on those established by the UK Foresight programme (see Office of Science and Technology, 1999; Energy Futures Task Force, 2000; and Foresight 2003), which have been applied widely within government over various timescales to 2050. These scenarios were only selected after detailed consideration of possible alternatives (Watson, 2002). One possible alternative was to follow the approach taken by the Royal Commission on Environmental Pollution (RCEP, 2000). The RCEP scenarios were developed to explore different ways of achieving a 60% cut in UK carbon emissions by 2050. The uncertainties underlying the extent and nature of a possible shift towards hydrogen mean that such a 'goal driven' approach is too prescriptive for an initial analysis of hydrogen transitions. By contrast, the Foresight scenarios provide a framework for exploring different possibilities in terms of individual values and governance systems. These differences will then, in turn, lead to different outcomes for hydrogen – some that are very positive, and others that are quite limited. Moreover, specific variations on the basic scenarios to examine specific 'goal driven' objectives (e.g. 60% cut of carbon dioxide emissions in the transport sector) or constraints (e.g. maximum growth rate of fuel cell manufacturing industry) can be incorporated later.

The scenario exercise underpins the analysis of different possible modes of hydrogen production, transportation, storage and use in 2050. The results formed a key step in the development of a set of transition pathways, each of which are assessed in section 5 from technical, policy, environmental and economic perspectives. The schematic in Figure 3-1 shows how the development of the scenarios relates to these further elements of the project.

Section 3.1 sets out the basic Foresight scenarios framework, including examples of its previous use within government. Section 3.2 builds on these previous uses, and elaborates each scenario with a specific focus on the consequences for hydrogen production, transmission and use. Section 3.3 then moves the focus to the quantification of UK energy demand and hydrogen's possible contribution by 2050. This quantification process again builds on previous exercises, particularly that by the Performance and Innovation Unit (PIU) within the Cabinet Office (Performance and Innovation Unit, 2001). This process of quantification is clearly subjective and was exposed to debate at a stakeholders' meeting in April 2004.

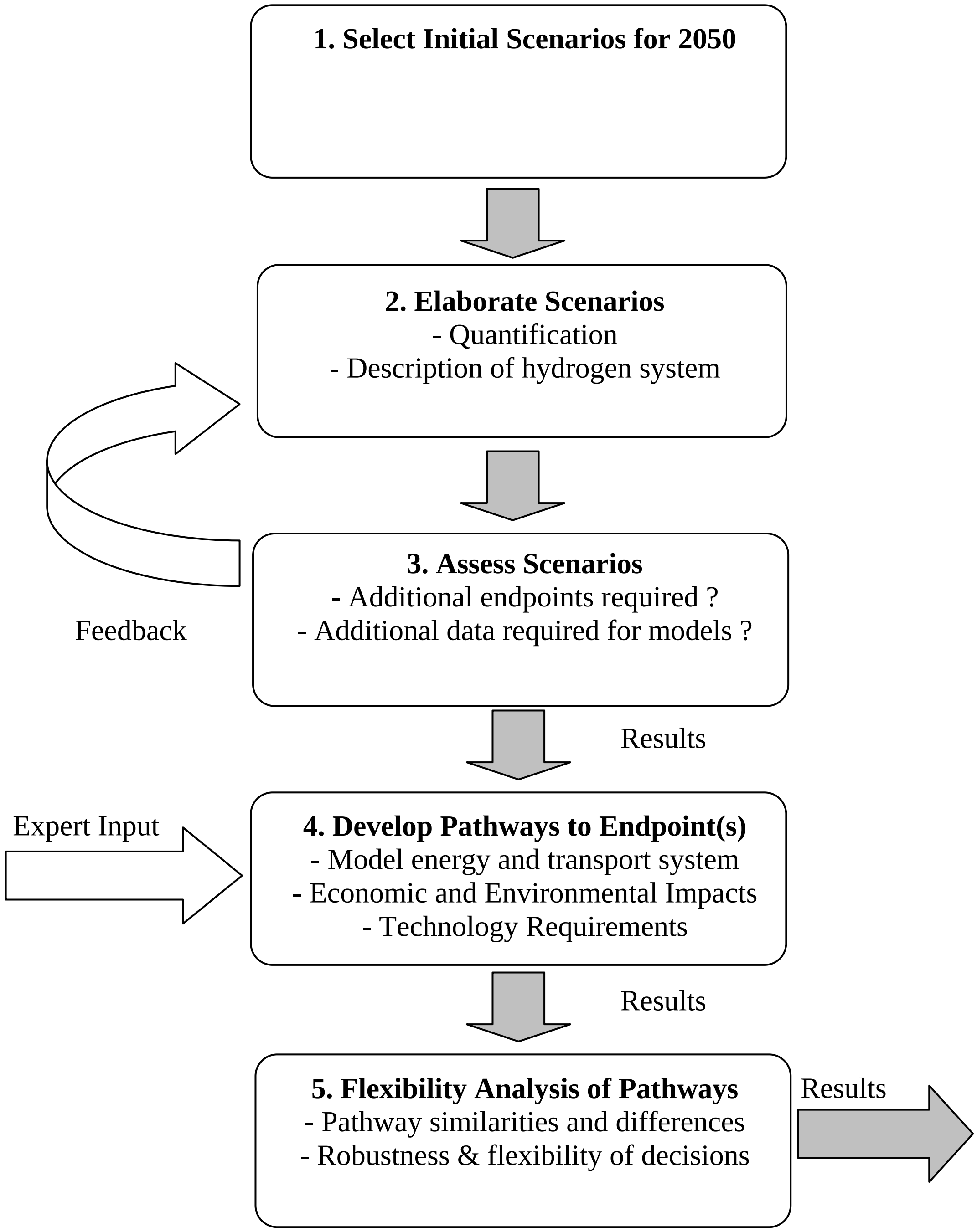


Figure 3-1 : Steps in the analysis of UK hydrogen futures

3.1 The Scenario Framework

The scenarios used in this exercise were adapted by SPRU from a framework developed for the Intergovernmental Panel on Climate Change, and summarised in its *Special Report on Emissions*

Scenarios (Nakicenovic and Swart, 2000). The adapted SPRU scenarios were originally commissioned by the Office of Science and Technology (OST) for the UK Foresight Programme (Office of Science and Technology, 1999). The OST report examined environmental futures over the next 20 to 50 years and has subsequently been used in projects for other government departments. One of the most recent examples of direct uses of the SPRU scenarios framework is the *Fuelling the Future* study by the Energy Futures Task Force (2000) of the Energy and Natural Environment Panel of Foresight. The SPRU scenarios were also employed by the UK Cabinet Office Performance and Innovation Unit (PIU) in its assessment of UK energy policy, within which the PIU team developed its own results for 2020 and 2050 (e.g. Energy Review Advisory Group, 2001).

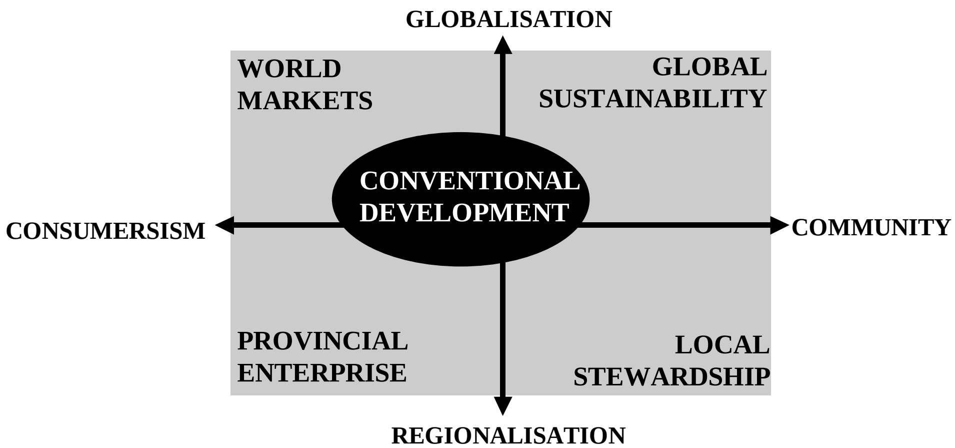


Figure 3-2 : The four contextual futures scenarios

The SPRU scenarios are developed from two main variables or dimensions of a largely qualitative nature. The first dimension is values (individuals/consumers vs. community) and the second is governance (autonomy vs. interdependence). This means that technology is not viewed as autonomous and following its own independent path. It is rather viewed as mainly the product of the combination of dominant values and governance systems being explored. This allows the degree of expected hydrogen use in 2050 to vary according to different scenario circumstances. When the two dimensions of the SPRU/Foresight scenarios are combined, they yield four possible future states (see Figure 3-2).

These four scenarios can be characterised as follows (Foresight, 2003):

- *World Markets.* People aspire to personal independence, material wealth and mobility to the exclusion of wider social goals. Integrated global markets are presumed to be the best way to deliver this. Internationally co-ordinated policy sets framework conditions for the efficient functioning of markets. The provision of goods and services is privatised wherever possible under a principle of ‘minimal government’. Rights of individuals to personal freedoms are enshrined in law.

- *Provincial Enterprise.* People aspire to personal independence and material wealth within a nationally-rooted cultural identity. Liberalised markets together with a commitment to build capabilities and resources to secure a high degree of national self-reliance and security are believed to best deliver these goals. Political and cultural institutions are strengthened to buttress national autonomy in a more fragmented world.

- *Global Sustainability*. People aspire to high levels of welfare within communities with shared values, more equally distributed opportunities and a sound environment. In the UK, there is a belief that these objectives are best achieved through active public policy and international co-operation within the European Union and at a global level. Social objectives are met through public provision, increasingly at an international level. Markets are regulated to encourage competition amongst national players. Personal and social behaviour is shaped by commonly held beliefs and customs.

- *Local Stewardship*. People aspire to sustainable levels of welfare in federal and networked communities. Markets are subject to social regulation to ensure more equally distributed opportunities and a high quality local environment. Active public policy aims to promote economic activities that are small scale and regional in scope, and acts to constrain large-scale markets and technologies. Local communities are strengthened to ensure participative and transparent governance in a complex world.

The scenario exercise reported here was conducted in two parts. The first part focused on the overall drivers and inhibitors for the use of hydrogen as an energy carrier in the UK. The second part built on the work of the PIU and the government's Interdepartmental Analysts Group (IAG, 2002) to quantify the contribution of hydrogen within the UK energy mix. During this second phase, the project team identified those technologies for production, transportation, and end-use which were most likely to dominate in the given socio-economic framework.

3.2 Drivers and inhibitors for hydrogen to 2050

This section sets out the context for hydrogen production and use in the UK in 2050. To help focus the analysis, the team selected drivers and inhibitors to hydrogen in a number of related categories. Each category was then addressed in the context of the four Foresight scenarios. The categories and issues covered by these drivers and inhibitors can be summarised as follows:

- *Security of energy supply*. This includes issues of resource depletion, especially of oil and natural gas, and energy diversity. It also covers the operational security of the energy system.
- *Environmental impacts*. This includes local issues of urban air quality from vehicle and other emissions. It also covers the extent to which global issues such as climate change will provide an impetus for hydrogen development.
- *Quality of life*. This includes individual quality of life as well as the overall 'public good'. These two dimensions are often in conflict with each other, for example in personal transport.
- *Trade and competition*. This covers issues that are directly related to the globalised/protectionist axis of the Foresight scenario framework. It includes the extent to which trade is free and competitive, and the implications this has for the availability of technologies and resources for hydrogen energy systems.
- *Technological change*. This is related to the previous category, and covers the extent to which new technologies for hydrogen production, transport, storage and use will be developed.
- *Policy environment*. This includes the extent to which there will be direct policy intervention to encourage hydrogen, and the balance between this and market driven development.
- *Empowerment*. This captures the extent to which individual decision making about energy and transport choices will be possible by consumers, and the implications of this for hydrogen use.

The elaboration of each scenario does not necessarily address each of these categories in detail. However, it provides a guide for the kinds of issues that need to be covered to justify the subsequent quantitative judgements about the role of hydrogen in 2050. Initial storylines describe the general socio-economic environment and circumstances pertaining to the introduction of hydrogen. These storylines are developed in more detail in later sections where the results from the quantitative energy and transport modelling analysis are presented.

3.2.1 World Markets

This is a scenario in which the development of energy and transport systems is dominated by an emphasis on low energy prices. Issues such as supply security and the environment are regarded as secondary, and any action to address these is left to the market. As a result, the UK's energy diversity is low due to a primary dependence on the cheapest energy sources. Any environmental measures are taken through the internalisation of external costs. There is little appetite for this given the low policy priority attached to environmental protection; a possible exception might be the internalisation of urban pollution costs (driven by personal health considerations).

Politically, this scenario does not favour government intervention in markets. The Kyoto Protocol is abandoned, with some residual emissions trading schemes between private firms, and there is no action to curb the continuing rapid increase in (particularly international) air travel. In general, environmental standards are weak, and there is little support for the taxation of high-carbon fuels since such action would inhibit consumer freedom. Against this background, hydrogen receives no special government support and has to compete with other energy carriers.

The key drivers for consumer goods markets in this scenario are style, design and fashion. Innovation is intensive but short term, and novelty has a high value. For transport, there is an emphasis on high-speed technologies that are mainly available to those consumers with high purchasing power. In practice, this might mean privately owned roads that charge for use, enabling those who can afford it to avoid congestion. Whilst consumer power is high for those with high disposable incomes, the political power of individuals (particularly those with lower incomes) is weak.

Against this background of weak government intervention, an emphasis on the lowest cost energy sources and a consumer-driven culture, there are few opportunities for the establishment of hydrogen energy systems. However, there will be some niche marketing opportunities for hydrogen in areas such as portable, consumer electronics, uninterruptible power supplies and fuel cell vehicles. The latter will focus on premium vehicles that will be sold to consumers on the basis of novelty. It will be limited by a patchy infrastructure that only serves affluent areas and private roads. Hydrogen development for domestic, commercial and industrial energy uses is expected to be minimal and fossil fuels will remain the dominant primary energy source.

Although the prospects for hydrogen within this scenario seem poor, there is an alternative interpretation that was not explored in detail by the project team. It was suggested that a technical breakthrough might occur that could make the use of hydrogen much cheaper. For example, a low cost fuel cell or a highly efficient storage technology could be developed as a spin-off from general innovation within the economy. If such a breakthrough were made, there might be a sudden switch to the widespread use of hydrogen in both transport and stationary energy applications. Against this, it might be argued that hydrogen is a secondary fuel and its cost in stationary energy applications must always be more expensive than that of the primary fuel used to produce it; however, if the innovation was in biological hydrogen production even this objection might be circumvented. The value of any such breakthrough would clearly be enhanced in any circumstance in which the price of conventional primary fuels were to start rising sharply due to scarcity.

3.2.2 Provincial Enterprise

In this scenario nation states or regions are inward looking and protectionist. Decision making and political power are nationally focused, and the economy is corporatist with an emphasis on ‘national champion’ firms, and products that are ‘made in Britain’. Against this background, policies for energy and resource use are dominated by security concerns. There is a preference for the use of the UK’s own energy resources rather than importing them from abroad.

This aversion to imports may, in the medium term, lead to a shift in favour of hydrogen as a major transport fuel. This will mean hydrogen for private cars as well as some hydrogen powered rail and bus systems. As UK oil and gas reserves are exhausted, the search for alternatives leads to the production of hydrogen and electricity from a diverse mix of renewables (especially wind and wave power), nuclear power and coal. There is also a significant drive for energy efficiency which will give some impetus to fuel cell commercialisation for transport applications and combined heat and power systems. Although supply security is the most important driver for hydrogen, this is reinforced by some measures to improve urban air quality. Climate change, and approaches to mitigate carbon emissions are not seen as a priority unless there is strong evidence that the UK is being directly affected.

Innovation for the development of hydrogen-related technologies is relatively slow since the nationalistic political and economic culture limits the impact of imported technologies, international collaboration and learning. However, this same nationalism leads to a concerted government-led programme to build a centralised hydrogen delivery infrastructure.

3.2.3 Global Sustainability

In this scenario, the global economic and political systems are highly interconnected, with minimal parochial and protectionist influences. Competition is seen as an important means of delivering wider social and environmental goals. Prices of energy sources have been adjusted upwards to take into account the external costs of pollution. Kyoto was successfully implemented and the targets largely met through a strong international emissions trading regime. Successor agreements are in force to deliver further cuts in greenhouse gas emissions, using the contract and converge principle to achieve stabilisation.

In the UK, there has been an acceptance for many years of the Royal Commission target of a 60% cut in carbon dioxide, and this has now been achieved. This process has been driven by the desire to improve local air quality, reduce noise levels, improve visual amenity, and reduce resource depletion concerns as well as climate change. However, energy security concerns have been mitigated by strong international co-operation and trade. Pollution mitigation efforts are primarily cost driven, with the cheapest measures being implemented first.

This emphasis on low cost mitigation is tempered by some intervention in the market to maintain the diversity of UK energy sources. A key question for government within this context is whether to allow (and possibly part-finance) a renewed nuclear power programme. Whilst this would help to mitigate carbon emissions and generate large amounts of hydrogen through electrolysis, there are wider sustainability arguments for using renewable energy instead if at all possible. Much depends on the development of solutions to long-term nuclear waste management. The outcome also depends on the extent to which the pricing of carbon improves nuclear economics. It is difficult to predict how this issue will be resolved and so, the project team assumed a mixture of renewables and nuclear power to generate hydrogen within this scenario.

For transport, there is a strong emphasis on collective solutions, including car sharing and public transport. These are backed up by policy intervention with congestion charges, and tough emissions standards. Local hydrogen grids first emerged around areas of high traffic and population density. The dominant technology for producing hydrogen in these early initiatives is electrolysis, and electricity remains the dominant energy carrier.

By 2050, national initiatives have started to standardise these local hydrogen grids, and regional grids are beginning to emerge. One of the spin-off effects of this is that some homes and businesses are starting to use hydrogen directly in fuel cells. Innovation in hydrogen systems is relatively rapid due to strong international co-operation and standardisation.

3.2.4 Local Stewardship

In this scenario local and regional decision making predominate. The over-riding factors driving energy and transport choices are supply security, local environmental issues and local employment. There is some international action to mitigate problems such as climate change, but there is considerable local autonomy in implementation. The Kyoto Protocol was successful, and subsequent agreements are in place with varying degrees of compliance.

In the UK, the emphasis is on the efficient use of local energy resources, particularly local renewables but perhaps also fossil fuels (e.g. in coalfields). The economy is driven by co-operative principles, with approaches such as local exchange trading schemes (LETS) becoming more important and the stock market losing its central status. Within this, the factors that shape which energy sources are used include visual amenity, noise and social cohesion. The average distance travelled per person has fallen markedly due to a reduction in long distance and international travel. There is also an increasing use of non-motorised modes for short distance travel.

This is a relatively low innovation scenario, with a moderate scope for international co-operation and central government support for hydrogen technologies. There are many drivers for hydrogen development, but these have been partly countered by difficulties in finding the appropriate local energy sources to produce it. Nevertheless, hydrogen is an important energy carrier for public transport by 2050, supplied by local hydrogen grids. As an extension of these, some homes and businesses have installed CHP schemes to use hydrogen in fuel cells, though the technology has been slow to mature.

3.3 Quantifying hydrogen's contribution in 2050

3.3.1 Background assumptions

The quantitative analysis of each scenario draws on the storylines described in section 3.2 above and data developed by the PIU and Interdepartmental Analysts Group (IAG) using the same Foresight scenario framework (IAG, 2002). Key background data requirements for the analysis of hydrogen's contribution include the rates of economic growth and energy demand growth. For each of the Foresight scenarios, the PIU team allocated an average economic growth rate and an implied growth rate for UK energy demand (see Table 3-1). These values were used as starting points for the model analysis within each scenario. Implicit in the figures for average demand growth shown in Table 3-1 is a consideration of the increase in energy services demand (by end-use sector and technology type) offset against the expected improvement in energy intensity (i.e. the energy required to deliver a given service, again disaggregated by end-use sector and technology type) – see Appendix 3. A limited sensitivity analysis was later carried out on these parameters using the THESIS model to assess, for example, the effect on carbon dioxide emissions in the *World Markets* scenario of realising only half the expected energy intensity improvements.

	WM	**PE**	**GS**	**LS**
Economic growth (% per year)	3%	1.5%	2%	1%
Average energy demand growth (% per year)	0.65%	0.42%	-0.44%	-0.94%

Table 3-1 : Economic and energy demand growth assumptions [Source: Energy Review Advisory Group, 2001]

To put these figures into context, it is important to note that UK primary energy demand has increased by around 0.75% per year[2] since 1960 (DTI, 2002). The projected PIU figures, which were applied within the hydrogen transition pathways, assume that the average rate for the next 50 years will be significantly lower than this historic average across all scenarios. The ERAG elaborated the scenarios to 2050 to develop the expected energy demand in 2050 for the four main sectors – domestic households, transport, industry and services – shown in Table 3-2 compared with the equivalent figures for 2000.

	Actual (2000)	**WM**	**PE**	**GS**	**LS**
Domestic	533	576	529	426	349
Services	265	329	310	213	226
Transport	638	1359	1101	646	403
Industry	465	360	401	241	211
Total	1902	2624	2341	1526	1189

Table 3-2 : Scenarios of energy demand by sector for 2050 (TWh) [Source: Energy Review Advisory Group, 2001]

With this background data in mind, the Tyndall Hydrogen project team developed some additional quantitative information to characterise the role of hydrogen within each scenario. The first step in this process focused on the contribution of hydrogen to energy demand within each of the four sectors shown in Table 3-2. In common with the PIU's figures for energy demand, the quantification of this contribution was based on judgements about the likely consequences of each scenario rather than any formal modelling work. As Table 3-3 shows, the result was a range of contributions in many cases since the team were unable to agree a single figure.

[2] In fact, by a considerably higher rate from 1960 until the late 1970s, then actually falling until 1985, when growth resumed at around the suggested 0.75% rate, sustained until the current date.

	WM	**PE**	**GS**	**LS**
Transport	5%	15-25% (5%)	80-100% (10-20%)	20% Including 20-50% for buses
Domestic	2% Portable fuel cell appliances	10-20%	20-30% Fuel cell systems	20-50% (5-10%)
Industry	Negligible	15-20%	30% Mainly CHP systems	20-50%
Services	2-5%	15-20%	30% Mainly CHP systems	20-50%

Table 3-3 : Hydrogen's contribution to UK energy demand in 2050 (figures in brackets are for 2030)

	WM	**PE**	**GS**	**LS**
Steam Methane Reforming	100%	15%	-	-
Coal	-	50% (no sequestration)	10% (with sequestration)	10% (with sequestration)
Renewables	-	25%	50%	90%
Nuclear Power	-	10%	40%	-

Table 3-4 : Potential sources of hydrogen in the UK in 2050

Having established the likely contribution of hydrogen to energy demand, the next step developed some figures for hydrogen production. Overall, the team felt that this was likely to be achieved by a combination of a number of technologies including steam methane reforming and the electrolysis of water. A brief survey of these technological options has been presented in section 2.2 of this report and more detail can be found in the separate Tyndall Centre Working Paper (Dutton, 2002). Table 3-4 summarises the project team's views on the likely mix of hydrogen production technologies and input fuels under each scenario. It is important to note that these are illustrative, not exhaustive, scenarios. For example, the *Global Sustainability* scenario contains a high proportion (40%) of hydrogen production from nuclear power because it was considered that this was the only scenario where a high nuclear penetration was likely. It might be argued that an alternative scenario with less (or zero) emphasis on nuclear is equally likely in this world context, requiring more hydrogen from renewables or coal with carbon sequestration. It will become apparent later that the proportion of hydrogen produced from renewables in the basic GS scenario is already very demanding, so a further increase in the amount of renewable capacity there seems unlikely; placing the balance all on coal with carbon sequestration would make little real change to the conclusions of the study, except that the known problems of nuclear waste disposal and decommissioning would be replaced with the need to sequestrate very large amounts of carbon. It is noteworthy that in the *Global Sustainability* world achieving a low carbon energy system may still require difficult environmental decisions, strongly influenced by public opinion.

It is important to note that the electrolysis route will have particularly important implications for the rest of the UK energy system. If renewable, fossil or nuclear electricity is diverted to produce hydrogen, this electricity will not be available to help meet the conventional electricity demand. The implications of this will be assessed in detail within the next section. The IAG scenario data used by the PIU includes some information that will aid this task. However, as the IAG report acknowledges, their work made 'no attempt … to take into account the likely changes in electricity generation under each of the scenarios' (IAG, 2002).

The figures the IAG have produced are for energy consumption in the form of electricity (in mtoe), and the share of electricity generated from combined heat and power (CHP) schemes. These are summarised in Table 3-5.

	WM	**PE**	**GS**	**LS**
Electricity Consumption (mtoe)	40	33	30	25
CHP electricity for industry	19%	15%	33%	33%
CHP electricity for services	6%	6%	15%	15%

Table 3-5 : Electricity consumption and the contribution of CHP in 2050 [Source: IAG, 2002]

In view of the IAG's limited analysis of the electricity generation mix in 2050, the project team developed a view of the likely situation for each scenario. This will act as a rough guide for the modelling work to be conducted in the next phase of the project. The team's views for each scenario can be summarised as follows:

- Under *World Markets*, electricity supply would be dominated by gas and possibly coal-fired generation. Some of the cheapest renewables might make small contributions, and nuclear power would be phased out.
- For *Provincial Enterprise*, there might be a policy of maintaining a diverse mix of technologies that use accessible resources. This suggests that electricity could be generated from roughly equal amounts of nuclear, renewables and coal.
- Under *Global Sustainability*, the mix would be dominated by renewables and nuclear (though this would depend on consent and solutions being developed to problems of radioactive waste management). Fossil generation might be used to balance out some of the intermittent renewables.
- For *Local Stewardship*, generation would be renewables-based. However, there might be a continued role for coal in areas which have local resources, and for balancing intermittent renewables.

4 The *THESIS* model

The Tyndall Hydrogen Economy Scenario Investigation Suite (THESIS) is a software tool for predicting the potential carbon dioxide savings at any timescale into the future arising from different strategies of implementing a hydrogen energy economy.

The model incorporates various current scenarios for the development of the economy in general and the energy supply sector in particular. Starting from these "baseline" scenarios, the implications of various carbon dioxide targets and possible technology growth rates are assessed.

The model is designed to incorporate elements of both a "top-down" approach in which total energy growth is specified – as, for example, from the contribution of the Energy Review Advisory Group (ERAG), 2001a, 2001b, to the UK Energy White Paper – and a "bottom-up" approach from projections of population size, household size, vehicle use, etc.

