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# The production of hydrogen fuel from renewable sources and its role in grid operations

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ABSTRACT

Understanding the scale and nature of hydrogen's potential role in the development of low carbon energy systems requires an examination of the operation of the whole energy system, including heat, power, industrial and transport sectors, on an hour-by-hour basis. The Future Energy Scenario Assessment (FESA) software model used for this study is unique in providing a holistic, high resolution, functional analysis, which incorporates variations in supply resulting from weather-dependent renewable energy generators. The outputs of this model, arising from any given user-definable scenario, are year round supply and demand profiles that can be used to assess the market size and operational regime of energy technologies. FESA was used in this case to assess what – if anything – might be the role for hydrogen in a low carbon economy future for the UK.

In this study, three UK energy supply pathways were considered, all of which reduce greenhouse gas emissions by 80% by 2050, and substantially reduce reliance on oil and gas while maintaining a stable electricity grid and meeting the energy needs of a modern economy. All use more nuclear power and renewable energy of all kinds than today's system. The first of these scenarios relies on substantial amounts of 'clean coal' in combination with intermittent renewable energy sources by year the 2050. The second uses twice as much intermittent renewable energy as the first and virtually no coal. The third uses 2.5 times as much nuclear power as the first and virtually no coal.

All scenarios clearly indicate that the use of hydrogen in the transport sector is important in reducing distributed carbon emissions that cannot easily be mitigated by Carbon Capture and Storage (CCS). In the first scenario, this hydrogen derives mainly from steam reformation of fossil fuels (principally coal), whereas in the second and third scenarios, hydrogen is made mainly by electrolysis using variable surpluses of low-carbon electricity. Hydrogen thereby fulfils a double facetted role of Demand Side Management (DSM) for the electricity grid and the provision of a 'clean' fuel, predominantly for the transport sector. When each of the scenarios was examined without the use of hydrogen as a transport fuel, substantially larger amounts of primary energy were required in the form of imported coal.

The FESA model also indicates that the challenge of grid balancing is not a valid reason for limiting the amount of intermittent renewable energy generated. Engineering limitations, economic viability, local environmental considerations and conflicting uses of land and sea may limit the amount of renewable energy available, but there is no practical limit to the conversion of this energy into whatever is required, be it electricity, heat, motive power or chemical feedstocks.

## 1. Introduction

This paper evaluates three possible pathways towards a sustainable energy economy in the United Kingdom (UK), meeting the challenging and conflicting requirements of energy security and an 80% reduction in the UK's greenhouse gas emissions by 2050, including carbon dioxide ($CO_2$). For each of these pathways there are two variants: one with hydrogen used as a transport fuel, and one without.

While many other pathways have been proposed [1–4], and the issue of electricity generation capacity margin has been considered [5], this paper is unique in examining in detail the issue of grid balancing on an hour-by-hour basis, all sectors of the economy (domestic, industry and commerce) and all uses of energy and fuels (electricity, heat, transport and chemicals) out to 2020 and 2050. It is important to note that future scenario analysis is not the same as predicting the future, but by making best estimates of the quanti-

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ties involved, especially the biggest and most significant ones, this paper gives a good insight into the amounts of each new energy source required, and the practical implications for energy policy in terms of the grid balancing challenge and energy conversions required.

Many other scenarios take a primarily economic view of what technologies are likely to succeed, or which ones offer the least-cost transition pathway, especially those using a MARKAL model [6–9]. Economic models are hostage to the prices of fossil fuels, especially of oil and natural gas. In turn, these depend on how much of these fuels are being used by every other country. In contrast, this paper takes a view that pure economics are a poor predictor of the best technology options, but rather, practical imperatives ultimately drive the economics. Consideration of the total resources available for each energy source and the operational characteristics of the related technologies is more reliable and a necessary precursor to the economic analysis. However, it is recommended that further studies be undertaken to understand more about how economic factors operate within this functional framework. The authors of this paper subscribe to the Peak Oil theory [10], as well as Peak Gas and Peak Coal. Another useful model-building principal has been that young industries, such as the renewable energy industries, start growing at an exponential rate. Indeed, the global wind industry, for example, has consistently grown at 26% per year for the last 16 years, as did the nuclear industry in its early days [11]. As the installed capacity of renewable generation approaches the limit of availability, this rate is expected to slow down, so that the installed capacity will grow in a classic S-shaped curve. The growth rate of renewable energy industries during the middle and latter portions of an S-curve can be predicted from the ultimate available resource. Similarly, the years in which extraction of oil and gas reach their peaks and start declining can be predicted from their current extraction rates and the estimated reserves [12]. Unless there is a good reason for supposing otherwise, the UK's share of these fuels will, in the future, be in proportion to the global extraction rate. As most countries in the world strive for a comfortable, modern lifestyle and a prosperous economy, equitable 'contract and converge' scenarios are assumed. This may be considered by some to be overly optimistic—why would the UK constrain itself to only consume its fair share of any fossil fuel by some future date? Nevertheless, the scenarios presented here are just some of many possible ways in which the UK may meet its commitments to reduce greenhouse gas emissions, and other researchers are welcome to try others. In this paper, the assumption is that UK consumptions of oil and gas will decline as domestic sources of these fuels decline.

It is not within the scope of this paper to anticipate all possible technology developments as these are subject to too much uncertainty, but the analysis is based upon more reliable assumptions about each broad technology area. It is conceivable, for example, that nuclear fusion would prove viable by 2050, but it is not explicitly included here, because the assumption is made that its output profile will, for functional and economic reasons, be as inflexible as nuclear fission is today. Thus fission and fusion are both simply classed as nuclear power.

Radical technological advances in other areas such as advanced batteries or super-capacitors are also unpredictable. However, the scenarios do anticipate some progress, reflected in a steady increase in the number of road-miles that are powered by electricity, for example, and modest increases in energy efficiencies of all vehicles.

The scenarios used reflect no large changes to lifestyles or macroeconomic conditions as these are also outside the scope of the paper. The future is notoriously hard to predict. Will increasing energy prices cause a deep and protracted economic depression, or will the economy grow on the back of a boom in new green technologies? Will people change their behaviour – perhaps foregoing foreign travel and consumer goods – either voluntarily or due to fiscal reform by government, for example, as proposed by the Green Fiscal Commission [13], whereby environmental revenue-neutral taxes can be both popular and effective? These things are not known, but for the purposes of this paper, only slow changes to the energy intensity of the economy are assumed and so a growth or contraction of the economy as a whole would result in a general scaling up or down of total energy consumption of all kinds. The grid balancing issues created by increasing penetrations of intermittent renewable energy would remain, although the greenhouse gas emission reduction commitments get harder or easier to meet, depending upon the general change in energy consumption.

Some reductions in energy consumption from technological improvements are already included in the model, for example, in the amounts of energy used in space heating.

## 2. Methodology

The model used in this paper was written in Microsoft Excel in order to make the calculations as visible as possible and in the hope that it will be used in the future by as many people as possible to create their own energy models and bring their own insights into solving the challenges of energy security and climate change.

### 2.1. Overview of the model

At the heart of the model is an hourly time-step through one representative year. Most of the weather data and the electricity demand data behind the model were measured in 2001. This data has been converted into capacity factors for each technology, as a function of time throughout the year, and embedded in the hourly time-step model. The sources of data are described in sections below.

The columns of the hourly worksheet then calculate the ways in which the electricity grid accommodates variations in supply and demand. The input worksheet contains data on the overall supply and demand of energy including, for example, the total amount of onshore wind power generated in a year, and other quantities such as electrical generation efficiencies and carbon intensities. Thus, the input worksheet defines each scenario in each year. The model is rerun for the years 2007, 2020, 2030, 2040 and 2050, and for each scenario pathway.

The profiles worksheet contains diurnal profiles of heat demand and off-peak (economy 7) demand profiles, plus profiles of driving patterns and electric vehicle charging. The background worksheet contains some pre-processing information including, for example, the size of the virtual energy storage provided by electric vehicle charging and the time shifting of heating loads.

The output worksheet does a lot of post-processing to convert the total demand for energy and fuels into consumption of specific fuels (i.e. coal, oil, gas and hydrogen). One important assumption of the model is that any fuel or form of energy can be converted into any other fuel or form of energy in a modern industrial economy, with appropriate conversion efficiencies. Fig. 1 illustrates the possible energy vectors.

In particular, it should be noted that hydrogen is not just a fuel but also an industrial process gas with significant uses in today's economy, mainly for the production of ammonia and tar cracking [14]. These uses of hydrogen are expected to continue into the future, especially ammonia production.

The electricity model treats the whole of the UK as a single bus, i.e. all electrical generation and loads are connected to the same grid (strictly speaking the term 'grid' specifically relates to the transmission network, but in this paper we use it more loosely to include both transmission and distribution networks) and that grid can cope with all possible flows from region to region within the UK.

