Article:

Dutton, A.G. and Page, M. (2007) The THESIS model: an assessment tool for the transport and energy provision in the hydrogen economy. International Journal of Hydrogen Energy, 32 (12). pp. 1638-1654. ISSN 0360-3199

https://doi.org/10.1016/j.ijhydene.2006.09.040

Published paper

Dutton A.G.; Page, M. (2007) The THESIS model: An Assessment tool for the transport and energy provision in the hydrogen economy. International Journal of Hydrogen Energy, 32(12), pp.1638-1654.

THE THESIS MODEL: AN ASSESSMENT TOOL FOR TRANSPORT AND ENERGY PROVISION IN THE HYDROGEN ECONOMY

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Abstract – A comprehensive energy analysis software tool (*THESIS*) has been developed for assessing the impact of major technological shifts in the provision of energy for integrated transport, electrical power, and heating/cooling applications. Historically, transport and electrical power have been treated as independent sectors, but, in the case where hydrogen fuel cells are extensively used in motive applications, complex inter-dependencies arise between the two (e.g. production of hydrogen by electrolysis of water, alternative use of hydrogen for electricity storage and subsequent regeneration). The *THESIS* model characterises a country's (or region's) primary energy flows, energy distribution system, secondary energy production processes (e.g. electricity generation), and end-use consumption, including a major sub-model of the Transport sector which keeps track of the size of vehicle fleets and the penetration rate of alternative fuels. The model enables the comparison of varying strategies for hydrogen introduction against the metrics of overall energy consumption, demands for primary fuel, and carbon dioxide emissions reductions. A case study is presented of the application of *THESIS* to a high hydrogen penetration scenario within the context of the UK energy economy to 2050, selected from a wider study into potential hydrogen scenarios under different contextual futures [1].

Keywords – Hydrogen economy, Transport

1. Introduction

The 2002 UK Energy White Paper [2] adopted the target to cut UK carbon dioxide emissions by 60% of current levels by 2050, in order to mitigate the effects of global warming. The justification for such a move towards a "low carbon" energy economy is further supported by other environmental and strategic arguments, e.g. reduced urban pollution and security of energy supply. In particular, considerable international interest is being shown in the use of alternative fuels for transportation, since for many nations Transport is the largest growing source of carbon emissions. Hydrogen is being widely considered as one such alternative fuel, but, since it is a secondary fuel, hydrogen must always be produced via some other primary energy supply, which may often result in emissions of carbon dioxide. For example, steam methane reforming (SMR) will result in significant carbon dioxide emissions unless implemented alongside a carbon dioxide sequestration strategy; electrolysis using electricity supplied from the national grid network (i.e. not from a dedicated renewable or nuclear power supply) will most probably result in emissions elsewhere in the electricity supply network (i.e. from the fossil fuel plant next in merit order). The likely level of these emissions over time and the long term prospects for the hydrogen economy to deliver sustainable reductions in the time frame beyond even 2050 must be estimated in order to decide what immediate priority should be accorded to hydrogen within an overall carbon reduction strategy.

The carbon reduction potential of introducing hydrogen into the energy supply infrastructure depends on:

(i) the type of conventional energy supply capacity displaced,

(ii) the new plant required to produce, store, and distribute the hydrogen,

(iii) the measures (if any) taken to limit harmful emissions associated with the hydrogen production, and,

(iv) the end-use efficiency of hydrogen use.

The first three of these will vary between different countries and even locally within a given country; all four are likely to vary with time.

Most analyses of future electricity demand and Transport growth are carried out completely independent of each other (reflecting the reality that these functions are commonly the responsibilities of separate government departments). Hydrogen as an energy carrier bridges this great divide, necessitating a comprehensive, integrated analysis of primary fuel supply, electrical power (and other secondary energy carrier) production, energy distribution, and end-use efficiency gains. The model described in this paper has been established to carry out such a comprehensive analysis.

Among previous studies in this area, Eyre et al. [3] assessed the carbon reduction potential (well-to-wheels) of various fuel-switching options, notably including explicit consideration of the displacement effects of utilising renewable powered electricity for hydrogen production, Ogden [4] developed concepts for a wide range of possible hydrogen energy system architectures, and Kruger assessed the electric power requirements to fuel the California [5], United States [6], and world [7] vehicle fleets with electrolytic hydrogen. Although these studies take some account of the impact of producing hydrogen on electricity demand, they do not simultaneously consider demand growth among other end-use electricity users, which is the intent of the integrated model described in the current paper.

The Transport sector sub-model is based on some of the techniques found in the UK National Transport Model (NTM), developed by the Department for Transport as "an integrated, multi-modal model developed from the framework of models used for the 10 Year Plan"[8]. It covers road and rail modes and incorporates the capacity to calculate carbon dioxide emissions. The Vehicle Market Model, which forms part of the NTM, only considers conventionally fuelled vehicles, but does have the capacity to model incremental technological improvements. The NTM is used for forecasting up to ten years into the future, but omits certain modes of transport (e.g. aviation) and is not particularly sophisticated in its handling of a number of other aspects of transport (e.g. freight). Its outputs include traffic volume, emissions from transport, congestion and costs, but the wider implications of these forecasts are not currently considered.

2. An integrated model of energy use and supply

The Tyndall Hydrogen Economy Scenario Investigation Suite (*THESIS*) is a software tool for predicting the effect of various fuel-switching strategies on primary energy consumption and potential carbon dioxide emissions at any user-selected timescale into the future. Although developed specifically to explore the implementation of a hydrogen energy economy, the model is applicable to the analysis of any fuel-switching strategy involving conflicting use of energy resources (e.g. biomass v. bio-fuels).

The user must specify one or more scenario(s) 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 can be assessed.

The model is designed to incorporate elements of both a "top-down" approach in which total energy growth is specified (see section 2.1) and a "bottom-up" approach from projections of population size, household size, vehicle use, etc.

Figure 1 shows the conceptual flow of information through the *THESIS* model overlaid with the approximate 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 requirement to use a minimum line thickness).

For the UK, *THESIS* considers four end-use sectors: Transport, Domestic, Services, and Industry. The major inputs to the model are the primary fuel and electricity demands by these end-use sectors. These energy demands are input as top-down targets in all sectors except Transport, where a vehicle stock model is 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 and energy consumption characteristics was not readily available at the level of disaggregation required. Such data could usefully be included in future development of the model.

Having derived the electricity and end-use fuel demands within each sector, *THESIS* then determines the required electricity production and overall 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 both conventional power systems and innovative hydrogen production/storage/distribution 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 potentially 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).

2.1 Future growth of energy demand by sector

The *THESIS* model requires the user to make some a priori assumptions about trends in end-use demand. These assumptions might be in the form of a simple input profile of future demand (disaggregated by fuel) for an end-use sector or, in the case of the Transport sector, a more complex set of profiles for new vehicle sales (disaggregated by vehicle size and technology).

Inherent in any sectoral profile of future end-use demand are assumptions about economic growth, the relationship between growth and energy demand, and changes in the efficiency of the provision of energy services (sometimes called energy intensity). For example, in drawing up storylines (i.e. future projection of energy use and technology development) based on the Foresight Futures scenario set [9] during the UK Government's assessment of energy policy in 2001-03, the Energy Review Advisory Group (ERAG) [10, 11] and the Interdepartmental Analysts Group (IAG) [12] jointly assumed a relatively weak relationship between economic growth and energy demand growth, dependent on prevailing international circumstances. Only in case of very strong growth (3%) did the IAG consider it likely that energy demand would increase. For the environmentally sensitive world regime case known as *Global Sustainability* used as the basis for this study (see section 6), the IAG assumed a GDP growth rate of 2% associated with a fall in overall energy demand (-0.44% per year), resulting in the relatively low sectoral energy demands shown in Table 1. This fall in demand was considered likely to fall unevenly across the four end-use sectors, with Industry energy demand falling by almost 50% while Transport energy demand remained approximately constant. Since the use of a single rate figure does not match current trends and would therefore give rise to a discontinuity in the profile, these rates were used to project sectoral demand levels in 2050 and then a cubic spline fitting routine applied to the data in each sector (see figure 2), so that the shape of the projected demand profile depends on the last historic value, the mean rate of historic change for a representative number of years (e.g. 30 years for the data in Figure 2, except Industry: 15 years), and the expected future value and rate of change in 2050. (For simplicity, the rate of change in 2050 was set equal to the mean trend line from 2000 to 2050.) Hydrogen was then introduced against this background based on the general rules of the scenario [13] as described in section 6.

3. The Transport sector population model

Since the Transport sector already contributes approximately 26% of UK carbon dioxide emissions and it is the single sector where hydrogen can be expected to have the biggest impact, *THESIS* includes a detailed Transport sector sub-module, developed by the Institute for Transport Studies (ITS) at the University of Leeds.

The transport vehicle population model was designed to be quick and easy to use so as to facilitate the testing of different scenarios and intra-scenario variations. It is based around the four main energy consuming transport modes: Road, Rail, Air and Water. The model uses readily accessible, mostly aggregated data sources so as to speed up construction and use.