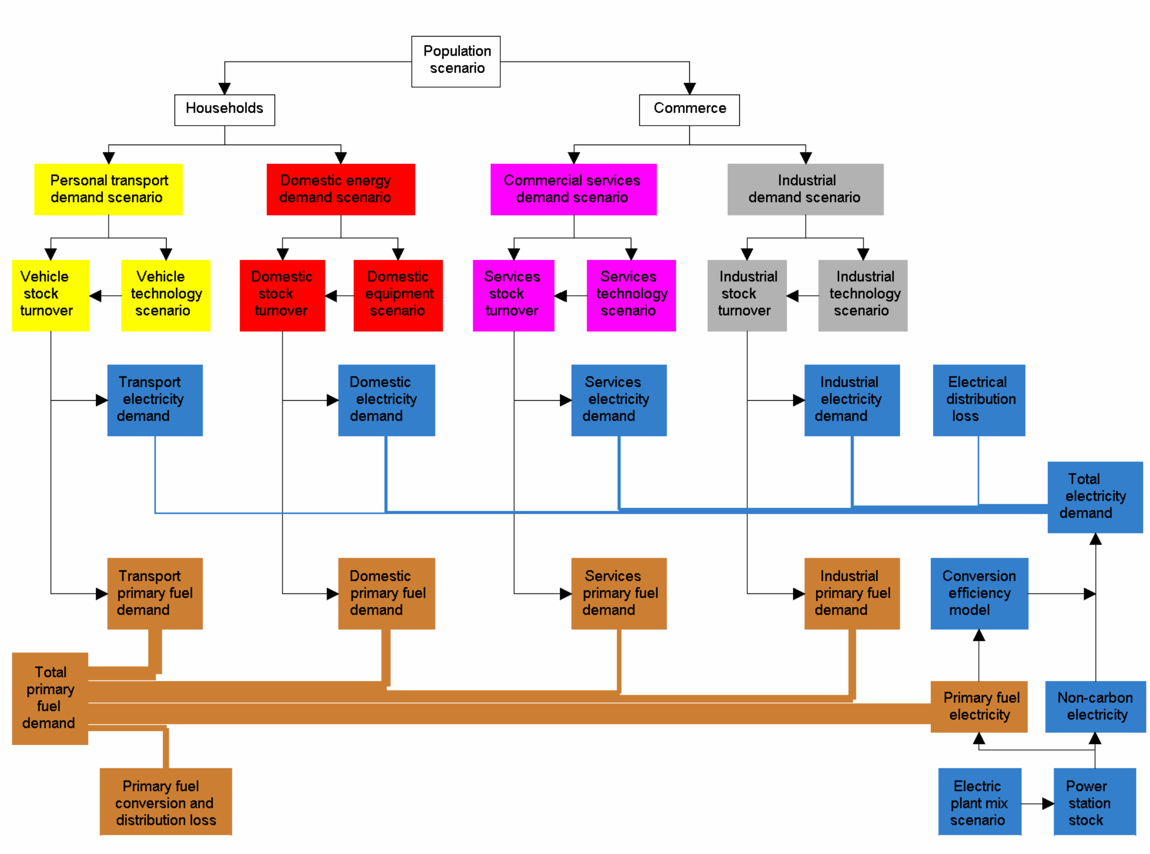


Figure 4-1 : Information and energy flows in the THESIS model

Figure 4-1 shows the initial conceptual flow of information through the model. Due to lack of early agreement on population scenarios within Tyndall, the top level of the model (Population and Households/Commerce) was not implemented and the demand side of the model was implemented on a per demand sector basis, using the four sectors: Transport, Domestic, Service, and Industry.

Figure 4-1 also shows the base case of the primary fuel and electrical energy supply proportions for the UK in 2000 (note that electrical demand to transport is much less than shown due to minimum line thickness), based on the energy supply by sector as recorded in Energy Paper 68 (DTI, 2000).

The model demonstrates the changes in these energy flows (and hence in output carbon emissions) due to various hydrogen production, distribution, and utilisation strategies.

The major inputs are the sectoral primary fuel and electricity demands. These are input as top-down targets in all sectors except Transport, where a vehicle stock model can be used instead. It was originally intended to include a similar model for Domestic and Service/Commerce building stock, but suitable input data on building types was not readily available at the level of disaggregation required and it was not clear what criteria would then need to be used to differentiate the uptake of hydrogen within these different stock types. Such data could usefully be included in future development of the model.

Having derived the electricity and primary fuel demands within each sector, *THESIS* then determines the required electricity production and primary fuel demands allowing for process and distribution losses. The electrical power station stock is monitored and new plant commissioned as demand rises and older plant is retired. In the case where hydrogen is used as a secondary energy carrier, the hydrogen production and storage & distribution capacities are regulated appropriately. A major output from the model is the stock turnover and new plant requirements year by year.

The total primary energy requirement is then determined together with the associated carbon emissions. A separate balance sheet of sequestrated carbon is kept for large hydrogen production plants from fossil fuels (smaller plants are assumed to vent their carbon dioxide to atmosphere due to high per unit costs of sequestration).

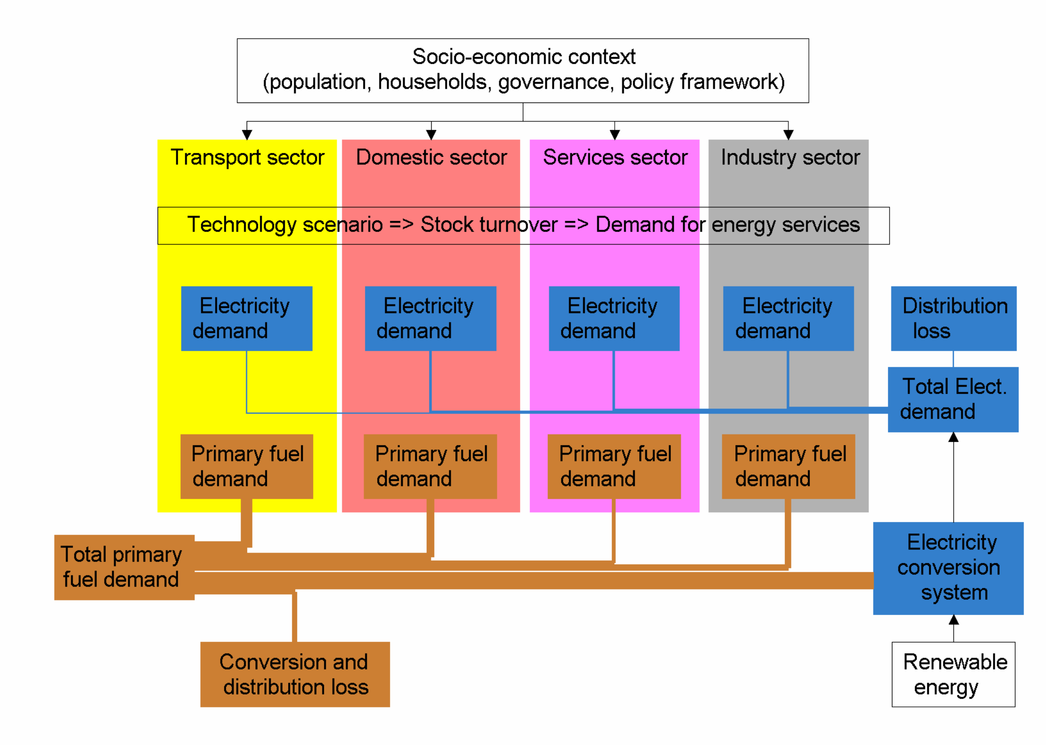


Figure 4-2 : Information and energy flows in the THESIS model

Figure 4-2 shows the top level inputs to the *THESIS* model required to be developed for each socio-economic scenario.

Scenario definition

A scenario is defined by the following parameters:

- the rate of growth of the economy and the rate of growth of energy services,
- the rate of improvement of energy intensity,
- the expected penetration of hydrogen energy technologies (by sector)
- the type and characteristics of new electric plant capacity
- the proportions of different types of electric plant in new build capacity
- the type and characteristics of hydrogen production (and storage/distribution) plant
- the proportions of different types of hydrogen production (and storage/distribution) plant in new build capacity
- performance improvements due to end-use of hydrogen

4.1 End-use sector demand

The end-use sector demand input to the *THESIS* model can either be derived in a top-down fashion from the initial conditions and the target end-states or in a bottom-up fashion assuming certain market growth rates and efficiencies. The top-down approach was used exclusively in the Domestic, Service, and Industry sectors, and the bottom-up approach in the Transport sector using the Transport vehicle population model developed by ITS.

When fitting to the target end-state, a cubic-spline fit was made between the two end-states using historic data to define the initial gradient in 2000, and the average gradient between the end-states to define the final gradient in 2050. Since this approach is essentially defining energy consumption, it implicitly includes all assumptions made about end-use energy intensity improvement made by the ERAG (Energy Review Advisory Group, 2001) – see Appendix 3.

Each scenario was first modelled in a “Baseline” state with no hydrogen. Hydrogen was then introduced to displace existing “conventional” demand according to a prescribed pathway, the objective of the model being to determine the potential environmental benefits ensuing from a hydrogen economy and the infrastructural implications of that change compared with the Baseline case. At this stage, there was the opportunity to include an end-use efficiency improvement from the use of hydrogen, e.g. for a fuel cell CHP system displacing a conventional domestic gas boiler and some electricity demand.

The “Baseline” sector demands under each scenario are shown in Figure 4-3 in the context of trends from the previous 30 years.

Since natural gas is an important primary feedstock for hydrogen production, it was decided to assume that the use of Coal and Petroleum in the non-Transport sectors would be phased out by 2030 across all scenarios. This maximises the likely pressure on natural gas resources when assessing the viability of the hydrogen economy within any given scenario (it also reduces carbon emissions in the Baseline scenario set, so that the improvements evaluated from the use of hydrogen are likely to be conservative).

Since the proportional use of electricity is increasing in all non-Transport sectors, simply extrapolating existing rates of expansion would result in all energy use being given over to electricity in some sectors within the 50 years study band. This was not considered likely, given that space and water heating can usually be supplied most efficiently from a primary fuel source, and caps were placed on the penetration of electricity within each end-use sector (Domestic 25%, Industry 27.5%, Services 42.5%) common across all scenarios.

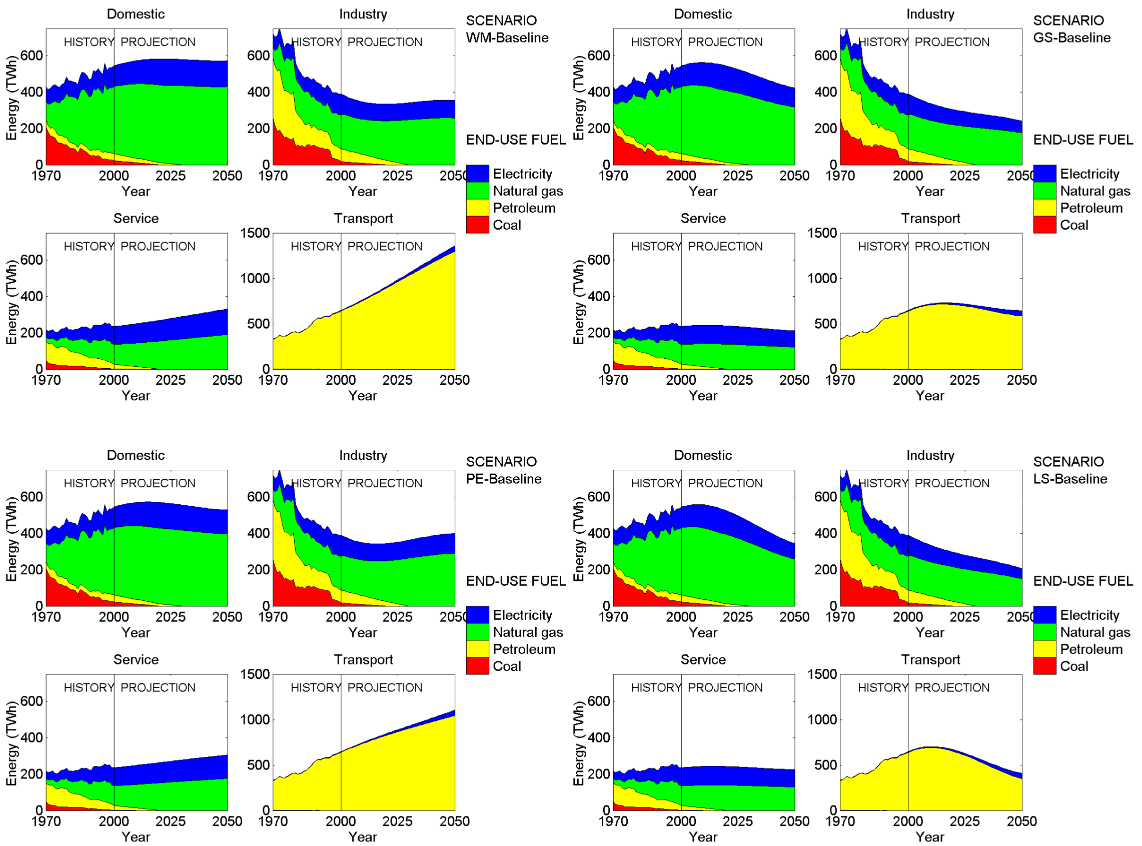


Figure 4-3 : Baseline sectoral demand (by end-use energy source) extrapolations for the four scenarios (note change of scale for the Transport sector)

While the validity of these assumptions is open to debate in the wider context, they are justified here since they allow for a common basis of comparison for the introduction of hydrogen within the different scenarios.

4.2 Transport vehicle population model

The transport sector currently accounts for approximately 26% of carbon dioxide emissions in the UK (DfT, 2003) and it is the sector in which emissions are increasing most rapidly. A detailed transport vehicle population model has therefore been developed to forecast the fuel consumption of the transport sector to 2050 and so explore trends in this sector in more detail. The model may either be run in stand-alone mode or as an input component to the *THESIS* model.

The UK transport vehicle population model was designed to be quick and easy to use so as to allow the use of an iterative procedure to develop pathways for testing the different scenarios. It is based around the four main energy consuming transport modes: road, rail, air and water. The model uses readily accessible and relatively aggregate data sources so as to speed up construction and use and is conceptually relatively simple, though maintaining enough functionality to allow the differentiating features of the scenarios to be represented.

Section 4.2.1 describes the development of the components of the model and details the inputs. Section 4.2.2 explores the assumptions made under each scenario, with the transport inputs discussed in some detail in section 4.2.3. Section 4.2.4 shows the model outputs and section 4.2.5 the conclusions.

4.2.1 Development of the model

For the rail, air and water sectors, the required inputs are the levels of different types of activity (by different vehicle types) for all years up to 2050. These are combined with fuel consumption factors to predict total fuel consumed (by fuel type) for every year up to 2050. As the road sector is the major source of emissions, a more sophisticated approach is used, involving basic modelling of the vehicle fleet (stock turnover for a wide variety of different vehicle types) and the use of fuel consumption equations (NAEI, 2004) that take into account vehicle speeds on three different road types (urban, rural, and motorway).

The model consists of a series of Excel workbooks, one each for Water and Air, and two for Road and Rail, which distinguish between Great Britain and Northern Ireland, because much of the data on road and rail transport is reported in this way and the overall *THESIS* model operates for the whole of the UK. All the sub-models have a similar conceptual structure, the two road transport workbooks are the most complex, but are identical in structure.

For all the sub-models the basic assumption used is that:

Level of activity x *fuel consumption factor = total fuel consumed*

Levels of activity and fuel consumption factors are built into the sub-models for 2000, 2001 and 2002. The inputs to the sub-models are therefore the *changes* in the levels of activity and the *changes* in the fuel consumption factors expected over the forecasting period (2003 – 2050).

Road transport sub-model

Road transport is at present the dominant source of carbon dioxide emissions within the transport sector. The road transport sub model is the most complex for this reason and also because data is available to facilitate a fairly detailed approach. The road transport sub-model has the structure:

No. of vehicles (stock) x *kilometrage per vehicle* x *fuel consumption (speed) = total fuel used*

Stock: The vehicle stock is disaggregated by vehicle type and vintage. The vehicle classes used in the model are shown in Table 4-1. Fuel sources used at present are: petrol (52.73% total road fuel consumption), diesel (47.24% of total road fuel consumption), and Liquid Petroleum Gas (LPG) (with a mere 0.03% of total road fuel consumption). Fuel types with a very minor share are not included in order to simplify the process. All vehicle types (except motorcycle which has very low energy consumption) have at least one hydrogen fuelled future vehicle type, a Hydrogen Fuel cell (HFC) vehicle. For cars a Hydrogen Internal Combustion Engine (HICE) and a diesel Hybrid have also been included.

The vehicle stock is divided into 15 different age categories, from vehicles which are less than 1 year old to vehicles which are between 13 and 14 years old and those which are over 14 years old. This allows the dissemination of new vehicle types to be modelled. Survival factors for each vintage of vehicle, that is, the proportion of that vehicle type and age surviving to the next year, were calculated from those implied by the stock figures calculated for 2000, 2001 and 2002. The survival rates for alternatively fuelled vehicles were assumed to be the same as those for diesel cars. Survival rates are assumed to remain constant over the period modelled.

Car	Petrol	small (< 1.4 l)		Heavy goods	Diesel	Rigid
		medium (1.4 - 2.0 l)				Artic
		large (> 2.0 l)			HFC	Rigid
	Diesel	small (< 2.0 l)				Artic
		large (> 2.0 l)		Light goods	Petrol	
	Hybrid	small			Diesel	
		large			HFC	
	HFC	small		Bus or coach	Diesel	
		large			HFC	
	HICE	small		Motorcycle		small (<=50cc)
		large				medium (50 - 499cc)
						large (>=500cc)

Table 4-1 : Road vehicle classes

Stock for forecast years is calculated from the new buy for the forecast year and the survival factors. The inputs for the stock part of the sub-model are therefore the changes in the new buy from the previous year.

Data for the base years were taken from the Vehicle Licensing Statistics (VLS) series published by Transport Statistics: DfT (DTLR, 2001a, DfT, 2002 and DfT, 2003).

Kilometrage: Vehicle kilometrage data was taken initially from the relevant editions of Transport Statistics Great Britain (DfT, 2003). These figures for total vehicle kilometres by vehicle type were modified by using the NAEI dataset (uk_fleet_composition_projections_v2.xls) of vehicle kilometres by vehicle type and propulsion type (NAEI, 2004). This allows the total kilometres figures for car and light goods vehicles to be split by propulsion type.

Kilometrage per vehicle was obtained by dividing through by total stock for that vehicle type. It was not possible to differentiate between different car sizes, so these were given the same kilometrage per vehicle. It was assumed that for alternatively powered vehicles, these would have the same kilometrage per vehicle as diesel vehicles.

Speeds: Speeds are used as an input to the fuel consumption factors, they are broken down into the different vehicle types, but also three different road types; motorway, rural and urban. The speed data was taken from DfT (2003) using the average speed for each road type and vehicle. After initial studies it became obvious that this approach resulted in under-estimation of the total fuel used due to:

(i) the non-linear relationship between speed and fuel consumption,

(ii) increased fuel use during start-up and acceleration (particularly in urban areas),

(iii) the mean speeds clearly having been measured on open, free-moving roads.

It was therefore decided to adjust the speeds used for each road type until the estimated total fuel consumption for road transport in 2000 was matched and then to use these speeds as the basis for the scenario projections.

Fuel consumption factors: For conventional vehicle types these are taken from the NAEI (2004) dataset - the spreadsheet entitled vehicle_emissions_v8.xls, sheet "Fuel". The parameters are arranged in columns and annotated a to j and x. these are used in the fuel factors sheet to construct the equation which gives fuel used:

Fuel used (g/km) $= (a + b.v + c.v^2 + d.v^e + f.\ln(v) + g.v^3 + h/v + i/v^2 + j/v^3).x$

where v is the speed in km/h.

The coefficients vary by vehicle type and vintage. For non-conventional vehicles (Hybrid, HFC and HICE) the treatment of fuel consumption was cruder, with a simple non-speed-related factor being used. Information for cars was taken from Ricardo (2002), which gives estimated "well to wheels" emissions of CO_2 and hydrogen consumption for various important future car vehicle types. Conversion of "well to wheels" CO_2 figures to "tank to wheels" figures for diesel was carried out by multiplying by the given conversion factor of 0.895 (Ricardo 2002). Conversion from CO_2 emissions (g/km) to amount of fuel used (g/km) was done using a conversion factor derived from Ntziachristos et al. (2000) which gives a factor of 3.138 to convert from mass of diesel to mass of CO_2 emissions. This is very similar to the figure given in the DEFRA fuel conversion factors (3.142). For hydrogen powered car types amount of hydrogen consumed was given directly by Ricardo.

Fuel consumption figures for PSV and LGV were taken from Hart et al. 2000; rigid HFC HGV fuel consumption was assumed to equal that of PSV; while that for articulated HFC HGV was assumed to be in the same ratio to rigid HFC HGV fuel consumption as for conventional HGV.

The final figures used for non conventional road vehicle types are given in Table 4-2.

Vehicle Type	Fuel	Fuel consumed (g/km)
Car – diesel hybrid	diesel	29.7
Car – hydrogen ICE	hydrogen	22.7
Car – hydrogen fuel cell	hydrogen	11.6
LGV – hydrogen fuel cell	hydrogen	18.8
PSV – hydrogen fuel cell	hydrogen	84
Rigid HGV – hydrogen fuel cell	hydrogen	84
Articulated HGV – hydrogen fuel cell	hydrogen	149

Table 4-2 : Fuel consumption figures for non-conventional vehicles (for references, see text)

Results: Results (total fuel consumed) are available for all vehicle vintages and types on the three different road types for all the modelled years. For simplicity, various macros are used to extract more aggregate information for further analysis.

Rail transport sub-model

Rail is a relatively minor mode as far as fuel consumption is concerned. It currently accounts for only 3% of carbon dioxide emissions in the transport sector (DfT, 2003). Available data on fuel consumption for rail is very basic resulting in fairly crude modelling of this sector. It was not possible to find fuel consumption factors for hydrogen powered trains and therefore, in view also of the comparatively low contribution of Rail to overall Transport provision, hydrogen was not introduced into the rail sub-model. The units used are thousands of kilometres for passenger trains and millions of tonne kilometres for freight trains. Table 4-3 shows the rail vehicle classes. The classes chosen broadly reflect variations in vehicle type. The kilometrage data was taken from SRA(2003) which provides annual kilometrage by company. The final data was determined by splitting the company kilometrage data by the proportions of each train type and then summing the totals by the region that the train company is located.

Intercity	Diesel
	Electric
Regional	Diesel
	Electric
London and South East	Diesel
	Electric
Freight	Diesel
	Electric

Table 4-3 : Rail vehicle classes

It would be relatively simple to introduce a hydrogen fuel cell train in a future version of the model and so to examine the effect of expanding use of hydrogen in the rail sector.

Fuel consumption factors: Fuel consumption factors were taken from the NAEI (2004) inventory and are for a typical service pattern.

Air transport sub-model

The air transport model is sub-divided into domestic and international flights and passenger and freight. It was assumed that all flight emissions from domestic flights and half of the emissions from international flights are allocated to the UK. In the case of international flights this means one Land and Take Off sequence (LTO) and one leg of a return journey. The hydrogen plane assumptions used in the model are based on estimates from CRYOPLANE, which is a European project funded to consider the implications of introducing hydrogen fuelled airplanes into the market (CRYOPLANE, 2003). The units were thousands of aircraft movements and thousands of kilometres. Table 4-4 shows the aircraft classes used.

The LTO figures were taken from DfT(2003), as was the average cruise distance for domestic flights (total kilometrage divided by LTO). The cruise distance for international flights was taken from CAA(2003).

The aircraft stock was not modelled to the same level of detail as road transport because of lack of data. Instead aircraft activity types were considered as shown in Table 4-4. While aircraft stock turnover could not therefore be modelled directly, relatively modest changes in aircraft activity were used to represent relatively low rates of change in aircraft fleets. Changes in aircraft stock were also considered when deciding on the future changes in the fuel efficiency of different aircraft activities.

Domestic Flights		International Flights	
	LTO		LTO
B737-400 Passenger	Cruise distance	B767 300 R Passenger	Cruise distance
	LTO		LTO
'Cryoplane' Passenger	Cruise distance	'Cryoplane' Passenger	Cruise distance
	LTO		LTO
B737-400 Cargo	Cruise distance	B767 300 R Cargo	Cruise distance
	LTO		LTO
'Cryoplane' Freight	Cruise distance	'Cryoplane' Freight	Cruise distance

Table 4-4 : Aircraft classes

Fuel consumption factors: Fuel consumption factors were taken from EMEP (2002), which provide kilogrammes of fuel consumed by the LTO phase and cruise distance phase (based on distance) for a B737-400 and a B767 300. The figures for the "CRYOPLANE" were calculated on the assumption that the aircraft would use a similar technology to conventional aircraft and that therefore the hydrogen consumed can be calculated from the relative energy density of the hydrogen fuel.

Water transport sub-model

Very little data exists for the Water transport mode; however, shipping only accounts for 3% of carbon dioxide emissions in the UK (DfT, 2003).

Activity was broken down into millions of tonne kilometres by inland and sea going water transport. Data was taken from (DfT, 2003). It was assumed that the fuel consumed by water transport would stay the same over the forecasting period.

4.2.2 Use of the scenarios

The transport model was designed so that the scenarios could be used to explore how the transport industry might look in 2050. The four scenarios were used to develop the yearly inputs in terms of new buy, kilometrage, speed and fuel consumption for the transport model. The first step was to convert the qualitative descriptions of the scenarios into quantitative inputs. Outline scenario descriptions are provided in Table 4-5. In the case of *World Markets*, for example, car ownership and hence congestion are expected to increase (DTI, 1999), in which case speeds are likely to fall in the absence of further investment in road infrastructure; low energy prices and little investment in alternatively fuelled vehicles will ensure that petrol and diesel fuelled vehicles remain the norm under this scenario.

These qualitative descriptions provided a starting point for the construction of the inputs to the transport model; further elaboration was provided by the scenarios document (Watson et al, 2004), which estimated the energy demand in each sector, including Transport, and the proportion of this total energy use which might conceivably come from hydrogen by 2050.

Table 4-6 indicates that under all scenarios except *Local Stewardship* Transport energy demand is expected to increase by 2050 and in the case of *World Markets* will more than double. The scenarios represent a wide range of possible levels of hydrogen use in the transport industry over the next 50 years. For example, in *Global Sustainability* high investment in low energy and low emission vehicles driven by high energy prices and an emphasis on environmental gains results in 80% to 100 % of the energy used by Transport coming from hydrogen in 2050.

	World Markets	***Global Sustainability***	***Provincial Enterprise***	***Local Stewardship***
Technology change	Low investment	High Investment	Low Investment	High investment at local level.
New technologies	ICT in cars	Low energy, Low emission vehicles	Little innovation	Alternatively fuelled vehicles
Energy Prices	Low	High	High	High
Car Ownership	High growth	Moderate growth	Low growth	Falls
Congestion	Increases (all modes)	Investment reduces congestion	Increases (due to lack of investment)	Congestion reduced
Bus Use	Falls	Increases	Falls	Increases

Table 4-5 : Outline scenario descriptions [Source: adapted from DTI (1999)]

	World Markets	***Provincial Enterprise***	***Global Sustainability***	***Local Stewardship***
Energy demand in 2050 (TWh)[1] ***638 TWh (2000)***	1359	1101	646	403
% Hydrogen use in Transport in 2050[2]	5 %	15-25% 5% (2030)	80-100% 10-20% (2030)	20% Including 20-50% for buses

Table 4-6 : Transport demand for energy and hydrogen in 2050 [Sources: [1]Energy Review Advisory Group (2001) and [2]Watson et al (2004)

The descriptions were then quantified in terms of speed, fuel consumption, and new buy inputs for each of the four scenarios. Section 4.2.3 briefly describes the process for introducing hydrogen into the transport sector and provides an example of the process for constructing the New Buy input sheet for the road transport model, given that this element has the most relevance for the hydrogen economy.

The “Baseline” scenarios were realised in the Transport vehicle population model by extrapolating the current aggregate kilometrage figures to 2050 using the proportionate increases in energy demand cited in the ERAG report (see Appendix 3) and using these as targets while manipulating the New Buy rates for each vehicle type. The net fuel use was then calculated, by first accounting for current commitments towards vehicle efficiency improvements and then implementing a constant rate of improvement to realise the ERAG energy intensity improvement targets. The total kilometrage by vehicle type by scenario is shown in Figure 4-4.