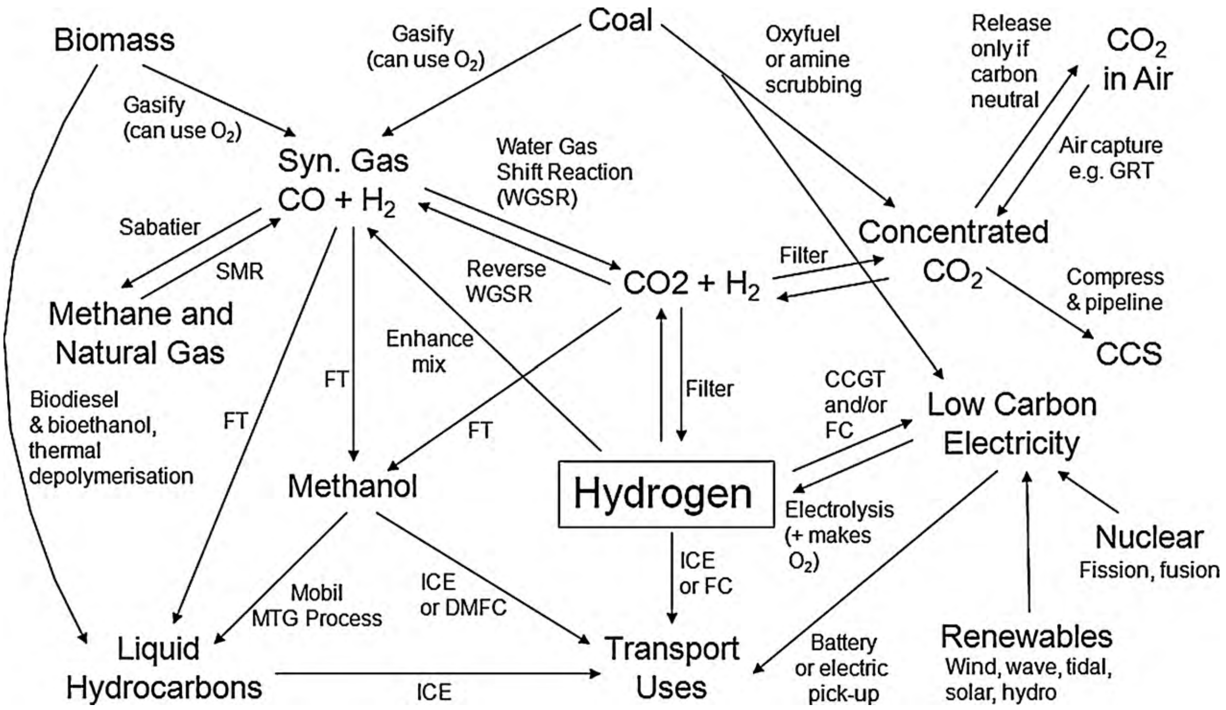

**Fig. 1.** Possible fuel and energy conversion vectors. See glossary for meanings of abbreviations.

Considerable investment will be needed for such an unconstrained grid to become a reality as the amount of renewable generation increases [4,15]. For simplicity of modelling, transmission and distribution losses are incorporated into total electricity demand as a simple percentage increase on the electrical demand profile.

### *2.2. Models of intermittent renewable energy sources*

Weather data was measured in 2001 where required. Much of the data was previously assembled and used for a earlier study into the possibility of supplying the UK's energy needs from renewable energy [16].

Wind speed data was downloaded from the BADC United Kingdom Wind Energy Database (UKWED) [17]. For onshore wind power, 37 sites were chosen, both inland and coastal. For offshore wind, 36 coastal sites were chosen as proxy for the wind speeds offshore. In each case, the wind speeds had been measured at 10 m above ground level but were extrapolated to typical turbine hub height – 80 m onshore and 100 m offshore – using the log law and assumed surface roughness factors. For offshore wind speeds there was a further increase in wind speed to account for the low roughness of the sea and consequent higher wind speeds offshore.

Wind speeds were converted into wind power using a generic wind turbine power curve previously used [18]. This power curve has a cut-in speed of $3\,\mathrm{m\,s^{-1}}$, a rated wind speed of $13\,\mathrm{m\,s^{-1}}$ and a cut-out wind speed of $25\,\mathrm{m\,s^{-1}}$.

The UK was divided into regions and the wind power from each region was weighted according to its estimated wind resource. Onshore, this resource was heavily weighted towards Scotland and offshore, this was weighted towards areas with accessible shallow sea bed. The total wind power in each hour of the year was normalised by the installed capacity to give a capacity factor in each hour of the year. This process resulted in annual average capacity factors of 29.3% onshore and 42.8% offshore. These numbers are remarkably consistent with the estimates of capacity factor evident in the EWEA projections of wind power to 2030, of 24–30% onshore and 42–45% offshore [11].

Solar irradiance data was measured at 32 sites around the UK. Again, this data was obtained from the BADC [17]. The solar resource was assessed for each region of the UK and weighted according to the urban land use in each region, on the assumption that solar devices – both photovoltaic and solar thermal – would be rooftop mounted. 73% of the estimated solar resource is therefore located in England. The solar irradiance data was calculated as a solar capacity factor by dividing the average irradiances ($\mathrm{W\,m^{-2}}$) by 1000. The resulting UK weighted annual average capacity factor is 11.08%.

Wave heights were measured at 6 locations off the West coast of Britain by the UK Met. Office Marine Automatic Weather Station (MAWS) network. Three of these were in the South West approaches and off the coast of Wales: Turbot Bank, Seven Stones and Aberporth. The other three were off the West coasts of Scotland and Ireland: RARH, K4 and K5. The wave heights were converted into powers using the power curve of a Pelamis wave power device and then into a capacity factor for each hour of the year. The annual average capacity factor is 28.3%.

Tidal power as a function of time was calculated in a similar way to the tidal power model in 'Sustainable Energy—without the hot air' [1]. In this model, the power available is proportional to the cube of tidal stream velocity, which was calculated from a lunar cycle of 29,531 days, with generation on both flow and ebb tides. This means that the ratio of spring to neap tidal power is just over 4. The tidal power is not in phase with the real tides of year 2001, but as the tides bear no relation to the weather (with the exception of extreme storm surges), it is sufficient to make the pattern of variation realistic. The tidal power is representative of one large tidal power scheme in one part of the UK, for example the Bristol Channel: i.e. there is no aggregation from different sites. This means that tidal power experiences 4 peaks in each 25-h period. The annual average capacity factor of tidal power was 24.1%.

Temperature data was used to calculate space heating demands, and was measured as 1-min averages at Rutherford Appleton Laboratory, Oxfordshire, UK. This data was averaged into 1-h averages for use in the model. Gaps in the data were filled from time series from the same time of day on other days in the same month. Temperatures for each day were then shifted up or down to be consistent with the Central England Temperature Record [19].

### 2.3. *Calculating net demands for electricity and fuel*

The total annual energy and chemical demands on the UK energy economy are shown in Fig. 2. Under all scenarios, total energy demand steadily declines between 2007 and 2050 for a number of reasons. One is technological improvement: for example, more efficient engines and better insulated homes. Another is reduced conversion losses (the top slice of Fig. 2). As the amount of electricity generated from fossil fuels declines, so do the thermal losses of fossil-fuelled power stations. Also, with the electrification of surface transport, electric motors are more efficient than internal combustion engines. In addition to these effects, the thermal losses at nuclear power stations are not included; nuclear energy input is accounted as a supply of primary electricity, not the energy equivalent of the nuclear fuel.

Most inputs are straightforward, but the heating and transport demands need some clarification.

### 2.4. *Heating*

Solar water heating subtracts from the water heating demand in each day, with the assumption that solar heat can be stored in a large hot water cylinder. Unrestricted water and space heating tend to follow a pattern of high demand in the mornings and evenings, with lower demand in the middle of the day and very low demand at night [20]. The model lets the default water heating profile follow this pattern, but space heating is assumed to follow a flat profile based on the 24-h average of ambient temperature and a 'no-heat' temperature of 15.5 °C, giving a total of 2126.9 degree-days of heating. Both heat pumps and CHP are assumed to follow a flat profile. To assume otherwise would severely disrupt the electricity demand profile through the interaction of these devices with the electricity grid. From 2007 to 2050 the efficiencies of heating devices are assumed to improve over time: gas boilers improve from 69.5% to 85.5% efficiency and the coefficient of performance (COP) of heat pumps improves from 3.1 to 6, in line with assumptions made in the Supergen HDPS project [21].

As a simplification, all fuel for heating in the model comes from gas. This effectively shifts heating loads onto gas and away from other fuels such as coal, oil and biomass. However, this will not change the overall demand for fuel significantly, nor will it affect the production or use of hydrogen significantly. Over time, the percentage of heating from gas boilers decreases and the percentages of heat pumps and CHP increase. Compared to the Supergen HDPS model, the amount of CHP used is low (only 15% in 2050) and the amount of heat pump heat is high (50% in 2050). The reason is that in an increasingly electrified economy, in which primary energy is available in the form of electricity, and grid electricity is decarbonised, the way to decarbonise heating is to use more electricity [1].

### 2.5. *Transport*

Aviation is assumed to continue to rely on liquid hydrocarbons, but to use them more efficiently, such that the carbon emissions from aviation in 2050 are almost the same in 2050 as in 2005, in line with government targets [4]. An inclusion of 10% biofuels allows a net increase in aviation fuel by 10% to allow for the projected growth in aviation. Surface transport fuels (road, marine and rail) reduce over time, with an assumption of increased fuel economy [4] and a switch to electricity and hydrogen. The proportion of electric vehicles (battery electric and plug-in hybrids) grows to 70% by 2050. This does not equate to a 70% fall in transport fuels since the range of electric vehicles is less than that of hydrogen or hydrocarbon fuelled vehicles. Journeys under 50 m, for example, comprise over 90% of journeys but only about 50% of total miles travelled in motorised transport [22]. Therefore a further factor is applied to indicate the fraction of distance travelled that could be electrified. This factor rises from 0.5 in 2007 to 0.7 in 2050 with assumed improvements in technology.