For the Rail, Air and Water sectors, the required inputs are the levels of different types of activity (specified as total kilometrage by different vehicle types) for all years up to the target end-date (e.g. 2050). These are combined with fuel consumption factors to predict total fuel consumed (by fuel type) for each year. 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 Transport sub-module consists of a series of Excel workbooks, one for each transport mode (additional workbooks can be added, as appropriate, if it is desired to sub-divide regions to suit the availability of input data, such as is the case for the UK, which distinguishes between Great Britain and Northern Ireland in national statistics for Road and Rail. All the sub-models have a similar conceptual structure, the Road workbook being the most complex.

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

Total fuel consumed (kg) = Level of activity (km) x *fuel consumption factor (kg/km)*

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.

3.1 Road transport sub-model

Road transport is at present the dominant source of carbon dioxide emissions within the Transport sector. For this reason, the road transport sub model is the most complex; facilitated by the availability of data to support a relatively detailed approach. The road transport sub-model (Figure 3) performs the basic algorithm:

Total fuel consumed = No. of vehicles (stock) x kilometrage per vehicle x fuel consumption (speed)

Stock: The vehicle stock is disaggregated by vehicle type and vintage. The vehicle classes used in the model are shown in Table 2. Fuel sources used for the last of the base years (2002) in the UK are [14]: petrol (53% total road fuel consumption), diesel (47% 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. However, additional vehicle types could easily be added for future applications.

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.

Stock for future forecast years is calculated from the new buy for the forecast year and the application of the survival factors to the previous year's stock. The explicit user input for the stock part of the sub-model is therefore any 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 [14, 15, 16].

Kilometrage: Vehicle kilometrage data was taken initially from the relevant editions of Transport Statistics Great Britain[14]. 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 and propulsion type[17]. This allows the total kilometrage figures for cars 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 alternatively powered vehicles 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 [14] 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:

- the non-linear relationship between speed and fuel consumption,
- increased fuel use during start-up and acceleration (particularly in urban areas),
- the mean speeds data clearly having been measured on open, free-moving roads.

It was therefore decided to adjust the mean speeds assumed for each road type until the estimated total fuel consumption for road transport in 2000 [18] was matched and then to use these speeds as the basis for the future scenario projections.

Fuel consumption factors: For conventional vehicle types these are taken from the NAEI dataset [17] (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 [19], 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.

Fuel consumption figures for public service vehicle (PSV) and light goods vehicle (LGV) were taken from Hart et al. [20]; rigid HFC heavy goods vehicle (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 3.

3.2 Other Transport modes

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 UK transport sector [14]. 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 shows the rail vehicle classes. The classes chosen broadly reflect variations in vehicle type. The kilometrage data was taken from Strategic Rail Authority [21] which provides annual kilometrage by operating 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 within which the train company is located.

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 inventory [17] 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 [22]. The units were thousands of aircraft movements and thousands of kilometres. Table 5 shows the aircraft classes used.

The LTO figures were taken from [14], as was the average cruise distance for domestic flights (total kilometrage divided by LTO). The cruise distance for international flights was taken from the Civil Aviation Authority's annual report [23].

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 5. 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.

Fuel consumption factors were taken from EMEP [24], 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 gas turbine type engine, so no end-use efficiency improvement over kerosene was assumed.. Hydrogen for air transport was assumed to be liquefied (for volumetric reasons) with appropriate penalty for energy lost in liquefaction.

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 [14].

Activity was broken down into millions of tonne kilometres by inland and sea going water transport. Data was taken from [14]. It was assumed that the fuel consumed by water transport would stay the same over the forecasting period.

3.3 Outputs from the transport sub-model

The main outputs of the transport sub-model are (for all the modelled years):

- Total conventional fuel used
- Total hydrogen fuel used
- And therefore total energy consumed in TWh

For road transport vehicle stock (by vintage and type) and total kilometrage (by road and vehicle type) are also calculated and the outputs can be disaggregated in terms of 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.

4. Electricity and primary fuel supply model

4.1 Electricity plant capacity model

Electricity plant is characterised according to primary fuel type, unit rated capacity, unit efficiency, expected lifetime, load factor, and the rate of deterioration of load factor and efficiency with time.

A baseline year must be selected for the electricity plant model; for the case study of the UK, the base year was taken as 2000, when the overall total capacity was just short of 80 GW (including 4.5 GW of CHP). Individual plant characteristics of UK power stations are listed by plant name and company in the *Digest of UK Energy Statistics (DUKES)* [18]. *THESIS* uses a look-up table of future electrical production capacity, load factor, and efficiency aggregated for each fuel type according to current plant lifetime. If the total available electrical capacity (allowing for a specified security margin) for a given year is insufficient to meet the projected demand then *THESIS* will implement a new power plant according to a new-build merit order specified by the user. For example, the user might specify that after 2030, 50% of new-build electricity capacity should be offshore wind energy and 50% nuclear. If the projected deficit in energy is less than the minimum plant size, the algorithm will defer implementing the new plant until the threshold is exceeded.

Table 6 shows the characteristics of the electricity generating plant specified for *THESIS* applied to the UK electricity network.

The model includes the distribution loss for electricity (Table 7) which, for the sake of simplicity in the case study of section 6, has been assumed to remain a constant proportion of generation to 2050. All electrolysis plant is assumed to incur this distribution loss, although arguably it may not be appropriate for large scale 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 7), the initial required values having been estimated from UK national energy statistics [18].

5. Inclusion of hydrogen as an energy vector in *THESIS*

5.1 Hydrogen production, storage, and distribution model

Hydrogen production capacity in *THESIS* must be specified in terms of basic rated capacity, primary fuel stock, efficiency of energy conversion, load factor, and plant lifetime. Improvements in the performance of hydrogen production technologies can be specified for future years. *THESIS* keeps track of all plant stock against nominal lifetime; if new build capacity is required the most up to date technology will be selected.

For the UK case study, three principal hydrogen production technologies were defined:

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

(ii) electrolysis of water (the source of electricity can be allocated as coming specifically from renewable or nuclear power, or being supplied from the general grid network) – two plant sizes,

(iii) coal gasification.

For these sample technologies, current and future capacity and efficiency values were taken from the literature, in particular the wide ranging report by Wurster and Zittel [25]. Typical values are shown in Table 8 and Table 9.

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

For the UK case study, four principal hydrogen storage technologies were included:

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

(ii) liquefaction,

(iii) compression,

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

Hydrogen distribution plant is similarly characterised according to unit rated capacity, storage duration, component lifetime, and throughput efficiency. Four basic distribution routes are considered in the current version of the model:

(i) direct use,

(ii) cylinder and truck,

(iii) replaceable tank,

(iv) pipeline (local/long distance).

It was originally intended to include criteria for triggering the growth of hydrogen pipeline networks once a given threshold level of hydrogen production and distribution had been achieved, but this was abandoned when it was realised that the approach was impractical without including the overall geographical context (which could only be achieved via a geographical information system). A move to the installation of long distance pipelines is therefore implemented on the basis of absolute production level exceeding a given threshold. The lack of a geographical context also means that it was not possible to consider the effects of constraints caused by the (possibly slow) development of distribution and refuelling infrastructure on the penetration of hydrogen powered vehicles into road transport (see also section 6.1).

5.2 Hydrogen as an end-use fuel

Hydrogen is introduced by specifying a displacement of existing primary or secondary fuel demand within each end-use sector. Improvements in hydrogen end-use technologies are defined as an efficiency improvement by sector by specifying an energy intensity parameter. When the transport vehicle population sub-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. 0.69-0.75 for current-day electrolysis systems, depending on capacity, rising to, say, 0.75-0.81 by 2050).

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.

5.3 THESIS model outputs

When the *THESIS* model runs it produces a yearly picture of the energy demand requirements by sector and associated energy flows. Selected variables for each year are collected into an appropriate output table and saved for later analysis. Typical output parameters may be 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.

6. Case study: High hydrogen penetration in the UK

As a case study, the *THESIS* model was applied to the possible development of the hydrogen vehicle market within the UK in an environmentally conscious world with effective international agreements to curb greenhouse gas emissions. The scenario used was one of four originally developed for the UK Foresight programme [9] and subsequently used by the ERAG and IAG [10, 11, 12]. Known as *Global Sustainability* the scenario is characterised by a high level of importance attached to community values (as opposed to individual/consumer values) and a high degree of international interdependence in governance (as opposed to autonomy). For the UK this was taken to mean high levels of welfare within strong communities and a significant role for international cooperation. It is important to note that this scenario is the most highly optimistic in terms of the development of hydrogen as a fuel due to the importance attached to the environment and the high degree of globalisation which facilitates the development of relevant technology.

Overall energy demand by sector for this scenario was available from the ERAG studies [10, 11] and the project team developed some additional quantitative information to characterise the possible role of hydrogen within the scenario [13]. Several variants on the *Global Sustainability* scenario were developed and are summarised in Table 1. Details of the other scenarios studied within the project are given in the final project report [1].

