Hydrogen Transport and the
Spatial Requirements of Renewable Energy

James I. Oswald, Andrew J. Oswald and Hezlin Ashraf-Ball

No 903

# WARWICK ECONOMIC RESEARCH PAPERS

## DEPARTMENT OF ECONOMICS

THE UNIVERSITY OF
WARWICK

# Hydrogen Transport and the Spatial Requirements
## of Renewable Energy

James I. Oswald*
Andrew J. Oswald
Hezlin Ashraf-Ball

University of Warwick

May 2009

## Abstract

Unlike oil and coal, which are compressed forms of energy, renewable energy requires unusually large land areas.  This article calculates the consequences of a switch to hydrogen-cell vehicles powered by electricity from wind turbines.  It then re-does the calculation for three other green energy sources: wave power; biofuels; solar energy.  We argue that policy-makers and social scientists need to understand the significant spatial demands of a move to a carbon-free society.

## Hydrogen Transport and the Spatial Requirements
## of Renewable Energy

1. Introduction

This article studies the implications of a move to green transport. Our starting assumption is that global warming is one of the main problems, and arguably perhaps the most severe single problem, of the 21st century (see, for example, Stern 2007). In order to reduce carbon emissions, society as a whole will have to move away from fossil fuels. In particular, most economies must switch from a reliance on petroleum; the world currently consumes 90 million barrels a day.[1] It seems likely, throughout the developed and developing world, that sustainable energy practices will eventually become central. This article explores one consequence of renewable-energy use. Its focus is 'green' transport, but the broad message is general. The article does not fit neatly into any one discipline, but rather lies at the borders of economics, engineering science, social policy, and geography.

The most recent (October 2008) amendment to the UK Government's Climate Change Bill aims 'to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline'. This target had previously been set at 60%, and even at that level was considered ambitious. According to estimates by the Department for Environment, Food and Rural Affairs (DEFRA), the UK's $CO_2$ levels fell by an approximate figure of 6.4% between the years 1990 and 2005 (http://www.defra.gov.uk/environment/climatechange/internat/un-kyoto.htm). At that rate, the UK would only reach around a 25.6% reduction in carbon emissions by 2050. It should also be noted that during the 1990s the UK significantly changed its proportions of coal and natural gas burnt – in 1990 burning 49.84 MTOE (Million Tonnes Oil Equivalent) of coal and 0.56 MTOE natural gas, by 1999 these figures were 25.51 and

---

[1] We shall not attempt here to summarize the debate about the science and social science of climate change, but early contributions and helpful introductions can be found in Azomahou et al (2006), Beckerman (2001), Nordhaus (1991), Cline (1992), Holtz-Eakin and Selden (1995), Raehsler (1996), IPCC (2001), Peterson (2004), and Robinson (2005).

27.13, and remain fairly equal (Source: DUKES Long-Term Trends Tables, BERR http://www.berr.gov.uk/whatwedo/energy/statistics/source/electricity/page18527.html). The motivation behind this was predominantly economic and far from exclusively environmental, hence part of the 6.4% reduction may have been brought about inadvertently. Thus the challenge is significant, and radical changes in approach are likely to be necessary to fulfil the 80 % target. One such change will need to take place in the transport sector, which is responsible for around one third of the UK's energy usage. We analyse it here as one of the contributions that will be required.

## 2. The Main Ideas

The article discusses an implication of climate change that we believe is important but that has attracted almost no attention from economists and social scientists. A 'greener' way of living, the later analysis demonstrates, is going to have spatial consequences for the economy. These are likely to be extreme. The reason is that to a greater extent than fossil fuels -- which are intrinsically highly compressed forms of energy[2] -- renewable energy needs exceptional quantities of land.[3]

We provide simple calculations designed to aid an understanding of this spatial effect. In particular, this article works out the magnitude of the required land-area changes. We also try to contribute indirectly to ideas on the economics of land regulation (eg. Cheshire and Sheppard 2002, 2004) and more broadly to a research area -- the economics of land -- that authors such as Metzemakers and Louw (2005) argue has, wrongly, been treated by modern economists as of only marginal importance. The article's spirit follows Leamer and Storper (2001) in inquiring into the geography of the world to come.