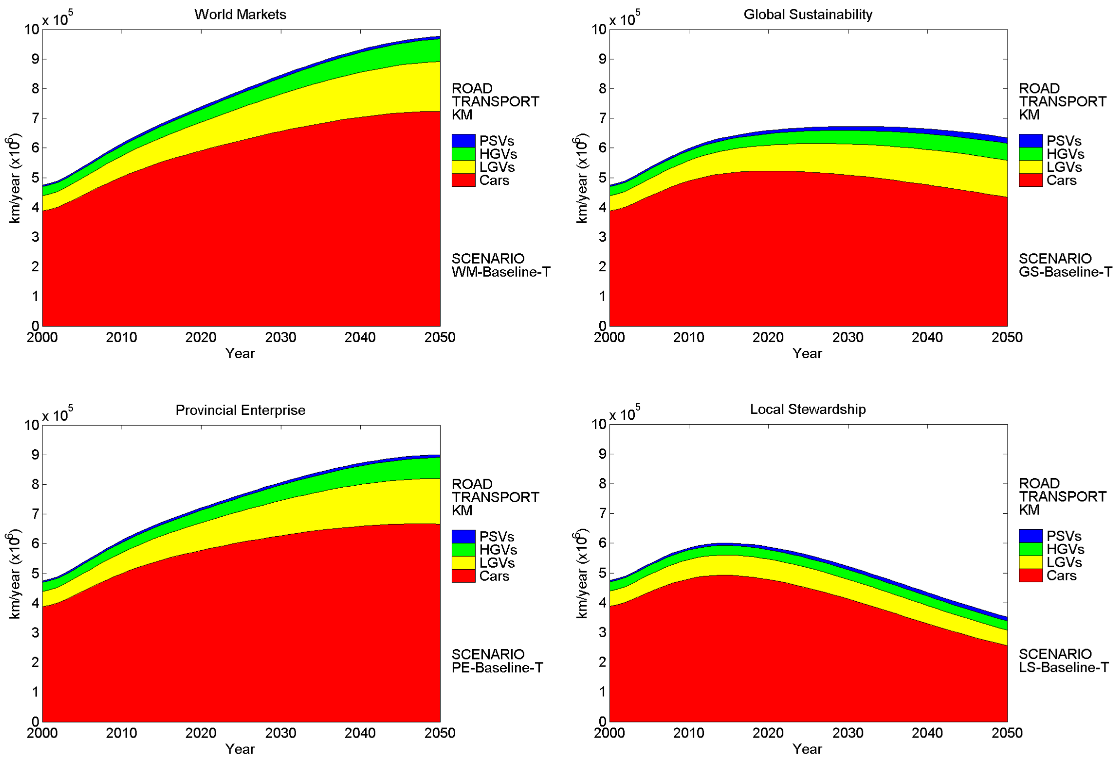


Figure 4-4 : Road transport sector development (total kilometrage per year by vehicle type) by scenario (“Baseline” case)

4.2.3 The introduction of Hydrogen into transport

Critical questions in the process of determining model inputs for hydrogen-powered vehicles are:

- at what point in the future should hydrogen be introduced into each Transport scenario?
- what take-up rate would be necessary after this introduction date in order to meet the nominal percentage hydrogen energy use by 2050 shown in Table 4-6?
- is this take-up rate feasible (and, if not, what might a feasible rate be)?

As has already been suggested, the problem of feasibility is complex. The introduction of hydrogen-powered vehicles requires not only development of suitable manufacturing facilities (including the whole fuel cell supply chain) but also parallel developments in refuelling infrastructure, hydrogen production, and hydrogen storage devices, all of which have potential bottlenecks and possible resource limitation problems (e.g. platinum for fuel cell catalysts). The implication is that growth of the industry is likely to encounter rate-limiting factors with likely increased carbon dioxide emissions wherever parallel development is inhibited (e.g. increased use of fossil-derived electricity if renewable electricity growth is too slow).

The hydrogen vehicle introduction dates were determined using both the DTI (1999) report to determine aspects such as the rate of technological change, demand for energy and the demand for transport for each of the scenarios and the Ricardo (2002) paper which suggests two potential routes and time frames for the introduction of hydrogen cars in the UK. These two routes are designated as "low carbon" and "hydrogen priority", which closely match the assumptions used in the *Local Stewardship* and *Global Sustainability* scenarios respectively.

For each of the scenarios, assumptions were made as to which modes of transport would be most likely to convert to using hydrogen first and in the case of scenarios with low hydrogen targets (e.g. *World Markets*), which would be the most unlikely modes of transport to be fuelled by hydrogen in 2050. It is widely felt in the literature that hydrogen vehicles are most likely to breakthrough first in the bus market (Foley 2001, DTLR *et al* 2001b and Pridmore and Bristow 2002) given the advantages of a common refuelling point, lack of space constraints for fuel storage, and the need to reduce urban emissions of local air pollutants. Three hydrogen-powered buses are already being introduced in London as part of the CUTE project (TfL, 2003). Another possible introduction strategy is through other fleet vehicles, such as light goods vehicles, which again could share a common refuelling point. The most unlikely mode of transport to convert to hydrogen in this time period are probably heavy goods vehicles and thus the only scenario in which hydrogen fuel cell heavy goods vehicles feature is *Global Sustainability* (facilitated by early development in the other vehicle types). The Ricardo (2002) dates were used in conjunction with the scenario descriptions as a guideline for determining when hydrogen could be introduced for each of the scenarios. The "low carbon" route, identified with the *Local Stewardship* scenario suggested that hydrogen cars would be introduced in 2030. Given the assumption that hydrogen would be used first in buses and LGV's these vehicle types have been given an earlier introduction date than cars. In *Provincial Enterprise*, where innovation is slower and the hydrogen target (15-25% by 2050) is lower, the hydrogen introduction dates are later, see Table 4-7.

	World Markets	***Provincial Enterprise***	***Global sustainability***	***Local Stewardship***
Car	-	2026	2016	2030
Light goods	2030	2031	2010	2021
Heavy goods	-	-	2019	-
Bus	2011	2021	2003	2016

Table 4-7 : Introduction dates for hydrogen vehicles in the Road Transport model

Market Penetration of Hydrogen

The next stage was to estimate the market penetration rate of hydrogen through the fleet given the start dates in Table 4-7 and the hydrogen and overall Transport sector targets for 2050 (Table 4-6). The total vehicle stock for each vehicle type within each scenario was known from the "Baseline" runs; it was then assumed that hydrogen vehicles would substitute for these on a like for like basis.

Next, the introduction dates for each type of hydrogen vehicle were determined as in Table 4-7 and estimates made of the percentage rates of New Buy increase required each year to meet the target number of hydrogen vehicles by 2050. In each case a seed production of about 0.5% of the particular vehicle fleet was assumed to have been developed by the introduction date and the percentage increases allowed to act on this seed. The resulting penetration of hydrogen vehicles through the fleet for each given vehicle type by scenario is shown in Figure 4-5.

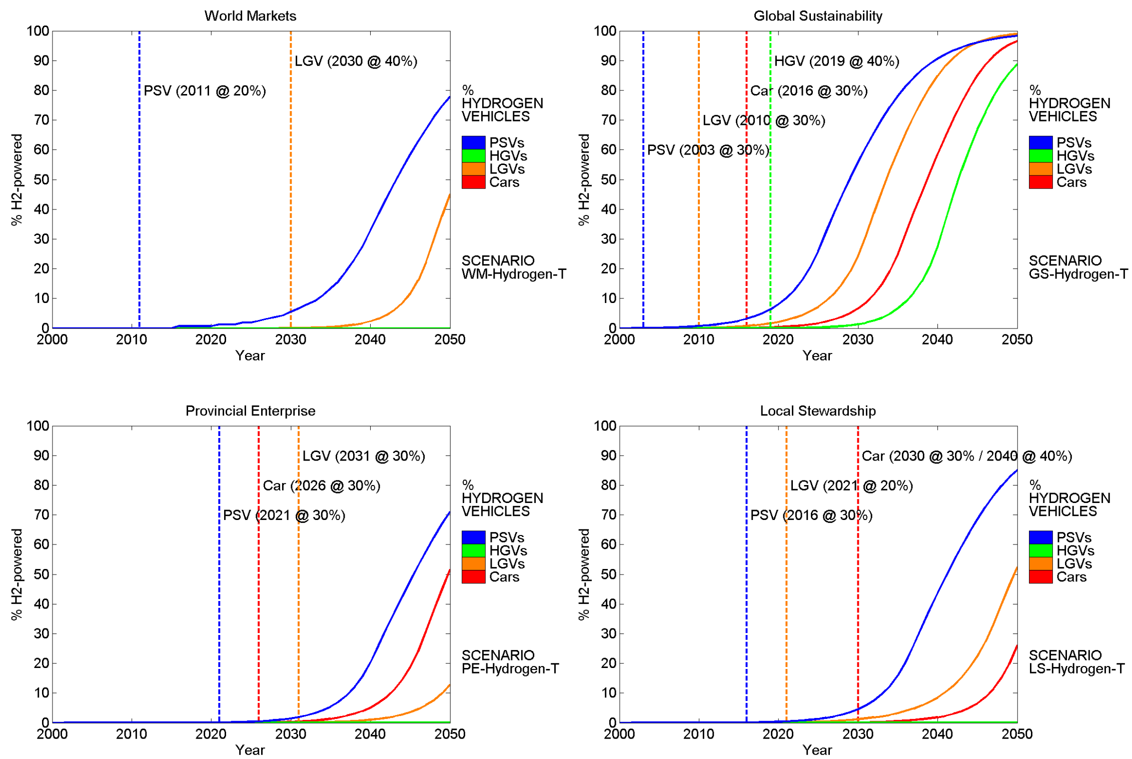


Figure 4-5 : Penetration of hydrogen-powered vehicles into the Road Transport sector by scenario

In the *Local Stewardship* case, for example, a fleet of 197,000 hydrogen buses (85% of the total fleet) could be developed by 2050 from the introduction date of 2016 with a rate of increase of 30% per year.

Finally, the increases in hydrogen vehicles were subtracted from the total vehicle stock originally calculated to ensure that as the hydrogen vehicles penetrate the market they take the place of conventional (fossil-) fuelled vehicles.

As an example, a contraction of the New Buy input sheet for the *World Markets* scenario is presented in Table 4-8. A positive percentage change for a particular year creates an increase in the number of vehicles of that type being purchased from the previous year and a negative percentage a decline.

For initial runs the same improvements in fuel consumption were assumed for the hydrogen fuel cell vehicles as for the conventional fossil-fuelled vehicles. There is then the opportunity to carry out a sensitivity analysis of variations in assumed fuel efficiency improvements on overall carbon dioxide emissions.

A similar process was carried out for Air Transport, where it was assumed that the same hydrogen penetration levels were achieved in each scenario as for Road Transport.

			2000	2001	2002	2003	2004	2005	2006	2007	2008	…	2049	2050
Car	Petrol		N/A	N/A	N/A	2.2	2.15	2.1	2.05	2	2		1.51	1.50
	Diesel		N/A	N/A	N/A	2.7	2.69	2.68	2.67	2.66	2.65		2.23	2.22
	HFC		N/A	N/A	N/A	0	0	0	0	0	0		150.00	150.00
	HICE		N/A	N/A	N/A	0	0	0	0	0	0		0.00	0.00
HGV	Diesel	Rigid	N/A	N/A	N/A	2.85	2.85	2.85	2.74	2.74	2.74		2.17	2.17
		Artic	N/A	N/A	N/A	1.07	1.07	1.07	1.1	1.1	1.1		1.52	1.52
	HFC	Rigid	N/A	N/A	N/A	0	0	0	0	0	0		0.00	0.00
		Artic	N/A	N/A	N/A	0	0	0	0	0	0		0.00	0.00
LGV	Petrol		N/A	N/A	N/A	2.58	2.58	2.58	2.48	2.48	2.48		-0.90	-1.10
	Diesel		N/A	N/A	N/A	2.58	2.58	2.58	2.48	2.48	2.48		1.97	1.96
	HFC		N/A	N/A	N/A	0	0	0	0	0	0		50.00	50.00
PSV	Diesel		N/A	N/A	N/A	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1		-30.00	-35.00
	HFC		N/A	N/A	N/A	0	0	0	0	0	0		10.00	10.00
M/c	All		N/A	N/A	N/A	0	0	0	0	0	0		0.00	0.00

Table 4-8 : Example input sheet for road transport new buy (*World Markets*)

4.2.4 Model Outputs

The main outputs of the model (by vehicle and fuel type) by year are:

- Total Energy use TWh
- Vehicle Stock
- Vehicle Kilometrage
- Hydrogen (and conventional fossil) fuel demand.

The overall changes in the Transport sector by scenario are shown in Figure 4-6 for the "Baseline" scenario set. The overall demand patterns are essentially the same in the "with-hydrogen" cases.

The hydrogen introduction dates and vehicle penetration rates have already been presented in Figure 4-5 and the resulting end-use fuel demands are shown in Figure 4-7. The assumed rates of market penetration for Road Transport vary between 20% and 40%. These may be considered to be on the high side, given the parallel developments which are required in hydrogen production, energy infrastructure, and hydrogen fuel cell and storage material extraction and component manufacture (see also Section 5.2).

In the *Local Stewardship* scenario energy use falls over the 50 year period. This is due to a fall in demand for personal motorised travel and an emphasis on local solutions to transport problems. Hydrogen is dominant in the bus industry, which sees an upturn in use.

In the *World Markets* scenario energy demand has more than doubled due to an increase in the less environmentally sustainable modes of transport such as the car and air travel. This scenario has the largest increases in energy demand and the lowest use of hydrogen. Hydrogen has only broken through in the bus industry and has a small share of the light goods vehicle market.

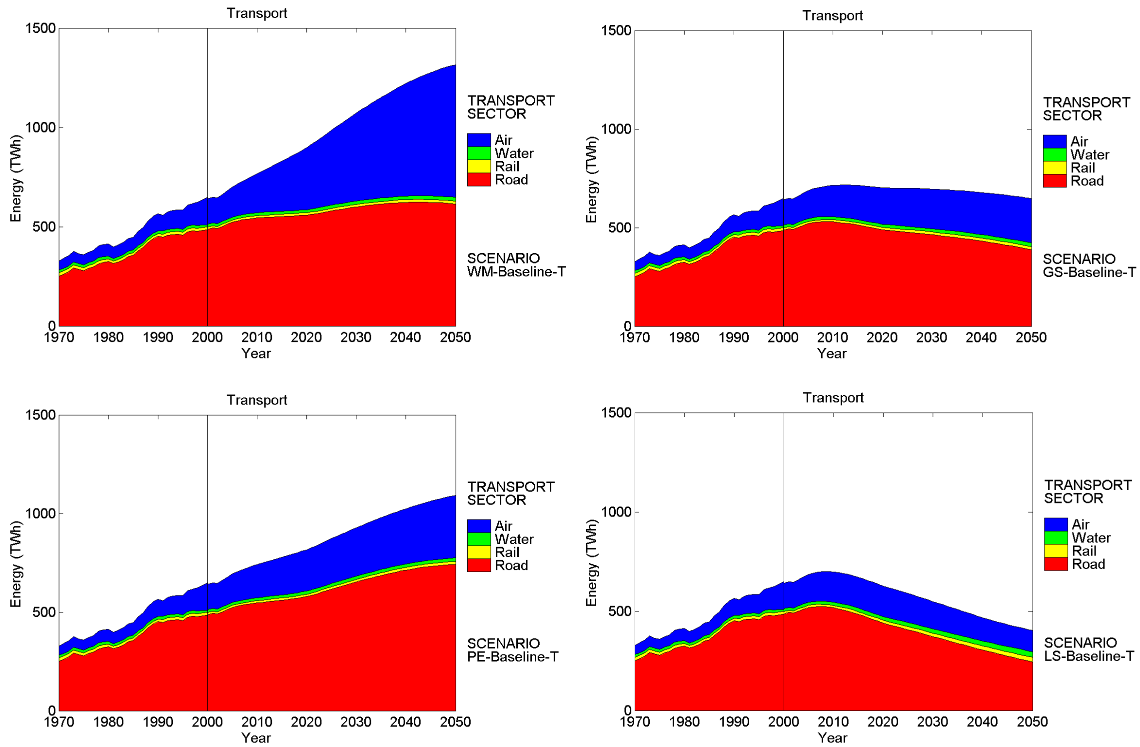


Figure 4-6 : Transport sector development by scenario (“Baseline” case)

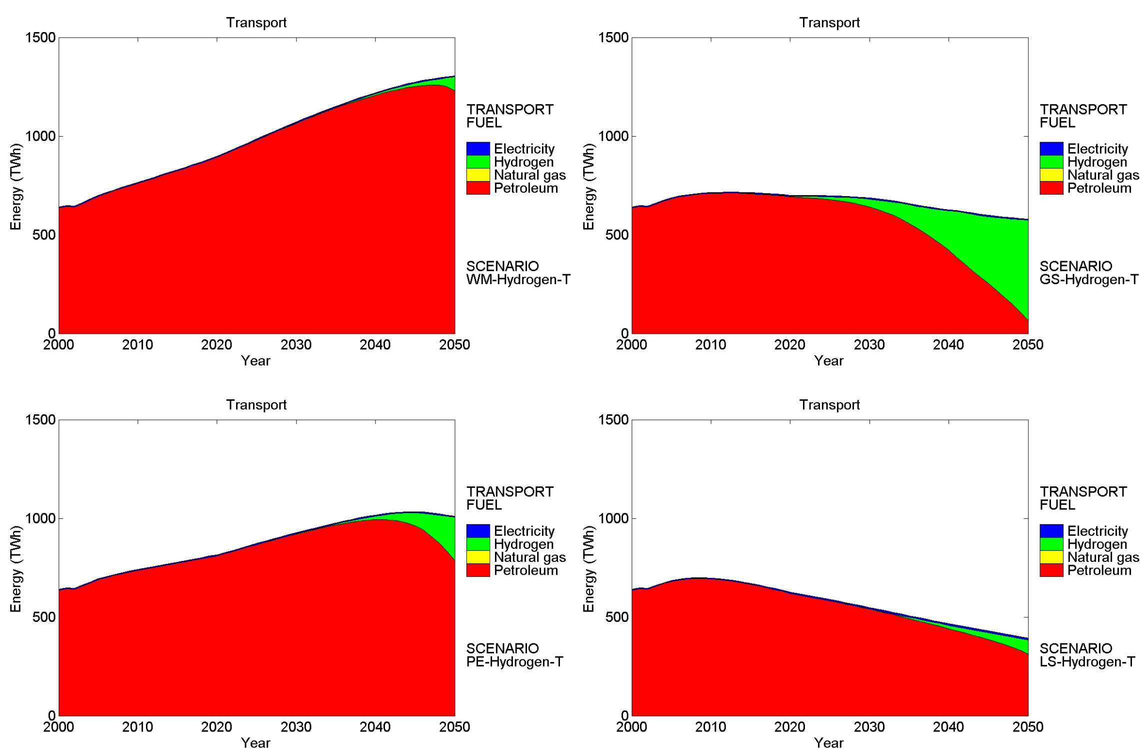


Figure 4-7 : Utilisation of hydrogen as a fuel in the Transport sector by scenario

In the *Global Sustainability* scenario energy use has grown slowly. This is due to increasing the energy efficiency of vehicles and the move to more sustainable modes of transport for longer distance trips. One of the major contributors to energy demand is international air trips which have increased in number due to the need to be connected globally. Hydrogen vehicles have been introduced for all modes with the exception of Water and Rail.

In the *Provincial Enterprise* scenario energy demand has increased. This is due to an increased dominance of the private car as a means of transport and reliance on road freight as a means of transporting goods. By 2050 Hydrogen has been introduced in the bus, LGV, and car market to meet the target of 15-25%.

4.2.5 Conclusions

The transport vehicle population sub-model is designed to forecast overall fuel consumption based on vehicle stock, kilometrage, fuel consumption and vehicle speed. It is intended that this fuel demand is then fed forward into the wider *THESIS* model in order to estimate the overall energy demand and carbon dioxide emissions resulting from up-stream hydrogen production and conventional fuel distribution. A sensitivity analysis according to varying hydrogen vehicle introduction dates and market expansion rates can easily be carried out within the context of any given scenario.

Although the sub-model can only approximately reproduce specific targets for future years (as can be achieved by taking the extrapolated overall demand and sub-dividing that by fuel), a more realistic picture of vehicle populations and fleet growth is obtained. Most particularly, the transport vehicle population sub-model indicates that quite rapid growth in hydrogen take-up would be required to meet the most extravagant of the scenario targets and, in the event that these are considered unrealistic, can provide better estimates of likely penetration at reduced implementation rates.

As with all models, the results must be interpreted in the light of the underlying assumptions. For example, as has already been noted, the input vehicle speeds (averaged across only three road types to simplify the modelling process) required some adjustment to match the national aggregate road fuel consumption figures.

The model could be further developed in future to include different vehicle types. An area of special relevance may be biofuels, which, in conjunction with the overall *THESIS* model, could be assessed for the most appropriate implementation routes and compared with other uses of the original biomass or, indeed, crop area.

4.3 Electricity and primary fuel supply model

Electricity Plant Capacity Model

Electricity plant is characterised according to unit rated capacity, efficiency, lifetime, load factor, and load factor/efficiency deterioration with time.

The baseline year for the electricity plant model was taken as 2000, using Table 5.13 from DUKES (DTI, 2001), which lists all operating power stations by name and company, citing the fuel, installed capacity, and year of commissioning. The overall total capacity in 2000 was just short of 80 GW (including 4.5 GW of CHP).

Some plant (amounting to a total capacity of 6.2 GW) is listed in DUKES as dual-fuel, mostly coal/oil or coal/gas with some oil/gas and diesel/gas. For simplicity, at the top level, dual-fuel plants using coal have been entered into the model as coal-fired and those not using coal as oil-fired. There is some confusion in the categorisation of small renewables and waste plant. Again for simplicity, sewage and landfill gas, poultry litter, and meat and bone meal have been entered in the THESIS model in the general category "waste".

Estimates of plant lifetime were taken from the PIU report (Performance & Innovation Unit, 2002) as shown in Table 4-9.

Asset Type	**Lifetime (years)**
Conventional fossil fuel power stations	40 years
Combined cycle power stations	30 years
Nuclear power stations	40 years
Wind power stations	20 years
Hydro power stations	100 years
Electricity transmission and distribution wires	50 years
Gas pipelines and terminals	60 years
Oil refineries	50 years

Table 4-9 : Electricity generating plant lifetimes (after Performance & Innovation Unit, 2002, p.200)

On this basis a retirement profile for existing electricity capacity can be constructed (Figure 4-8). This clearly shows the need to replace almost 50% of 2000 capacity by 2018, rising to 90% by 2030. In fact, since *DUKES* appears to list only the year of first commissioning (and not the date of subsequent upgrades) and actual plant retirements will depend on commercial and technical conditions rather than the nominal figures given above, Figure 4-8 might be considered to be on the pessimistic side. On the other hand, the EU Large Combustion Plant Directive (LCPD) may force the premature retirement of most of the UK's coal-fired power stations by 2016, and some of the nuclear capacity has published retirement dates less than the 40 years assumed here.

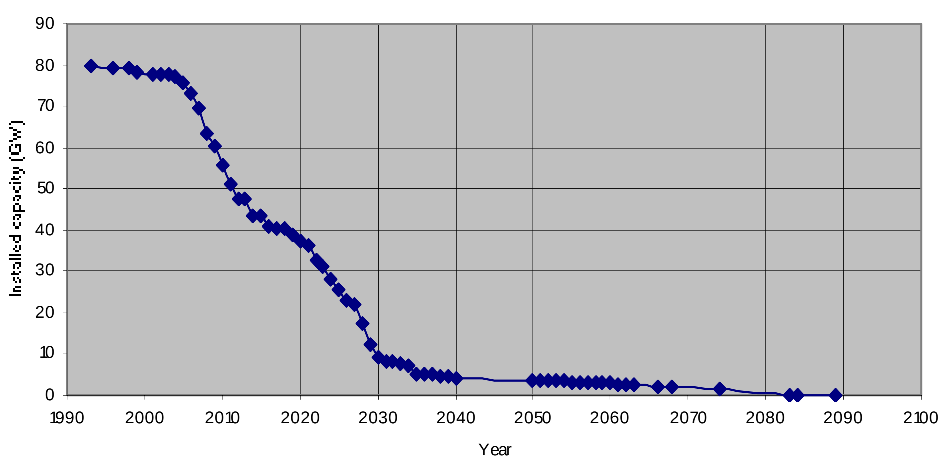


Figure 4-8 : Projected retirement of current (year 2000) electricity generating plant capacity

A short term, higher level approach to electricity plant generating mix is provided by Energy Paper 68 – Annex D (DTI, 2000), which projects the electricity generation (GWh) by individual fuel type every 5 years between 1990 and 2020.

ALL Year Typical size (MW) Efficiency Load factor Lifetime (years)	2000	2020	2050
Coal	2000 0.33 0.8 40	2000 0.35 0.8 40	2000 0.35 0.8 40
Petroleum (diesel generator, oil-fired)	200/1000 0.33/0.35 0.3/0.5 40	2000 0.35/0.35 0.3/0.5 40	
Natural gas	1500 0.55 0.8 30	1500 0.575 0.8 30	1500 0.575 0.8 30

ALL Year Typical size (MW) Efficiency Load factor Lifetime (years)	2000	2020	2050
Nuclear	1000 - 0.8 40	1000 - 0.8 40	1000 - 0.8 40
Renewables (wind power: on-/off-shore)	20/200 - 0.25/0.4 15/20	50/500 - 0.25/0.4 15/20	50/500 - 0.25/0.4 15/20
Imports	1000 1.0 1.0 50	1000 1.0 1.0 50	1000 1.0 1.0 50

Table 4-10 : Electricity generating plant characteristics

New electric capacity is introduced according to a technology profile specific to each scenario. The basic plant sizes, efficiency improvements, and load factors have not been varied between scenarios and are shown in Table 4-10. No conventional coal- and oil-fired steam turbines and diesel engines for electricity generation are built after 2030, even in the *Local Stewardship* scenario, where it could certainly be argued that coal may have a bigger role to play. This is justified when the goal of the project is to consider the impact of hydrogen production on the overall energy system, which will impact most on the gas and renewable electricity supplies. Modern pressurised water nuclear reactors are also assumed to be replaced by one or more of the currently developing "fourth generation" of reactors after 2015. Of particular note here is the wide range of very recent potential reactor designs (see, for example, Schultz, 2003), some of which are specifically designed to produce heat (e.g. for feeding into thermo-chemical cycles for hydrogen production) rather than electricity as their primary energy generating function. There has been insufficient time to include these in any detail in the current study; although they could be expected to reduce the overall carbon dioxide emissions in the energy system, the public acceptability of such reactors seems questionable.

The model includes the distribution loss for electricity (Table 4-11) which, for the sake of simplicity, has been assumed to remain constant to 2050. All electrolysis plant has been assumed to incur this distribution loss, although arguably it may no longer be appropriate for large hydrogen electrolysis plant placed close to renewable or nuclear power plants.

Similarly, the fuel-processing and distribution losses associated with the primary fuels, coal, oil, and natural gas, have also been assumed constant with time (Table 4-11), the initial required values having been estimated from UK national energy statistics (DTI 2002).

Energy source	Coal	Petroleum	Natural gas	Electricity
Conversion and distribution loss	0.135	0.075	0.13	0.11

Table 4-11 : Primary fuel and electricity conversion and distribution losses

4.4 Hydrogen Production, Storage & Distribution Model

Three principal hydrogen production technologies have been included:

(i) steam methane reforming (SMR) – three plant sizes,

(ii) electrolysis of water (using electricity specified as being sourced from renewable electricity, nuclear electricity, or mains grid) – two plant sizes,

(iii) coal gasification.

Improvements in the performance of hydrogen production technologies can be specified with time. For the model results reported in this report, these improvements were assumed to be the same across all scenarios. Current and future values are taken from the literature, in particular the wide ranging report by Wurster and Zittel, 1994.

Hydrogen production plant (Table 4-12 and Table 4-13) is characterised according to unit rated capacity, hydrogen production efficiency, lifetime, and load factor.

Four principal hydrogen storage technologies have been included:

(i) direct use (no storage, possibility to include pumping losses),

(ii) liquefaction,

(iii) compression,

(iv) solid state storage (e.g. metal hydride).