A “baseline” scenario was realised in the transport vehicle population model by extrapolating the current aggregate kilometrage figures to 2050 using the proportionate increases in energy demand shown in Table 1 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 required energy intensity improvement targets. The potential carbon dioxide emissions reductions for such a scenario were also developed through to 2050.

6.1 Introduction of hydrogen into the Transport sub-model

The introduction of hydrogen requires some scenario-specific judgements, particularly relating to:

- At what point in the future should hydrogen fuelled technology be introduced?
- What take-up rate would be necessary after this introduction date in order to meet the nominal percentage hydrogen energy use by 2050?
- Is this take-up rate feasible (and, if not, what might a feasible rate be)?
- Will hydrogen vehicles simply replace conventional vehicles on a one-to-one basis or will they be bought in addition to conventional vehicles, at least until the technology and supporting infrastructure is established?
- What is the most likely hydrogen production supply chain?
- What impact will the selected production chain have on the rest of the energy supply system?

The problem of a feasible take-up rate is complex. The introduction of serious commercial hydrogen-powered vehicle production 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, materials for hydrogen storage containers, and the development of an appropriate refuelling network for private vehicles). 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. an increased use of fossil-derived electricity if renewable electricity growth is too slow).

Ricardo [19] has described two potential routes and time frames for the introduction of hydrogen cars in the UK, designated as “low carbon” and “hydrogen priority”. The latter is broadly analogous to the *Global Sustainability* scenario, with a fuel cell vehicle available for market dissemination after 2020.

Assumptions must also be made as to which modes of transport would be most likely to convert to using hydrogen first (if at all). It is widely felt in the literature that hydrogen vehicles are most likely to breakthrough first in the bus market (see, for example, Foley [26] and Pridmore and Bristow [27]) 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. A number of hydrogen-powered buses are already being introduced in London as part of the EC-funded CUTE project. 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 the short to medium term are probably heavy goods vehicles and thus hydrogen fuel cell heavy goods vehicles feature fairly late in the *Global Sustainability* scenario (facilitated by early development in the other vehicle types). The Ricardo [19] dates were used as a guideline for determining when hydrogen could be introduced for each mode: namely 2003 for the bus, 2010 for light goods vehicles, 2016 for cars, and 2019 for heavy goods vehicles. The next stage was to estimate the market penetration rate of hydrogen through the vehicle fleet after the initial seed. This rate is particularly difficult to estimate due to the large number of factors involved which include not only the development and mass production of hydrogen technology, but also the availability of a convincing refuelling infrastructure. A further complication is consumer reaction to the new types of vehicle combined with any Government incentives which might be used to encourage their take up. Because of this uncertainty two different market growth rates were used for hydrogen vehicles: a high rate of 30% per annum (40% for HGVs) which is considered an upper bound and a lower rate of half the high rate. The total vehicle stock for each conventional (fossil-fuelled) vehicle type within each scenario was known from the baseline run; it was then assumed that hydrogen vehicles would substitute in each road transport mode on a like for like basis. Finally, the increases in hydrogen vehicles were subtracted from the total vehicle stock originally calculated to ensure that as the hydrogen vehicles penetrated the market they displaced the equivalent number of conventional (fossil-) fuelled vehicles (Figure 3).

The initial introduction dates and subsequent growth of the four main road transport vehicle fleets are shown in Figure 4a. It is assumed that the “introduction date” for a given hydrogen fleet represents an initial seed penetration level of approximately 0.5% of the new buy market for that Road transport mode;

the new buy market for hydrogen vehicles in that mode is then assumed to grow at the indicated percentage year on year. For example, for Cars, this implies that a market of some 10,000 new hydrogen vehicles is established by 2016, growing to 13,000 in 2017, etc. Even though a growth rate of 30% per year might seem high (given the underlying equivalent growth rates in hydrogen production, storage tanks, catalyst materials, etc.), the impact on the overall fleet only becomes apparent some 15 years after the initial introduction, but at this rate of growth the target of almost complete penetration by 2050 could be realised.

Figure 4b shows the effect on penetration of hydrogen vehicles into vehicle fleets if market growth proceeds at only half the assumed growth rates of Figure 4a. In this case, vehicle fleets are only just becoming significant by 2050 and the market is far from mature.

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 as for Road Transport.

Note that, since the baseline model [10] assumes a relatively large increase in the proportion of heavy goods vehicles compared to cars and a large expansion of international air travel, with parallel developments in the efficiency of conventional (fossil-fuelled) power trains, potential efficiency gains from using fuel cells in small vehicles may be outweighed by heavy duty power uses.

The cumulative effect on hydrogen fuel demand for both versions of the scenario are shown in Figure 5.

6.2 Impacts of the Global Sustainability scenario on energy demand

The resulting requirements for hydrogen production and installation of new electric plant are shown in Figure 6 and Figure 7 respectively.

Figure 6 shows two variants of the high growth case (high road vehicle diffusion rate). The first (shown in Figure 6a and referred to as GS-Hydrogen-T) assumes that the bulk of the required hydrogen is supplied from electrolysis of water using electricity supplied exclusively from renewable or nuclear sources. This choice of production technology is driven by the "low carbon" requirements of the scenario's underlying assumptions (although SMR is utilised prior to 2030 since it is anticipated that up to that point most renewable and nuclear electricity would need to be dedicated to offsetting conventional electricity demand and would not necessarily be available for hydrogen production). In the other variant (Figure 6b, GS-Hydrogen-T2) it is assumed that the expansion of renewable and/or nuclear electricity is unable to meet steeply increasing 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, so SMR plant replaces more than half the desired electrolysis plant with substantial reductions in the requirement for nuclear and renewable electricity capacity. Figure 6c (GS-Hydrogen-T3) shows a lower growth in hydrogen production capacity if a low vehicle diffusion rate is assumed.

Note that the total hydrogen demand under the non baseline (hydrogen) *Global Sustainability* cases (GS-Hydrogen-T, T2, T3) includes approximately 30% penetration of hydrogen[1] into the Domestic, Service, and Industry sectors for heating and combined heat and power (CHP) units, on the assumption that if hydrogen has become ubiquitous in road transport it will inevitably find its way into use in the home and office. They also include full use of hydrogen in the air transport mode.

Figure 7 shows the installation of electrical generating capacity required to meet these demands compared with the baseline (without hydrogen) *Global Sustainability* scenario (GS-Baseline-T) (Figure 7a). The renewable (wind) capacity shown in Figure 7b for the GS-Hydrogen-T scenario has to supply the same fraction of conventional electricity demand as in the baseline scenario plus part (50%) of the new hydrogen production. The additional nuclear capacity compared with the baseline *Global Sustainability* scenario supplies 40% of the ultimate hydrogen demand (by electrolysis). The balance of hydrogen demand is supplied by coal gasification.

For the high growth case, where hydrogen production is primarily by electrolysis powered from renewable and nuclear electricity (GS-Hydrogen-T), Table 10 shows the allocation of hydrogen supply to end-use

[1] This 30% penetration offsets the equivalent amount of conventional electricity and natural gas heating demand.

demand in 2050. The additional installed renewable (wind) capacity compared with the baseline *Global Sustainability* scenario is 173 GW. Wind produces half the total hydrogen supply and road transport consumes about 42% of this. Therefore 72 (= 0.42 x 173) GW of installed wind capacity is dedicated to providing 50% of the hydrogen production for road transport (the balance coming from nuclear and other sources). For comparison, the low growth case (GS-Hydrogen-T3, not shown in Table 10) for the hydrogen vehicle market requires 22 GW less of nuclear and 75 GW less of renewable electricity generating capacity than the high growth case.

The cost of the investment in additional electrical capacity in 2050 required to support the penetration of hydrogen shown in Table 10 should be compared with that required to support the petroleum industry and other alternative fuels to the same proportion of market share in the baseline (GS-Baseline-T) case. A continuing reliance on conventional fuels will obviously not have the same implications for the installation of electrical plant and therefore the effects of this are not evident in Figure 7a.

As discussed in Section 5.1, the most suitable technology for and the energy penalties arising from storage and distribution of end-product hydrogen are geography-dependent. In the absence of a geographic component to the model, constant (with time) efficiency values are assumed for each storage/distribution vector in the *Global Sustainability* scenario. The predominant storage vector for road transport end-use is assumed to be compression (efficiency 90%) with distribution by cylinder/truck (efficiency 90%); solid state storage (efficiency up to 95%); liquefaction (efficiency 70%) is assumed to supply air transport; the use of pipelines only become significant with high penetrations of road vehicles beyond 2040.

7. Discussion and conclusions

The variants of the *Global Sustainability* scenario provide interesting comparisons between different levels of hydrogen use, mainly in the transport sector. However, it is important to note that the *Global Sustainability* scenario itself is an extremely optimistic one in terms of future energy use. Figure 2 shows that for both the domestic and transport sectors, the baseline case represents a levelling off and to some extent a fall in future energy demand in these sectors, which is very much against current trends. This is assumed to come about as a result of significant improvements in the efficiency of end-use electrical appliances and conventional powered vehicles. The variants match the overall baseline energy demand, but assume that some of the energy is delivered via a hydrogen pathway, which imposes different demands on the way that the energy is produced (mostly substituting petroleum in the transport sector for a number of different ways of producing hydrogen), resulting in varying carbon dioxide emission profiles as shown in Figure 8.