---

[2] It is, in a sense, the result of countless years of fossilization of green energy.
[3] Through discussions with a mixture of researchers, we know that some scientists are aware of the conceptual issue discussed in the article, but the case does not appear to have been explored systematically or come to the attention of policy-makers. The problem is not mentioned in, for example, the Stern Report (2006). Nonhebel (2005) is the closest we have found to the argument of this article, but it does not make exactly the same point; Collins (1999) mentions that energy crops require much land; and Pimentel (1994) et al discuss the case of America's solar-power potential. Oswald et al (2008) discusses related issues about wind volatility.

As Neuhoff (2005) and Robinson (2005) make clear, most climate-change options come down to a single issue: how to marshal sufficient renewables-based electricity production. For people to continue to live in the current style of modern western society, these sources will in the future be required to produce carbon-neutral electricity on a huge scale. Many commentators point to energy types such as wind, solar, biomass and wave power. Despite its practical engineering challenges, wind energy has potential (see Coulomb and Neuhoff 2006, DeCarolis and Keith 2006, Keay 2005, and Neuhoff et al 2006), and much of the article's analysis is concerned with that renewable source. The complexity of future energy problems is perhaps not fully understood by most social scientists. Difficulties include those of having a diverse and reliable flow of energy (Grubb et al 2006). Giving up fossil-based energy will be costly in various ways (Pearce 1991, Weyant 1993, Smith 1998, Darmstatder 2003). Its precise speed in practice will depend, as Terrado et al (1989) show, on oil prices.

By going through some engineering calculations, the article sketches one consequence of the desire to reduce carbon emissions. As in Strachan and Lal (2004), our focus is partly upon wind power, but it is demonstrated below that the argument is more general than that. The style of our calculations will be unfamiliar to many economists and social scientists, so we have attempted to keep them as simple as possible.

We take the United Kingdom as an example.

As in most nations, energy use in the UK falls into four main categories. Office of National Statistics data show that the largest, at one third of all energy used, is transport. It consumes the equivalent of nearly 60 million tonnes of oil per year. Next, at approximately 50 million tonnes per annum, comes domestic household use – primarily for heat and light. Then comes energy used in the services sector, which totals 30 million tonnes. A further 20 million tonnes a year of oil-equivalent are consumed in the industry sector. Since 1970, these proportions have progressively altered. While industrial energy consumption has gradually declined, the rise of the car in society has seen energy use on the roads double. Such numbers make clear that a primary long-term issue is how to

replace the fossil fuel that is currently burned in car engines (and other forms of transport).

The so-called hydrogen economy offers potential (Ogden 1999, Turner 2004, Hoogwijk et al 2004). Schultz et al (2003) show that cutting emissions from transport, by converting from conventional petroleum-driven automobiles and trucks to hydrogen-powered vehicles, would make a major contribution to the counteraction of climate-change. In the UK, some politicians, including the Liberal Democrat Party as a whole, have called for subsidies for hydrogen-cell cars of this sort.

Hydrogen, however, is not a *source* of energy, but rather a carrier of energy. Cars can be made to run on hydrogen fuel, but to minimise environmental impact the hydrogen in turn has to be generated with renewables-based electricity. Currently, hydrogen is made principally from fossil fuel, which defeats the environmental purpose.

## 3. A Calculation using Wind Energy as a Source

A natural question is then the following: what would it take to run all of UK transport, in a carbon-neutral way, on hydrogen? The answer is, as argued below, disturbing. The requirement, we show, is for approximately 150,000 new wind turbines. This implies that an area approximately double the size of Wales would have to be given over to wind-powered turbines.

The following is a way of calculating the approximate number of turbines required to provide enough energy to fuel the UK's transport. It rests on the premise that wind turbines produce the energy (without emissions) which in turn is channelled to generate hydrogen and that this hydrogen is used to power vehicles. The wind turbines might be sited off-shore; the most efficient way to transport the energy inland is then as electric power. Once inland, the electricity can be used to electrolyse water into hydrogen at locations across the country. New motor vehicles would be required that are capable of storing and burning the hydrogen.