In scenario pathways that include hydrogen fuelled transport, the fraction of residual surface transport fuel that is substituted by hydrogen rises from 0 in 2020 to 50% in 2030 and 90% in 2050. It is in the period 2020–2030 that the global availability of crude oil and emissions targets are expected to fall most steeply. In practice,

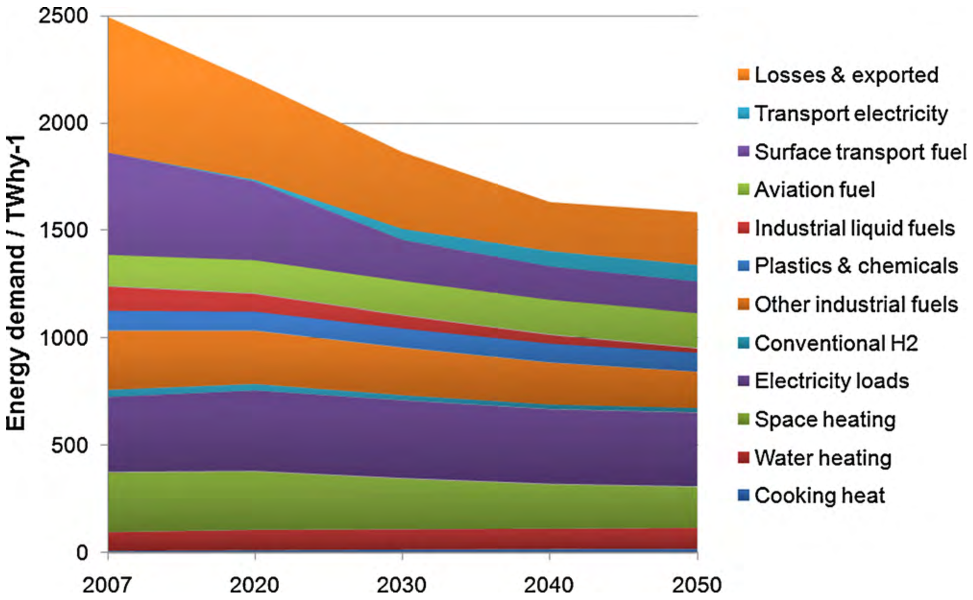

**Fig. 2.** Energy demand by end use application under all pathways.

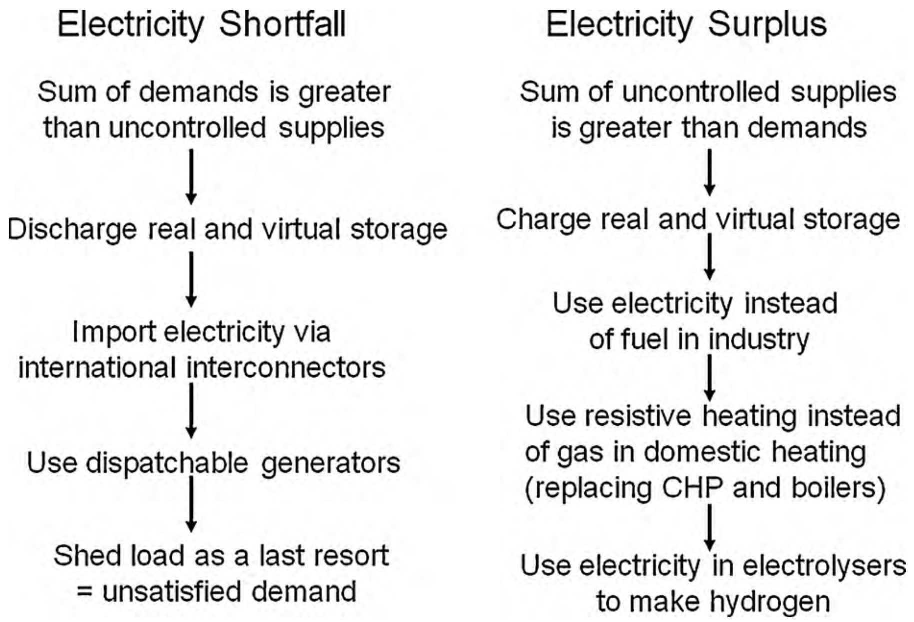

**Fig. 3.** Electricity merit orders.

hydrogen fuelled cars may start to be made well before 2020, but the 2020 scenario has been simplified.

### 2.6. Merit orders

In the time step model and in the post-processing, a hierarchy or merit order has been assumed for handling the surplus or deficit of each form of energy, as described in the following sections. These merit orders were designed to minimise energy conversion losses. Where possible, energy is used in a form as close as possible to that in which it is created. For example electricity from renewable energy or nuclear power is used as electricity wherever possible. It is always better to save fuel this way than to make hydrogen and then use that hydrogen to make electricity with a round trip efficiency of only 50% or less [1,23].

### 2.7. Electricity

The model first and foremost deals with variations in supply and demand of electricity in a low-carbon economy with lots of variable and intermittent sources of renewable energy. Near-perfect weather forecasting and demand forecasting is assumed. In answer to the often-asked question, ‘what happens when the wind stops blowing?’ the electricity grid does and will have a number of mechanisms to cope (see Fig. 3).

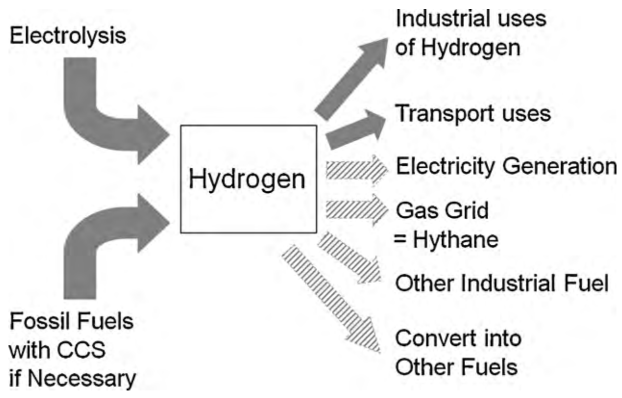

**Fig. 4.** Sources and uses of hydrogen.

As can be seen in Fig. 3, there is no merit order in the traditional sense of electrical generation merit order at this stage. The model does not care how the dispatchable generation is split between coal-fired and gas-fired generation hour-by-hour. Only at the end of the year (post-processing) is the requirement for fuel split up according to the availability of each. Fig. 3 also shows that hydrogen production by electrolysis is right at the end of the merit order and will only occur if there is a substantial surplus of electricity from renewable and nuclear sources. This is because it is always more efficient to displace fuel use directly than it is to create fuel in the form of hydrogen, even if that means some hydrogen has to be made from fossil fuels elsewhere.

### 2.8. Hydrogen

The post-processing part of the model then decides what to do about hydrogen. Even in today’s economy, large quantities hydrogen are made by steam reformation of fossil fuels, mainly natural gas (by SMR) for purposes of ammonia production (about half of hydrogen consumption), tar cracking, hydrogenation of vegetable oils and other processes. A lot of ammonia is used in the manufacture of fertiliser. Exact amounts are hard to discover, but consumption of hydrogen in the UK has been estimated from numbers for the whole world, which have been scaled down in proportion to the smaller population of the UK [14]. New uses of hydrogen as an energy vector, for example in transport applications, add to the demand for hydrogen. Any hydrogen produced by electrolysis first displaces the production of hydrogen from fossil fuels (see Fig. 4). The amount of hydrogen used in transport is an input to the model. Hydrogen is likely to be used as a transport fuel for a number of reasons:

(1) It reduces emissions of $CO_2$ from transport. These are emissions that would be more difficult to capture and sequester than $CO_2$ emissions from large point sources. Even hydrogen made from fossil fuels will create $CO_2$, but if that $CO_2$ is sequestered through CCS at the steam methane reformation (SMR) plant, or the coal gasification plant, then the hydrogen produced can be free of atmospheric $CO_2$ emissions.

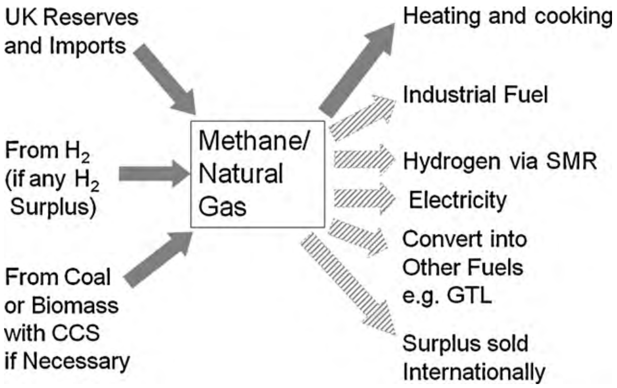

**Fig. 5.** Sources and uses of natural gas and methane.

(2) It causes much less damage to local air quality at the point of use, when compared to fossil-fuelled internal combustion engines, for example.
(3) It can improve the overall well-to-wheel/wind-to wheel efficiency of transport, for example, by the use of fuel cells that have higher efficiency than internal combustion engines.
(4) It uses up electrolytic hydrogen whose production provides a controllable load for DSM.

If any electrolytic hydrogen is left over after these high-priority uses, then hydrogen is also used for optional uses (hatched arrows in Fig. 3): electricity generation, feeding into the gas grid as Hythane, used as an industrial fuel or used to make other synthetic fuels, e.g. synthetic natural gas. Under none of the scenarios analysed was surplus hydrogen available before 2030 and, in the scenarios where hydrogen was used for surface transport, such applications used up all electrolytic hydrogen, and some fossil-derived hydrogen, until at least 2050.

### 2.9. Natural gas

Natural gas is a limited resource and the UK's available share in each year is an input to the model. The UK Government has a stated aim of reducing gas use in order to minimise imports of it by 27% by 2020 [4] and this is built into the model. Fig. 5 shows the sources and uses of natural gas.

The only essential use is for heating and cooking in the gas grid, and this takes top priority. The possibility of converting the whole of the natural gas grid to hydrogen is ruled out as unlikely, partly because of the complexity and expense, and partly because heating is assumed to be increasingly achieved via electricity using heat pumps and resistive heating. The use of natural gas is therefore expected to reduce anyway, progressively reducing reliance on the gas grid.

The option of using natural gas directly as a transport fuel is also not modelled, although this is quite likely as an interim solution. The question of whether some natural gas is used directly for transport, or whether it is converted into hydrogen and/or synthetic hydrocarbons by gas-to-liquids technology (GTL) is outside the scope of the paper. In any case, the direct use of natural gas does not change the overall picture very much. Natural gas is a gaseous fuel like hydrogen, but with a higher energy density and higher carbon content. It is therefore a half-way house between hydrogen and liquid fuels.

### 2.10. Liquid fuels

The sources of crude oil are more constrained than natural gas. Peak Oil is expected before Peak Gas because it has a lower reserves-to-production ratio [12] and already, liquid hydrocarbons are predominantly used as transport fuels and essential chemical feedstock [24]. Only if these uses are all satisfied is there a surplus of liquid fuel to export, or to subtract from national imports. Aviation is seen as the most difficult form of transport to decarbonise and, in the model, aviation uses the bulk of available liquid fuels by 2050. Liquid fuels can be made from almost any other fuel, but coal is used as a last resort (see Fig. 6).