The baseline scenario (GS-Baseline), leads to a significant reduction in carbon dioxide emissions over the 50 year period but does not meet the 2002 UK Energy White Paper target of 60% reduction by 2050 [2].

The high growth cases (GS-Hydrogen-T and GS-Hydrogen-T2) deliberately represent an extremely high level of hydrogen use in the transport and other sectors, but even the low growth case (GS-Hydrogen-T3) can be considered challenging. Along with the cited penetrations into the road transport sector, all these variants include full use of hydrogen in the air transport mode (for comparison, all other scenarios in the study – see [1] – assumed that hydrogen would not be used at all in the air mode).

The high growth case where hydrogen production is predominantly by electrolysis powered by renewable and nuclear electricity (GS-Hydrogen-T) does achieve the 60% reduction in carbon dioxide emissions by 2050 target, but requires a very significant increase in renewable and nuclear electricity generation capacity. From Table 10, the total increase required in energy from electricity generation in 2050 would be approximately 992TWh, split between air transport (302TWh), road transport (414TWh) and hydrogen production for use in other sectors (276TWh), with some hydrogen produced by coal gasification. It is assumed that a large proportion of this hydrogen will come from renewables (wind) – approximately 544TWh. For comparison, the total supply of electrical energy in 2004 (all generating sources) was 375TWh, of which 14.1TWh (less than 4%) was from renewable sources and 74TWh from nuclear [28]. Of the renewable generation, only 1.9TWh was from onshore and offshore wind, the rest was mostly from hydro (4.9TWh) and biofuels (7.3TWh). This scenario therefore implies an increase in the generation of electricity from renewable sources of the order of forty times, just to produce half the hydrogen required, *as well as* a significant expansion of the nuclear sector (from 74 to 524TWh) to provide most of the rest.

While all the renewable electricity in the model has been assumed to come from wind power, in reality it is expected that the demand would be spread across a range of technologies (e.g. wave, tidal current) as well as wind.

In the case where the rate of installation of renewable power plant is insufficient to meet demand and SMR, as the cheapest alternative, is assumed to supply the hydrogen demand (GS-Hydrogen-T2), there is a modest rise in natural gas consumption (10%), but a substantial increase in the expected carbon dioxide emissions, although some, at least, of this excess might be sequesterable. Ignoring sequestration, this case does not achieve the carbon dioxide emissions reduction target. 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.

For both of these high growth cases (GS-Hydrogen-T, T2) the overall UK hydrogen demand by 2050 is 200×10^9 Nm^3 per year. For comparison the current world production of hydrogen is estimated to be 500×10^9 Nm^3 per year [29].

In the low growth case (GS-Hydrogen-T3), where the take up of hydrogen powered vehicles is assumed to be half of that in the high growth cases, the target for reductions in carbon dioxide emissions is achieved, but only just. However, this case results in the additional emission of 758 million tonnes of carbon dioxide over the high growth, renewables/nuclear case (GS-Hydrogen-T) over the 50 year period (which equates to almost 1.3 years of emissions at 1990 levels). By 2050, the now undisplaced petroleum demand results in an additional 56 million tonnes of carbon dioxide emissions per year (plus a further 12 million tonnes of potentially sequesterable carbon). In this case overall UK hydrogen demand by 2050 is 135×10^9 Nm^3 per year. This is still significant and requires substantial investment in nuclear and renewable electricity generating capacity (see Figures 6c and 7c).

The scenario results indicate the scale of hydrogen production required and the potential carbon dioxide emissions savings from clean hydrogen production vectors based on electrolysis powered by nuclear and renewable power. It is likely that by 2030-2050 other innovative hydrogen production fuel chains may be available, for example based on high temperature thermochemical cycles, direct photo-splitting of water, or biological methods. Variants of the basic scenario could be developed based on these fuel chains with similar carbon dioxide savings and less impact on the electricity system, but with other impacts in terms of land-use, raw materials, irradiated waste, etc, Above all, the findings presented here serve to emphasise the scale of development required for any technology to ultimately displace carbon-producing fuels.

8. Conclusions

An integrated model (*THESIS*) of energy supply, transport provision, and the resulting carbon dioxide emissions has been developed and applied to a case study of hydrogen penetration in the UK energy system. The results indicate the benefit of considering energy and transport within a single framework and highlight the challenges and scale of change involved in any transition to a truly sustainable hydrogen energy economy.

The modular nature of the integrated model makes adaptation to other countries or other fuel mixes relatively straightforward.

Acknowledgements

This research was supported by the Tyndall Centre for Climate Change Research as project number IT1.26. The authors acknowledge the useful contributions of other members of the project team: Professor Abigail Bristow, now at the University of Loughborough, Ms Charlotte Kelly at the Institute for Transport Studies (ITS), University of Leeds, and Dr Jim Watson and Ms Alison Tetteh at the Science Policy Research Unit (SPRU), University of Sussex to the development of the THESIS model and, in particular, the basic scenarios for development of hydrogen in the UK.

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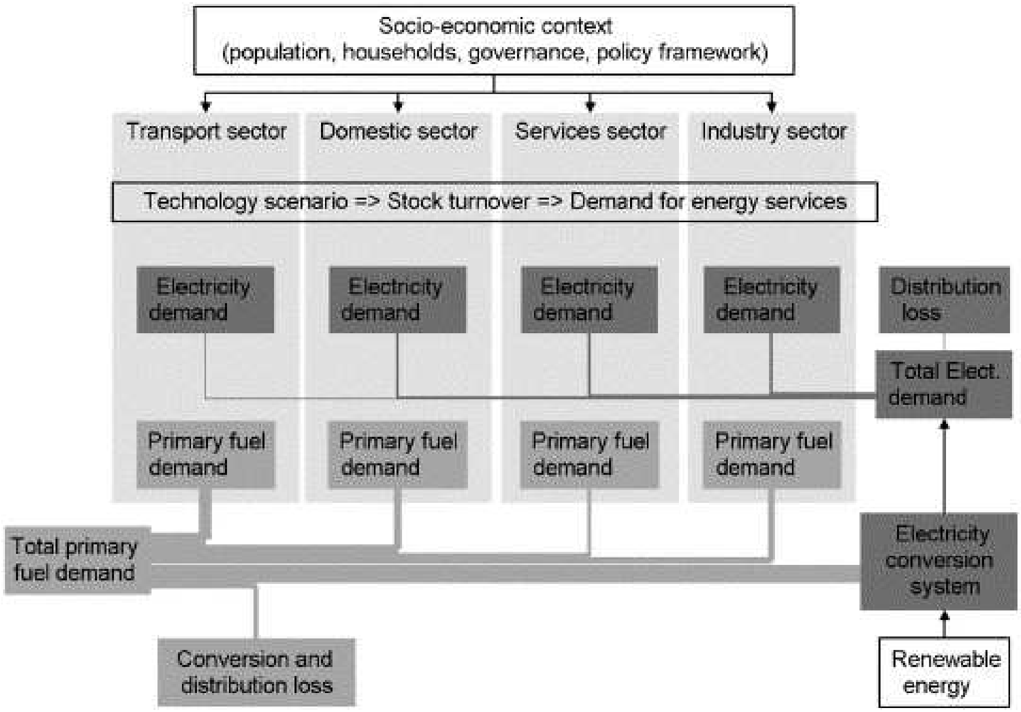


Figure 1: Information and energy flows in the *THESIS* model (diagram shows approximate proportions of energy flows in the UK energy economy in 2000)

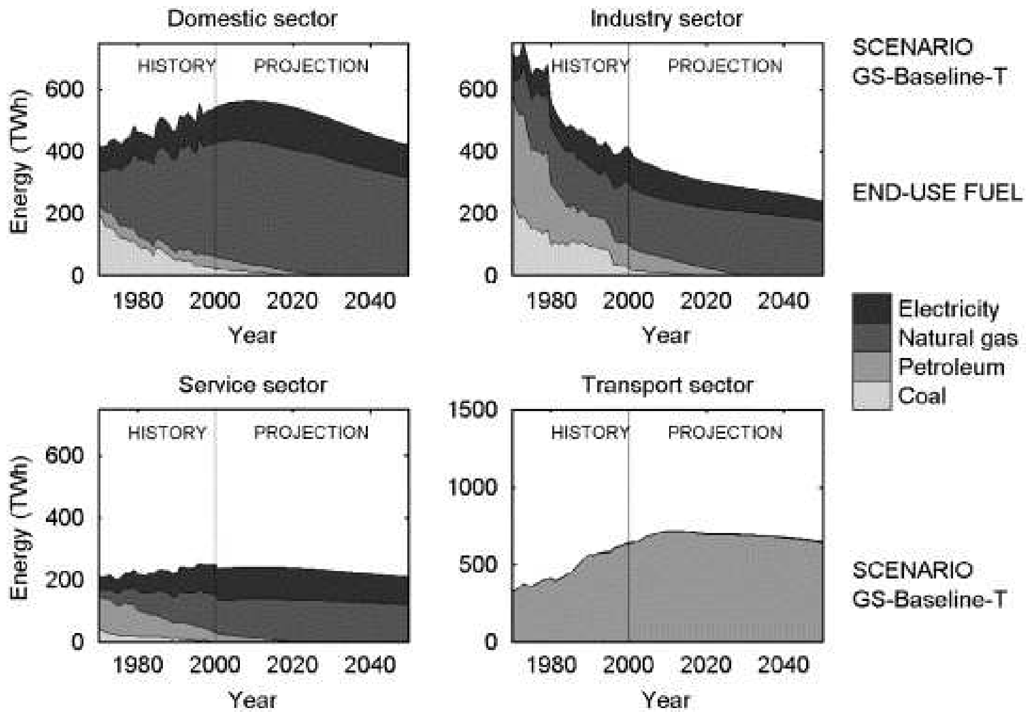


Figure 2: Baseline sectoral demand (by end-use energy source) history and future projection for a baseline (no hydrogen) scenario (note change of scale for the Transport sector)