4

Put in an elementary way, the wind-energy chain is:

| Wind | → | Electricity | → | Transport Inland | → | Hydrogen | → | Cars/Freight |

The most recent UK annual consumption of transport energy is 60 MTOE: this figure is taken from UK Energy in Brief 2008, Department for Business Enterprise & Regulatory Reform (BERR), July 2008. The energy figure has increased through the years but for the later calculations we take it to be a fixed number. The numerical findings are summarised in the coming pages, while the detail of the calculations can be found in the appendix.

The conversion of electric power into hydrogen (an energy store) is approximately 50% efficient, using the standard source, Bossel (2003). We have done independent calculations that accord with Bossel's estimate -- based on an electrical transmission efficiency of 95%; electrolysis of water to hydrogen and oxygen efficiency of 70%; and compression of hydrogen for storage at 75%. These combine to give a net energy efficiency of approximately 50%.

Using these figures, the annual renewable energy required can be calculated. For the transport sector, therefore, 120 MTOE will be required, which after converting into average hourly megawatts gives 159,000 MW. Here a conversion factor of 11.63 is again taken from UK Energy in Brief 2008.

At the time of writing, typical wind turbines are of 2MW power. To keep calculations relatively conservative, and to make the assumption, as seems reasonable, of some technical progress, we here assume that larger 3MW turbine units can be deployed. In that case, the number of wind turbine units required is 159,000/3 = 53,000 units.

The wind blows with varying intensity and the average annual power delivered is only a fraction of maximum rated power. This has to be catered for with a load factor term which for the United Kingdom as a whole is approximately 0.29 (Energy Trends Report, Department of Trade and Industry, March 2006). However, wind turbines off-shore receive somewhat higher wind levels. Therefore, to again make a relatively conservative estimate of the number of turbines required, a load factor of 0.35 is assumed for the calculation. The approximate number of wind turbines required is therefore $53,000/0.35 \approx$ 151,500 units of 3MW size.

To keep the wind turbines in a reasonably windy area, they might be placed in the sea and strung around the periphery of Great Britain. What approximate density, assuming for simplicity a rectangular band of turbines, would be required? Given the overall north-south distance of 680 miles and east to west distance of 200 miles, the periphery is therefore 1760 miles or 2800 km. Hence to fit the 151,500 turbines in a rectangular band around the coastal periphery would require 54 units per kilometre.

Wind turbines create blockage to the wind, so in a group they have to be spaced apart to ensure that the wind is undisturbed for neighbouring wind turbines. An appropriate technical source in this case is the AEA Technology Report Sea Wind East, which argues that a spacing of 0.5km is reasonable. Hence there are two turbines per linear kilometre. An area of wind turbines 27 deep would thus give the required 54 wind turbines per km. It is thereby possible to work out the consequences. The implied area, given 151,500 units at 4 units per $km^2$, is $\sim$ 37,900 $km^2$. To put this into perspective, the total UK land area is 244,000 $km^2$. The area of Wales, for example, is approximately 20,000 $km^2$.

In short, approximately 151,500 wind turbines (rated at 3MW each) would be needed to generate enough electricity to manufacture sufficient hydrogen to provide the power for current UK transport needs. Put off-shore, a sensible spacing of these around the coastline of Great Britain (2,800km long) would require a band of wind turbines, encircling the country, approximately 13.5 km deep. If instead placed on-shore, bearing

in mind the slightly inferior wind conditions compared to off-shore, the coverage of turbines would be roughly twice the area of Wales.

## 4. The Calculation for Other Green Alternatives

Wind power is currently one of the more effective renewable technologies available, and turbines are being installed worldwide. However, other renewable energy forms such as wave power, bio-fuels and solar energy are also dispersed forms of power collection and require installations to garner the quantities of power for UK needs. Does this article's focus on wind-turbine energy produce a misleading picture?

It is straightforward to show that it does not. By repeating the same calculation, for each of these renewable sources, the spatial implications of each can be worked out in a straightforward manner. Table 1 below summarises these results.