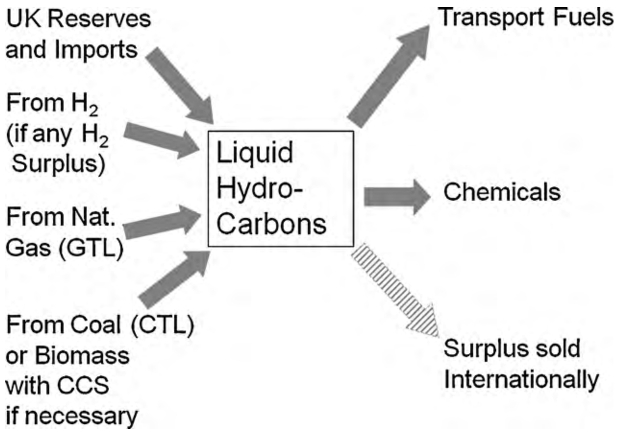

**Fig. 6.** Sources and uses of liquid hydrocarbon fuels.

### 2.11. Carbon dioxide emissions

The allowable $CO_2$ emissions in 2020 are given in The UK Low Carbon Transition Plan [25]. After 2020 and up to 2050, the allowable emissions are estimated from the first report of the Committee on Climate Change (CCC) [26]. The UK's target of an 80% cut in greenhouse gas (GHG) emissions by 2050 includes shipping and aviation, and also GHGs other than $CO_2$ (e.g. methane and oxides of nitrogen), if applied as interpreted by the Committee on Climate Change. These may fall at a slower rate than $CO_2$, see Fig. 2.28 on page 78 of the CCC report. By 2050, these other sources may comprise 50% of residual greenhouse gas emissions, meaning that $CO_2$ emissions must fall by about 90% from 1990 levels. This is an exceedingly challenging target (Fig. 7).

The model calculates the $CO_2$ emissions from all sources, subtracting the $CO_2$ captured by the biomass as it was grown. Each fossil fuel (coal, oil and gas) is multiplied by its carbon emission factor in order to calculate its contribution. Large, stationary sources of $CO_2$ are treated as point sources and are accounted separately from small scale distributed sources and those from transport fuels. If total emissions exceed the UK's permitted level for that year, carbon capture and storage (CCS) is required. Point sources of $CO_2$ are treated first, with a modest energy penalty roughly equiva-

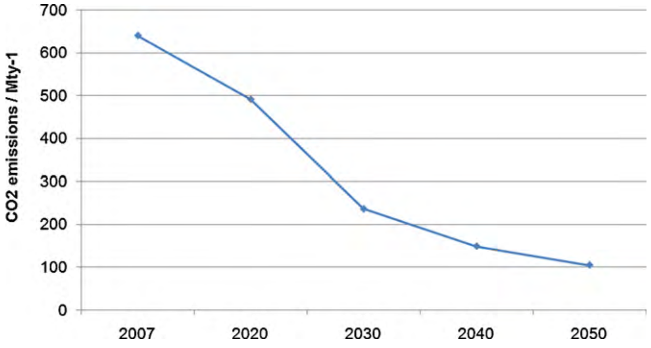

**Fig. 7.** Carbon dioxide emissions allowed under UK Government targets.

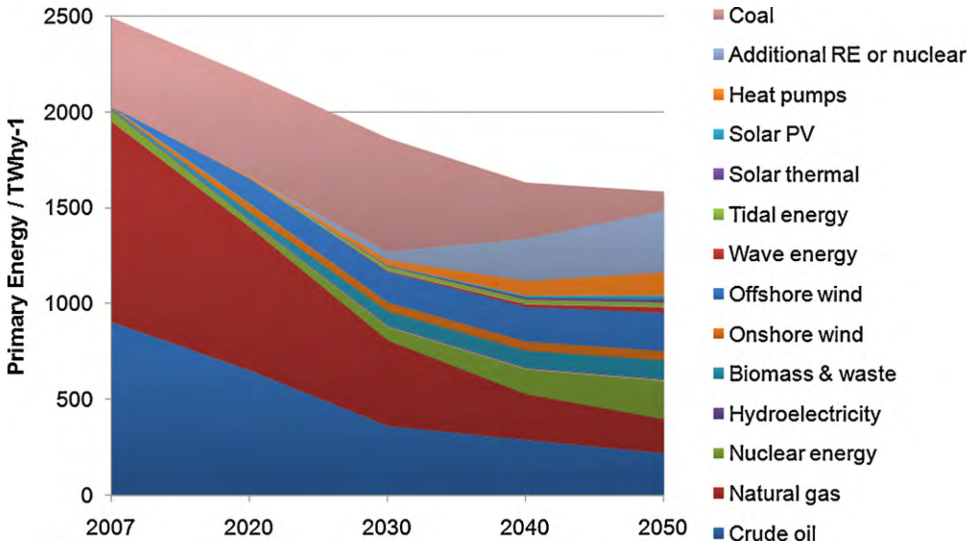

**Fig. 8.** Output from primary energy sources.

lent to post-combustion CCS and an assumed effectiveness of about 90%, consistent with amine scrubbing. The energy penalty of point-source CCS is assumed to be 0.18 kWh/kg $CO_2$, in line with the expected efficiency drop of a coal fired power station fitted with CCS by amine scrubbing.

If emissions still exceed allowance, then more costly CCS must be undertaken with greater energy cost, equivalent to capturing $CO_2$ from the air or by capturing the remaining 10% of $CO_2$ emissions from point sources. The energy penalty estimate comes from 'Sustainable Energy—without the hot air' [1] and is roughly 3 times as big as the point source penalty.

### *2.12. Scenarios modelled*

The energy supply inputs to the model for each year are shown in Fig. 8. Pathways 2 and 3 are different from pathway 1 in that they have an extra quantity of low-carbon electricity generation, either as offshore wind power (pathway 2) or as nuclear power (pathway 3). Another variation explored is the absence of vehicles running on pure hydrogen fuel, as distinct from synthetic or fossil liquid hydrocarbon fuels.

#### *2.12.1. Scenario for 2007*

The model was first made to work for 2007 (the last year for which a complete set of statistics were available at the time), in order to understand UK energy use today as fully as possible. Other years modelled are 2020, 2030, 2040 and 2050 to give a picture of the magnitudes and rates of change to 2050 and the achievement of an 80% cut in $CO_2$ emissions.

Overall energy and fuel demands for the year 2007 were taken from government statistics [24]. Other energy demand data were estimated as part of the values used in the Supergen HDPS project [21]. It was apparent that, to reconcile the two sets of data, the domestic use of gas quoted in government statistics was too small to represent all the space heating when boiler losses are included. Some of the other users of gas, e.g. 'services' on page 20 of [24] must therefore include some space heating as well. Other parameters, e.g. the percentage of homes employing each form of heating and some efficiency factors, also came from the Supergen HDPS project.

Energy supplied from each source, including renewable sources in 2007, also came from government statistics.

#### *2.12.2. Scenario for 2020*

The data for renewable energy supply in 2020 come partly from government targets [3,4]. Data on energy use and, in particular, domestic heating technologies come mainly from the Supergen HDPS Deep Green scenario [21]. Many of the renewable energy generation levels also originate from the Supergen HDPS project. Government targets are well enough defined that all three pathways are identical in their 2020 scenarios: the UK government has a target of 15% of energy to be supplied from renewable sources, and greenhouse gas emissions to be 18% lower than 2008 levels in 2020 [25].

Nevertheless, the numbers in the UK Renewable Energy Strategy [3] are illustrative only and appear overoptimistic. Total primary energy in 2020 is estimated by the FESA model to be about 2200 TWh $y^{-1}$, even with some efficiency improvements. 15% of this would be 330 TWh $y^{-1}$. If we use the given numbers to add up the proportion of total energy required from biomass, (including biofuels and biogas) for renewable transport fuels, renewable heating, and electricity production, the UK would need about 120TWh per year, even if the renewable transport fuel obligation is amended so that only 5% of fuel is to come from biofuels. Globally, it is estimated that total biomass energy used is about 7GJ per person per year and has been for some time, if the total biomass energy use is divided by world population [2,27–30]. The UK's share of this might be just over 120 TWh $y^{-1}$, but only if most of this is imported and only if global biomass/biofuel production can be radically improved without harming ecosystems or food production. The model presented here does allow an increasing amount of biomass to be used: 10 TWh $y^{-1}$ in 2007 and 40 TWh $y^{-1}$ in 2020, rising to 100 TWh $y^{-1}$, but not until 2050 when a sufficient supply chain might be in place.

The estimates for solar heating also appear very high and imply a high installation rate. On the other hand, if all the UK's Round 2 and 3 offshore wind farms are built by 2020, then its installed capacity offshore wind would total 35 GW, and annual wind energy production could be 130 TWh $y^{-1}$ at a capacity factor of 43%. This might largely make up for the shortfall.

### *2.13. Pathways*

The scenarios provide a snapshot of the situation in a given year. By combining the scenarios in chronological order, 'pathways' were constructed that show the growth curves of a given technology or market. Three broad scenario pathways were modelled, as described in Sections 2.13.1, 2.13.2 and 2.13.3. In 2020, all the pathways are identical, but after that, differing assumptions cause the pathways to diverge. The difference between the three pathways is in their primary energy supply (Fig. 8). On top of this, each pathway has 2 variations: one in which some hydrogen is used for transport, termed the 'With Hydrogen Vehicles' version, and another in which all non-electrified transport is fuelled by liquid hydrocarbons, termed the 'No Hydrogen Vehicles" version. In the latter cases, hydrogen is still used, either as an industrial gas produced by electrolysis using surplus electricity, or created by gasification of fossil fuels and turned into synthetic hydrocarbon fuels. In each pathway, the total primary energy supplies add up to almost the same total as in Fig. 2. Again, the total reduces over time due to improvements in technology efficiencies and reductions in conversion losses, rather than any change in behaviour.

#### *2.13.1. Pathway 1—high coal*

The starting point was to use a reasonably large estimate of each renewable energy source available in each year, based on an ensemble of scenarios and resource assessments [1–3,8,11,16,21,31–33]. Nuclear power was assumed to reduce until 2020, in line with the government scenario, then slowly grow to 200 TWh $y^{-1}$, which is a much larger amount than the UK has ever used before. Added to these sources were the assumed availabilities of constrained fossil fuels (gas and oil) and the UK's share of them, based on a 'contract and converge' model (see Section 2.14). Coal was then used to make up any shortfall in primary energy, as the cheapest, 'inferior' fuel.