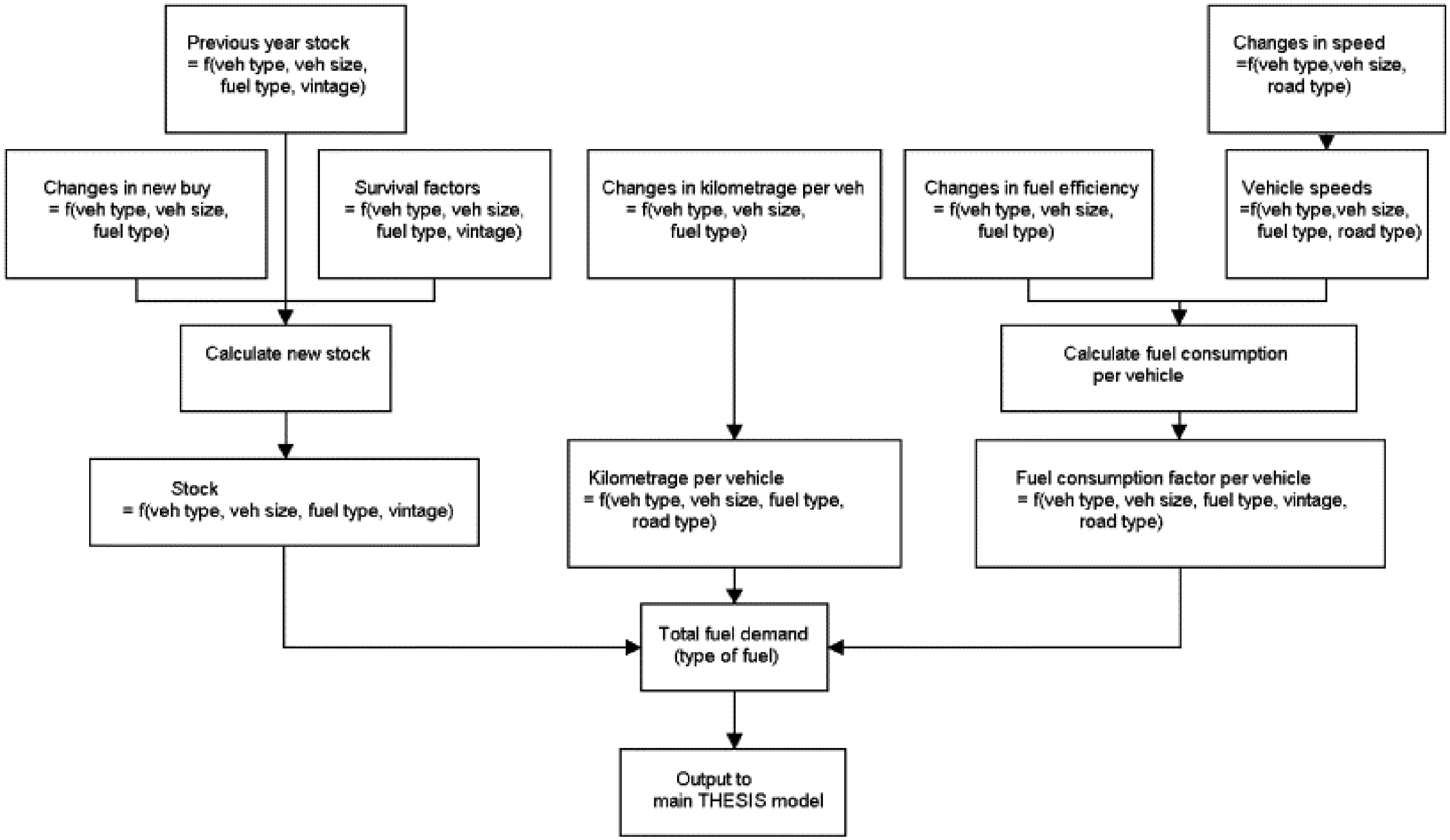
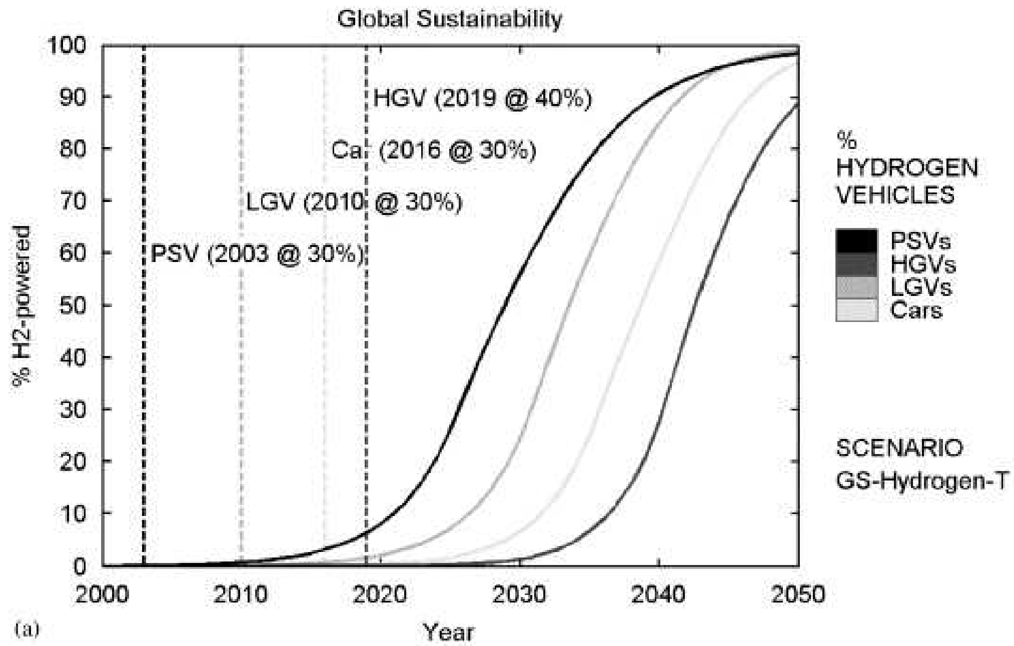
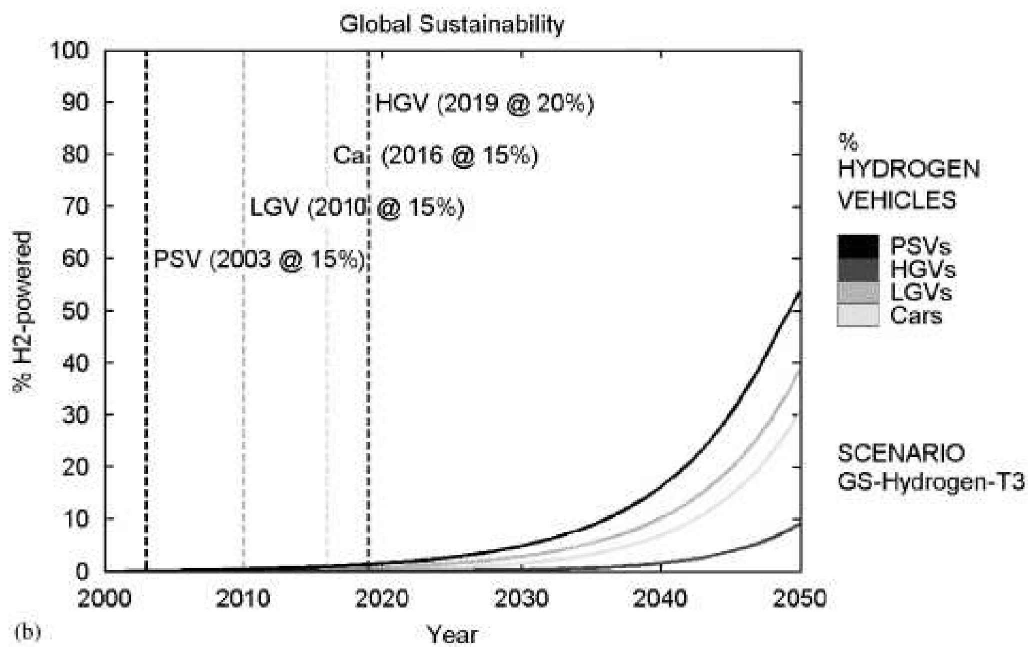