Table 1

The different land-area requirements of each kind of renewable technology

| Parameters/Technology | Wind | Wave [1] | Bio fuel [2] (ethanol) | Solar energy [3] |
|---|---|---|---|---|
| *Unit Power* | 3MW | 0.75MW | | 111kWh/$m^2$/year |
| *Type* | Wind Turbines | Pelamis | Sugar beet | Photovoltaic cells |
| *# of units* | 151,500 | 707,000 | | |
| *Area required (km2)* | **37,900** | **20,700** | **424,080** | **24,000** |
| *Size of 'strip' around UK* | 13.5 x 2800 km | 7.4 x 2800 km | | |

[1, 2, 3,] *correspond to the calculations in the appendix for each technology to provide green energy for transport*

Note: Total UK land area is 243, 000 $km^2$; UK costal periphery is approximately 2800 km.

A common theme emerges from the four columns of Table 1. For the different energy types, the land requirement varies from approximately 20,000 to 400,000 km$^2$.

The central and consistent point is that the power-per-land-unit size of each of these is, in each case, fundamentally worse than equivalent fossil-fuel methods.

There is one rather different type of non-fossil-fuel alternative, namely, nuclear power. It leads of course to other concerns (including how to deal with radioactive waste and the diversion from investment in renewable technologies -- see, for example, Mitchell and Woodman 2006), but nuclear power stations could in principle provide the necessary electricity to produce the hydrogen to fuel the United Kingdom's transport needs. For example, the 154,000 MW of power could be generated with 130 new nuclear power stations each of 1,200MW generating capacity. Such a capacity is probably realistic, because Sizewell B, the UK's newest nuclear station, has an output of 1,200MW. Nevertheless, we do not explore this avenue further, because the purpose of the article is to explore the spatial feasibility of green, non-nuclear, non fossil-fuel energy.

One special advantage of wind turbines should be mentioned. It is that in a spatial sense they might be interwoven with other fuel sources. If sited on-shore, the production of solar or bio-fuel power could occur in the area between the individual wind turbines. This would use land more efficiently, and, given the variability in wind supply, it would potentially offer a kind of smorgasbord of energy sources. Under any such scheme, however, many wind turbines would (because of the sheer number required) need to be sited close to where people currently live in the UK. How acceptable this would be to the United Kingdom's population remains an open question politically.

5. Conclusions

The central point made in this article is that a carbon-free society needs huge areas of land to be devoted to the production of energy. Although a small number of energy scientists are aware of this, social scientists and policy-makers are not. Economists, in

particular, have given little thought to the geographical demands of clean-energy-production; that is because today, in a world dominated by fossil fuels, the spatial issues connected with the supply of energy are relatively unimportant. Such fuels currently provide power in a highly condensed form (via millions of years of the compression of organic matter). Extraction requires comparatively tiny land areas.

As demonstrated in the article, renewable energy presents a different challenge. The calculations presented here show that a switch to renewable energy is likely to place significant spatial demands on society and the economy. To illustrate the argument, the article has attempted to work out the implications of changing from conventional petrol vehicles to hydrogen-cell vehicles powered by clean sources such as wind-generated electricity. This, it is shown, would require the construction in the United Kingdom of approximately 151,500 new wind turbines, each spaced half a kilometre apart. Such a switch would need an amount of land, either off-shore or on-shore, equal to 15% of the UK's space. For transport reasons alone, wind turbines would then have to cover an area twice the size of Wales. For illustrative clarity, the particular focus of the analysis has been upon wind power, but equivalent calculations set out in the article's appendix -- on wave, biofuel and solar -- try to explain that the article's point is a general one.

The reasons for doing the article's calculation are twofold. First, we take as axiomatic that it is desirable worldwide to use less fossil fuel and more renewable energy. Second, the transport sector has become the biggest single user of fossil fuel in an industrialized nation like the United Kingdom. On average, each citizen consumes one metric tonne of petroleum in this way per annum. To replace petrol vehicles with cars and trucks that run on hydrogen -- generated without any fossil fuel -- would in principle be feasible. However, it requires, among other things, the production of vast amounts of replacement electricity in a clean sustainable way. These estimates have thus focused upon the provision of renewable energy to the transport sector. Transport accounts, however, for only approximately one third of the energy used in a modern industrialized economy. The remaining two thirds of that energy will also eventually have to be provided in a way

that avoids carbon emissions.  This will exacerbate the spatial consequences associated with green energy.

**Appendix:**

**Calculations for Wind and Three Other Renewable Energy Sources**

(i)      Wind Power

Current UK annual consumption of transport energy = 60 MTOE (taken as fixed into the future).