In the first pathway, the above levels of renewable and nuclear power were as assumed with coal playing a large role. As observed by David MacKay, the UK's energy requirement is very large and "every BIG helps!" (as opposed to 'every little helps') [1]. The amount of electricity used is only about 400 TWh, but the total of primary energy consumed by the UK is of the order of 2000 TWh. The amount of renewable energy required to achieve complete sustainability would therefore also be very large: not 100% of electricity but 100% of all energy, including heating, transport and industrial requirements.

This first pathway leaves the UK heavily dependent on coal, and unless the UK develops underground gasification of its deep coal reserves, this coal is likely to be imported. Although the amount of coal used is roughly in line with the UK's predicted fair share of global coal production, it leaves the UK in an undesirable position for the following reasons:

1. Globally, practically extractable coal reserves may not be as extensive as predicted by experts [12].
2. Other countries may also try to switch to coal as oil and gas reserves deplete.
3. The UK may therefore not be able to obtain enough energy (an energy security risk).
4. The UK economy may suffer due to the cost of importing fuels, especially if the prices of coal, oil and gas increase significantly (an economic risk). This will be a particular problem if there are spikes in the price of coal. The UK is also predicted to be a significant importer of oil and gas by 2050, as the UK's reserves decline. Thus the UK could be spending large sums of money on imports of all forms of fossil fuel.
5. Coal has very high carbon content, necessitating more CCS. This leaves the UK vulnerable to technological risk, as large-scale CCS technology is still in its infancy, and would leave the UK in danger of missing its greenhouse gas reduction commitments (legal and environmental risk).

#### *2.13.2. Pathway 2—high renewable energy*

In the second pathway, the amount of variable renewable resource is doubled compared to the first. This results in a much lower consumption of coal and different energy vectors predominate: for example, more hydrogen is made by electrolysis than from steam reformation of coal in 2050. This pathway also requires new technology, particularly in the marine sector. Because there is a limited area of accessible sea bed with a depth of less than 50m, this pathway may require floating wind turbines for example. The extra renewable energy is modelled as extra offshore wind, but in practice, the extra energy would be a mixture of all renewable energy sources. The effect on grid balancing over a year would be much the same whatever the source of intermittent renewable energy: in particular, onshore wind, offshore wind and wave power are expected to be fairly well correlated to each other when aggregated over the UK. The extra energy is shown in Fig. 8 as a wedge rising from 0 in 2020 to an extra 320 TWh in 2050. A total of 520 TWh $y^{-1}$ would be generated from offshore wind power by 2050, which almost doubles the total amount of energy generated by renewable energy in 2050.

#### *2.13.3. Pathway 3—high nuclear*

In the third pathway, the amount of nuclear power is increased still further, from 200 TWh to 520 TWh $y^{-1}$. This would require a radical change in technology and policy to include fast breeder reactors and much more efficient use of each kg of uranium. The renewable generation is returned to the same level as in the High Coal pathway, thus the extra wedge in Fig. 8 now represents nuclear power. Nuclear power is modelled as a completely constant and inflexible electricity generator. This will reduce the variations in net supply and demand compared to pathway 2.

#### *2.13.4. Variation on pathways—no hydrogen vehicles*

Each of the three pathways described above include the use of some vehicles that run on hydrogen fuel. Hydrogen can improve local air quality and reduce carbon dioxide emissions from transport, regardless of whether the hydrogen is used in a fuel cell or an internal combustion engine, and regardless of the source of that hydrogen: hydrogen can be made from fossil fuels with CCS, or it can be made by electrolysis of water using low-carbon electricity. However, it is possible that hydrogen may not be used in vehicles in its pure form, but within, increasingly synthetic, liquid hydrocarbon fuels, which act as a carrier for the hydrogen whilst adding some further calorific value to it. This may be driven by technical constraints, if certain technological or cost improvements are not realised, or public acceptance the new technologies is low. Each pathway therefore has a 'no hydrogen vehicles' (or 'no H2Vs') variation, in which transport is powered only by electricity and liquid hydrocarbon fuels. Hydrogen is still embedded within these fuels, but being intrinsic to the liquid hydrocarbons – as in today's fossil hydrocarbons – the hydrogen is less visible to consumers. In this situation, hydrogen still plays a vital role and is still made by the same routes, but is delivered, stored, converted and used differently.

When the hydrogen is carried within hydrocarbon fuels, sources of carbon dioxide are increased and the probability of $CO_2$ capture from the air is increased. This study assesses when this becomes necessary and what effect it has on the energy economy as a whole.

### *2.14. Fossil fuel assumptions*

The future global extraction rates of oil, gas and coal have been predicted using Hubbert peak theory [34]. Knowing just today's extraction rate and the estimated total global reserves [12], it is possible to construct an approximate production curve for each year in the future for each fossil fuel source. There are unknowns, for example the extent of heavy oils and deep reserves of gas in

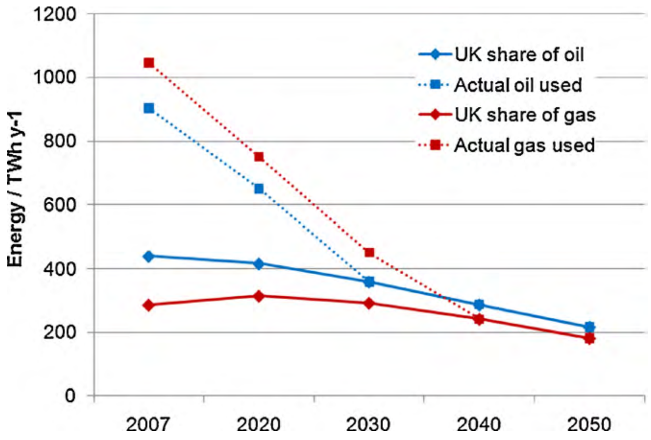

**Fig. 9.** The UK's use of oil and gas in all pathways compared to its 'fair share' of global resources.

the continental shelf, but Hubbert theory has been fairly good in the past at predicting the year of peak production of oil in some nations. The reserves-to-production (*R*/*P*) ratios used in the model were 133 years for coal, 47 years for oil and 60 years for gas. The *R*/*P* ratios and historic extraction rates were used to estimate total reserves and hence the shape of each curve. The *R*/*P* ratio used for oil was actually slightly greater than that in BP's estimate (42 years), based on recent data and curve fitting.

The predicted extraction rates of oil, coal and gas have been multiplied by the UK's predicted future population in each year [35] and divided by predicted global population in the same year [29] to give the UK's 'fair share' of each fuel. In 2007, the UK is using far more than its fair share of each fuel, and even if government targets are met, this situation is likely to continue beyond 2020. The government does have a target of reducing gas consumption by 27% by 2020 [4], but the remaining gas consumption in 2020 is still well above the global per capita average (Fig. 9).

The UK's consumption of gas and oil are inputs to the model, because these are closest to their predicted peaks, with the lower R/P ratios than coal. Oil and gas are also likely to be the premium, more desirable fuels, since they have a lower carbon content than coal (especially gas) and are easiest to transform into transport fuels (especially oil). Coal is the least constrained and is left to 'take up the slack' supplying the remaining energy demand not met by renewables, nuclear power or oil or gas.

### 2.15. Interconnectors

The model includes international electrical interconnection growing from 2 GW in 2007 to 10 GW in 2050. This is a fairly modest level given the amount of renewable generation on the UK system. There may be benefits to having a much larger interconnection [36,37], and the costs of interconnection are falling, especially those of HVDC links. However, the import and export of electricity are difficult to model. Should the UK respond to the needs of European electricity grids, or should Europe respond to our grid balancing needs? Will they result in a net import or export of energy? These questions are outside the scope of the study as they would require a similar analysis, but on a European scale.

The model simply assumes that a modest amount of interconnection imports when the UK is short of electricity and exports when there is a surplus. This is carried out as the first measure in the electricity balancing merit order, on the assumption that it is always better to use renewable or nuclear electricity to displace fossil-fuelled generation, rather than use it up in resistive heating or to make hydrogen. This principle applies even when the displaced fossil generation is in another country.

### 2.16. Energy storage and controllable loads

The model uses today's pumped storage (four sites in Wales and Scotland) plus a virtual store based on time shifting of heat pumps, CHP, electric heating and vehicle battery charging. In order to do this, the UK will require a system of controllable loads and a sophisticated communication system. The government has a stated aim that smart meters will be installed in every home by 2020 and this study assumes that the smart capability includes the controlling and time shifting of loads. Even in today' system, the charging of batteries in electric vehicles tends to take place at night using off-peak electricity, thereby helping to level out the electricity demand. Controllable loads will go further, encouraging some time shifting in response to short-term variations in renewable energy generation.