Year **PlantType**	**2000**		**2015**		**2030**		**2050**	
	Capacity	**Eff.**	**Capacity**	**Eff.**	**Capacity**	**Eff.**	**Capacity**	**Eff.**
Small SMR plant	500 (4.38)	0.75	500 (4.38)	0.77	500 (4.38)	0.78	500 (4.38)	0.79
Medium SMR plant	5,000 (43.8)	0.78	7,500 (65.7)	0.80	10,000 (87.6)	0.81	10,000 (87.6)	0.82
Large SMR plant	50,000 (438) largest is 3x this	0.82	150,000 (1314)	0.83	300,000 (2628)	0.84	500,000 (4380)	0.84
Electrolysis (small)	1,000 (8.76)	0.69	1,000 (8.76)	0.71	1,000 (8.76)	0.73	1,000 (8.76)	0.75
Electrolysis (large)	30,000 (262.8)	0.75	30,000 (262.8)	0.77	50,000 (438)	0.78	100,000 (876)	0.81
Coal gasification	(500)	0.55	(1000)	0.56	(2000)	0.58	(4000)	0.6
Other	The analysis has not so far included partial oxidation of hydrocarbons, biomass gasification, biological hydrogen (photosynthesis or fermentation), nuclear thermal or solar thermal hydrogen, etc.							

Table 4-12 : Hydrogen production plant capacity and assumed efficiency – capacity values stated in Nm^3 of H2 per hour (million Nm3 of H2 per annum)

Hydrogen storage plant is characterised according to unit rated capacity, storage duration, component lifetime, and throughput efficiency.

Four principal hydrogen distribution routes have been considered:

(i) direct use,

(ii) cylinder & truck,

(iii) replaceable tank,

(iv) pipeline (local/long distance).

Hydrogen distribution plant is characterised according to unit rated capacity, storage duration, component lifetime, and throughput efficiency. Some consideration was paid to the development of possible criteria for triggering the growth of hydrogen pipeline networks once a threshold level of hydrogen production and distribution had been achieved. A crude measure based on absolute production level was adopted, since a more sophisticated approach would need to consider geographical contexts.

ALL Year Unit size (Nm^3/h) Efficiency Load factor Lifetime (years)	2000	2020	2050
Small SMR plant	500 0.75 0.9 15	500 0.775 0.9 15	500 0.79 0.9 15
Medium SMR plant	5,000 0.78 0.9 20	8,000 0.80 0.9 20	10,000 0.82 0.9 20
Large SMR plant	50,000 0.82 0.9 25	200,000 0.83 0.9 25	500,000 0.84 0.9 25

ALL Year Unit size (Nm^3/h) Efficiency Load factor Lifetime (years)	2000	2020	2050
Electrolysis (small)	1,000 0.69 0.9 20	1,000 0.72 0.9 20	1,000 0.75 0.9 20
Electrolysis (large)	30,000 0.75 0.9 20	40,000 0.775 0.9 20	100,000 0.81 0.9 20
Coal gasification	50,000 0.55 0.9 20	200,000 0.575 0.9 30	500,000 0.60 0.9 30

Table 4-13 : Additional hydrogen production plant characteristics (unit size, efficiency, load factor, and lifetime

Hydrogen is introduced by specifying a displacement of existing primary or secondary fuel demand. Improvements in hydrogen end-use technologies are defined as an efficiency improvement by sector by specifying an energy intensity parameter. If the transport vehicle population model is used then the fuel efficiencies must be entered explicitly via that model instead. Dramatic efficiency savings are claimed for fuel cell vehicles compared to modern internal combustion engine vehicles, but there are also ambitious emissions targets for conventional IC engines, which are fully represented within the transport vehicle population model. These conventional improvements are implicit in the energy demand projections, so fuel cell vehicles will have to compete in future markets against much-improved vehicle performance. At the same time, fuel cell vehicle performance is yet to be proven and the reaction of consumers may not be to replace like with like.

The efficiency of hydrogen production can be specified for each production technology against time horizons selected by the user (e.g. 0.69 for current-day electrolysis systems or 0.81 for current-day SMR).

Hydrogen storage and distribution losses are allocated to primary fuel consumption according to the proportion of hydrogen plant for that fuel.

Hydrogen primary fuel consumption is added to the appropriate Total primary fuel demand within Hydrogen plant and therefore incurs the full fuel processing/distribution loss for that primary fuel. It is arguable that larger plant should have a lower fuel processing /distribution loss.

The overall hydrogen penetration level by sector is specified for certain key years as an input to the model. Input values are interpolated to individual years. New hydrogen plant is then introduced according to a technology pathway specific to each scenario.

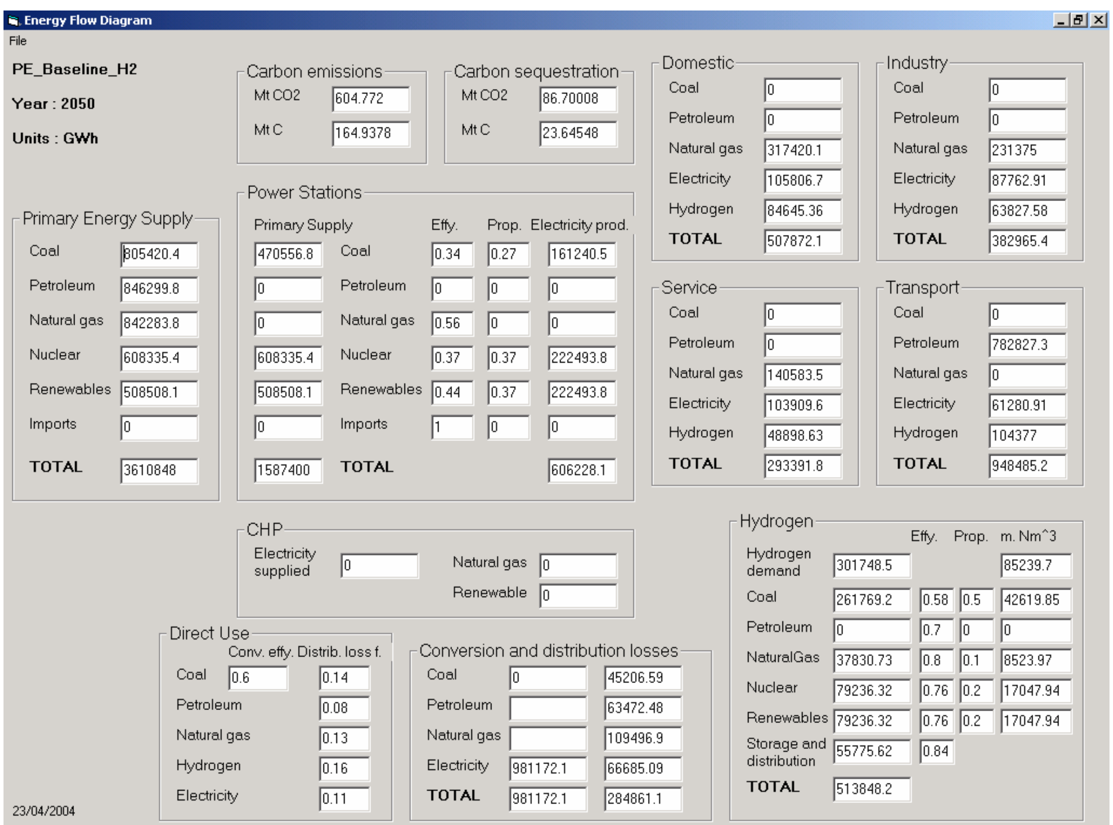


Figure 4-9 : Sample output screen from *THESIS*

4.5 THESIS model outputs

When the *THESIS* model runs it produces a yearly picture of the energy demand requirements by sector and associated energy flows (see, for example, Figure 4-9). Selected variables for each year are collected into an appropriate output table and saved for later analysis. Typical output parameters are total primary energy supply, total electricity supply, primary fuel demand (by fuel type), total carbon dioxide emissions, energy consumption by end-use sector, fuel consumption by end-use sector, electricity production (by fuel type), and hydrogen production, storage, and distribution volumes. The model also estimates and outputs the new plant requirements for electricity generation and hydrogen production, storage, and distribution each year.

A more detailed discussion for the outputs from the set of contextual futures follows in Section 5.

5 Hydrogen scenario transition pathways

5.1 Hydrogen economy transition pathways to 2050: the basic scenarios

During the PIU Energy Review, the Energy Review Advisory Group (Energy Review Advisory Group, 2001b) developed the Foresight scenario framework to derive possible end-use energy demands by sector for 2050. Their methodology accounted for:

(i) change in the economic growth rate (by scenario),

(ii) change in the demand for energy services,

(iii) change in the energy intensity (i.e. the efficiency with which energy is used).

The precise figures and projections to 2050 can be found in the Energy Review Advisory Group report (and are reproduced in Appendix 3 of this report), but the net implications for annual percentage energy demand growth per sector compared with historic rates is presented in Table 5-1. It is clear that the Energy Review Advisory Group figures represent challenging targets under all the scenarios.

	WM	PE	GS	LS	Last 30 years (mean)
Economic Growth (% per year)	3.00	1.50	2.00	1.00	
Average Energy Demand Growth (% per year)	0.65	0.42	-0.44	-0.94	
Average Domestic Demand Growth (% per year)	0.1553	-0.0151	-0.4472	-0.8433	1.01
Average Services Demand Growth (% per year)	0.4336	0.3142	-0.4359	-0.3179	0.77
Average Transport Demand Growth (% per year)	1.5238	1.0972	0.0249	-0.9146	3.59
Average Industry Demand Growth (% per year)	-0.5106	-0.2957	-1.3059	-1.5679	-1.71

Table 5-1 : Economic growth and projected energy demand growth for the four scenarios compared with historic trends [Source: Energy Review Advisory Group, 2001]

Within this overall framework, it was further necessary to assign the proportions of demand in the Domestic, Industry, and Service sectors required for heating and power. This was done according to the current rate of increase of electricity consumption in each sector, with a limiting proportion of electricity penetration defined. These rates and limits are shown in Table 5-2. Domestic and commercial building scale Combined Heat and Power (CHP) units are assumed to operate within these overall electric power demand limits. No limit was placed on the possible penetration of electricity into the Transport sector, though in practice this penetration remained very low across all scenarios. CHP was modelled as displacing a given amount of end-user electricity demand and an associated amount (depending on the type of CHP plant).of primary fuel heating demand.

An overall end-user energy demand projection was then derived by fitting a cubic spline between the current total energy demand per sector (magnitude and historic rate of increase determined over the last 5 years) and the nominal 2050 total energy demand per sector (magnitude and required mean rate of increase/decrease).

Sector	**Annual % electricity increase**	**Limiting proportion of electricity in total demand**	**Year Coal use phased out for heating**	**Year Petroleum use phased out for heating**
Domestic	1.13	25	2020	2030
Services	5.25	42.5	2010	2020
Transport	4.0	100.0	Not used	Beyond 2050
Industry	1.8	27.5	2020	2030

Table 5-2 : Assumed percentage electricity increase by sector, with limiting penetrations, and phasing out of other fuels

The use of coal and oil as end-use heating fuels was assumed to be phased out in all sectors (nominal date variable by scenario, if required). Natural gas therefore becomes the heating fuel of choice in all the model runs. Biomass and/or biofuels were not considered explicitly in the analysis, since it was assumed that their uptake would be unaffected by the penetration of hydrogen within the timescale considered (for further discussion see Section 6.2).

The preliminary results of the modelling exercise were presented at a Stakeholders' Workshop held at SPRU on 28 April 2004. These comprised, for each scenario:

(i) "Baseline" projections to 2050 assuming no hydrogen introduction,

(ii) "Baseline" projections to 2050, assuming hydrogen penetrations according to Table 3-3,

(iii) "Baseline" projections to 2050, assuming hydrogen penetrations according to Table 3-3 for Domestic, Service, and Industry, but using vehicle population model for Transport.

Following feedback from the workshop, a revised set of scenarios was produced, with the output from the vehicle population model fully integrated into the *THESIS* analysis. These results are presented in the following pages as:

(i) "Baseline-T" projections to 2050 assuming no hydrogen introduction (using vehicle population model for the Transport sector),

(ii) "Hydrogen-T" projections to 2050, assuming hydrogen penetrations according to Table 3-3 (using vehicle population model for the Transport sector)

A sensitivity analysis was then carried out to explore the effect of:

(i) assumptions about energy intensity improvement on *World Markets* Transport growth,

(ii) hydrogen-powered vehicle growth rate in the high-penetration *Global Sustainability* scenario,

(iii) restricted Renewables/Nuclear deployment in the *Global Sustainability* scenario with hydrogen.

The remainder of this section presents brief descriptions of the parameters used to specify electricity generation and hydrogen production within each scenario, together with some representative results from the transition pathways. The penetration of hydrogen into the four end-use sectors is shown in Figure 5-1 (c.f. Baseline scenarios in Figure 4-3).

Section 5.2 then presents some comparisons between the various transition pathways in terms of total hydrogen production capacity, changes in electrical generation capacity, and primary natural gas demand.

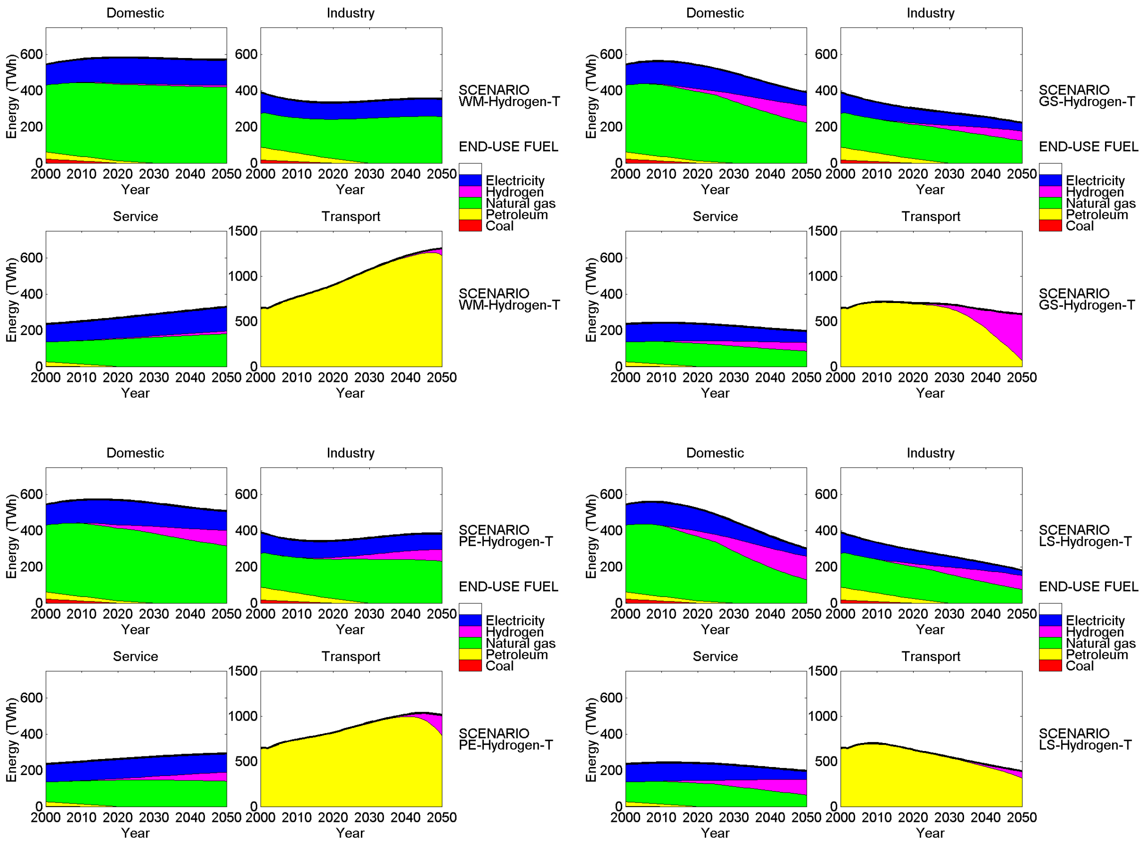


Figure 5-1 : Hydrogen scenario end-use demand by sector (note change of scale for the Transport sector)

World Markets

World Markets features only a low level of hydrogen demand, insufficient to promote technology development, except, perhaps, in the area of small, portable devices. By 2050 hydrogen production is predominantly from SMR (small/medium plants) with conventional storage technologies. Some electrolysis is likely to be used for small levels of production in niche areas (but electricity is drawn from the bulk supply and is not generated from specific low carbon sources). Given the low overall demand and the likelihood of niche applications, small scale hydrogen production from electricity may dominate in the short term.

To achieve the nominal target of maximum 5% penetration in the Transport sector, it is assumed that hydrogen is introduced quite early (2011) to the bus fleet (on the grounds of reducing inner city vehicle emissions) and somewhat later (2030) in the LGV fleet (where a certain amount of ribbon development is possible to support fleets in urban areas and along motorways, without requiring wide scale deployment), while cars remain petrol-/diesel-powered, see Figure 4-5.

The electricity mix is price-driven and features predominantly coal, natural gas, and renewables with a strong imports market.

WM Year Electricity generating type	2000	2020	2050
Coal	0.314	0.15	0.2
Petroleum	0.018		
Natural gas	0.393	0.5	0.4
Nuclear	0.212	0.08	
Renewables	0.025	0.2	0.3
Imports	0.038	0.07	0.1

Table 5-3 : Assumed proportion of electricity generation by technology (*World Markets*) in 2000, 2020, and 2050

WM Year Hydrogen source	2000	2020	2050
Coal			
Petroleum			
Natural gas	0.9	0.8	0.9
Electricity (Bulk)	0.1	0.2	0.1

Table 5-4 : Assumed proportion of hydrogen production by technology (*World Markets*) in 2000, 2020, and 2050

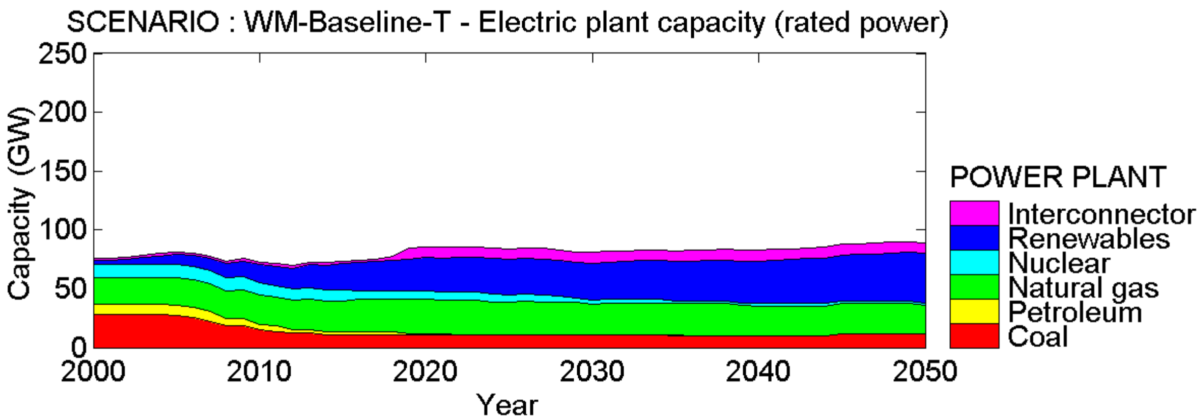
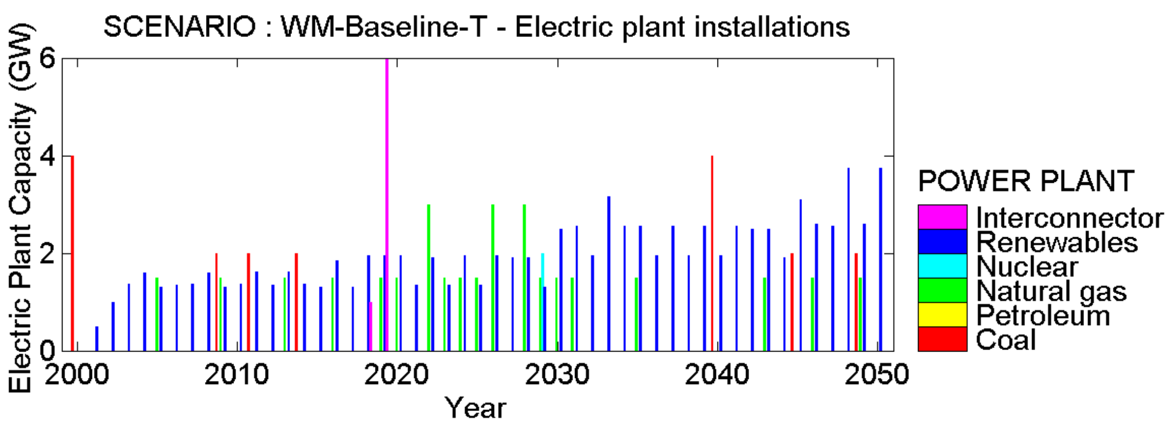


Figure 5-2 : *World Markets* Baseline Integrated Transport scenario – projected total electric plant capacity (GW)



Total electric plant capacity installed (2000-2050)
Coal : 18000 MW
Petroleum : 0 MW
NaturalGas : 33000 MW
Nuclear : 2000 MW
Renewables : 97870 MW
Imports : 7000 MW

Figure 5-3 : *World Markets* Baseline Integrated Transport scenario – projected annual electric plant installations (GW)

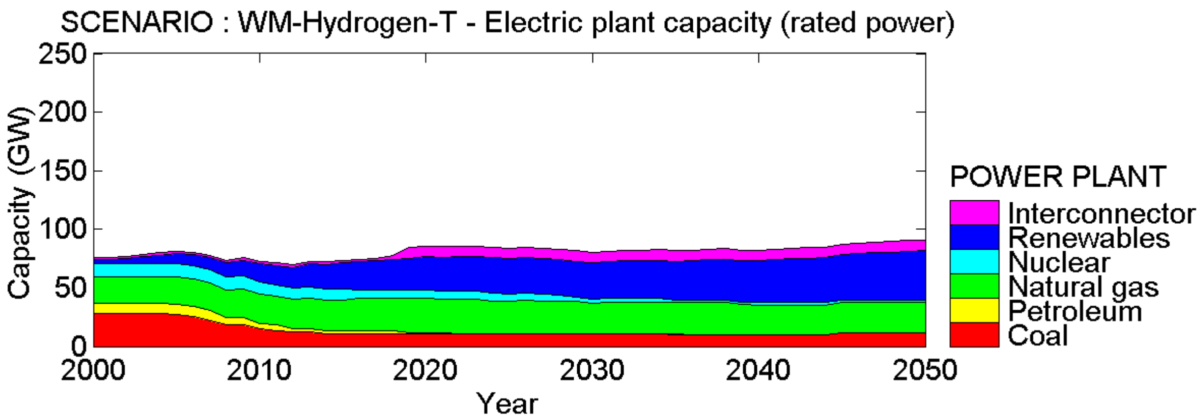


Figure 5-4 : *World Markets* Hydrogen Integrated Transport scenario – projected total electric plant capacity (GW)

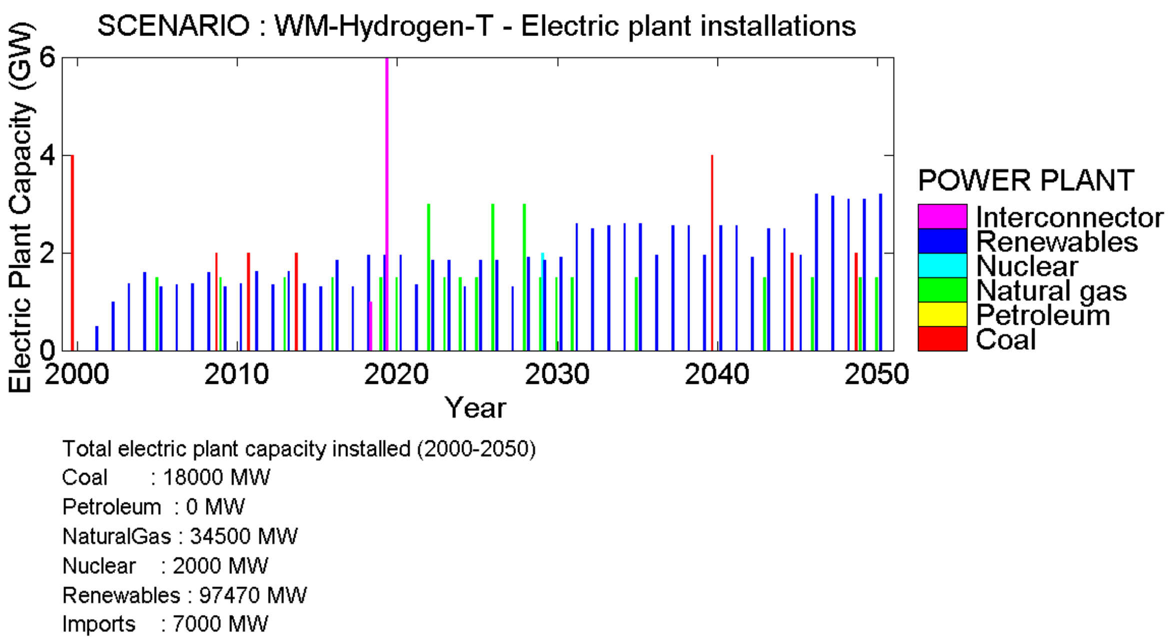


Figure 5-5 : *World Markets* Hydrogen Integrated Transport scenario – projected annual electric plant installations (GW)

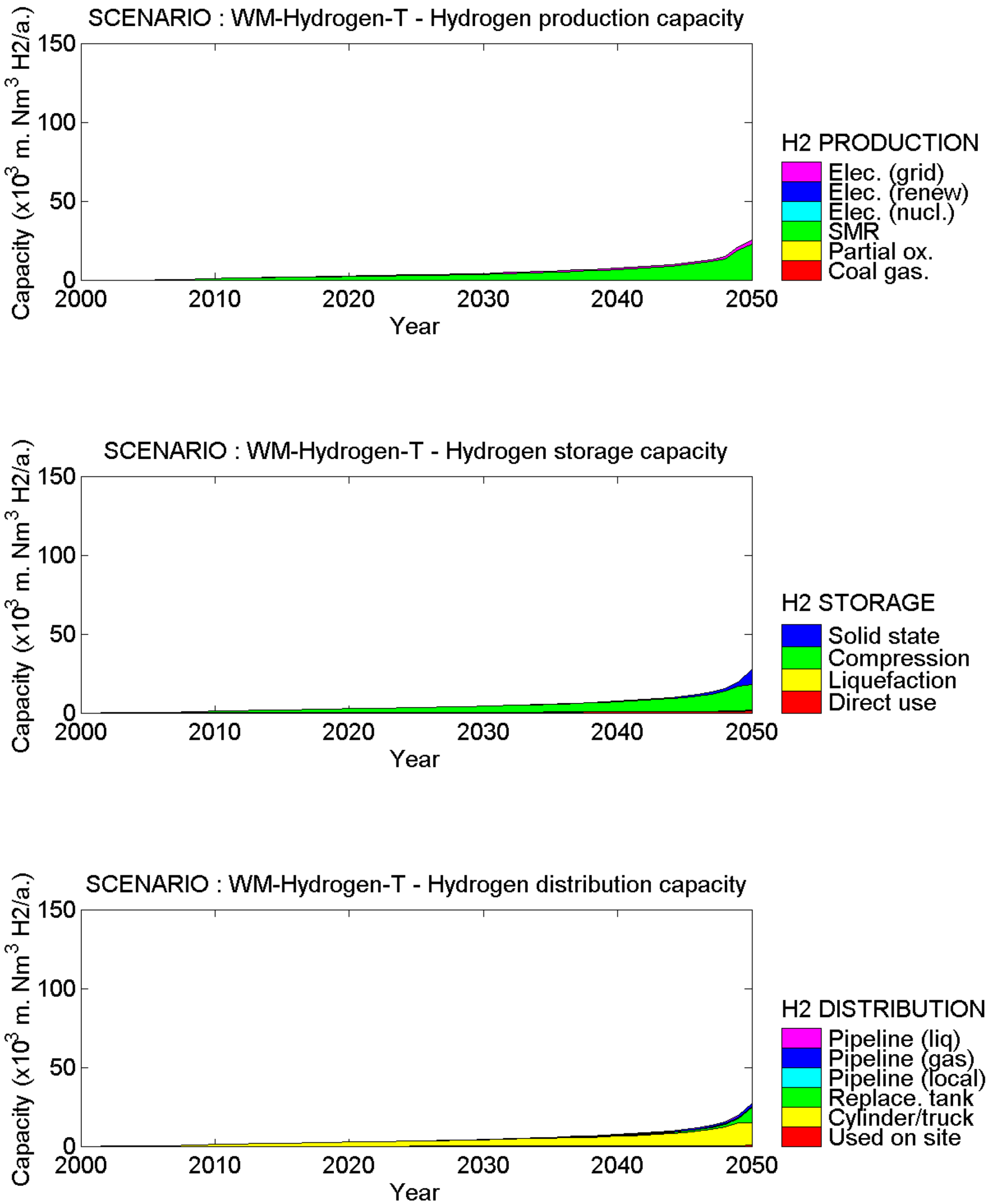


Figure 5-6 : *World Markets* Hydrogen Integrated Transport scenario – projected hydrogen production, storage, and distribution capacities (billion Nm^3 H_2/a)

Provincial Enterprise

One of the principal features of *Provincial Enterprise* is reliance on local resources. It therefore seems likely that gasification of coal will be prominent in the UK as a major hydrogen production technology (though environmental concerns are low on the agenda and no major efforts at carbon dioxide sequestration are made). Hydrogen replaces imported fuels wherever possible.