Conversion of electric power > hydrogen ≈ 50% efficient, Bossel (2003).

Electrical transmission efficiency = 95%

Electrolysis of water to hydrogen and oxygen efficiency = 70%

Compression of hydrogen for storage = 75%

=> Net energy efficiency = 0.95 x 0.7 x 0.75 ≈ 50%


Annual renewable energy required = 60 / 0.5 = 120 MTOE.

Converting to average hourly MW: 120 x 1000 x 11.63 x 1000/(365 x 24) = 159,000 MW.  (Conversion factor of 11.63 taken from UK Energy in Brief 2008).


Assuming 3MW turbines, number of units required = 159,000/3 = 53,000 units.

Taking into account an annual offshore load factor of 0.35, approximate number of wind turbines required = 53,000/0.35 ≈ 151,500 @ 3MW each.


If turbines are strung around the coastline of GB:

GB straight line distance north to south = 680 miles

Straight line distance west to east = 200 miles

Periphery = 2 x (680+200) = 1760 miles = 2800 km

=> Width of necessary band of turbines, if rectangular = 151,500/2800 = 54 units/km

To account for required spacing between turbines of 0.5km (hence 2 per linear km).

 => Area of wind turbines 27 deep (13.5km) gives required 54 wind turbines/km.

Implied area given 151,500 units @ 4 units per $km^2 \approx$ 37,900 $km^2$.

(ii) Wave

The number of Wave Energy Converters (WEC) needed to supply the energy to meet the UK transport fuel need in the form of hydrogen has been calculated assuming the use of a WEC developed by Ocean Power Delivery Limited (OPD) known as the *Pelamis*. The unit is a hinged contoured device that consist of 4 tubes with a total length of 120 m and diameter of 3.5m. Each unit weighs 700 tonnes including the ballast. The device is chosen on the basis that it is one of the most developed wave devices in the UK. The energy pathway to producing hydrogen follows the same pattern as for wind and is shown in Figure A2.1:

| Wave | → | Electricity | → | Transport Inland | → | Hydrogen | → | Cars/Freight |

Figure A2.1 The energy pathway from wave to hydrogen

The average power requirement of 159,000 MW, determined from the wind calculation (including the 50% energy efficiency for converting electricity to hydrogen fuel), can be used again here. The *Pelamis* has a rated power of 0.75MW (maximum achievable power), but the variation in wave power with time means the average annual output is

only a fraction of this. The DTI record the annual average power output (load factor) to be 35% of the maximum rated power (Ref: DTI, Load Factors, June 2003). This is applicable to a good UK location but the East coast operates at a fraction of the wave powers and a national value of 30% is used in the calculation here.

The total number of *Pelamis* required is therefore calculated using Equation A2.1

$$Total\ Pelamis\ required = \frac{159,000}{0.75}\frac{MW}{MW} \times \frac{1}{0.30} = 707,000 units$$

Equation A2.1

To ensure that each *Pelamis* is subjected to minimal wave disturbance from adjacent units, each unit is placed 0.15km apart. The UK mainland periphery is 2800km, and by using Equation A2.2, the number of Pelamis encircling GB is shown to be 19,000 units.

$$No\ of\ Pelamis\ in\ a\ line\ encircling\ GB = \frac{2800km}{0.15km} \approx 19,000 units \qquad \text{Equation A2.2}$$

However, a total of 707,000 units is required and so the strip of Pelamis units must be 36 units deep as calculated below (Equation A2.3) :-

$$No\ of\ Pelamis\ deep = \frac{707,000}{19,000} = 37 units \qquad \text{Equation A2.3}$$

An axial gap of 0.2km between each *Pelamis* is required in the ocean, and hence the width of the device encircling GB can determined using Equation A2.4.

$$Width\ of\ strip\ encircling\ UK = 0.2km \times 37 units \approx 7.4km\ deep \qquad \text{Equation A2.4}$$