Figure 3: Information flow in the Transport sub-model



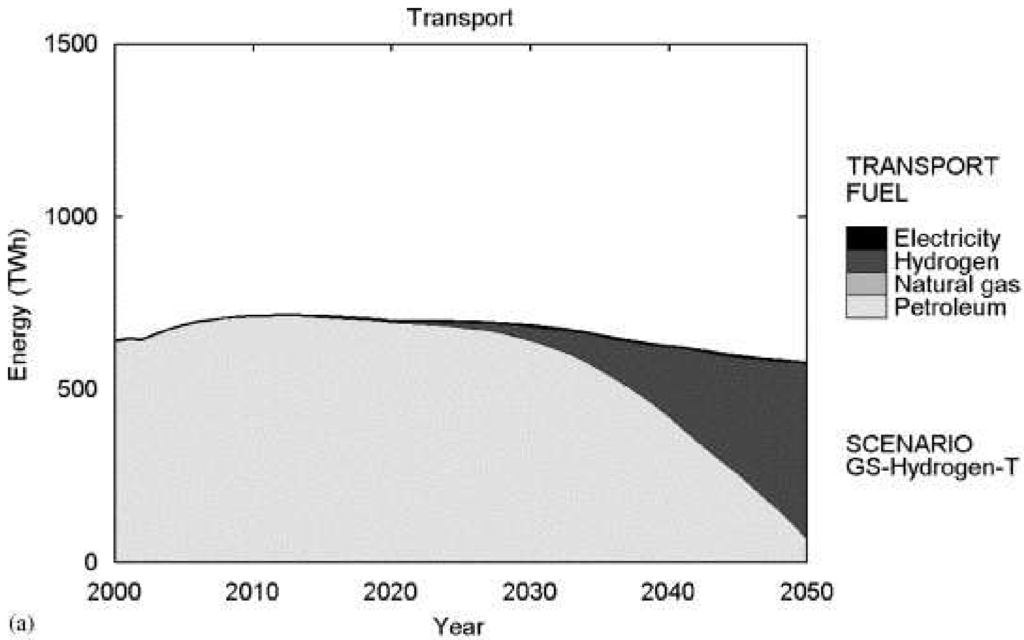
(a)



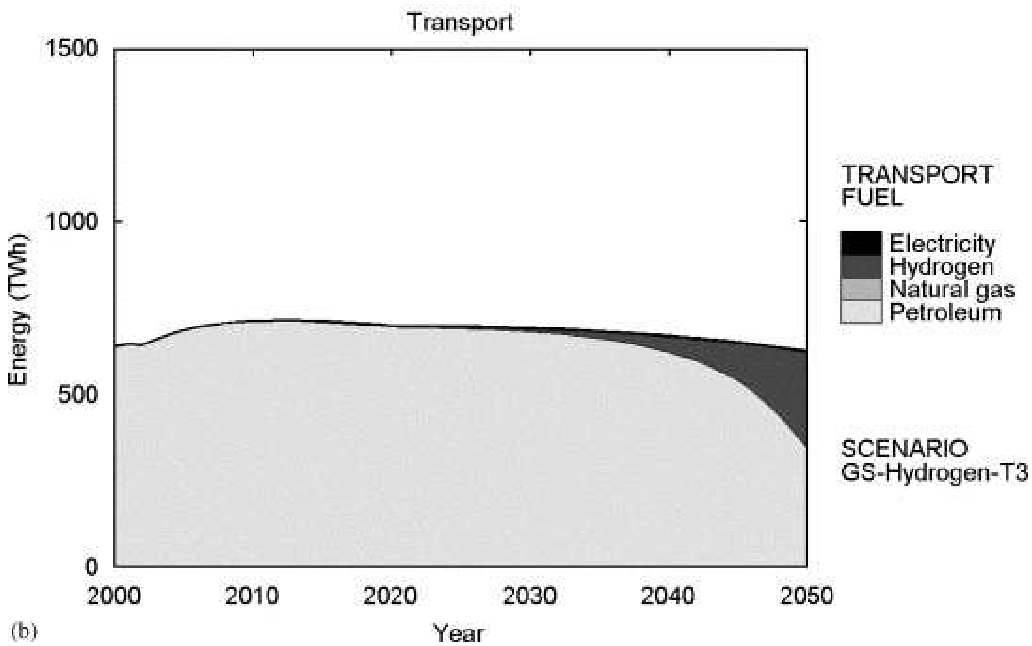
(b)

Figure 4a: Penetration of hydrogen-powered vehicles into the Road Transport sector for the *Global Sustainability* scenario (high Road vehicle diffusion rate) showing introduction year at 0.5% market penetration and subsequent growth rate for public service vehicles (PSVs), light goods vehicles (LGVs), heavy goods vehicles (HGVs), and cars

Figure 4b: Penetration of hydrogen-powered vehicles into the Road Transport sector for the *Global Sustainability* scenario (low Road vehicle diffusion rate) showing introduction year at 0.5% market penetration and subsequent growth rate for public service vehicles (PSVs), light goods vehicles (LGVs), heavy goods vehicles (HGVs), and cars



(a)



(b)

Figure 5a: Utilisation of hydrogen as a Transport fuel for the *Global Sustainability* scenario (high Road vehicle diffusion rate) – note graph also includes high penetration of hydrogen in the Air Transport mode

Figure 5b: Utilisation of hydrogen as a Transport fuel for the *Global Sustainability* scenario (low Road vehicle diffusion rate) – note graph also includes high penetration of hydrogen in the Air Transport mode