The electricity mix is price-driven with an emphasis on indigenous resources. The latter benefits a new-build programme for coal-fired and nuclear power stations and a greater development of renewable energy. Natural gas is reserved for heating use.

The comparatively late hydrogen vehicle introduction dates (buses 2021, cars 2026, and LGVs 2031) mean that the impacts of hydrogen on the scenario are not really felt until the 2040s. It was originally intended to model the introduction of hydrogen cars only after 2036, but this would have required new buy growth rates in excess of 100% to achieve the target penetration level by 2050, which was considered unrealistic.

PE Year Electricity generating type	2000	2020	2050
Coal	0.314	0.2	0.4
Petroleum	0.018		
Natural gas	0.393	0.4	
Nuclear	0.212	0.15	0.3
Renewables	0.025	0.2	0.3
Imports	0.038	0.05	

Table 5-5 : Assumed proportion of electricity generation by technology (*Provincial Enterprise*) in 2000, 2020, and 2050

PE Year Hydrogen source	2000	2020	2050
Coal		0.2	0.5
Petroleum			
Natural gas	0.9	0.6	0.1
Electricity (Renewables)	0.05	0.1	0.2
Electricity (Nuclear)	0.05	0.1	0.2

Table 5-6 : Assumed proportion of hydrogen production by technology (*Provincial Enterprise*) in 2000, 2020, and 2050

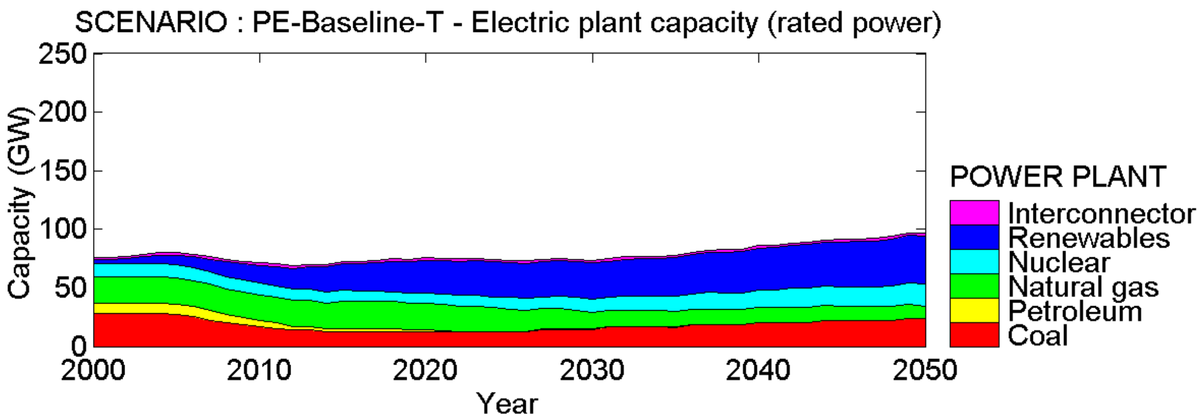


Figure 5-7 : *Provincial Enterprise* Baseline Integrated Transport scenario – projected total electric plant capacity (GW)

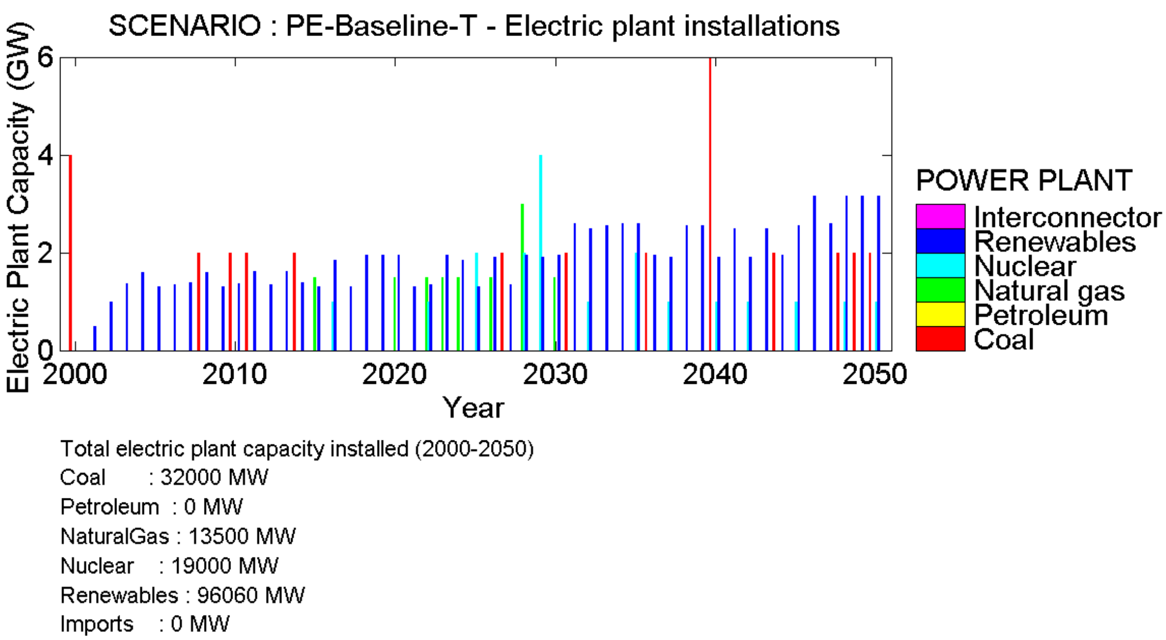


Figure 5-8 : *Provincial Enterprise* Baseline Integrated Transport scenario – projected annual electric plant installations (GW)

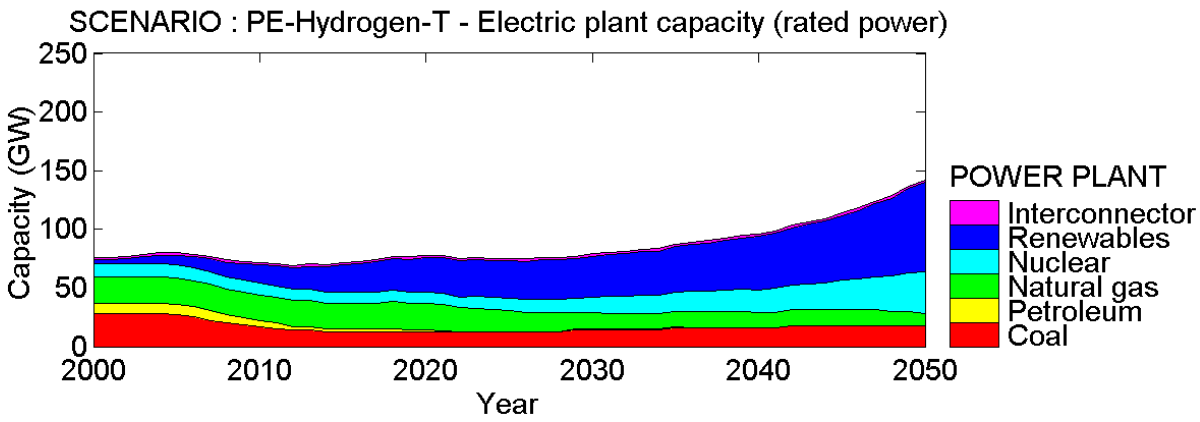
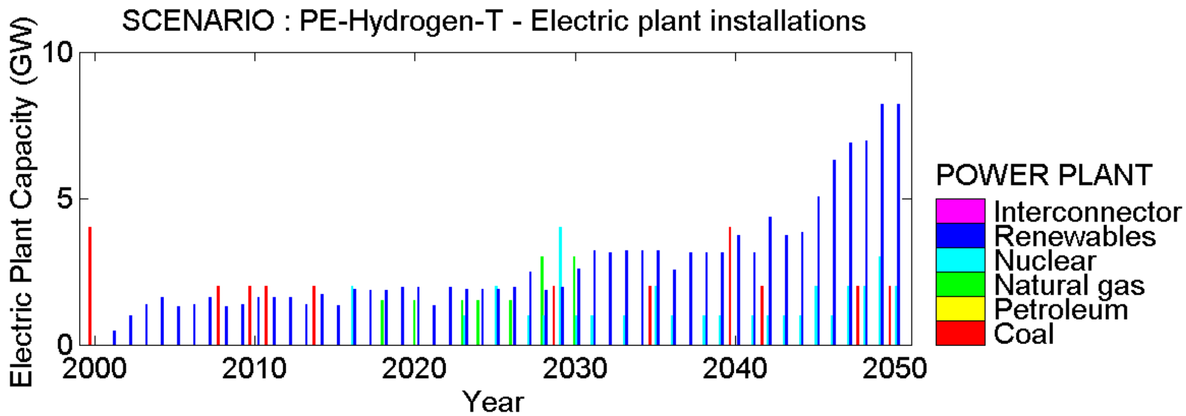


Figure 5-9 : *Provincial Enterprise* Hydrogen Integrated Transport scenario – projected total electric plant capacity (GW)



Total electric plant capacity installed (2000-2050)
Coal : 26000 MW
Petroleum : 0 MW
NaturalGas : 13500 MW
Nuclear : 35000 MW
Renewables : 138380 MW
Imports : 0 MW

Figure 5-10 : *Provincial Enterprise* Hydrogen Integrated Transport scenario – projected annual electric plant installations (GW)

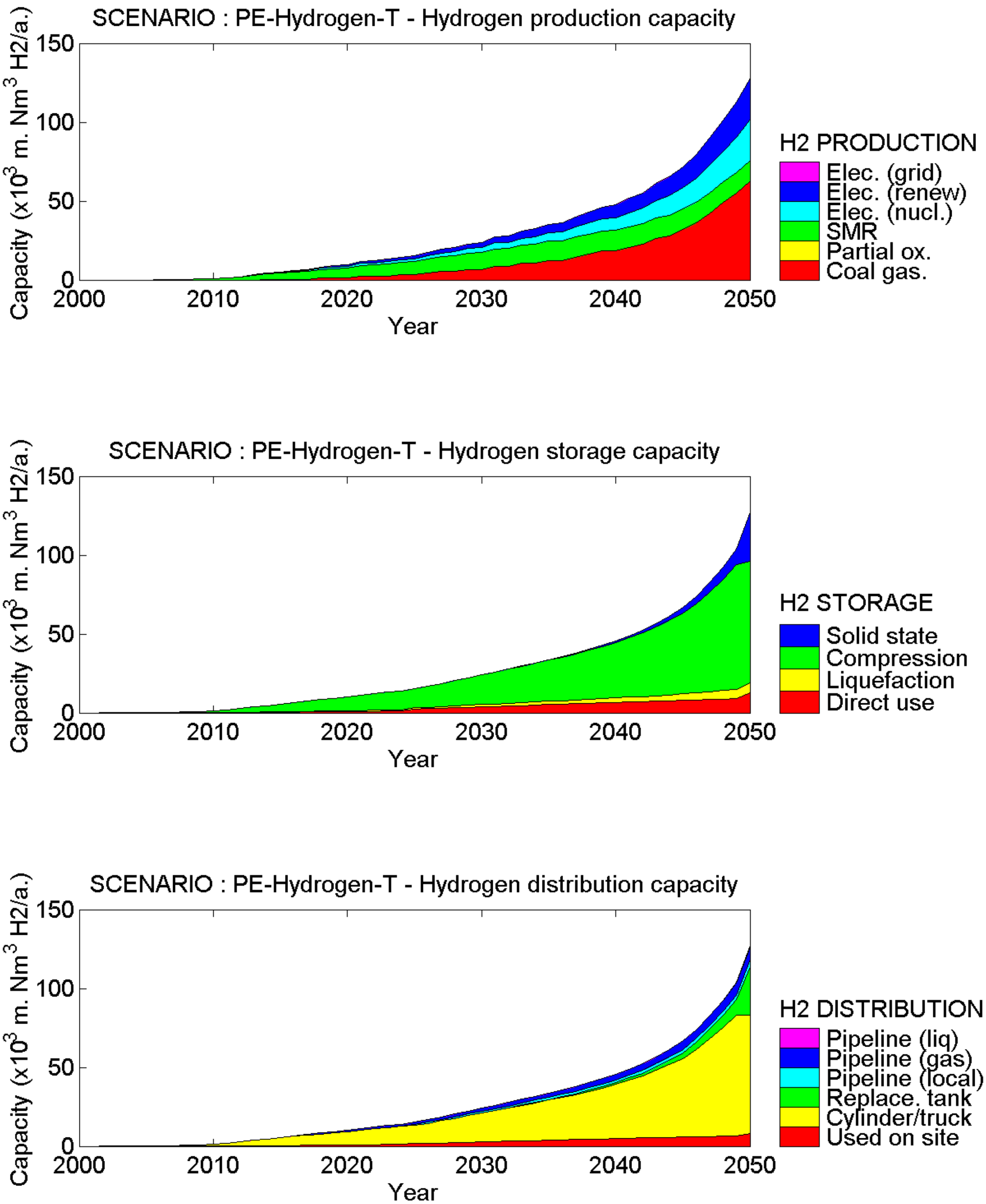


Figure 5-11 : *Provincial Enterprise* Hydrogen Integrated Transport scenario – projected hydrogen production, storage, and distribution capacities (billion Nm^3 H_2/a)

Global Sustainability

High penetrations of hydrogen (particularly in the Transport sector) and strong environmental protection measures drive the expansion of low carbon hydrogen sources. Coal is used with sequestration. Rapid development of hydrogen technologies leads to the realisation of solid-state storage modules for vehicles by 2025.

Considering electricity generating mix under this scenario, the environmental hazards of coal and large scale carbon sequestration must be balanced against those of nuclear power (see also section 3.3.1). In this case, the project team opted to phase out coal in the medium term and reduce natural gas over the longer term; the balance being taken up predominantly by renewables, with a sizeable nuclear sector (despite protests from some environmental groups).

The additional electric plant capacity required to support this level of hydrogen production can be seen by comparing Figure 5-12 with Figure 5-14 and Figure 5-13 with Figure 5-15. There is a modest reduction of 1500 MW in installed gas capacity over the 50 years period, but a marked increase of 65,000 MW of nuclear capacity and over 210,000 MW (nameplate capacity) of renewables, on top of the already high installation of 106,000 MW in the *Global Sustainability* base case. This requires an average installation rate of 6 GW/year, compared with the more than 10 years it has taken the UK to install its first 1 GW of wind energy.

GS Year Electricity generating type	2000	2020	2050
Coal	0.314		
Petroleum	0.018		
Natural gas	0.393	0.55	0.2
Nuclear	0.212	0.15	0.25
Renewables	0.025	0.2	0.5
Imports	0.038	0.1	0.05

Table 5-7 : Assumed proportion of electricity generation by technology (*Global Sustainability*) in 2000, 2020, and 2050

GS Year Hydrogen source	2000	2020	2050
Coal		0.05	0.1
Petroleum			
Natural gas	0.9	0.4	
Electricity (Renewables)	0.05	0.35	0.5
Electricity (Nuclear)	0.05	0.2	0.4

Table 5-8 : Assumed proportion of hydrogen production by technology (*Global Sustainability*) in 2000, 2020, and 2050

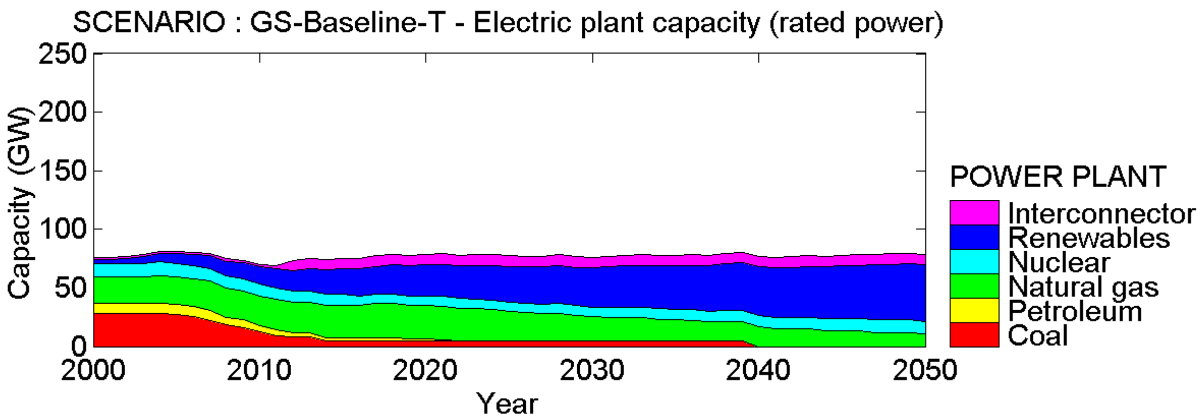
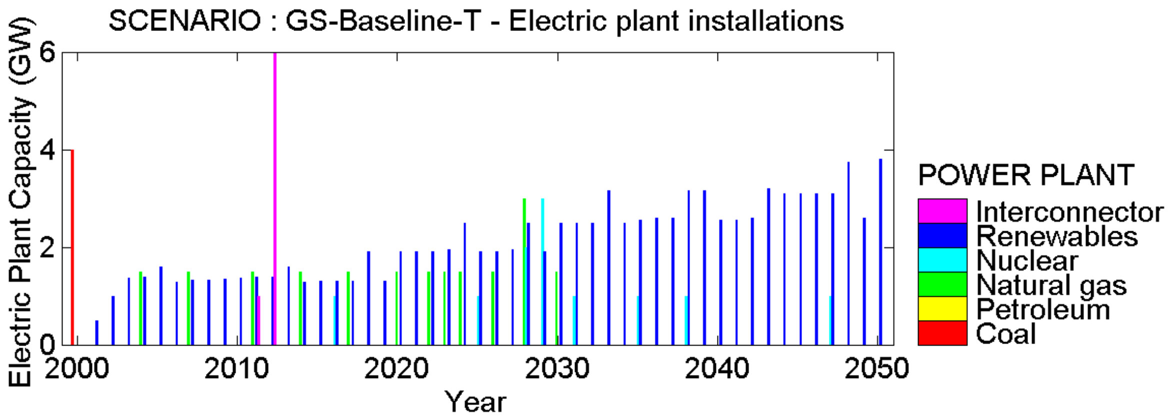


Figure 5-12 : *Global Sustainability* Baseline Integrated Transport scenario – projected total electric plant capacity (GW)



Total electric plant capacity installed (2000-2050)
Coal : 4000 MW
Petroleum : 0 MW
NaturalGas : 19500 MW
Nuclear : 11000 MW
Renewables : 106110 MW
Imports : 7000 MW

Figure 5-13 : *Global Sustainability* Baseline Integrated Transport scenario – projected annual electric plant installations (GW)

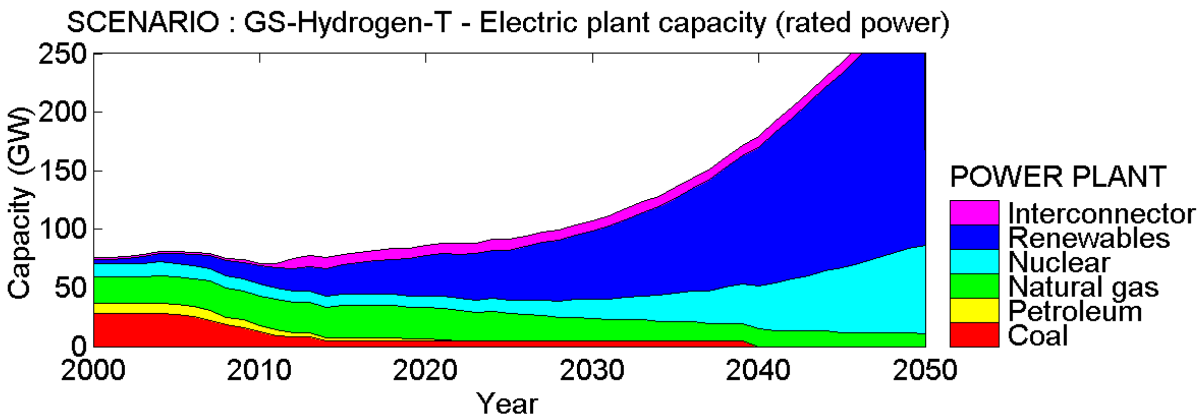
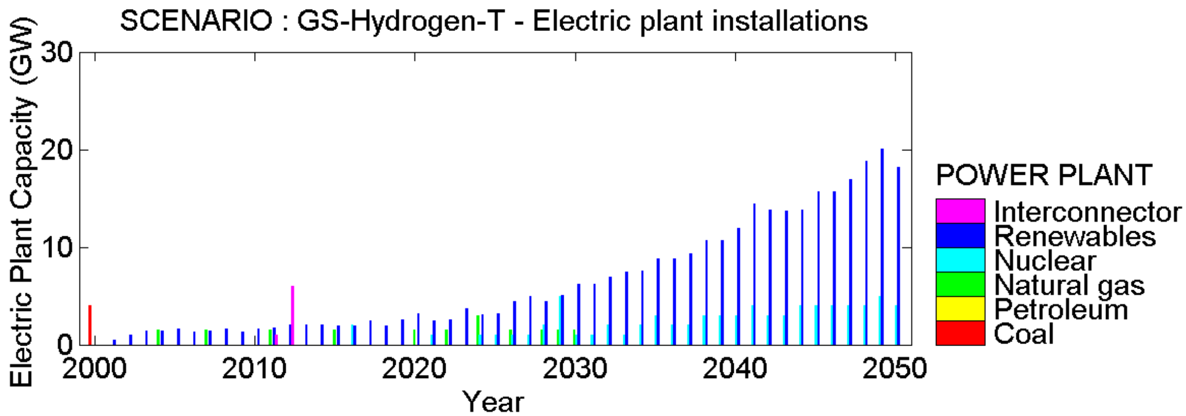
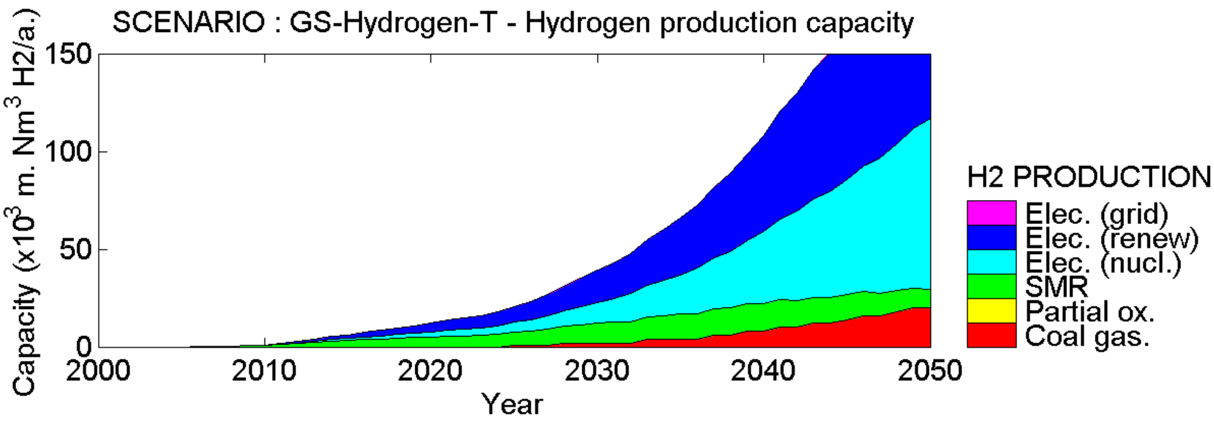


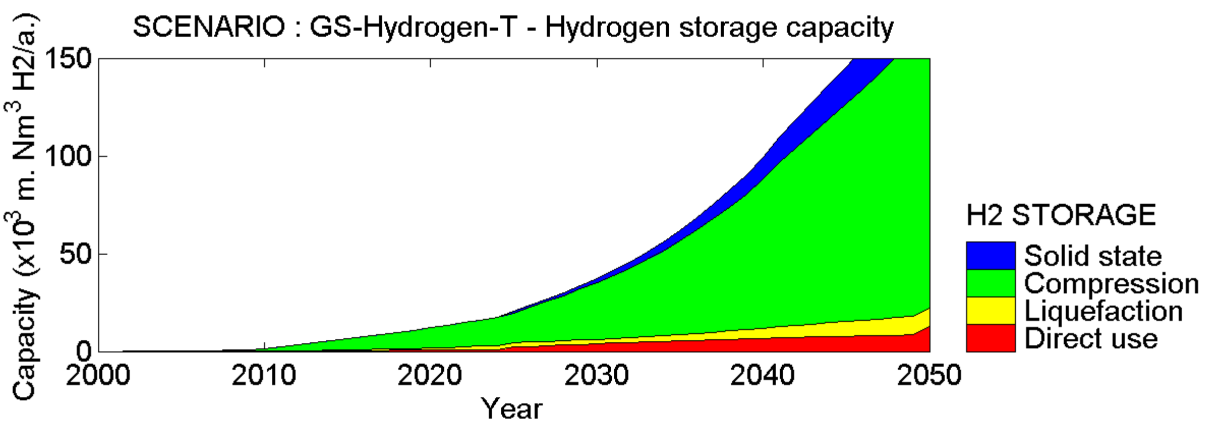
Figure 5-14 : *Global Sustainability* Hydrogen Integrated Transport scenario – projected total electric plant capacity (GW)



Total electric plant capacity installed (2000-2050)
Coal : 4000 MW
Petroleum : 0 MW
NaturalGas : 18000 MW
Nuclear : 76000 MW
Renewables : 325150 MW
Imports : 7000 MW

Figure 5-15 : *Global Sustainability* Hydrogen Integrated Transport scenario – projected annual electric plant installations (GW)





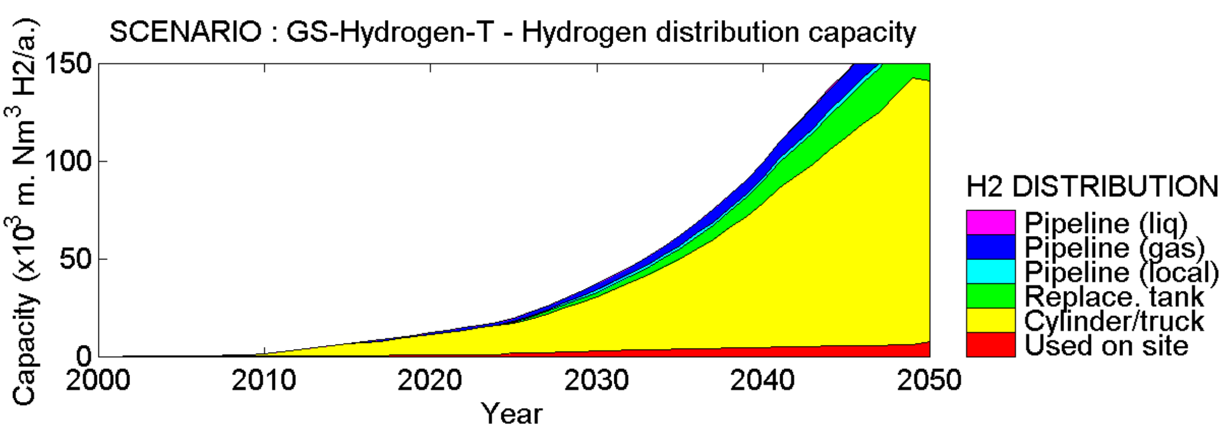


Figure 5-16 : *Global Sustainability* Hydrogen Integrated Transport scenario – projected hydrogen production, storage, and distribution capacities (billion Nm^3 H_2/a)

Local Stewardship

In the *Local Stewardship* scenario the demand for energy services is the lowest out of all the scenarios and, with assumed improvements in energy intensity, it is the only scenario in which the overall energy demand actually decreases in *all* sectors. This is largely due to the reduction of 35% in road transport and stabilisation of air transport at the 2000 level (see Figure 4-3, Figure 4-4, and Appendix 3). The electricity mix by 2050 is largely renewables, supported by a declining contribution from natural gas.