Total surface area required is $= 7.4 \times 2800 = 20,700 km^2$

(iii) Biofuel

The energy pathway to generate ethanol as a biofuel is given in Figure A3.1 below. Ethanol is considered a good transport fuel which can be burnt in today's automotive engines and has similar storage properties to petrol and diesel. The important point to note here is that some of the energy harvested as crops must be reallocated to planting, tending and fertilising the crop and is therefore represents a reduction to the fuel that can be passed for transport.
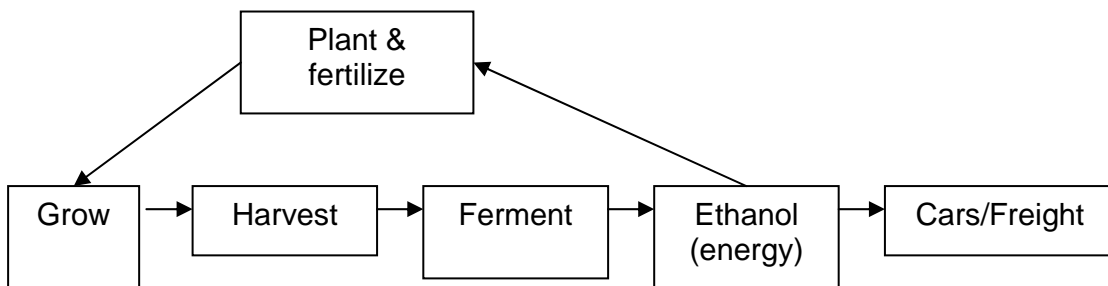


Figure A3.1 The energy pathway from sugar beet to ethanol

As before, the UK annual consumption of transport energy is 60 Million Tonnes Oil Equivalent (MTOE). Converting this to the preferred ISO units of Mega Joules (MJ) in equation A3.1

$$Annual\ power = 60MTOE \times \frac{1000}{1} \frac{TTOE}{MTOE} \times 11.63 \frac{GWh}{TTOE} \times 3.6 \frac{TJ}{GWh} \times 1{,}000{,}000 \frac{MJ}{TJ} = 2.51 \times 10^{12} MJ$$

Equation A3.1

In this study, sugar beet has been assumed as the feedstock and the relevant data for the manufacturing of bioethanol from this feedstock and the gross calorific value is reported as 26,720 MJ/tonne (El Sayed et al 2003 DTI project) and the reported energy loss for planting, tending and fertilising is given as 13,245MJ/tonne as per Table A3.1.

| Process involved in planting, tending and fertilising sugar beet | Energy use (MJ/tonne of bioethanol) |
|---|---|
| Cultivating | 1907 |
| Transport | 994 |
| Loading and preparation | 190 |
| Storage | 16 |
| Shredding | 28 |
| Diffusion | 904 |
| Pasteurisation | 565 |
| Fermentation | 120 |
| Distillation | 7841 |
| Plant construction | 100 |
| Plant maintenance | 82 |
| Distribution | 498 |
| **Total loss** | **13,245** |

Table A3.1 Energy loss in producing bioethanol

The net 'green available energy' is the difference between the gross energy harvested less the energy required to grow the crop, as per equation A3.2

$Green\ available\ bioethanol\ energy = (26,720 - 13,245)\ MJ/tonne = 13,475MJ/tonne$

Equation A3.2

The total mass of bio ethanol to meet the entire UK transport fuel requirement is therefore calculated as shown below, Equation A3.3.

$$Total\ mass\ of\ bioethanol\ required = \frac{2.51 \times 10^{12}\ MJ}{13,475\ MJ/tonne} = 1.86 \times 10^{8}\ tonne$$

15

According to El Sayed et al, 1 tonne of bio ethanol per year requires an area of 0.228 hectare. Therefore the total UK land area required is

$$Total \quad land \quad area \quad required \quad =$$
$$= 1.86 \times 10^{8} \, tonne \quad \times \frac{0.228}{1} \frac{hectare}{tonne} \times \frac{1}{100} \frac{km^{2}}{hectare} = 424,080 \, km^{2}$$

This is approximately twice the UK land area.