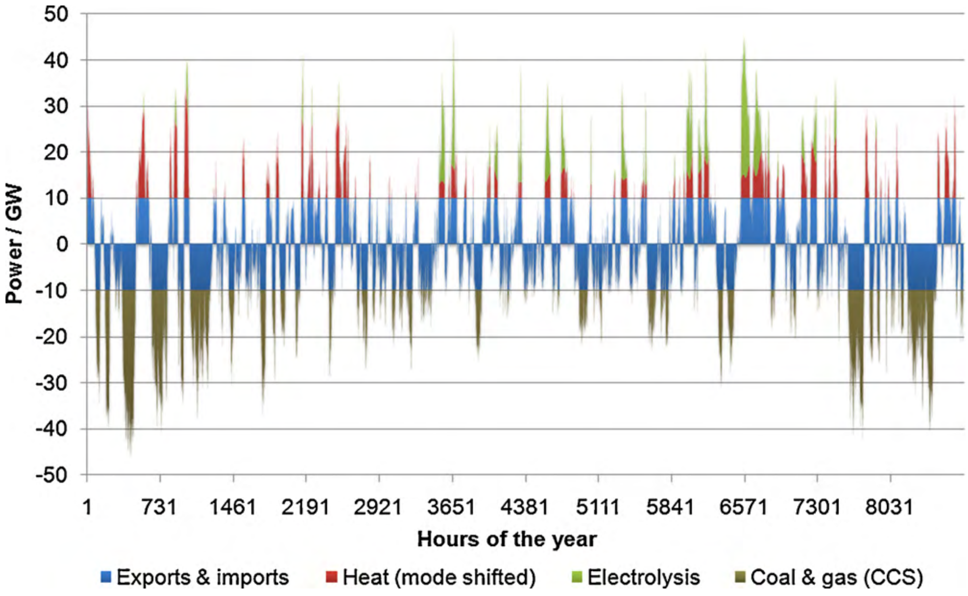

**Fig. 10.** Supply and demand balance throughout 2050 from High Coal pathway.

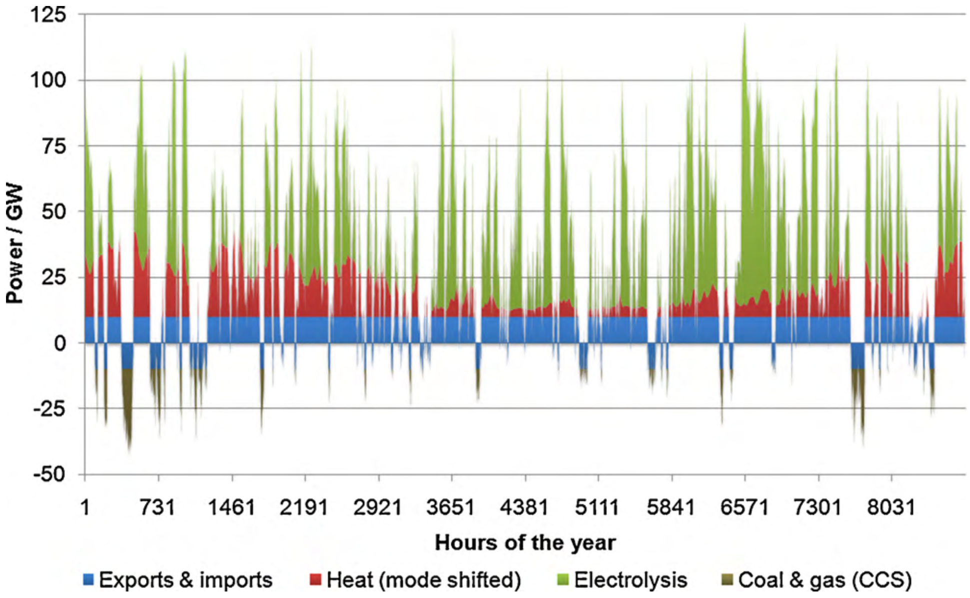

**Fig. 11.** Supply and demand balance throughout 2050 from High Renewable pathway.

The amount of this ‘virtual storage’ available is much greater than today’s pumped storage. The model assumes that 50% of a battery vehicle’s daily electricity consumption may be time shifted by up to 7 h. Similarly, 50% of all the electricity made or consumed in CHP, heat pumps and electric heating for water heating purposes may be time-shifted by up to 7 h, and space heating may be shifted by 1 hour without reduced comfort levels. In 2050, the resulting virtual energy store amounts to 157 GWh and 28 GW, well in excess of the 25 GWh and 3 GW of pumped storage.

More energy storage may be desirable in the future, particularly large hydro converted into pumped storage. Strathclyde University estimates the additional potential of pumped storage to be over 500 GWh [38]. Other energy storage technologies are unlikely to be economic in grid connected applications for the foreseeable future, especially at storage times greater than 1 day, as is required by variations in wind and wave power [18,39].

## 3. Results

The results show that (Figs. 10–24 and Table 1):

1. Electrolyser capacity factors are low, but in the High Renewable and High Nuclear pathways, the level might be acceptable, especially if the manufacturing cost of electrolysers can be reduced. In the High Coal pathway, there is so little electrolysis and its capacity factor is so low, that it may not worth building any grid-connected electrolysers to make hydrogen.
2. Note that in the High Nuclear pathway, less hydrogen is produced because more electricity is exported instead of going to electrolysis. The extra nuclear power creates a small surplus for more of the time than in the other scenarios.
3. The High Nuclear pathway also requires the least amount of dispatchable (backup) generation. Almost none was needed, and the little that was needed only ran for 1 h in the year.