Local energy sources (renewables and to a lesser extent coal) are selected for hydrogen production. Nuclear is not an option due to strong local activism. Installation rates for renewable electricity need to achieve 2-3 GW/year in the coming decade, rising to 7-8 GW/year by 2030, and 15 GW/year by 2050.

LS Year Primary fuel source	2000	2020	2050
Coal	0.314	0.15	0.1
Petroleum	0.018		
Natural gas	0.393	0.45	0.25
Nuclear	0.212	0.08	
Renewables	0.025	0.25	0.6
Imports	0.038	0.07	0.05

Table 5-9 : Assumed proportion of electricity generation by technology (*Local Stewardship*) in 2000, 2020, and 2050

LS Year Hydrogen source	2000	2020	2050
Coal		0.05	0.2
Petroleum			
Natural gas	0.9	0.5	
Electricity (Renewables)	0.05	0.4	0.8
Electricity (Nuclear)	0.05	0.05	

Table 5-10 : Assumed proportion of hydrogen production by technology (*Local Stewardship*) in 2000, 2020, and 2050

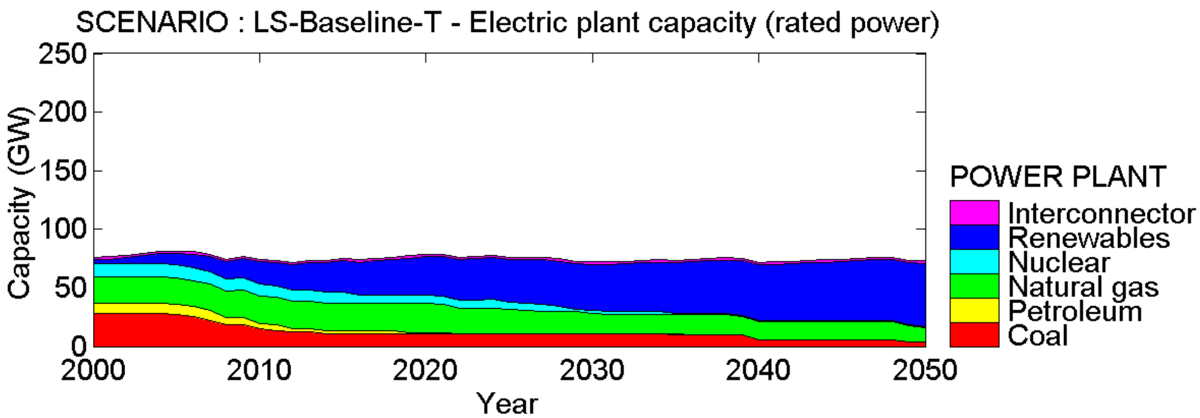
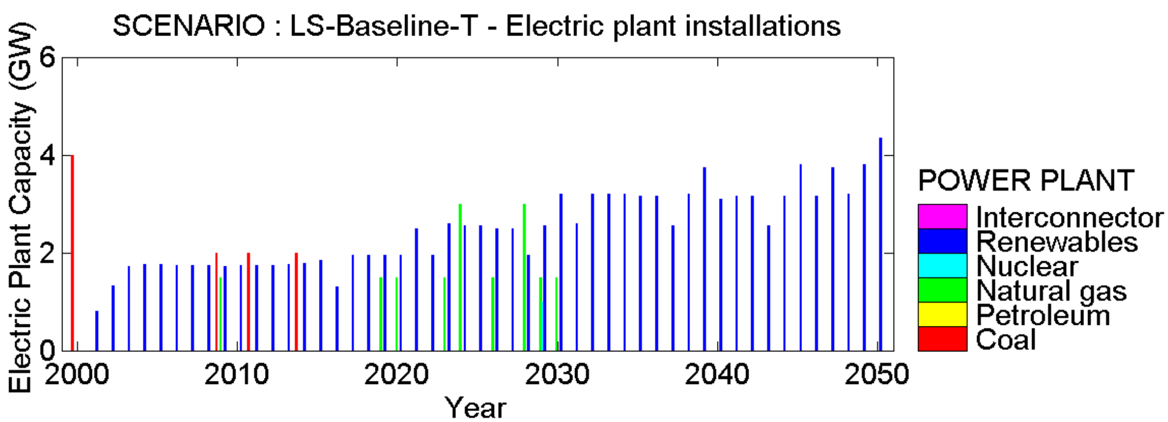


Figure 5-17 : *Local Stewardship* Baseline Integrated Transport scenario – projected total electric plant capacity (GW)



Total electric plant capacity installed (2000-2050)
Coal : 10000 MW
Petroleum : 0 MW
NaturalGas : 16500 MW
Nuclear : 1000 MW
Renewables : 124010 MW
Imports : 0 MW

Figure 5-18 : *Local Stewardship* Baseline Integrated Transport scenario – projected annual electric plant installations (GW)

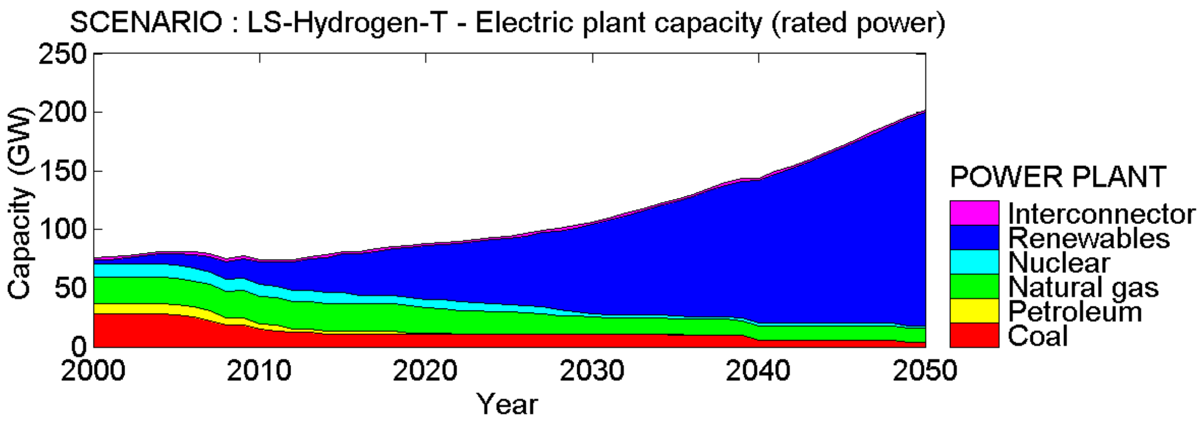


Figure 5-19 : *Local Stewardship* Hydrogen Integrated Transport scenario – projected total electric plant capacity (GW)

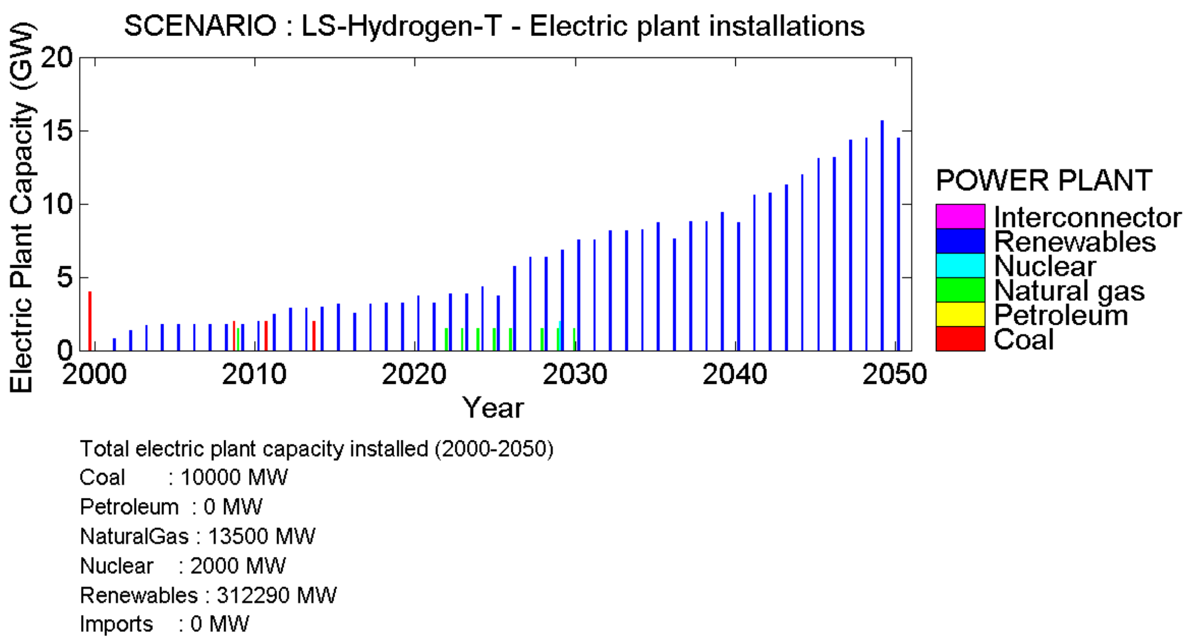


Figure 5-20 : *Local Stewardship* Hydrogen Integrated Transport scenario – projected annual electric plant installations (GW)

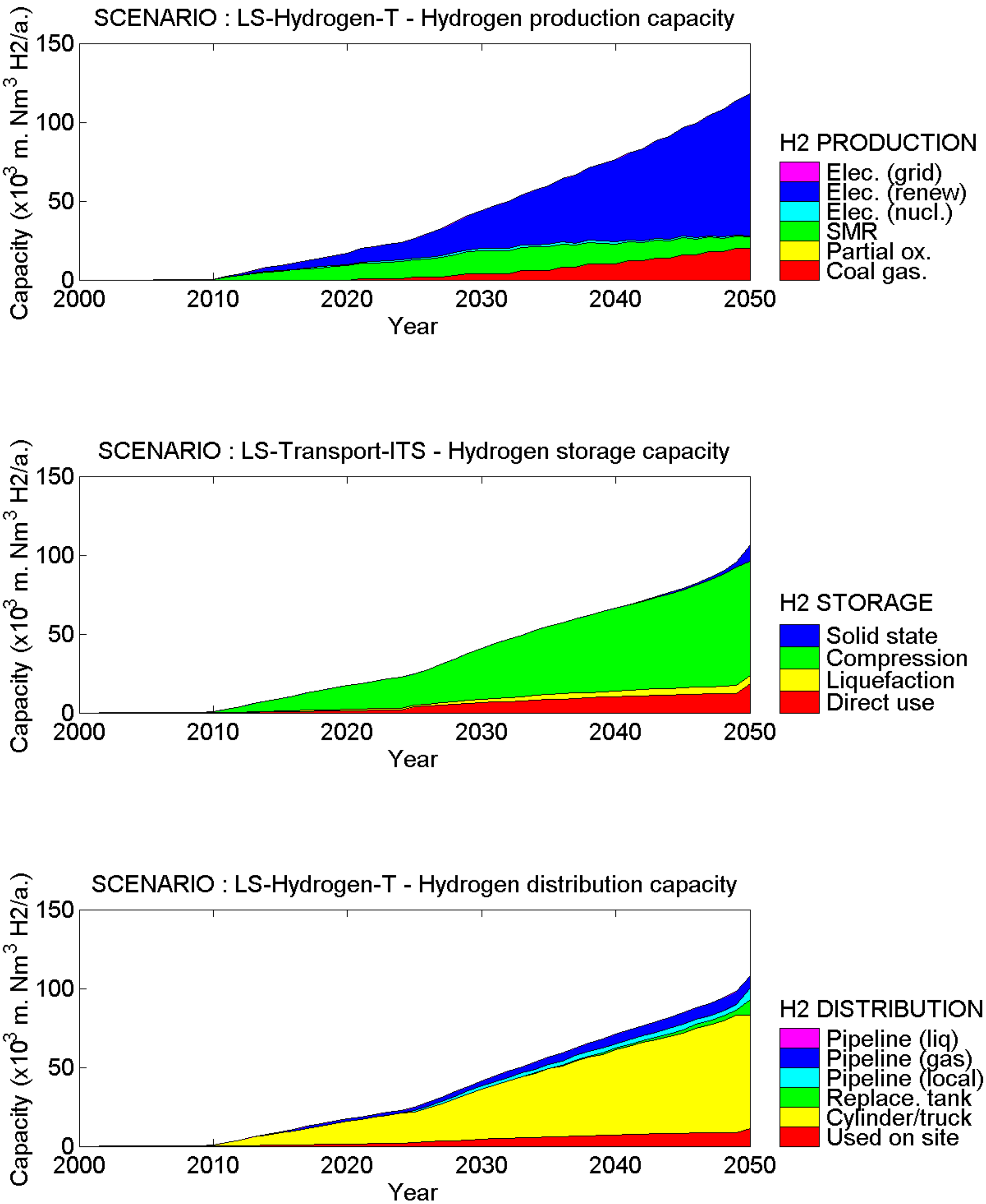


Figure 5-21 : *Local Stewardship* Hydrogen Integrated Transport scenario – projected hydrogen production, storage, and distribution capacities (billion Nm^3 H_2/a)

5.2 Hydrogen economy transition pathways to 2050: outcomes and variations

The total primary energy requirement under the different scenarios is shown in Figure 5-22. In common with the convention used in UK national energy statistics, the total primary energy is expressed in terms of the equivalent coal energy (so actual nuclear and renewable electricity supply is scaled up to the equivalent required coal input for a steam-powered station). It is clear that the hydrogen economy is not a low energy economy, since high hydrogen penetrations (*Global Sustainability* and *Local Stewardship*) can result in increases of 30%-35% in total primary energy by 2050 compared to the base case without hydrogen for a given scenario.

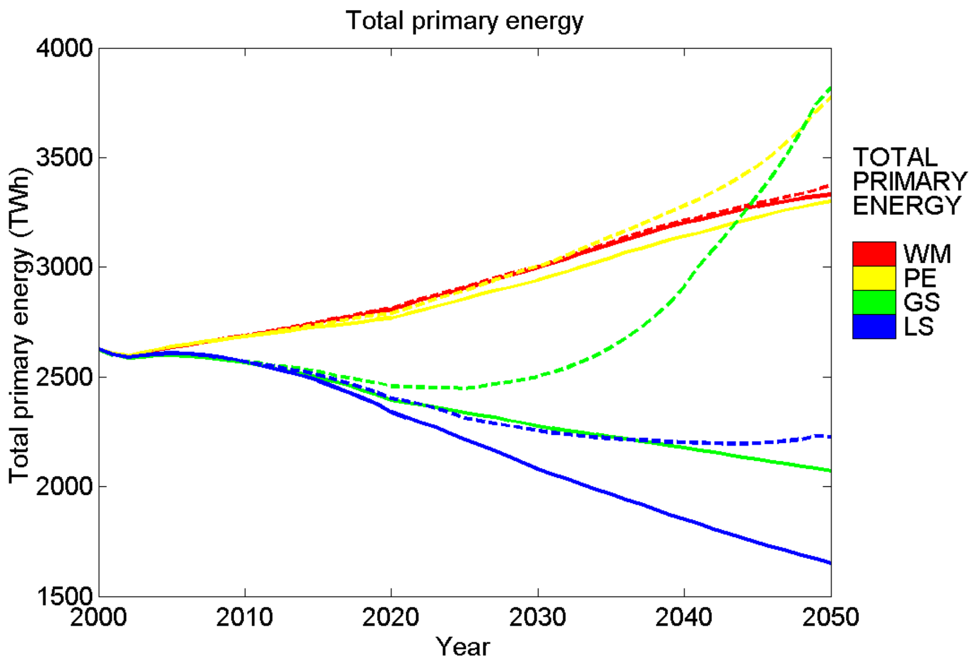


Figure 5-22 : Total primary energy requirement for Baseline-T scenarios (solid line) and Hydrogen-T scenarios (dashed line)

In fact, the electricity supplied (Figure 5-23) shows very steep rise in electricity demand for all scenarios except *World Markets* and for the *Global Sustainability* scenario, in particular. This reflects the emphasis on electrolysis in most scenarios and the very large Transport demand within the *Global Sustainability* scenario.

The total aggregate installed hydrogen production capacity needed for each scenario in the fifty year period to 2050 is shown in Table 5-11, assuming the plant lifetimes listed in Table 4-12 and Table 4-13.

The total aggregate electric generating capacity installations required for each scenario over the same fifty year period is shown in Table 5-12, comparing the cases with and without the hydrogen economy. Note that, due to the load factor which must be applied to renewable (wind) electricity generating capacity, the total required nameplate capacity installations in the without-hydrogen case are surprisingly similar across all the scenarios, despite the considerably lower demand in the *Local Stewardship* case, in particular. The minimum average rate of installation of renewable electricity generation is 2 GWe per year (in *World Markets* where, as will be seen later, this is barely sufficient to keep net emissions around 1990 levels) and does not vary substantially between the scenarios.

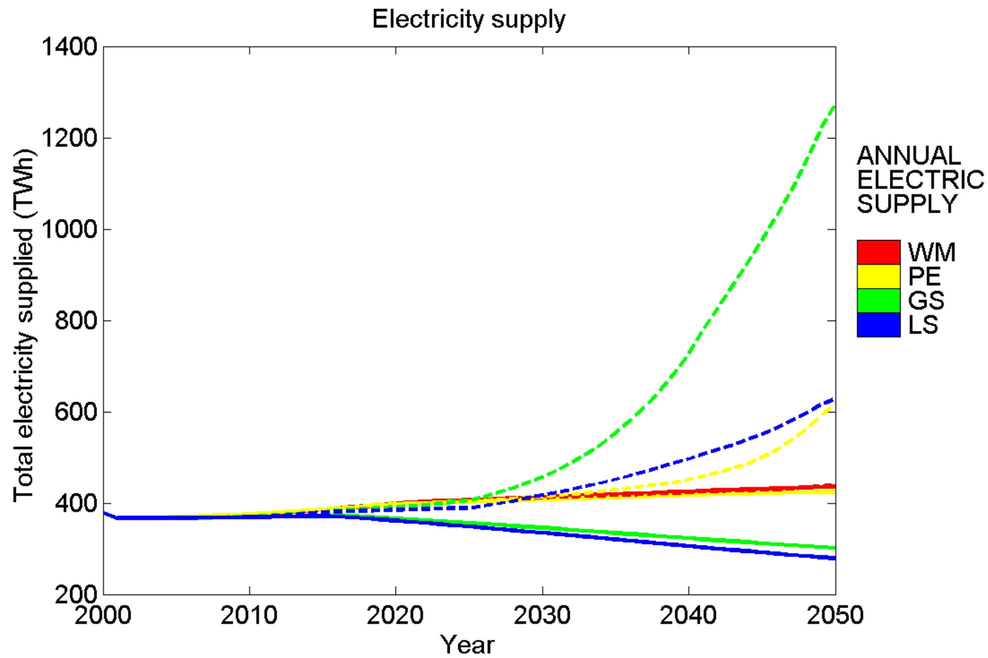


Figure 5-23 : Electricity supply requirement for Baseline-T scenarios (solid line) and Hydrogen-T scenarios (dashed line)

Installed hydrogen production capacity 2000-2050 (x10^6 Nm^3) SCENARIO	Coal gasification	SMR	Electrolysis	TOTAL
WM-Baseline-T	0	0	0	0
WM-Hydrogen-T	0	27,244	3,013	30,257
PE-Baseline-T	0	0	0	0
PE-Hydrogen-T	64,500	24,432	58,675	147,606
GS-Baseline-T	0	0	0	0
GS-Hydrogen-T	20,000	20,170	225,885	266,055
GS-Hydrogen-T2	20,000	116,320	111,751	248,071
GS-Hydrogen-T3	13,000	13,135	155,586	181,722
LS-Baseline-T	0	0	0	0
LS-Hydrogen-T	20,000	22,215	116,753	158,969

Table 5-11 : Installed hydrogen production capacity 2000-2050 by scenario

Installed electricity generating capacity 2000-2050 (GW) SCENARIO	Coal	Petrol.	NG	Nuclear	Renew.	Imports	TOTAL
WM-Baseline-T	18.0	0.0	33.0	2.0	97.9	7.0	157.9
WM-Hydrogen-T	18.0	0.0	34.5	2.0	97.5	7.0	159.0
PE-Baseline-T	32.0	0.0	13.5	19.0	96.1	0.0	160.6
PE-Hydrogen-T	26.0	0.0	13.5	35.0	138.4	0.0	212.9
GS-Baseline-T	4.0	0.0	19.5	11.0	106.1	7.0	147.6
GS-Hydrogen-T	4.0	0.0	18.0	76.0	325.2	7.0	430.2
GS-Hydrogen-T2	4.0	0.0	18.0	42.0	205.4	7.0	276.4
GS-Hydrogen-T3	4.0	0.0	18.0	54.0	249.2	7.0	332.2
LS-Baseline-T	10.0	0.0	16.5	1.0	124.0	0.0	151.5
LS-Hydrogen-T	10.0	0.0	13.5	2.0	312.3	0.0	337.8

Table 5-12 : Installed electricity generating capacity 2000-2050 by scenario

Primary natural gas mean annual consumption (TWh) SCENARIO	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050	TOTAL 2000-2050
	1146.7	1268.8	1321.5	1319.0	1319.0	63,751
WM-Hydrogen-T	1147.6	1273.7	1329.4	1334.1	1370.2	64,551
PE-Baseline-T	1126.3	1209.6	1198.8	1114.6	1031.1	56,803
PE-Hydrogen-T	1126.5	1209.9	1183.9	1058.7	925.8	55,048
GS-Baseline-T	1144.0	1224.2	1163.2	1008.4	869.6	54,094
GS-Hydrogen-T	1144.1	1215.4	1126.2	920.0	695.6	51,013
GS-Hydrogen-T2	1144.4	1225.3	1168.9	1065.2	1072.9	56,766
GS-Hydrogen-T3	1144.1	1214.7	1118.9	893.8	674.4	50,459
LS-Baseline-T	1122.5	1155.6	1076.7	928.1	795.3	50,783
LS-Hydrogen-T	1122.6	1146.3	1022.6	763.4	494.8	45,496

Table 5-13 : Primary natural gas mean annual consumption 2000-2050 by scenario

The point about renewables nameplate capacity is relevant again when considering the with-hydrogen cases, especially in the split between nuclear and renewable electricity supplying electrolysis hydrogen production plant in *Global Sustainability* compared with *Local Stewardship*. In both these scenarios, the mean average rate of installation of renewable electricity generation is 6 GWe per year.

The scenarios contain only moderate installations of steam methane reforming (SMR) plant. This is because in circumstances where there is a high penetration of SMR (90% in *World Markets*) there is a low overall penetration of the hydrogen economy (due to lack of market competitiveness) and where there is a high penetration of the hydrogen economy (*Global Sustainability* and *Local Stewardship*) there is either an emphasis on low emissions (and hence high penetration of electrolysis using zero carbon electricity in *Global Sustainability*) or use of local resources (*Local Stewardship*), in which cases methane is not the first choice primary fuel.The net result is that, for the scenarios presented here, the implementation of a hydrogen economy has only a very moderate effect on natural gas supply (Table 5-13). This conclusion is, of course, dependent on realising the very high installation rates for renewable and nuclear electricity, both of which have public acceptability issues associated with them.

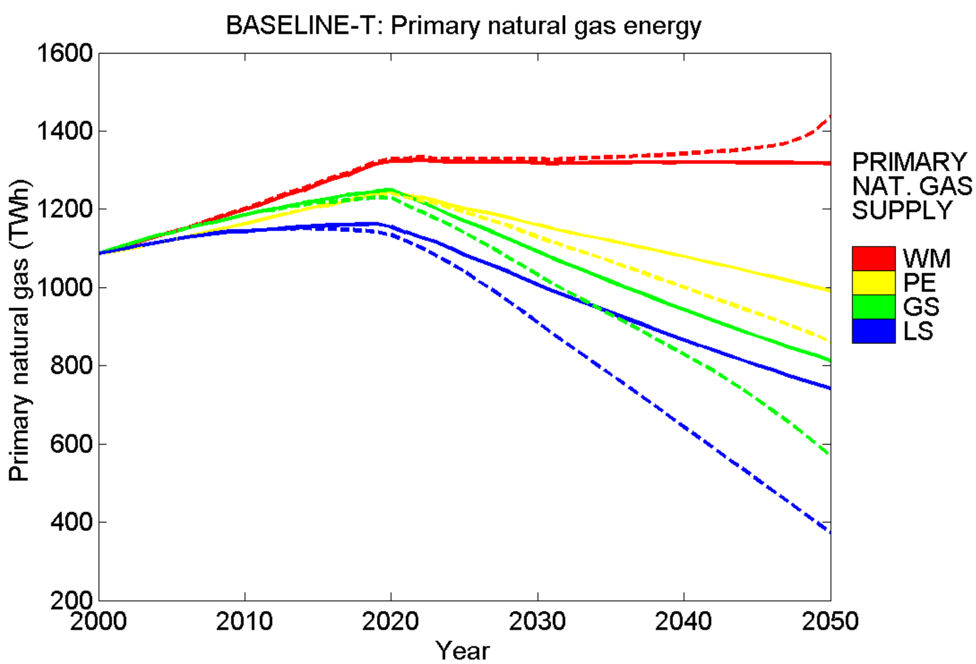


Figure 5-24 : Primary natural gas energy requirement for Baseline-T scenarios (solid line) and Hydrogen-T scenarios (dashed line)

In practice, it might be argued that the already high renewable electricity penetration in the *Global Sustainability* "Baseline" scenario (averaging > 2 GW per year over the 50 years period) is already very high and that the additional hydrogen demand might more likely be met by additional SMR plant (with consequences for overall security of supply and carbon dioxide emission levels). A variant of the *Global Sustainability* scenario has been run under this assumption (see below).

Carbon dioxide emissions relative to 1990 levels are shown in Figure 5-25 for each of the scenarios presented in Section 5.1. There is a slight rise in emissions under the *World Markets* and *Provincial Enterprise* scenarios due to the use of SMR in both scenarios and coal gasification in *Provincial Enterprise*. Under the *Local Stewardship* and particularly *Global Sustainability* scenarios the hydrogen economy creates the environment for substantial reductions in carbon dioxide emissions. If the potential to sequester carbon dioxide at large hydrogen production plants (Figure 5-26) is realised then the emissions under *Provincial Enterprise* can also be reduced.