<u>(iv) Solar Energy - Photovoltaic cells</u>

Solar energy can be captured using photovoltaic (PV) cells which directly convert solar energy into electricity. We have demonstrated already that the UK's annual consumption of transport energy is 60 MTOE, equivalent to $2.51 \times 10^{12}$ MJ (Equation A3.1). The PV cells can be located locally to the user and so transmission losses may be ignored. This makes the energy pathway as shown below.

```
┌─────────┐    ┌─────────────┐    ┌──────────┐    ┌──────────────┐
│  Solar  │ ─► │ Electricity │ ─► │ Hydrogen │ ─► │  Cars/Freight │
└─────────┘    └─────────────┘    └──────────┘    └──────────────┘
```
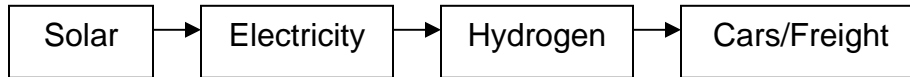
Figure A4.1 The energy pathway from solar to hydrogen as transport fuel

The efficiency of the electrolysis of water to hydrogen is 70%, and compression of hydrogen for storage is 75%, which gives a net efficiency of 53%. The energy required from the PV cells is thus $4.58 \times 10^{12}$ MJ as shown in equation A4.1 below.

$$Energy\ required\ from\ PV\ to\ hydrogen = \frac{2.51 \times 10^{12} MJ}{0.53} = 4.74 \times 10^{12} MJ\ /\ year$$

Equation A4.1

The electrical power produced from $1m^2$ of PV solar panels located in London is 111 kWh/$m^2$.year (ref: BP solar energy article, 2000. BP assumed module area efficiency of 13.5%). From this the total area needed to supply annual UK transport need is calculated from Equation A4.2.

$$PV\ cell\ area = \frac{4.74 \times 10^{12}\ MJ\ \times 1 \times 10^{6}\ \frac{J}{MJ}\ year^{-1}}{111000\ Js^{-1}.m^{-2}.year^{-1} \times 3600\ s.} = 11,861 \times 10^{6}\ m^{2}$$

Equation A4.2

Therefore, the total area needed for the PV cells is ~ 12,000km$^2$. However, extra space is required around these for access, maintenance and equipment, and by engineering judgement 100% is considered sufficient for these purposes. Hence the total land area required is 24,000km$^2$. Some of this land area could come from residential or commercial land space, principally rooftops, although clearly not all this land space would be appropriate for the purpose – some buildings are located in the shade, some have uneven roof shapes, some would not be structurally sound enough to support the weight of solar PV cells, etc.

## References

Azomahou, T., Laisney, F., and Van, P.N. (2006) 'Economic development and CO2 emissions: A nonparametric approach', Journal of Public Economics, 90, 1347-1363.

Beckerman, W. (2001) 'Argument in the greenhouse: The international economics of controlling global warming', Economic Journal, 11, F194-F196.

Bossel, U. (2003) 'Efficiency of hydrogen fuel cell, diesel-SOFC-hybrid and battery electric vehicles', European Fuel Cell Forum, Oberrohrdorf.

BP Solar Energy article (2000)  www.bpsolar.com

Cheshire, P. and Sheppard, S. (2002) 'The welfare economics of land use planning', Journal of Urban Economics, 52, 242-269.

Cheshire, P. and Sheppard, S. (2004) 'Land markets and land market regulation: Progress towards understanding', Regional Science and Urban Economics, 34, 619-637.

Cline, W.R. (1992) The Economics of Global Warming, Institute for International Economics, Washington DC.

Collins, L. (1999) 'Renewable energy from energy crops – A global perspective', Geography, 84, 169-172.

Coulomb, L. and Neuhoff, K. (2006) 'Learning curves and changing product attributes: The case of wind turbines', Cambridge Working Articles in Economics, University of Cambridge, CWPE 0618, February.

Darmstatder, J. (2003) 'The economic and political setting of renewable energy: Where do things stand?', RFF Discussion Articles, Resources for the Future: Washington DC, DP 03-64, December.

DeCarolis, J.F. and Keith, D.W. (2006) 'The economics of large-scale wind power in a carbon-constrained world', Energy Policy, 34, 295-410.

Department of Trade and Industry DTI (November 2000)  UK Energy in Brief , London.

DTI and Carbon Trust (June 2003) 'Renewables Innovation Review', London www.dti.gov.uk/files/file21955.pdf

DTI (July 2006) UK Energy in Brief, London.  p.13  www.dti.gov.uk/files/file32387.pdf

El Sayed M.A., Matthew R. and Mortimer N.D. (March 2003) 'Carbon and energy balances for a range of biofuels options', DTI Project Number B/B6/00784/REP http://www.dti.gov.uk/files/file14925.pdf?pubpdfdload=03%2F836

Grubb, M., Butler, L. and Twomey, P. (2006) 'Diversity and security in UK electricity generation: The influence of low-carbon objectives', unpublished article, Faculty of Economics, University of Cambridge.