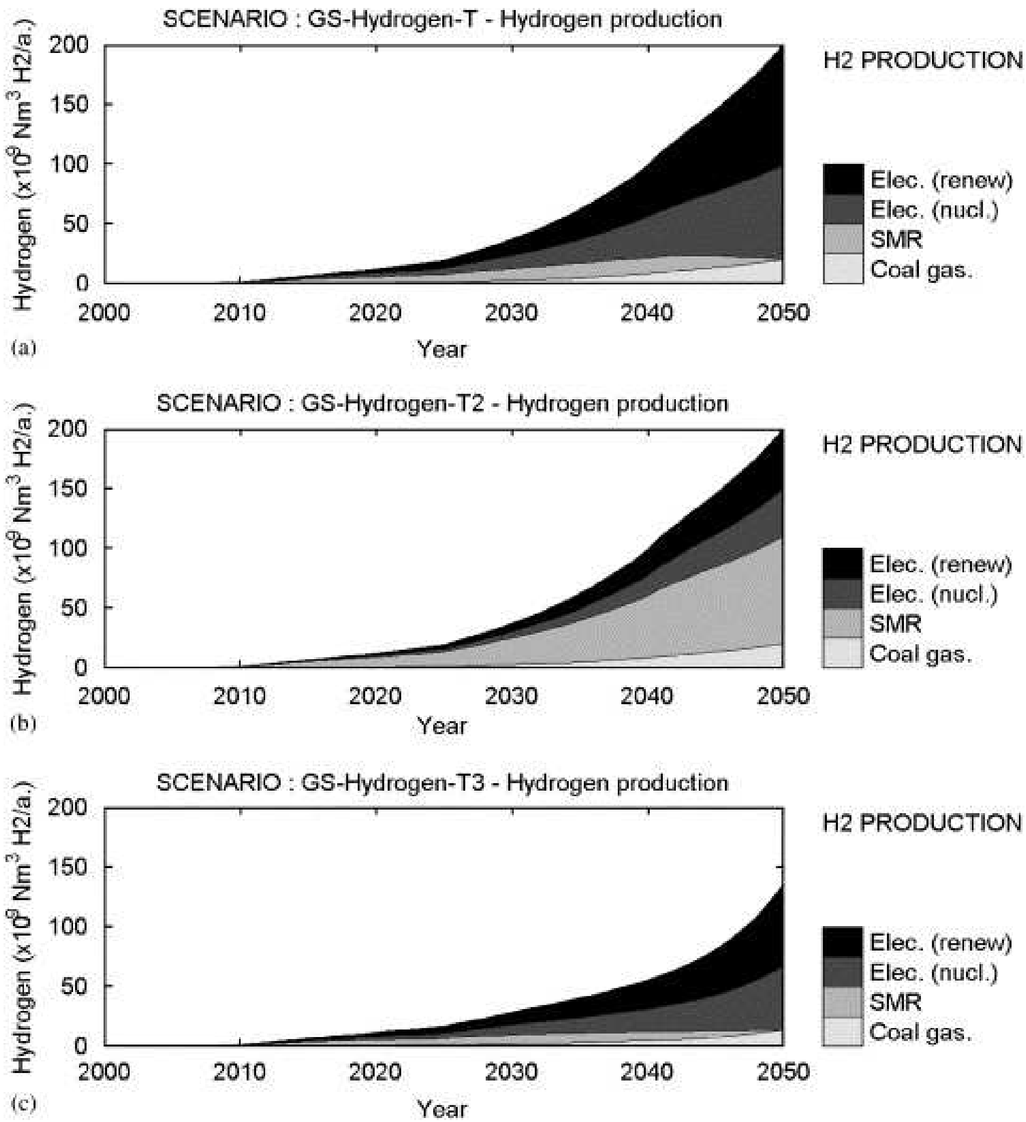
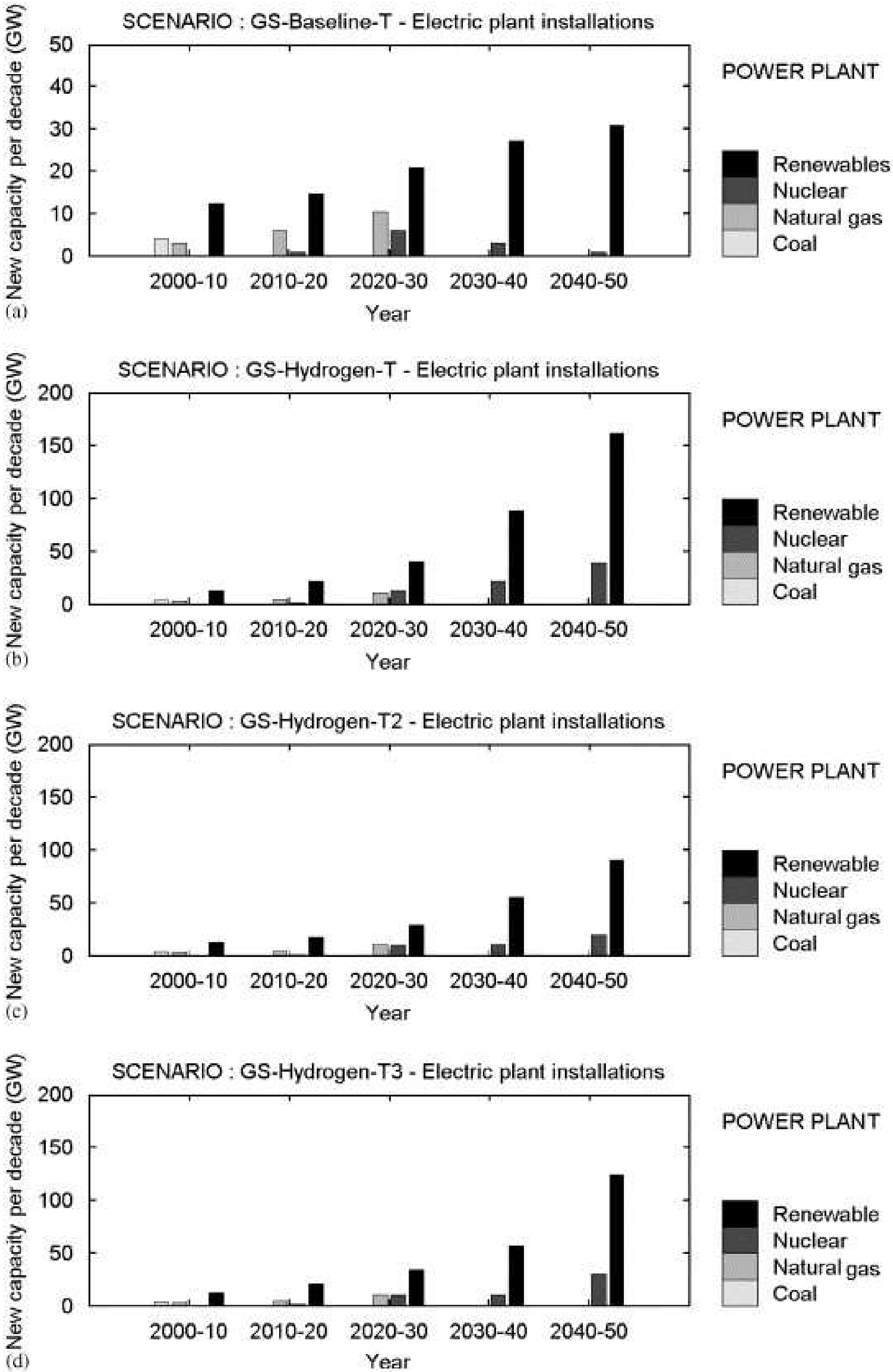


Figure 6a: Hydrogen production per year under the *Global Sustainability* scenario (high Road vehicle diffusion rate) – hydrogen production predominantly by electrolysis powered from renewable and nuclear electricity

Figure 6b: Hydrogen production per year under the *Global Sustainability* scenario (high Road vehicle diffusion rate) – SMR hydrogen production meets failure to achieve sufficient expansion in renewable and nuclear electricity capacity

Figure 6c: Hydrogen production per year under the *Global Sustainability* scenario (low Road vehicle diffusion rate)



SCENARIO : GS-Baseline-T - Electric plant installations
New capacity per decade (GW)
50
40
30
20
10
0
2000-10
2010-20
2020-30
2030-40
2040-50
Year
(a)
POWER PLANT
Renewables
Nuclear
Natural gas
Coal
SCENARIO : GS-Hydrogen-T - Electric plant installations
New capacity per decade (GW)
200
150
100
50
0
2000-10
2010-20
2020-30
2030-40
2040-50
Year
(b)
POWER PLANT
Renewable
Nuclear
Natural gas
Coal
SCENARIO : GS-Hydrogen-T2 - Electric plant installations
New capacity per decade (GW)
200
150
100
50
0
2000-10
2010-20
2020-30
2030-40
2040-50
Year
(c)
POWER PLANT
Renewable
Nuclear
Natural gas
Coal
SCENARIO : GS-Hydrogen-T3 - Electric plant installations
New capacity per decade (GW)
200
150
100
50
0
2000-10
2010-20
2020-30
2030-40
2040-50
Year
(d)
POWER PLANT
Renewable
Nuclear
Natural gas
Coal

Figure 7a: New electrical plant installations per year under the baseline *Global Sustainability* scenario (no Hydrogen) – note different scale compared to 7b, 7c and 7d

Figure 7b: New electrical plant installations per year under the *Global Sustainability* scenario (high Road vehicle diffusion rate) – note graph also includes high penetration of hydrogen in the Air Transport mode

Figure 7c: New electrical plant installations per year under the *Global Sustainability* scenario (high Road vehicle diffusion rate) – SMR hydrogen production meets failure to achieve sufficient expansion in renewable and nuclear electricity capacity

Figure 7d: New electrical plant installations per year under the *Global Sustainability* scenario (low Road vehicle diffusion rate) – note graph also includes high penetration of hydrogen in the Air Transport mode

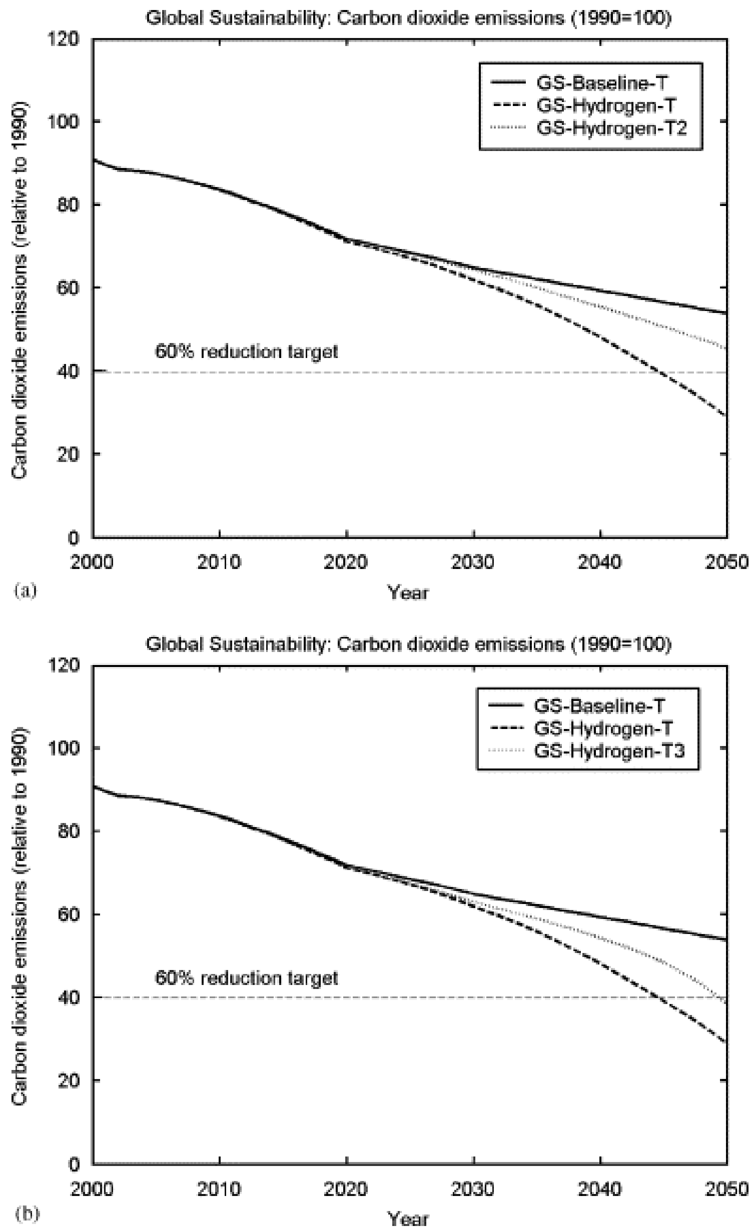


Figure 8a: Projected carbon dioxide emissions to 2050 relative to 1990 levels under the *Global Sustainability* scenarios without hydrogen (Baseline-T), high road vehicle diffusion rate fuelled by electrolysis (Hydrogen-T), and high road vehicle diffusion rate fuelled by SMR (Hydrogen-T2)