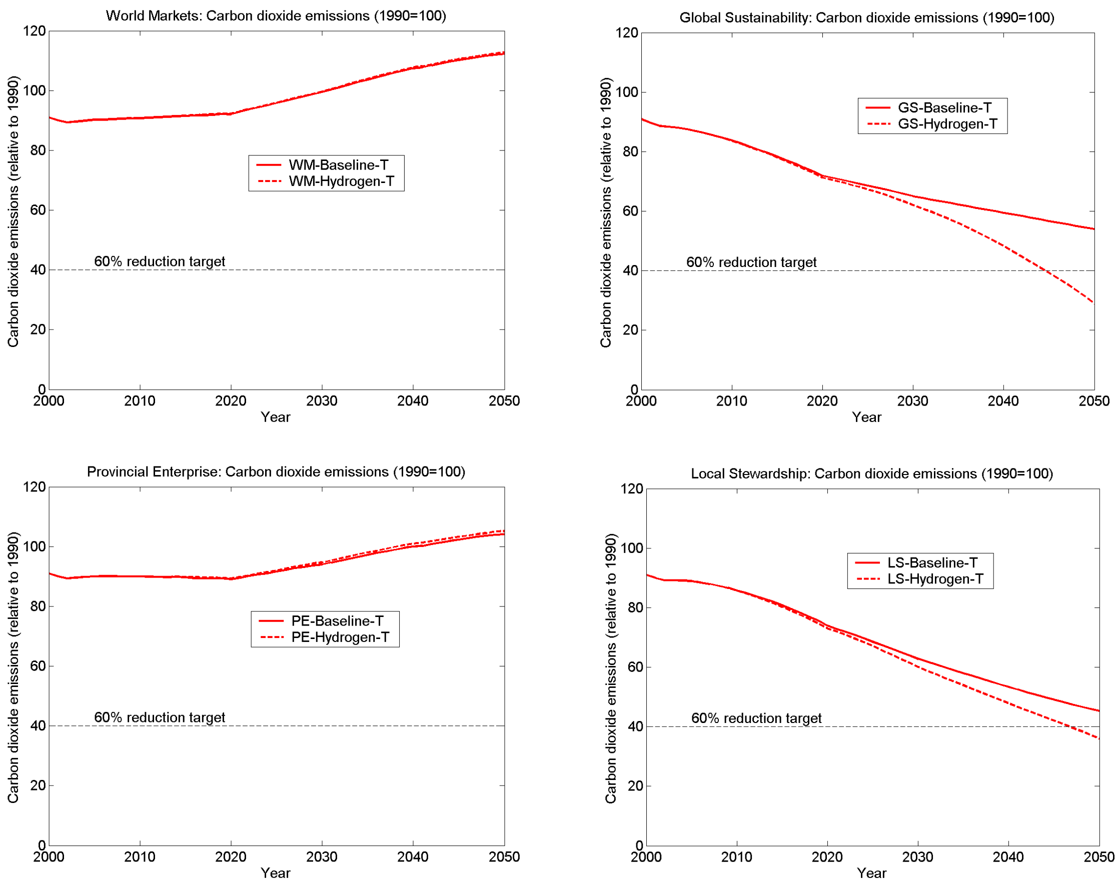


Figure 5-25 : Projected carbon emissions (MtC) to 2050 relative to 1990 levels for the 4 major HYDROGEN-T scenarios compared with the BASELINE-T emissions

It is clear from Figure 5-25 that the UK target of 60% emissions reductions by 2050 is unlikely to be met under the *World Markets* or *Provincial Enterprise* scenarios. Both *Global Sustainability* and *Local Stewardship* are close to the 60% target without the use of hydrogen, but can substantially exceed it with the development of a significant hydrogen economy.

With such a complex model, it is impossible to determine the sensitivity of the results to every input. Fortunately, the scenarios themselves already embody a wide range of demand and market conditions. However, a number of inputs were selected for further examination, namely:

(i) assumptions about improvements in vehicle fuel consumption (both conventional and hydrogen vehicles) to 2050,

(ii) the growth rate of the hydrogen vehicle fleet, and

(iii) the possible lack of availability of sufficient hydrogen production resources.

It is clear from an examination of the figures in Appendix 3 that the ERAG projections for improvement in energy intensity to 2050 are very ambitious. The effect on overall consumption of realising only half the projected improvement in energy intensity for *Road Transport only* is shown in Figure 5-27. The effect is to increase Petroleum consumption in 2050 (already 65% above 2000 levels in the base case scenario) by a further 15% above 2000 levels and carbon dioxide emissions by a further 31 million tonnes (5.7%) relative to 2000.

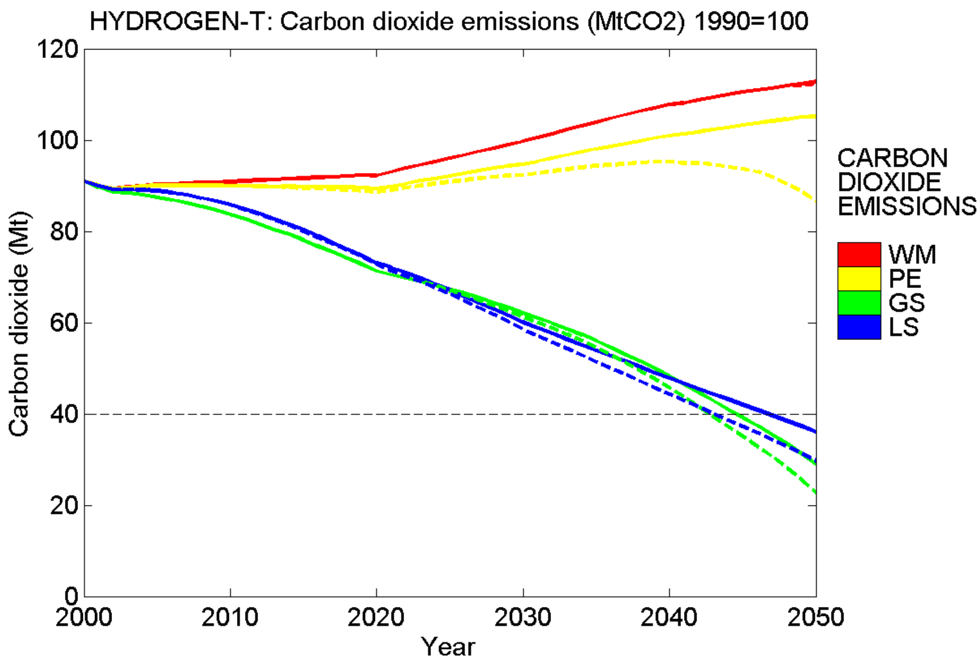
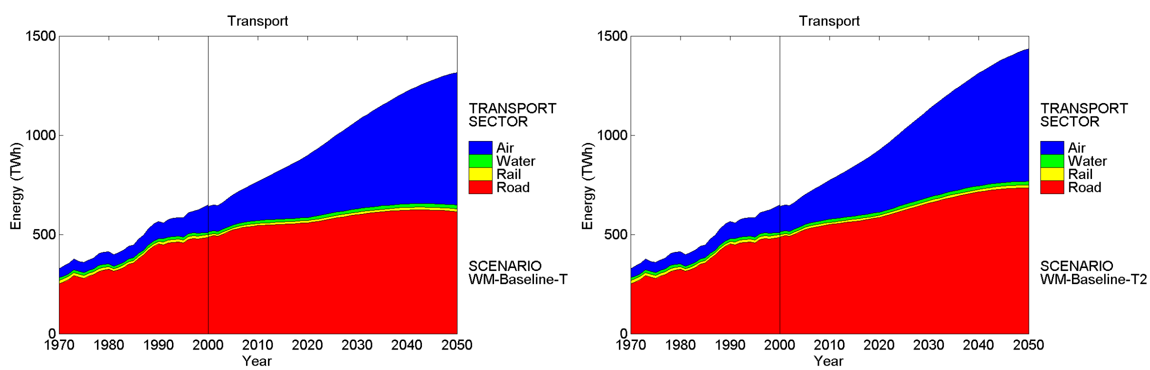


Figure 5-26 : Additional potential savings on carbon emissions (MtC) to 2050 relative to 1990 levels for the 4 major HYDROGEN-T scenarios (solid lines) including potential to sequester carbon dioxide at large hydrogen production plants (dashed lines)

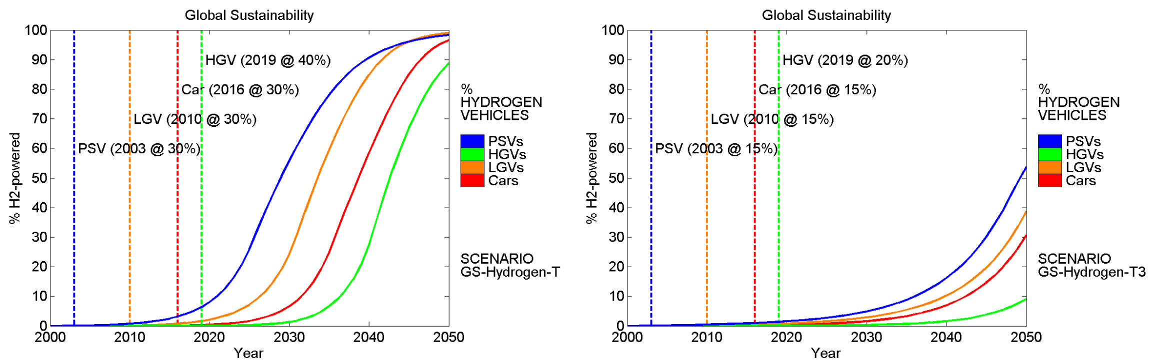


(a) WM-Baseline-T base case (b) WM-Baseline-T2 high energy intensity case

Figure 5-27 : *World Markets* scenario -- effect of halving year on year improvements in energy intensity assumed by ERAG.

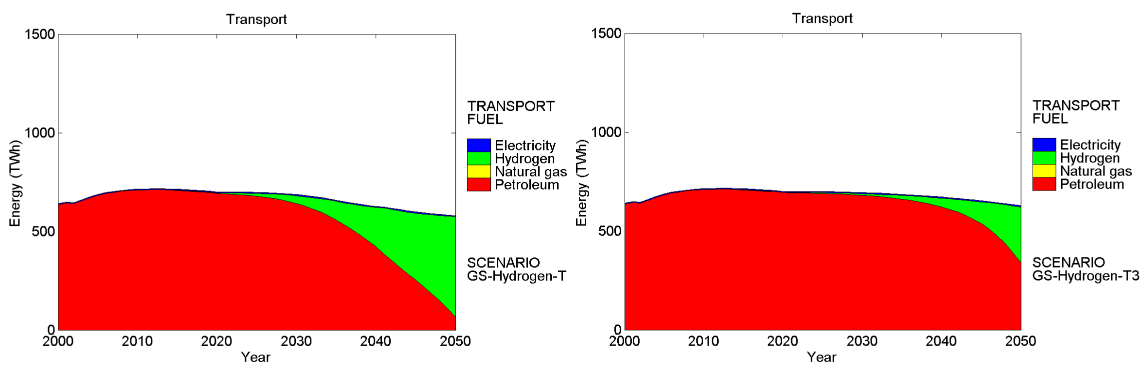
The realistic growth rate of the end-use hydrogen vehicle fleet is critical to the scenarios developed in this study. Figure 5-28 shows the effect on penetration of hydrogen vehicles into vehicle fleets of halving the assumed growth rate in the *Global Sustainability* scenario case. The cumulative effect on hydrogen fuel demand is shown in Figure 5-29 and the resulting change in installation of hydrogen production capacity and electric plant requirements in Figure 5-30 and Figure 5-31 respectively. The overall hydrogen demand is reduced from 200 x 10^9 Nm^3 to 135 x

10^9 Nm^3 (compared with the current total world hydrogen production of about 500 x 10^9 Nm^3) in 2050, saving the need to install 22 GW of nuclear and 75 GW of renewable electricity generating capacity with the additional emission of 758 million tonnes of carbon dioxide over the 50 years period (which equates to almost 1.3 years of emissions at 1990 levels). However, by 2050, the now undisplaced Petroleum demand will result in an additional 56 million tonnes of carbon dioxide emissions per year (plus a further 12 million tonnes of potentially sequesterable carbon).



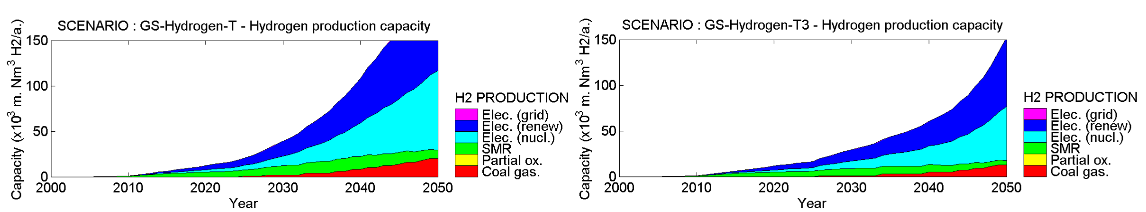
(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T3 low hydrogen growth case

Figure 5-28 : *Global Sustainability* scenario – effect on hydrogen penetration of halving hydrogen vehicle new buy growth rate (dashed line = introduction date at 0.5% of new buy; solid line = fleet penetration at given new buy growth rate)



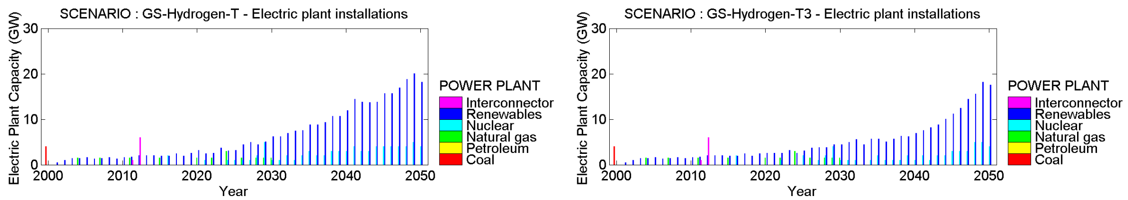
(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T3 low hydrogen growth case

Figure 5-29 : *Global Sustainability* scenario – effect on hydrogen demand of halving hydrogen vehicle new buy growth rate



(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T3 low hydrogen growth case

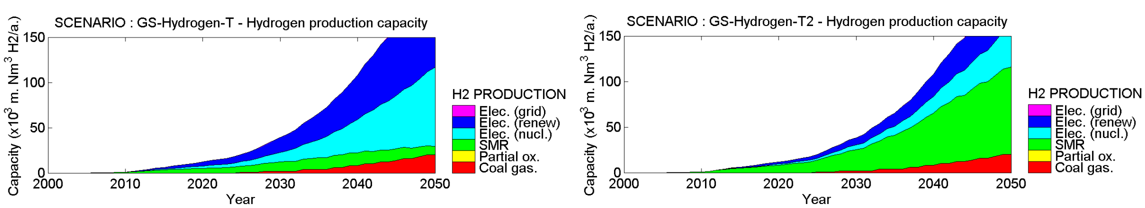
Figure 5-30 : *Global Sustainability* scenario – effect on development of required hydrogen production capacity of halving hydrogen vehicle new buy growth rate



(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T3 low hydrogen growth case

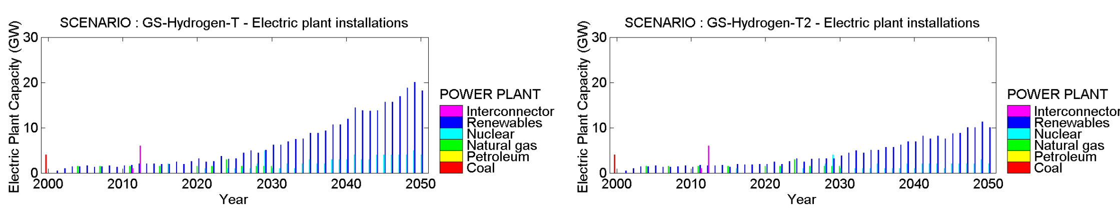
Figure 5-31 : *Global Sustainability* scenario – effect on required electric plant installation of halving hydrogen vehicle new buy growth rate

Arguably an even more critical question is what might happen if the demand-side of the hydrogen economy expands rapidly, as projected in the basic *Global Sustainability* case, but the expansion of renewable and/or nuclear electricity is unable to meet the ensuing hydrogen demand. In this case, one might expect the demand to be fulfilled through rapid installation of the cheapest technology, which is likely to be natural gas. In this case (scenario GS-HYDROGEN-T2) SMR plant replaces more than half the desired electrolysis plant (Table 5-11 and Figure 5-32) with substantial reductions in the requirement for nuclear and renewable electricity capacity (Table 5-12 and Figure 5-33) and a modest (10%) rise in natural gas consumption. The result is a substantial increase in the expected carbon dioxide emissions (Figure 5-34), although some, at least, of this excess might be sequesterable. A possible variant on this theme is that the electrolysis plant would be installed and the electricity be supplied from quick-to-install gas turbines, with potentially an even bigger emissions penalty.



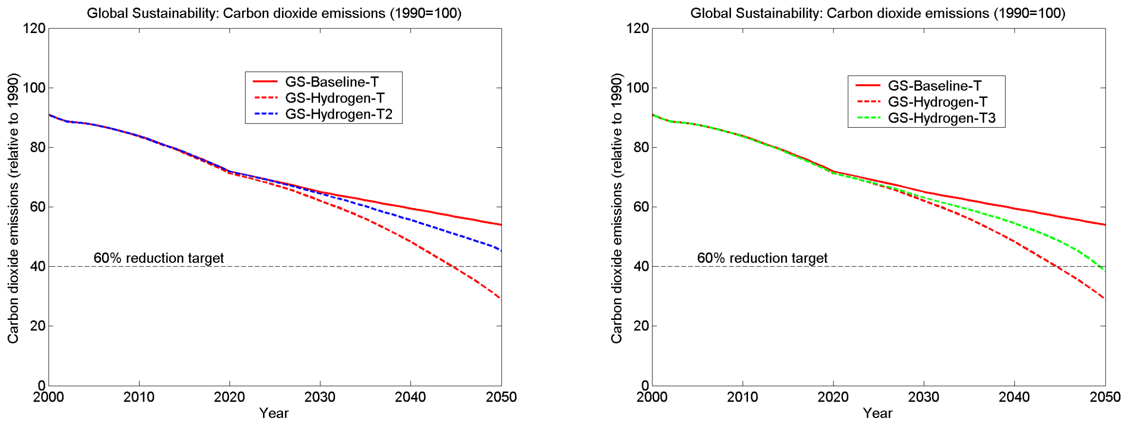
(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T2 reduced electrolysis case

Figure 5-32 : *Global Sustainability* scenario – effect on development of required hydrogen production capacity of restricted electricity supply to support electrolysis



(a) GS-Hydrogen-T baseline (b) GS-Hydrogen-T2 reduced electrolysis case

Figure 5-33 : *Global Sustainability* scenario – effect on development of electric plant installation of restricted electricity supply to support electrolysis



(a) (b)

Figure 5-34 : Projected carbon emissions (MtC) to 2050 relative to 1990 levels for the 2 *Global Sustainability* scenario variants representing widespread use of SMR rather than electrolysis for hydrogen production (a) or a halving of the hydrogen vehicle new buy growth rate (b)

6 Discussion

6.1 Stakeholder workshop on UK Hydrogen Futures to 2050

A workshop was held on 28th April 2004 to allow stakeholders to comment on the hydrogen futures scenarios and the preliminary model results. The workshop was attended by 15 people from government, consultancies, private firms and academia. Background presentations were made by members of the project team on the scenarios and the modelling work. These were followed by two discussion sessions to generate feedback on the project's work to date. The first discussion session concentrated on the general scenario framework and the project team's suggested targets for hydrogen in 2050 (Watson et al, 2004); the second followed on from a full description of the modelling procedure and the presentation of specific pathways to the hydrogen economy under each scenario. Whilst the discussion of the scenarios was general in nature, the workshop was asked to comment in more detail on the modelling results and suggested pathways.

6.1.1 Discussion of the Hydrogen Scenarios

Comments on the scenarios can be grouped into five themes. The first focused on *dynamics* of hydrogen developments that were not sufficiently reflected in the scenarios. It was felt that the introduction of hydrogen would not happen in a linear or predictable manner. The development of infrastructures, technologies and policies is likely to depend on interactions with other energy carriers and systems (e.g. the increasing trend towards distributed generation in the electrical power network). UK hydrogen developments are also heavily contingent upon initiatives and programmes in other countries. Interactions with electricity and biomass were thought to be particularly important since both could be major contributors to hydrogen production. Furthermore, many attendees saw electricity and biomass as competitors for hydrogen. For example, advances in battery technology might make electricity storage more attractive (as an alternative to the use of hydrogen storage), and biomass might develop as an important vehicle fuel.

A second theme that emerged in the discussion focused on the scenario *process* used by the project team. One attendee rightly observed that the Foresight scenarios provide 'extreme' visions of the future, whilst the reality is likely to be a mixture of these and other futures. Others thought they should have been more explicit in two respects: the way in which the quantitative indicators were established, and the relative weighting given to the various drivers and inhibitors for hydrogen in 2050.

The third theme that was addressed in the discussion was timescales. This fitted well with the focus of the project modelling work (and the subsequent workshop session) on pathways to 2050. A number of participants were concerned that a focus on 2050 in the scenarios was not enough, and that the actual pathways to 2050 are at least as important. If the 2050 goals are to be achieved (e.g. with respect to carbon emissions), there is a need for government and corporate actions in the short to medium term (now, in 2010, in 2020 and so on). There is also a need to take into account the role of consumers, and the assumption that they will make energy choices based on price. What policies and measures will persuade them to start demanding hydrogen-based technologies and infrastructures? Further reasons were given for focusing on the short to medium term - including long capital stock turnover rates, long lead times for new nuclear build (if a sufficient capacity of renewables is not available), and the need to create and open up future options by acting now.

The fourth theme centred on the possibility of *shocks* that could affect hydrogen development. In many cases, participants felt that these were not given sufficient attention within the scenarios. There were three types of shock mentioned in the discussion - rapid climate change (which could give greater urgency for deep emissions reductions), a scarcity of oil and other fossil fuel resources (which might lead to more rapid development of hydrogen for transport), and water scarcity. Participants were less clear about the impact of these shocks on hydrogen, since a shift towards this energy carrier is only one of several possible responses. Shocks were discussed further in the afternoon session, particularly with respect to the *World Markets* scenario.

A fifth theme in the discussion focused on the *challenges* that need to be overcome to enable the widespread use of hydrogen. One general comment was that it is still unclear whether hydrogen would deliver large reductions in greenhouse gas emissions. For example, substantial technical progress is needed to allow this hydrogen to be produced by low or non-carbon energy sources including renewables, sequestration and nuclear power. Some participants thought that this would not happen through revolutions in technology, but would be more likely to occur through a process of evolution (since advances in processes such as electrolysis and certain storage technologies would be bounded by physics).

Several participants questioned the extent to which carbon sequestration will allow large quantities of hydrogen to be produced. Although some argued that this technology is proven, others were concerned about leakage rates and issues of public acceptability. Many drew attention to the very large amounts of renewable electricity generation within some of the scenarios (particularly *Global Sustainability*). They argued that this is based on 'heroic' assumptions about the ability of the electricity grid to cope with increases in power plant capacity - for example to include tens (or even hundreds) of rated GW of renewable capacity. A further set of comments focused on the need to make breakthroughs in fuel cell technology and on hydrogen distribution and storage to reduce costs. Some participants pointed out that catalyst materials for fuel cells (especially platinum) are particularly costly and that a breakthrough to produce a substantially lower-cost catalyst could revolutionise the fuel cell market. Others thought that small-scale 'bottom-up' developments in hydrogen would help to overcome some of the cost issues. The consensus was that hydrogen would eventually have a bigger impact in Transport than in other sectors.

6.1.2 Discussion of the Hydrogen Pathways to 2050

The second part of the workshop was concerned with the hydrogen pathways to the end points within the scenarios. It focused on the interim results from the team's energy and transport modelling of these pathways. These were outlined in a presentation and summarised as a series of posters. The workshop was split into two breakout groups for this purpose, each of which covered two scenarios. Due to time constraints, the breakout groups were asked to comment on a few key aspects of the modelling results:

- The introduction date and speed of diffusion of fuel cells in buses, fuel cells in cars and fuel cells for domestic CHP. The policies and corporate strategies that could enable these trends, and the factors that might act as barriers to them.
- The extent to which the modelling of hydrogen production is plausible, with a particular focus on the capacity and mix of technologies for electricity production. The policies and corporate strategies that could enable these trends, and the factors that might act as barriers to them.

- The feasibility of the team's assumptions about the likely architecture of the hydrogen system, particularly trends in transport and storage.

World Markets

The breakout group for this scenario found it difficult to discuss the modelling results because of the team's assumption that hydrogen's contribution would be small. For fuel cells to become significant, their economics would have to change significantly. Fuel cells for vehicles currently cost around $1000/kW whilst internal combustion (IC) engines cost $10/kW. However, some participants raised the possibility of hydrogen for transport using IC engines.

Most members of the breakout group thought that fossil fuel price rises were very likely under this scenario, and that these might include abrupt price shocks. They would occur due to rapidly increasing demand for oil, particularly for air travel. The discussion focused on the timing of these shocks, and to what extent they would lead to fuel cell development. The group was not able to provide a judgement about when shocks might occur (though one opinion was that the end of the period would be most likely). Many thought that there would be a significant time lag of between 10 and 20 years between shocks and commercial availability of fuel cells. However, some members pointed out that oil price shocks are equally likely to encourage the use of alternatives to hydrogen (particularly biofuels) or substantial reductions in car use.

Some members of the breakout group thought that there would be significant developments of fuel cells for transport under *World Markets*, even if fossil fuel scarcity were not an issue. This was partly attributed to a pre-emptive strategy just in case circumstances changed. One attendee thought it likely that there would be a crossover between the market share of fuel cells and IC engines in the period 2027-2032. It was suggested that opportunities may emerge for high speed rail if the assumed rapid growth of air travel were to be restricted by availability of airports and/or flight slots. There was also a brief discussion of the niche markets in which fuel cells might make an impact under *World Markets*. Those mentioned included auxiliary power units for large trucks and portable fuel cells for mobile phones and laptops.

Global Sustainability

The break-out group considered that fuel cells in cars would be introduced in the period 2010-2016. By 2050, 90% of cars in the UK would use fuel cells under this scenario. To enable this trend, government support for UK technology is required. Demonstrations would be one option, with corporate/fleet vehicles as an initial target. There is also a need for policies that make the UK an attractive location for international firms to demonstrate and commercialise their products. Some forms of support would also encourage competing technologies such as hybrids (e.g. the Prius).

The group pointed out that the first demonstrations of fuel cell buses in the UK began in 2003 (as shown in the model inputs). By 2050, it was expected that these would also account for 90% of the market. This outcome is also dependent on government policies, e.g. to support further demonstrations after the current round (possibly in conjunction with other EU member states). Successful policies would need to address financial barriers to the use of fuel cell buses since they would be much more expensive than conventional alternatives - at least initially.

The break-out group discussed various options for hydrogen production. Whilst steam methane reforming is used for most hydrogen production at present, a number of other methods would contribute significantly by 2050. Coal gasification would be used by 2050 as long as carbon sequestration had been proven and was acceptable to the government. Opinion on the use of renewables for electrolysis was split. Although this was thought to be feasible - particularly if hydrogen production were geographically dispersed - some argued that the economics would not be favourable, and that intermittency of some renewables would be a problem. The use of nuclear power for thermo-chemical production of hydrogen was thought to be possible (and commercially attractive) using new reactor technologies after 2015. Finally, biomass was suggested as a source of hydrogen since some working demonstrations already exist. However, some group members thought it was more likely that biomass could be used directly as a transport fuel.

The group briefly discussed hydrogen infrastructure under this scenario. Whilst a number of options for storage and transport are under development, some problems with these would need to be solved. For example, more efficient liquefaction technologies are required (to avoid large energy penalties), and solid state hydrogen storage needs fundamental work to make it practical. The development of national pipelines under this scenario requires incentives by government and regulators to allow the private sector (e.g. oil companies) to make long term capital investments.

Local Stewardship

For the *Local Stewardship* scenario, the break-out group agreed with the team's assumption that fuel cell vehicles would be introduced around 2030. This date stems from an expectation of slow innovation under this scenario, and the possibility of earlier introduction of biofuels for transport. The commercialisation of fuel cell cars was also expected to be relatively slow due to a lack of policy incentives (e.g. congestion charges would not have much of an impact since this scenario implies reductions in car use). Having said this, it was argued that some regions of the UK might have cars earlier than this as a result of regional government policies and circumstances.