Holtz-Eakin D. and Selden, T.M. (1995) 'Stoking the fires – CO2 emissions and economic growth', Journal of Public Economics, 57, 85-101.

Hoogwijk, M., de Vries, B. and Turkenburg, W. (2004) 'Assessment of the global and regional, geographical, technical and economic potential of on-shore wind energy', Energy Economics, 26, 889-919.

Intergovernmental Panel on Climate Change (2001) Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC, Cambridge University Press, Cambridge.

Keay, M. (2005) 'Wind power in the UK: Has the Sustainable Development Commission got it right?', Oxford Energy Comment, Oxford Institute for Energy Studies, May.

Leamer, E. and Storper, M. (2001) 'The economic geography of the internet age', Journal of International Business Studies, 32, 641-665.

Metzemakers, P. and Louw, E. (2005) 'Land as a production factor', working article, Delft University of Technology, The Netherlands.

Mitchell, C. and Woodman, B. (2006) 'New nuclear power: implications for a sustainable energy system', working article, Centre for Management under Regulation, Warwick Business School.

Neuhoff, K. (2005) 'Large-scale deployment of renewables for electricity generation', Oxford Review of Economic Policy, 21, 88-110.

Neuhoff, K., Ehrenmann, A., Butler, L., Cust, J., Hoexter, H., Keats, K., Kreczko, A. and Sinden, G. (2006) 'Space and time: Wind in an investment planning model', Cambridge Working Articles in Economics, University of Cambridge, CWPE 0620, February.

Nonhebel, S. (2005) 'Renewable energy and food supply: Will there be enough land?', Renewable and Sustainable Energy Reviews, 9, 191-201.

Nordhaus, W.D. (1991) 'To slow or not to slow: The economics of the greenhouse effect, Economic Journal, 101, 920-937.

Ogden, J.M. (1999) 'Prospects for building a hydrogen energy infrastructure', Annual Review of Energy and the Environment, 24, 227-279.

Oswald, J., Raine, M., Ashraf-Ball, H. (2008) 'Will British weather provide reliable electricity?', Energy Policy, 36, 3212-3225.

Pearce, D. (1991) 'The role of carbon taxes in adjusting to global warming', Economic Journal, 101, 938-948.

Pimentel, D., Herdendorf, M., Eisenfeld, S. et al (1994) 'Achieving a secure energy future – Environmental and economic issues', Ecological Economics, 9, 201-219.

Raehsler, R.D. (1996) 'Statistical inquiry into the causes of global temperature changes', International Journal of Environment and Pollution, 6, 32-49.

Robinson, C. (2005) 'The economics of climate change', University of Surrey Economics Working Article and Memorandum to House of Lords Committee on Economic Affairs, January.

Schultz, M.G., Diehl, T., Brasseur, G.P. and Zittel, W. (2003) 'Air pollution and climate-forcing impacts of a global hydrogen economy', Science, 302, 624-627.

Smith, S. (1998) 'Environmental and public finance aspects of the taxation of energy', Oxford Review of Economic Policy, 14, 64-83.

Stephens J.H. (Editor) (2002) 'Kempe's Engineers Year-Book', CMP Information Ltd., Data & Information Services Division.

Stern, N.H. (2007) The Economics of Climate Change: The Stern Review, Cambridge University, London.

Strachan, P.A. and Lal, D. (2004) 'Wind energy policy, planning and management practice in the UK: Hot air or a gathering storm?', Regional Studies, 38, 551-571.

Terrado, E., Mendis, M. and Fitzgerald, K. (1989) 'Impact of lower oil prices on renewable energy technologies', Working article WPS 110, Industry and Energy Department, World Bank, February.

Turner, J.A. (2004) 'Sustainable hydrogen production', Science, 305, 972-974.

Weyant, J.P. (1993) 'Costs of reducing global carbon emissions', Journal of Economic Perspectives, 7, 27-46.