Figure 8b: Projected carbon dioxide emissions to 2050 relative to 1990 levels under the *Global Sustainability* scenarios without hydrogen (Baseline-T), high road vehicle diffusion rate fuelled by electrolysis (Hydrogen-T), and low road vehicle diffusion rate (Hydrogen-T3)

Table 1.

Projected energy demand by sector for 2050 (source [11]) and contribution limits for hydrogen (source [13]) under the *Global Sustainability* scenario

Global Sustainability	**Energy demand by sector**			**Hydrogen road**	**% hydrogen from**
scenario variant				**vehicle penetration**	**renewables/nuclea r**
GS-Baseline		TWh (2000)	TWh (2050)	0	—
	Domestic	533	426		
	Services	265	213		
	Transport	638	646		
	Industry	465	241		
	Total	1902	1526		
GS-Hydrogen-T	Total end-use demand by sector—as above			High	90
GS-Hydrogen-T2	Hydrogen penetration limits (by 2050):			High	45
	Domestic: 20–30% (fuel cell CHP)				
	Service: 30% (mainly fuel cell CHP)				
GS-Hydrogen-T3	Transport: 80–100% (not achieved in variant T3)			Low	90
	Industry: 30% (mainly fuel cell CHP)				

Table 2. Road vehicle classes

Car	*Heavy goods*
Petrol	Diesel
Small (<1.4 l)	Rigid
Medium (1.4–2.0 l)	Artic
Large (>2.0 l)	HFC
	Rigid
	Artic
Diesel	
Small (<2.0 l)	
Large (>2.0 l)	
Hybrid	*Light goods*
Small	Petrol
Large	Diesel
	HFC
HFC	*Bus or coach*
Small	Diesel
Large	HFC
HICE	*Motorcycle*
Small	Small (≤50cc)
Large	Medium (50–499cc)
	Large (≥500cc)

Table 3.

Fuel consumption figures for non-conventional vehicles (for references, see text)

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.

Rail vehicle classes

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

Table 5.

Aircraft classes

Domestic flights	
	LTO
B737-400 Passenger	Cruise distance
	LTO
‘Cryoplane’ Passenger	Cruise distance
	LTO
B737-400 Cargo	Cruise distance
	LTO
‘Cryoplane’ Freight	Cruise distance
International flights	
	LTO
B767 300 R Passenger	Cruise distance
	LTO
‘Cryoplane’ Passenger	Cruise distance
	LTO
B767 300 R Cargo	Cruise distance
	LTO
‘Cryoplane’ Freight	Cruise distance

Table 6.

Typical electricity generating plant characteristics input to *THESIS*

All	**Year**		
Typical size (MW)	**2000**	**2020**	**2050**
Efficiency			
Load factor			
Lifetime (years)			
Coal	2000	2000	2000
	0.33	0.35	0.35
	0.8	0.8	0.8
	40	40	40
Petroleum	200/1000	2000	
(diesel generator, oil-fired)	0.33/0.35	0.35/0.35	
	0.3/0.5	0.3/0.5	
	40	40	
Natural gas	1500	1500	1500
	0.55	0.575	0.575
	0.8	0.8	0.8
	30	30	30
Nuclear	1000	1000	1000
	—	—	—
	0.8	0.8	0.8
	40	40	40
Renewables	20/200	50/500	50/500

All	Year		
Typical size (MW)	**2000**	**2020**	**2050**
Efficiency			
Load factor			
Lifetime (years)			
(wind power-on/off shore)	—	—	—
	0.25/0.4	0.25/0.4	0.25/0.4
	15/20	15/20	15/20
Imports	1000	1000	1000
	1.0	1.0	1.0
	1.0	1.0	1.0
	50	50	50

Table 7.

Primary fuel and electricity conversion and distribution losses

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

Table 8. Typical hydrogen production plant capacity and assumed efficiency values for *THESIS*—capacity values stated in Nm^3 of H_2 per hour (million Nm^3 of H_2 per annum)

Year	**2000**		**2015**		**2030**		**2050**	
Plant type	**Capacity**	**Eff.**	**Capacity**	**Eff.**	**Capacity**	**Eff.**	**Capacity**	**Eff.**
Small SMR plant	500	0.75	500	0.77	500	0.78	500	0.79
	(4.38)		(4.38)		(4.38)		(4.38)	
Medium SMR plant	5000	0.78	7500	0.80	10,000	0.81	10,000	0.82
	(43.8)		(65.7)		(87.6)		(87.6)	
Large SMR plant	50,000	0.82	150,000	0.83	300,000	0.84	500,000	0.84
	(438)		(1314)		(2628)		(4380)	
	largest is 3x this							
Electrolysis (small)	1000	0.69	1000	0.71	1000	0.73	1000	0.75
	(8.76)		(8.76)		(8.76)		(8.76)	
Electrolysis (large)	30,000	0.75	30,000	0.77	50,000	0.78	100,000	0.81
	(262.8)		(262.8)		(438)		(876)	
Coal gasification		0.55		0.56		0.58		0.6
	(500)		(1000)		(2000)		(4000)	
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 9.

Additional hydrogen production plant characteristics (unit size, efficiency, load factor, and lifetime)

All	**Year**		
Unit size (Nm^3/h)	**2000**	**2020**	**2050**
Efficiency			
Load factor			
Lifetime (years)			
Small SMR plant	500	500	500
	0.75	0.775	0.79
	0.9	0.9	0.9
	15	15	15
Medium SMR plant	5000	8000	10,000
	0.78	0.80	0.82
	0.9	0.9	0.9
	20	20	20
Large SMR plant	50,00 0	200,00 0	500,00 0
	0.82	0.83	0.84
	0.9	0.9	0.9
	25	25	25
Electrolysis (small)	1000	1000	1000

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

Table 10.

Allocation of hydrogen supply to end-use demand in 2050 according to the *Global Sustainability* scenario with high road vehicle diffusion rate and hydrogen production predominantly by electrolysis powered from renewable and nuclear electricity (GS-Hydrogen-T)

Hydrogen	**Renewable (wind)**	**Renew. (wind)**	**Nuclear capacity**	**Nuclear**	**Coal gasified**	**Total**
production	**capacity (GW)**	**hydrogen** $(\times 10^9\,Nm^3)$	**(GW) [energy (GWh)]**	**hydrogen**	**hydrogen**	**hydrogen**
route	**[energy (GWh)]**	$[\times 10^9\,kg]$		$(\times 10^9\,Nm^3)$	$(\times 10^9\,Nm^3)$	$(\times 10^9\,Nm^3)$
Use of electricity (GS-Hydrogen-T scenario)		$[\times 10^9\,kg]$		$[\times 10^9\,kg]$	$[\times 10^9\,kg]$	$[\times 10^9\,kg]$
Conventional electricity demand	48 [151,000]	—	11 [76,000]	—	—	—
Hydrogen production for air transport	53 [166,000]	30.2 [2.7]	20 [136,000]	24.6 [2.2]	6.0 [0.55]	60.8 [5.4]
Hydrogen production for road transport	72 [227,000]	41.3 [3.7]	27 [187,000]	33.8 [3.1]	8.4 [0.75]	83.5 [7.6]
Hydrogen production for heating and CHP in domestic, industry, service sectors	48 [151,000]	27.5 [2.5]	18 [125,000]	22.6 [2.0]	5.6 [0.5]	55.7 [5.0]
Total	221 GW installed capacity [695,000 GWh]	$99 \times 10^9\,Nm^3$ $[8.9 \times 10^9\,kg]$	76 GW installed capacity [524,000 GWh]	$81 \times 10^9\,Nm^3$ $[7.3 \times 10^9\,kg]$	$20 \times 10^9\,Nm^3$ $[1.8 \times 10^9\,kg]$	$200 \times 10^9\,Nm^3$ $[18 \times 10^9\,kg]$

Note that road transport includes 27 million fuel cell cars, 7 million light goods vehicles, and 1 million HGVs and PSVs.