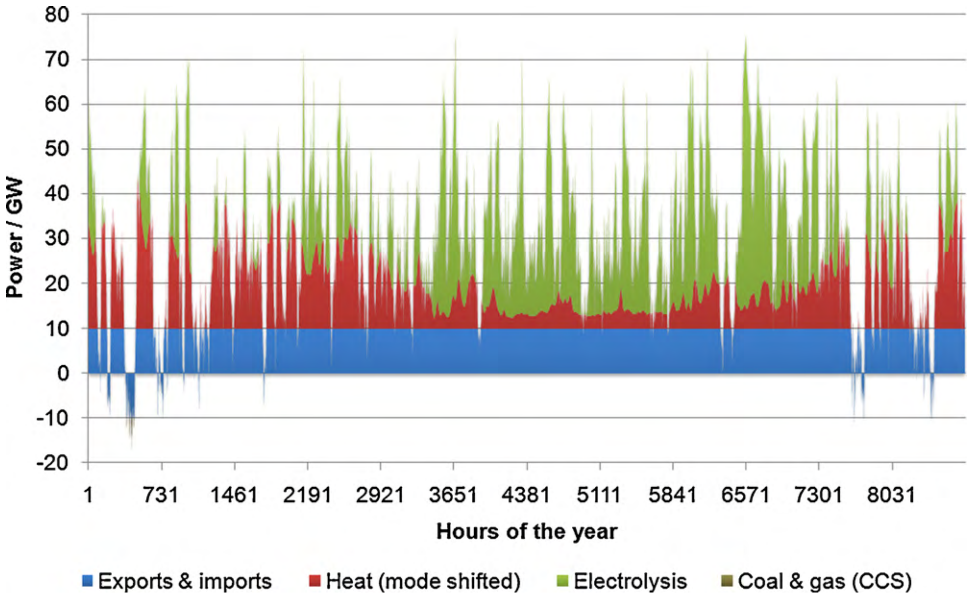

**Fig. 12.** Supply and demand balance throughout 2050 from High Nuclear pathway.

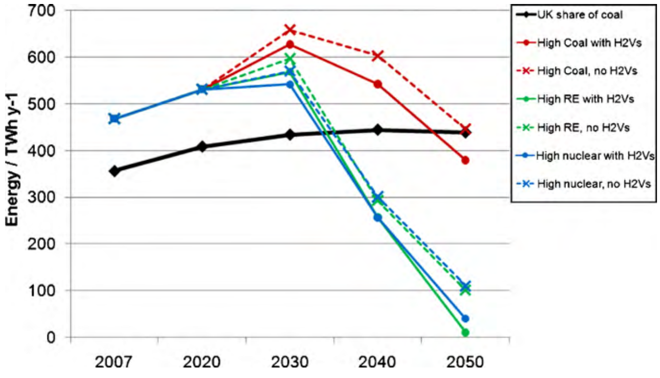

**Fig. 13.** The UK's use of coal compared to its 'fair share' of global resources.

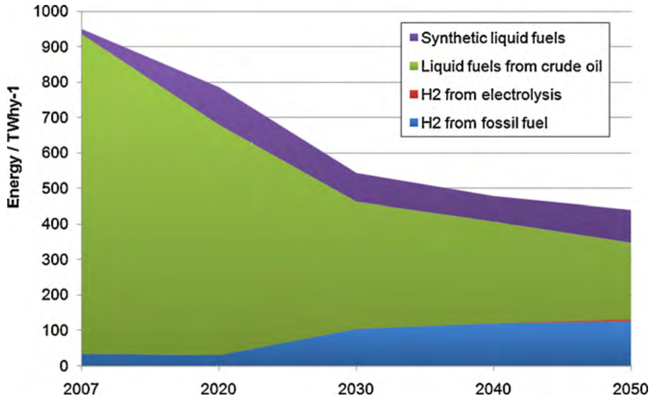

**Fig. 14.** Transport fuel sources in the High Coal pathway.

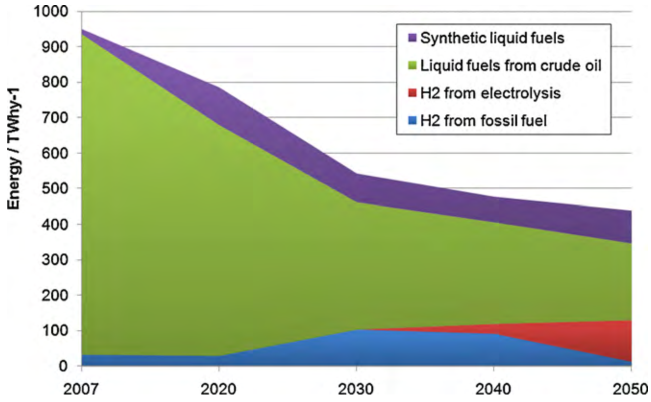

**Fig. 15.** Transport fuel sources in the High Renewable pathway.

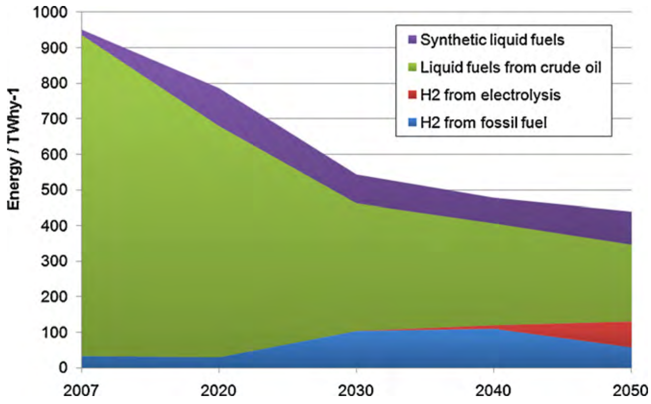

**Fig. 16.** Transport fuel sources in the High Nuclear pathway.

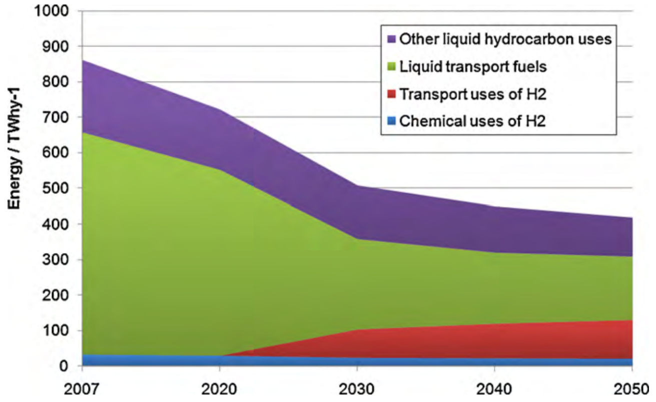

**Fig. 17.** Fuel use in all three pathways.

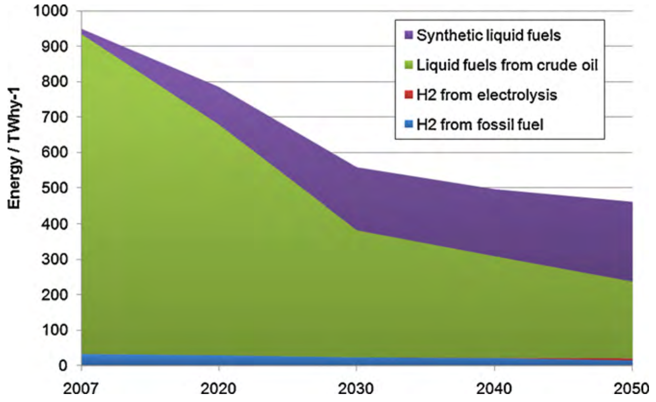

**Fig. 18.** Transport fuel sources in the High Coal pathway without hydrogen vehicles.

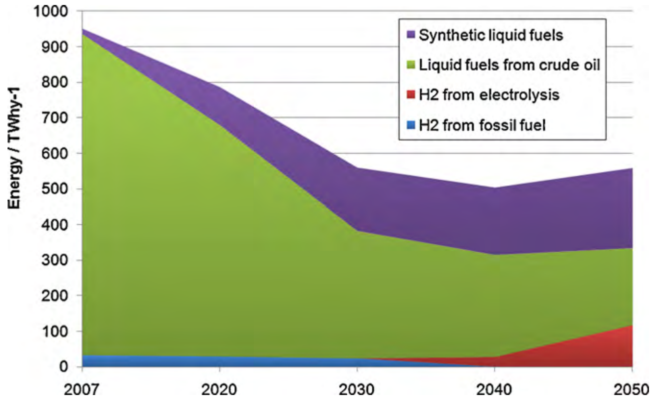

**Fig. 19.** Transport fuel sources in the High Renewable pathway without hydrogen vehicles.

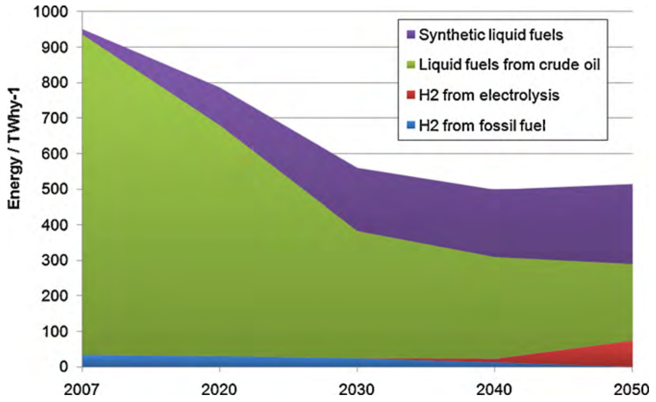

**Fig. 20.** Transport fuel sources in the High Nuclear pathway without hydrogen vehicles.

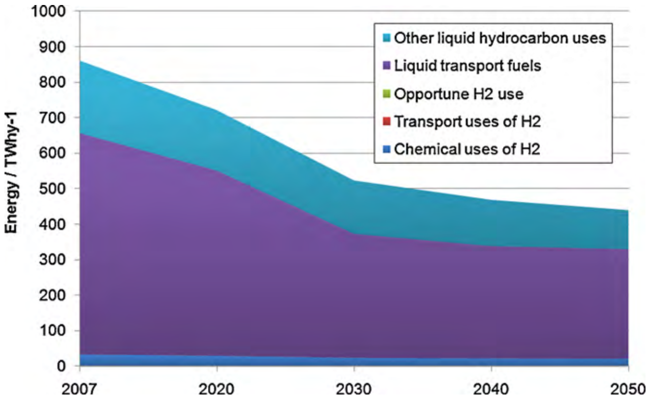

**Fig. 21.** Fuel use in the High Coal pathway without hydrogen vehicles.

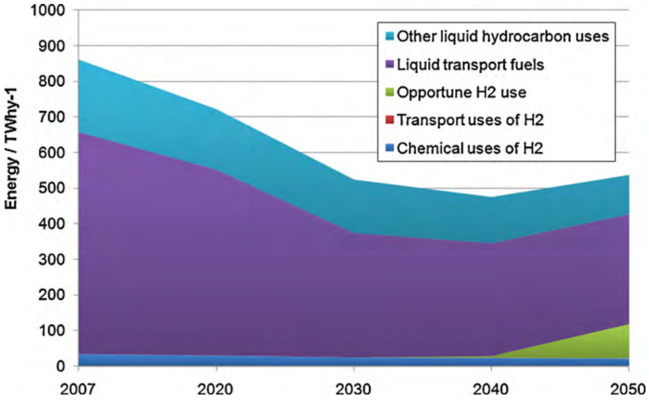

**Fig. 22.** Fuel use in the High Renewable pathway without hydrogen vehicles.

4. The High Renewable and High Nuclear pathways use more total electricity, closer to 800 TWh $y^{-1}$, whereas the High Coal pathways uses less than 600 TWh $y^{-1}$ of electricity. Not surprisingly, the High Coal pathway converts more coal directly into other fuels, bypassing electricity entirely.
5. None of the pathways completely avoid the need for carbon capture and storage at some point in their trajectory, but the High Renewables and High Nuclear Pathways do almost completely avoid the need for capture of $CO_2$ from air.
6. The pathways that include hydrogen vehicles need considerably less CCS than those that rule out hydrogen vehicles. This is because the inclusion of hydrogen fuelled vehicles results in lower $CO_2$ emissions from transport.

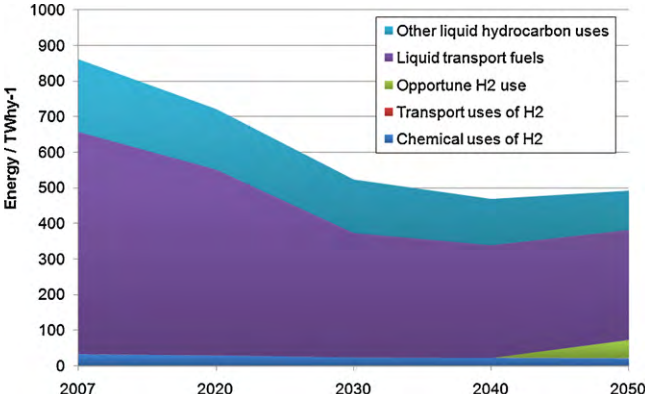

**Fig. 23.** Fuel use in the High Nuclear pathway without hydrogen vehicles.

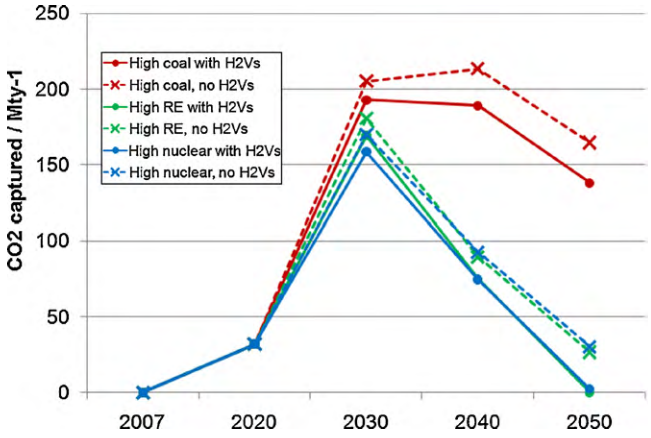

**Fig. 24.** Carbon Capture and Storage (CCS) required in all pathways.

7. All the pathways use their full quota of natural gas and crude oil. Even with such large amounts of nuclear and renewable energy, the UK still needs to use a lot of fossil fuels.
8. The amount of coal used varies greatly from one pathway to another. As expected, the High Coal pathway uses far more than the others. The pathways without hydrogen vehicles use between 70 TWh $y^{-1}$ and 90 TWh $y^{-1}$ more coal than those with hydrogen vehicles, i.e. 70–90 TWh more than shown in Figs. 2 and 8 by 2050. This is because:

(i) hydrogen powered vehicles are expected to be slightly more fuel efficient than hydrocarbon powered ones,
(ii) there are significant energy conversion losses in making synthetic hydrocarbon fuels,
(iii) the No Hydrogen Vehicles pathways necessitate more CCS, which carries a significant energy penalty.

## 4. Discussion

The model shows that the depletion of oil and gas reserves present the UK and the rest of the world with an enormous energy supply challenge. The demands of energy security and reduced greenhouse gas emissions will require every resource at our disposal. Looking at the energy sources that will be available in the years to 2050 reveals a radically different energy economy. Primary energy sources will consist mainly of low carbon electricity and coal.

Pathway 1 shows a UK heavily dependent on coal despite enormous investments in new renewable and nuclear powered generating capacity. Unless the coal energy is obtained by underground gasification of the UK's own deep coal reserves, most of this coal will be imported and cause the UK to be vulnerable to price escalation of imported coal. If the rest of the world also starts to switch from oil and gas to coal, such a price escalation is almost inevitable.