The prospects for fuel cell buses and other public service vehicles were thought to be better. An introduction date of 2016 was thought possible, though this would be more likely if some kind of crisis or shock were to occur. Subsequent diffusion was expected by many in the break-out group to be slow. However, some thought this would accelerate if the early experience of fuel cell buses was found to be positive.

There was only time for a brief discussion of stationary fuel cells for households. Under this scenario, some thought that many more experiments such as that in Woking would develop. This would increase the use of local private wire networks and decentralised energy technologies including fuel cells (though perhaps these would be for community heat and power rather than for individual households). Some regional infrastructure for hydrogen would develop as a result of this trend.

The break-out group thought that hydrogen would be mostly produced from renewables under this scenario. Regional variations in production would reflect regional differences in the demand for hydrogen. Renewables for hydrogen production would not only include wind (as in the models). They would also include energy crops and biomass wastes. In those regions where hydrogen production is significant, the electricity grid would also have to be developed to deal with much more decentralisation.

Provincial Enterprise

The break-out group devoted relatively little time to this scenario. A brief discussion of end-use technologies concluded that the UK fuel cell industry would need to be built up to deliver the extent of vehicle fuel cell diffusion shown by the modelling results. A supplementary market in this scenario might be fuel cells for auxiliary power units for heavy good vehicles.

The discussion of hydrogen production options focused on domestic coal since imported gas was thought to be less desirable. Whilst this might allow the UK to become less dependent on energy imports, it was difficult to see how the technology for coal-based hydrogen production could be developed without international collaboration. A similar argument was made about thermo-chemical hydrogen production from nuclear reactors. The issue of whether hydrogen was actually the right energy carrier for CHP systems was also raised.

The same type of problem was identified for the development of transport and storage infrastructure. Without international collaboration or access to international markets, group members thought that the UK would struggle to develop infrastructure technologies such as hydrogen liquefaction and long distance pipelines. However, the UK is leading in other technologies (e.g. metal hydride storage systems) that could be used instead.

6.1.3 Conclusions

A final discussion was held after the break-out sessions to share results and to help develop some overall implications from the four scenarios. The following themes emerged in the discussion:

- Production of hydrogen from renewables. The main issues were perceived to be the cost of electrolysis, the need to make planning permission easier, and the impact of intermittency. The latter was not seen as a problem by some attendees, at least until renewables reach 20% of electricity generation. However, it was clear that if the more ambitious scenarios for renewables were to be realistic, a diverse generating portfolio of renewables would be required. It was felt that further modelling should be carried out to include renewable options such as wave, biomass and tidal in addition to wind.
- Competition from biofuels. A common theme throughout the day was the potential for biomass and biofuels to compete with hydrogen - particularly for transport. Many of the drivers that might help the development of hydrogen production and infrastructure would also encourage biomass and biofuel developments. This point is discussed further in Section 6.2.
- Additional scenario work. Many attendees saw the need for additional modelling work to explore new scenarios. For example, the current methodology could be applied to broader scenarios in which hydrogen is only one of many solutions to environmental challenges. Alternatively, a set of scenarios could explore different levels of willingness to support hydrogen on the part of various stakeholders.
- Government action to support hydrogen. Attendees made the point that the DTI already wishes to raise the UK's profile in hydrogen, but that we lag behind other countries. Concrete support is required if this is to happen in practice - initiatives such as the low carbon vehicle partnership only work if they attract the large international vehicle manufacturers to do something (e.g. demonstrations, manufacture) in the UK.

6.2 Outstanding issues

It has been suggested that the model results represent too "linear" a pathway to hydrogen. Undoubtedly there will be shocks along the way (whether from fossil fuel prices or innovative new technologies) and it would certainly be possible to model specific shocks within the framework of given scenarios in future work, but it is also true that *the full environmental potential of a switch to hydrogen can only be realised by parallel developments in many different* *areas* (e.g. fuel cells, hydrogen storage system technology, hydrogen production system deployment, large scale renewable energy development, to name but a few). It is strongly suggested that rapid development due to shocks in certain of these areas may well potentially lead to an earlier introduction of the hydrogen economy, but the impact on carbon dioxide emissions will be reduced, and may even be negative, without the accompanying developments in the others. In such cases, alternative carbon dioxide reduction strategies may well be more effective in the short and even (where technologies get “locked” in) long term. These possibilities need to be explored further.

Of particular concern is the high growth in renewable electricity required in some of the scenarios. For example, installation rates of 2 GW/year from 2005 onwards rising to 15-20 GW/year by 2050 would be needed to match the *Global Sustainability* hydrogen production targets. This compares to 1 GW/year rising to 4 GW/year in the baseline case without hydrogen. For simplicity in the modelling, it was assumed that this would all be supplied by wind energy, but clearly a much more diverse portfolio would be required. The implication must surely be that a substantially electrolytic-supplied (low carbon) hydrogen economy will not be supportable without significant improvements in the diversity of renewable electricity technologies and their deployment rates. This is, of course, a “win-win” situation in terms of achieving an overall low carbon electricity system, even without a shift to hydrogen.

In the short to medium term, while the penetration of renewable electricity remains low, the use of electrolysis to produce hydrogen for transport use could actually result in increased carbon dioxide emissions due to the knock-on requirement to supply the existing electricity demand from fossil sources (see, for example, Dutton et al., 2003). Such short term disadvantages must be carefully assessed against the long term strategy and have already triggered considerable discussion. It is clear that an alternative, innovative, low (or zero) carbon, non-electrolytic hydrogen production technology would have major implications for the medium to long term sustainability of the hydrogen economy.

The role of biomass and bio-fuels as a complementary or competitor energy carrier to hydrogen will also be critical. Two key issues will be:

- whether large areas of land are best used to cultivate biomass for electricity production or for bio-fuels to process into the transport markets, and then,
- whether bio-fuels are seen as a competitor or just another part of the solution to control transport emissions alongside hydrogen.

The picture is complicated by the possibility that certain types of biomass might be grown specifically for hydrogen production or that land-use might be allocated to other non-energy industrial crops (with equal or greater carbon dioxide reduction potential). This uncertainty possibly contributes to the conflicting reports in the literature for the ultimate potential penetration of biomass into the electricity sector or bio-fuels into the transport fleet. A recent EC sponsored study (CONCAWE/EUCAR/JRC, January 2004) suggested that the potential contribution of bio-fuels to European transport fuel requirements was likely to be in the range of 10% to 15%, whereas other work has suggested that biomass could supply up to 100% of energy requirements (e.g. Klass, 1998).

Some commentators have queried whether hydrogen would ever be used directly for heating or CHP in the domestic sector or whether it is needed at all for storage in the power sector. In this context, it is important to realise the possible effect of “knock-on” developments. For example, although hydrogen arguably might not be the optimum fuel for CHP systems, it might conceivably be used for organisational rather than technical reasons where a widely developed hydrogen distribution network (e.g. for transport) already exists. Similarly, while hydrogen storage might not be developed initially to buffer intermittent renewable electricity generation, it might well be used for that purpose where substantial stocks are already being held to fuel transport fleets (indeed, some more radical commentators have suggested that parked vehicles may be used as distributed generators).

The modelling has given examples of a number of key decision points (e.g. introduction dates for vehicles, dates for decisions on whether to build new nuclear power plant or to rapidly expand the existing plans for renewable electricity) from which the alternative pathways for hydrogen development diverge. These decision points are variously technical (e.g. the need to develop a new kind of storage device) and institutional (e.g. the need for a large government investment programme to establish a national hydrogen grid), but will also be influenced by the behavioural response. The analysis has further assessed the sensitivity of the results to a limited number of variations in the initial parameters (such as growth rates of vehicle markets or renewable electricity production). The work could be extended to consider the flexibility of some of the transition pathways to see how robust policy, regulatory and technical decisions might be if there is a need to change to a different pathway.

7 Conclusions

This project has explored a set of alternative energy scenarios for the UK in 2050, with a particular focus on the possible role for hydrogen within each and development of the associated transition pathways. These scenarios range from a *World Markets* scenario in which there are no explicit drivers for hydrogen to a *Global Sustainability* scenario in which hydrogen becomes a central component of the UK energy system.

The results of the scenario exercise include storylines of the likely development of hydrogen technologies and infrastructure together with quantitative indicators of the contribution to UK energy demand. The detailed storylines and quantitative pathways from the current energy system to the alternatives for 2050 have been developed using linked transport and energy models. These pathways have been evaluated from technical, environmental and economic perspectives with the help of a stakeholder workshop.

The key findings are that:

- In a *Global Sustainability* type of world a high utilisation of hydrogen could be achieved within the context of a predominantly low carbon transport fleet over a timescale of 50 years (with large scale hydrogen vehicle introductions in the bus and light goods vehicle fleets by 2010 and in the car fleet by 2016, followed by annual new buy growth rates of 30%), but, in the absence of major hydrogen production technology innovations, would need to be supported by concurrent investment in additional renewable energy (or nuclear) capacity if the anticipated carbon dioxide emissions savings are to be achieved.
- While hydrogen introduction into the transport sector may be driven by automobile manufacturers, the benefits of reduced carbon dioxide emissions are unlikely be realised without appropriate political backing for low-carbon hydrogen production routes. In the *World Markets* and *Provincial Enterprise* type worlds, where community values are of low priority, the hydrogen production routes of choice remained largely fossil-fuel-based with little reduction (and even increases) of carbon dioxide emissions.
- The UK Government’s target of 60% carbon dioxide emissions reductions by 2050 are unlikely to be achieved without substantial changes in the transport sector; a shift to hydrogen as the major transport energy carrier could make the difference, but only in a world where environmental protection underpins cultural and political philosophy.

Appendix 1 : Energy units

OECD uses *tonnes of oil equivalent* (toe) as the basic unit to compare disparate energy balances. 1 toe is defined as 10^7 kilocalories (41.868 GJ), equal, within a few per cent, to the net heat content of 1 tonne of crude oil[3].

1 Mtoe	=	4.1868×10^4 TJ		
1 Mtoe	=	3.968×10^7 MBtu		
1 Mtoe	=	11630 GWh	=	average power of 1.33 GW over 1 year[4]
1 Mtoe	=	7.3 million barrels[5]		
1 TWh(e)	=	0.086 Mtoe (primary energy equivalent for hydro, non-thermal electric)		
1 TWh(e)	=	(0.086 / 0.33) Mtoe (primary energy equivalent for nuclear)		
1 Mtce	=	1 million tonnes of coal equivalent (= 0.697 Mtoe)[6]		
1 Mtce	=	8141 GWh		

Coal:

1 MW (thermal power) [**MWth**] = approx 1,000 kg steam/hour
1 MW (electrical power) [**MWe**] = approx MWth / 3

A 600 MWe coal-fired power station operating at 38% efficiency and 75% overall availability will consume approximately:

- Bituminous coal (CV 6,000 kcal/kg NAR):	1.5 Mt/annum
- Brown coal (CV 2,250 kcal/kg NAR):	4.0 Mt/annum

Hydrogen:

Lower heating value	=	10800 kJ/Nm^3	=	120.0 MJ/kg = 3.0 kWh/Nm^3
Upper heating value	=	12770 kJ/Nm^3	=	141.9 MJ/kg
Density (gaseous)	=	0.09 kg/m^3		
Density (liquid)	=	70.9 kg/m^3 (-252 ^oC)		
1 Nm^3 H_2	=	10,800 kJ (LHV)		
10^6 Nm^3 H_2	=	10,800 GJ (LHV)		
10^6 Nm^3 H_2	=	0.258×10^{-3} Mtoe		
1 Mtoe	=	3.877×10^3 million Nm^3 H_2		

1 kWh	=	3.6×10^{-3} GJ
1 million BTU	=	1.055 GJ

1 \$/GJ	=	0.25 p/kWh (@ \$1.44 = £1.00)

3 International Energy Agency web site: http://www.iea.org/stats/files/mtoe.htm

4 Royal Commission on Environmental Pollution preferred comparison

5 Oil Industry Conversions: http://www.nepo.go.th/ref/UNIT-OIL.html

6 World Coal Institute web site : http://www.wci-coal.com/facts_conversion.htm

Appendix 2 : Hydrogen characteristics and safety

Hydrogen characteristics[7]:

Units	Hydrogen	Natural gas	Gasoline
Lower Heating Value (MJ/kg)	120	50	44.5
Auto-ignition Temperature[8] (°C)	585	540	228-501
Flame Temperature (°C)	2045	1875	2200
Limits of Flammability in Air (Vol. %)	4-75	5.3-15	1.0-7.6
Minimum Ignition Energy[9] (µJ)	20	290	240
Limits of Detonation in Air[10] (Vol. %)	13-65	6.3-13.5	1.1-3.3
Theoretical Explosive Energy (kg TNT/m^3 gas)	2.02	7.03	44.22
Diffusion Coefficient in Air[11] (cm^2/s)	0.61	0.16	0.05

Standard atmosphere :	14.696 lbf in^{-2}	=	1.01325 x 10^5 Pa
	10^5 Pa	=	1 bar

7 IEA Greenhouse Gas R&D Programme : http://www.ieagreen.org.uk/h2rep.htm

8 Potential for spontaneous combustion (i.e. hydrogen is marginally safer)

9 Hydrogen appears more likely to ignite, but even the spark from a static electric discharge has sufficient energy to ignite natural gas, so the factor 10 difference has little practical significance

10 Explosive range of hydrogen is greater, but methane is explosive at much lower concentrations

11 Hydrogen mixes much faster in air than natural gas or gasoline vapour; this is an advantage in the open, but a disadvantage in enclosed spaces (hydrogen being very much lighter than air rises quickly, as does methane to a lesser extent; petrol fumes remain close to the ground)

Appendix 3 : The Energy Review Advisory Group (ERAG) Scenarios for Energy Demand to 2050

	WM	PE	GS	LS
Domestic sector				
Space heating	2.06	1.60	1.72	1.40
Water heating	1.40	1.30	1.21	1.04
Lights	2.04	1.58	1.59	1.28
Appliances	1.60	1.16	1.30	1.00
Service sector	1.55	1.30	1.34	1.22
Transport				
Cars	1.85	1.70	1.11	0.65
Light goods vehicles (LGV)	3.19	2.92	2.39	1.00
Heavy goods vehicles (HGV)	2.48	2.28	1.86	1.00
Public service vehicles (PSV)	1.63	1.63	3.58	2.39
Air	7.11	2.69	2.69	1.00
Other transport	1.66	1.29	2.75	2.75
Industry sector				
Heat	1.15	1.10	0.90	0.70
Power	2.21	2.11	1.80	1.25

Table A3.1: Energy services demand in 2050 relative to 2000 (reproduced from ERAG 2001b)

	WM	PE	GS	LS
Domestic sector				
Space heating	0.51	0.64	0.46	0.48
Water heating	0.65	0.68	0.63	0.58
Lights	0.65	0.57	0.49	0.41
Appliances	0.91	0.91	0.69	0.69
Service sector	0.80	0.90	0.60	0.70
Transport				
Cars	0.51	0.74	0.39	0.46
Light goods vehicles (LGV)	0.61	0.77	0.58	0.65
Heavy goods vehicles (HGV)	0.74	0.85	0.71	0.80
Public service vehicles (PSV)	0.62	0.77	0.58	0.71
Air	0.80	1.00	0.70	0.90
Other transport	0.80	1.00	0.50	0.75
Industry sector				
Heat	0.44	0.55	0.36	0.44
Power	0.72	0.78	0.61	0.72

Table A3.2: Energy intensity in 2050 relative to 2000 (reproduced from ERAG 2001b)

References

AEA Technology (2002), **Platinum and hydrogen for fuel cell vehicles**, available from Department for Transport (www.dft.gov.uk) at: http://www.dft.gov.uk/stellent/groups/dft_control/documents/contentservertemplate/dft_index.hcst?n=6620&l=2 (last accessed on 23 July 2004)

Berkhout F., Smith, A. and Stirling, A. (2003), **Socio-technological Regimes and Transition Contexts** SPRU Electronic Working Paper No. 106, SPRU, University of Sussex, September.

CAA (2003), **UK airline statistics 2003 – Annual**, see: http://www.caa.co.uk/erg/erg_stats/sgl.asp?sglid=1&fld=2003Annual (last accessed 23 July 2004)

CONCAWE, EUCAR, JRC (2004), **Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context – Well-to-Wheels Report, Version 1b**, January 2004, available from http://ies.jrc.cec.eu.int/Download/eh (last accessed 26 July 2004)

CRYOPLANE (2003), **Liquid Hydrogen fuelled Aircraft – System Analysis,** Full Technical Report, project funded by the European Community under the Competitive and Sustainable Growth Programme: http://www.aero-net.org/

Department for the Environment Transport and the Regions (1997), **National Road Traffic Forecasts (Great Britain)**, 1997

Department for Transport (2002), **Transport Statistics Bulletin**, Vehicle Licensing Statistics: 2002

Department for Transport (2003), **Transport Statistics For Great Britain (TSGB): 2003 Edition**, see: http://www.dft.gov.uk/stellent/groups/dft_control/documents/contentservertemplate/dft_index.hcst?n=8736&l=3

Department for Transport Local Government and the Regions (2001a), **Powering Future Vehicles Draft Strategy**, DTLR

Department for Transport Local Government and the Regions (2001b), **Transport Statistics Bulletin,** Vehicle Licensing Statistics: 2001

DTI (Department of Trade and Industry) (1999), **Actions for Sustainable Transport: Optimisation across modes,** Report of the Integrated Transportation Chain Futures Task Force

DTI (Department of Trade and Industry) (2000), **Energy Paper 68**, December 2000

DTI (Department of Trade and Industry) (2002), **Digest of UK Energy Statistics 2002**, London, The Stationary Office

Dutton, A.G. (2002), **Hydrogen Energy Technology**, Tyndall Centre Working Paper No.17, April 2002: http://www.tyndall.ac.uk/publications/working_papers/wp17.pdf (last accessed 23 July 2004)

Dutton, A.G. (2003), **The hydrogen economy and carbon abatement – implications and challenges for wind energy**, Wind Engineering, Vol. 27, No.4, p. 239-256, 2003

Dutton, A.G., Watson, J., Bristow, A., Page, M., Pridmore, A. (2003), **Integrating hydrogen into the UK energy economy**, 1st European Hydrogen Energy Conference (EHEC), Grenoble, France, 2-5 September 2003

Dutton, A.G., Watson, J., Bristow, A., Page, M., (2004), **Pathways to the hydrogen economy: a case study for the UK using the THESIS model**, in preparation

EMEP (2002), **EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition**, October 2002, available from: http://reports.eea.eu.int/EMEPCORINAIR3/en/B851vs2.4.pdf

Energy Futures Task Force (2000), **Fuelling the Future**, Foresight Programme

Energy Review Advisory Group (2001a), **Energy Scenarios to 2020**, Energy Review Working Paper e, Cabinet Office Performance and Innovation Unit, October 2002, available from: http://www.pm.gov.uk/output/page4250.asp

Energy Review Advisory Group (2001b), **Energy Systems in 2050**, Energy Review Working Paper f, Cabinet Office Performance and Innovation Unit, available from: http://www.pm.gov.uk/output/page4250.asp

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

Foley J (2001), **H_2 Driving the Future**, Institute for Public Policy Research

Foresight (2003), **Foresight Futures 2003: Revised Scenarios and Guidance**, London, Department of Trade and Industry, January 2003.

Gregoire-Padro, C. (2001), **US Department of Energy's Hydrogen Programme**, H2NET meeting: *Hydrogen: the Fuel for the Future*, Rutherford Appleton Laboratory, 13 June 2001, available from: http://www.h2net.org.uk/Events/AnnualMeeting_2001/RN_2.htm (last accessed 23 July 2004)

Hart D, Bauen A, Fouquet R, Leach M, Pearson P, Anderson D (2000), **Hydrogen supply for SPFC vehicles,** ETSU F/02/00176/REP, prepared on behalf of the Department of Trade and Industry, available from: http://www.dti.gov.uk/energy/renewables/publications/pdfs/f0200176.pdf

IAG (Interdepartmental Analysts Group) (2002), **Long Term Reductions in Greenhouse Gas Emissions in the UK**, February 2002, available from: http://www.dti.gov.uk/energy/greenhousegas/index.shtml (last accessed 23 July 2004)

International Energy Agency (2003), **Energy to 2050 Scenarios for a Sustainable Future**, OECD/IEA 2003

Kemp, R. and Rotmans, J. (2001), *The Management of the Co-evolution of Technical, Environmental and Social Systems*, Conference Paper for **Towards Environmental Innovation Systems**, Garmisch-Partenkirchen, 27-29 September 2001

Klass D.L. (1998), **Biomass for Renewable Energy, Fuels and Chemicals**, Academic Press, 1998

Larminie, J. & Dicks, A. (2000), **Fuel cell systems explained**, Wiley, 2000

Milborrow, D. (2001), **PIU Working Paper on Penalties for Intermittent Sources of Energy**, available from http://www.pm.gov.uk/output/page4250.asp (last accessed 23 July 2004)

Nakicenovic, N. and Swart, R. (eds.) (2000), **Special Report on Emissions Scenarios**, Cambridge University Press, Cambridge, UK

National Atmospheric Emissions Inventory (2004), **Emissions database**, see: http://www.naei.org.uk/ (last accessed on 23 July 2004)

Ntziachristos L and Samaras Z, 2000, **COPERT III - Computer Programme to Calculate Emissions from Road Transport - Methodology and Emission Factors**, November 2000

Office of Science and Technology (1999), **Environmental Futures**, Foresight Programme, March 1999

Performance and Innovation Unit (2002), **The Energy Review**, Cabinet Office, February 2002

Pridmore A and Bristow A (2002), **The role of Hydrogen in Powering Transport**, Tyndall Working Paper 19, April 2002, available from: http://www.tyndall.ac.uk/publications/working_papers/wp19.pdf (last accessed 23 July 2004)

RCEP (Royal Commission on Environmental Pollution) (2000), **Energy – The Changing Climate**, RCEP, June.

Ricardo Consulting Engineering Ltd (2002), **"Carbon to Hydrogen" Roadmaps for Passenger Cars: A study for the Department of Trade and Industry,** a study for the Department for Transport and the Department of Trade and Industry, see: http://www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_026217.hcsp (last accessed on 23 July 2004)

Schultz, K.R. (2003), **Use of the modular helium reactor for hydrogen production**, World Nuclear Association Annual Symposium, 3-5 September 2003, London

Strategic Rail Authority (2003), **Annual Report 2002/2003**, available at: http://www.sra.gov.uk/

Transport for London(2003), **Press release: all aboard for the first zero emission fuel cell buses**, http://www.transportforlondon.gov.uk/tfl/press-releases/2003/december/press-875.shtml (last accessed on 17 June 2004)

Watson, J (2002), **The Development of Large Technical Systems: Implications for Hydrogen**, Tyndall Centre Working Paper No.18 , April 2002, available from: http://www.tyndall.ac.uk/publications/working_papers/wp18.pdf (last accessed 23 July 2004)

Watson J, Tetteh A, Dutton, G, Bristow A, Kelly C, Page M (2004), **UK Hydrogen Futures to 2050,** Tyndall Centre Working Paper No. 46, February 2004, available from: http://www.tyndall.ac.uk/publications/working_papers/wp46.pdf (last accessed 23 July 2004)

Wu, X., Jenkins, N., Strbac, G., Watson, J., Mitchell, C., **Integrating renewables and CHP into the UK electricity system**, Tyndall Centre for Climate Change Research, Technical Report 13, March 2004

Wurster, R., Zittel, W. (1994), **Hydrogen energy**, published at the *Workshop on Energy Technologies to Reduce CO_2 Emissions in Europe*, ECN, Petten, April 1994, available at http://www.hyweb.de/gazette-e/

Tyndall°Centre
for Climate Change Research

The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

The Tyndall Centre is a partnership of the following institutions:

- University of East Anglia
- UMIST
- Southampton Oceanography Centre
- University of Southampton
- University of Cambridge
- Centre for Ecology and Hydrology
- SPRU – Science and Technology Policy Research (University of Sussex)
- Institute for Transport Studies (University of Leeds)
- Complex Systems Management Centre (Cranfield University)
- Energy Research Unit (CLRC Rutherford Appleton Laboratory)

The Centre is core funded by the following organisations:

- Natural Environmental Research Council (NERC)
- Economic and Social Research Council (ESRC)
- Engineering and Physical Sciences Research Council (EPSRC)
- UK Government Department of Trade and Industry (DTI)

For more information, visit the Tyndall Centre Web site (www.tyndall.ac.uk) or contact:

External Communications Manager
Tyndall Centre for Climate Change Research
University of East Anglia, Norwich NR4 7TJ, UK
Phone: +44 (0) 1603 59 3906; Fax: +44 (0) 1603 59 3901
Email: tyndall@uea.ac.uk

Tyndall°Centre
for Climate Change Research

Recent Tyndall Centre Technical Reports

Tyndall Centre Technical Reports are available online at
http://www.tyndall.ac.uk/publications/tech_reports/tech_reports.shtml

Warren, R. (2002). **A blueprint for integrated assessment of climate change**, Tyndall Centre Technical Report 1.

Gough, C., Shackley, S., Cannell, M.G.R. (2002). **Evaluating the options for carbon sequestration**, Tyndall Centre Technical Report 2.

Köhler, J.H. (2002). **Modelling technological change**, Tyndall Centre Technical Report 3.

Goodess, C.M. Osborn, T. J. and Hulme, M. (2003) **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events,** Tyndall Centre Technical Report 4.

Steemers, K. (2003) **Establishing research directions in sustainable building design.** Tyndall Centre Technical Report 5.

Macmillan, S. and Köhler, J.H., (2004) **Modelling energy use in the global building stock: a pilot survey to identify available data,** Tyndall Centre Technical Report 6.

Adger W. N., Brooks, N., Kelly, M., Bentham, S. and Eriksen, S. (2004) **New indicators of vulnerability and adaptive capacity**, Tyndall Centre Technical Report 7.

Skinner, I., Fergusson, M., Kröger, K., Kelly, C. and Bristow, A. (2004) **Critical Issues in Decarbonising Transport**, Tyndall Centre Technical Report 8

Gill, J., Watkinson, A. and Côté, I (2004). **Linking sea level rise, coastal biodiversity and economic activity in Caribbean island states: towards the development of a coastal island simulator,** Tyndall Centre Technical Report 9.

M. N. Tsimplis (2003). **Towards a vulnerability assessment for the UK coastline,** Tyndall Centre Technical Report 10.

Berkhout, F., Hertin, J. and Arnell, N. (2003). **Business and Climate Change: Measuring and Enhancing Adaptive Capacity,** Tyndall Centre Technical Report 11.

Palutikof, J. and Hanson, C. (2004) **Integrated assessment of the potential for change in storm activity over Europe: Implications for insurance and forestry,** Tyndall Centre Technical Report 12

Jenkins, N., Strbac G. and Watson J. (2004) **Connecting new and renewable energy sources to the UK electricity system**, Tyndall Centre Technical Report 13

Levermore, G, Chow, D., Jones, P. and Lister, D. (2004) **Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK,** Tyndall Centre Technical Report 14

Levermore, Bristow, A., Pridmore, A., Tight, M., May, T., Berkhout, F. and Harris, M. (2004) **How can we reduce carbon emissions from transport?** Tyndall Centre Technical Report 15

Brown, K., Boyd, E., Corbera-Elizalde, E Adger, W. N. and Shackley, S (2004) **How do CDM projects contribute to sustainable development**? Tyndall Centre Technical Report 16

Few, R. (2005) **Health and flood risk: A strategic assessment of adaptation processes and policies,** Tyndall Centre Technical Report 17

Tyndall°Centre
for Climate Change Research

Dutton, A. G., Bristow, A. L., Page, M. W., Kelly, C. E., Watson, J. and Tetteh, A. (2005) **The Hydrogen energy economy: its long term role in greenhouse gas reduction,** Tyndall Centre Technical Report 18