Pathway 1 also means increased emissions of $CO_2$. This pathway requires the greatest amount of CCS to be carried out, with its consequent energy penalty. Furthermore, pathway 1 requires substantial amounts of CCS from diffuse sources of $CO_2$, perhaps from the air, in order to meet $CO_2$ reduction targets. In the variant with no hydrogen vehicles, air capture of $CO_2$ may become necessary as early as 2030.

Unfortunately, the energy cost of CCS means that more electricity must be generated to compensate for this penalty. Since this is likely to be coal-fired generation as the fuel of last resort, this generation has its own large $CO_2$ emissions which must be captured too. Thus the energy system is 'chasing its own tail', capturing $CO_2$

**Table 1**
Results for the year 2050 from each energy pathway.

| Pathway | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| | High coal | | High renewable | | High nuclear | |
| Units are TWh $y^{-1}$ unless otherwise stated | With $H_2$ vehicles | No $H_2$ vehicles | With $H_2$ vehicles | No $H_2$ vehicles | With $H_2$ vehicles | No $H_2$ vehicles |
| $H_2$ for vehicles | 109.5 | 0 | 109.5 | 0 | 109.5 | 0 |
| Essential $H_2$ for industry | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 |
| $H_2$ from electrolysis | 5.9 | 5.9 | 117.5 | 117.5 | 73.0 | 73.0 |
| Electrolyser capacity/$GW_{(electrical)}$ | 31.1 | 31.1 | 107.1 | 107.1 | 61.4 | 61.4 |
| Electrolyser Capacity factor | 2.8% | 2.8% | 16.0% | 16.0% | 17.3% | 17.3% |
| $H_2$ from fossil fuel | 124.6 | 15.1 | 13.1 | 0 | 57.6 | 0 |
| Surplus $H_2$ for optional uses | 0 | 0 | 0 | 96.5 | 0 | 52.0 |
| Total electricity | 583.9 | 583.9 | 823.8 | 823.8 | 789.6 | 789.6 |
| Variable renewable energy | 320.4 | 320.4 | 640.4 | 640.4 | 320.4 | 320.4 |
| Variable renewable capacity/GW | 115.2 | 115.2 | 200.6 | 200.6 | 115.2 | 115.2 |
| Variable renewable Capacity factor | 31.7% | 31.7% | 36.5% | 36.5% | 31.7% | 31.7% |
| Dispatchable electricity | 24.9 | 24.9 | 8.9 | 8.9 | 0.07 | 0.07 |
| Nuclear energy | 200 | 200 | 200 | 200 | 520 | 520 |
| Transport energy | 362.9 | 384.8 | 362.9 | 384.8 | 362.9 | 384.8 |
| Electricity for transport | 75.9 | 75.9 | 75.9 | 75.9 | 75.9 | 75.9 |
| Hydrogen for transport | 109.5 | 0 | 109.5 | 0 | 109.5 | 0 |
| Liquid fuel for transport | 308.9 | 177.4 | 308.9 | 177.4 | 308.9 | 177.4 |
| Total natural gas used | 181.7 | 181.7 | 181.7 | 181.7 | 181.7 | 181.7 |
| Total crude oil used | 216.6 | 216.6 | 216.6 | 216.6 | 216.6 | 216.6 |
| Total coal used | 379.3 | 446.2 | 10.3 | 101.2 | 40.2 | 109.9 |
| $CO_2$ captured from point sources/$MtCO_2$ $y^{-1}$ | 124.6 | 116.7 | 0 | 26.7 | 2.2 | 28.9 |
| $CO_2$ captured from Air/$MtCO_2$ $y^{-1}$ | 13.3 | 47.9 | 0 | 0 | 0 | 1.2 |

from the additional electricity generation needed for the $CO_2$ capture. This is particularly bad when $CO_2$ must be captured from the air. Nevertheless, such a system does appear practical, for as long as coal is available in sufficient quantities and as long as sites for CCS are available. Even with the larger energy penalty of capturing $CO_2$ from the air, the extra coal burned to capture $CO_2$ from coal burning represents an increase in coal consumption of the order of only 25%.

Pathways 2 and 3 each have their own advantages and disadvantages, but both require much less coal and much less CCS. Pathway 2 generates slightly more hydrogen from electrolysis, but requires a greater capacity of electrolysers to be installed and needs more dispatchable electricity generation. Pathway 3 relies on nuclear power and therefore requires fuel in the form of uranium and a solution to the nuclear waste disposal problem. Both pathways 2 and 3 leave more natural gas available for conversion into hydrogen, where hydrogen vehicles are used, or liquid hydrocarbons in the variant where there are no hydrogen vehicles, thus saving the carbon emissions associated with producing synthetic fuels from coal. Part of the gas saving is caused by a conversion to electric heating whenever there is a surplus of electricity.

The use of hydrogen fuelled vehicles does create a market for electrolytic hydrogen that, in pathways 2 and 3, would otherwise go into industrial uses. These uses, referred to as 'opportune $H_2$ use' in Figs. 21 and 22, consist of electricity generation, use as an industrial fuel, conversion into synthetic hydrocarbons in combination with gasified coal, or injection into the gas network. Hydrogen may be injected into the natural gas network at a concentration of up to 12%, creating a mixture known as Hythane [40]. However, these opportune uses of hydrogen do not save as much fossil fuel energy as the direct use of hydrogen in vehicles. The lost energy is 70–90 TWh $y^{-1}$, including the energy penalty of extra CCS (Figs. 23 and 24).

Having no hydrogen vehicles does not imply that there would be no hydrogen in the economy. Hydrogen is needed, in conjunction with coal, to make synthetic fuel and it is also necessary for ammonia production, as it is today. In the pathway variants without hydrogen vehicles, most of the hydrogen is hidden in the model but it is still there. Some is created as a component of synthesis gas from coal and is then converted, with carbon monoxide (CO) and other gases, into synthetic hydrocarbons.

If pre-combustion CCS is chosen in electricity generation, then coal is converted to syngas (synthesis gas), and used to make more hydrogen via the Water Gas Shift Reaction (WGSR). The resulting $CO_2$ can be captured and stored, leaving pure hydrogen for use in either hydrogen vehicles or in electricity generation (IGCC). There exist important synergies: the same coal gasification plant can be run continuously producing stored hydrogen for both daily transport uses and occasional electricity generation. Furthermore, it should not be forgotten that as well as hydrogen, electrolysis produces oxygen, which can also be used as an industrial gas. One important use of oxygen is in the more efficient gasification of coal or biomass.

Finally, let us consider what happens under scenarios of extremely large amounts of renewable energy and/or nuclear power. A lot of surplus hydrogen would be produced and some of this would be converted into synthetic natural gas and hydrocarbon fuel [41,42]. If no fossil fuel input were required at all, this would result in zero or even negative net emissions as carbon is captured from the air. However, this never happens by 2050 for the UK as a whole, under any scenario examined. That is not to say that some niche markets in extremely remote locations may not require air capture of $CO_2$ to make liquid fuels before 2050. Also, at some time in the future, global $CO_2$ emissions must fall to zero, and fossil fuel extraction will completely cease. At this point, hydrocarbons can only be produced using carbon captured from the air, either directly or via biomass.

## 5. Conclusion

Whatever the mix of primary energy supply, hydrogen fuelled vehicles offer a route to lower $CO_2$ emissions and lower primary energy requirements than scenarios without hydrogen fuelled vehicles.

If the UK is to avoid being heavily dependent on imported fossil fuels, substantial amounts of hydrogen will be produced by electrolysis using surplus electricity as early as the 2030s.

## Acknowledgements

We should like to express our thanks to visiting student, Mike Forrester, who gathered most of the weather data behind the model of intermittent renewable resources, and to the BADC who provided most of that data. Thanks are also due to the Supergen HDPS project, funded by a grant from EPSRC, under which much of the work for this study was undertaken, and to the AFS team.

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## Glossary

*CCC:* Committee on climate change.
*CCGT:* Combined cycle gas turbine: fuel is burned in a gas turbine to generate electricity and the exhaust gases are used to raise steam and generate additional electricity.
*CCS:* Carbon capture and storage/sequestration–the collection, compression and underground storage of carbon dioxide in order to reduce atmospheric emissions of greenhouse gases.
*CHP:* Combined heat and power.
*CO:* Carbon monoxide.
$CO_2$: Carbon dioxide.
*CTL:* Coal-to-liquids conversion, making synthetic liquid fuels using Fischer–Tropsch.
*Dispatchable:* Controllable and can be called on when needed, e.g. conventional gas and coal-fired power stations.
*DMFC:* Direct methanol fuel cell.
*FC:* Fuel cell.
*FT:* Fischer–Tropsch reactions.
*GRT:* Global Research Technologies (USA). This company has a process for the capture of $CO_2$ from the air.
*GTL:* Gas-to-liquids conversion, making synthetic liquid fuels using Fischer–Tropsch.
$H_2O$: Chemical formula of water.
*Hythane:* A proprietary name given to mixture of hydrogen and methane.
*ICE:* Internal combustion engine.
*IGCC:* Integrated gasification combined cycle—the gasification of coal or biomass followed by combustion of the gases in a combined cycle power plant.
*MTG:* Mobil's methanol-to-gasoline process.
*Oxyfuel:* The combustion of coal using pure oxygen and recycled carbon dioxide in order to create flue gases free of atmospheric nitrogen.
*RWGSR:* Reverse water gas shift reaction, which converts hydrogen and carbon dioxide into water and carbon monoxide.
*Sabatier:* The Sabatier reaction, which converts synthesis gas into methane.
*SMR:* Steam methane reformation, for converting methane (natural gas) into hydrogen.
*Syn. Gas:* Synthesis gas: a mixture of gases, mainly carbon monoxide and hydrogen, created by gasification of fossil fuels or biomass and used to synthesise other chemicals.
*Thermal depolymerisation:* A high temperature, high pressure process for converting biomass into synthetic crude oil and gases, but not full gasification.
*WGSR:* Water gas shift reaction, which converts water and carbon monoxide into hydrogen and carbon dioxide.