Energy Solutions for 60% Carbon Reduction **Gordon Taylor** **Revised 2005-09-27**

Summary

This study was prompted by the Royal Commission on Environmental Pollution Report No. 22, "Energy - the Changing Climate", and by the U.K. Government Cabinet Office Performance and Innovation Unit (PIU) Energy Review. It adopts the target of a 60 % reduction in UK carbon emissions by 2050. It also recognises that UK and world oil and gas resources are approaching exhaustion. However, exergy analysis has revealed that the UK energy system has two main Thermodynamic Improvement Potentials (TIPs). These are in the heating of buildings, and in road transport, and amount to 26 % of the primary energy consumption. Also, the UK has vast potential resources of renewable energy - especially biomass and wind.

Technology options for energy saving, energy efficiency and renewables are compared directly for carbon saving. Those for energy efficiency include options that address the two main TIPs. A new analysis shows that Thermodynamic Heating from large scale Combined Heat and Power gives fuel and carbon savings of 76 % or more. However, the present CHP QA Criteria do not reward carbon savings correctly, so new criteria are proposed. The findings for heating include Not Micro-CHP or Fuel Cells, fuelled by Hydrogen, but District Heating from CHP, fuelled mainly by gas, with some biomass. Wind turbines could provide electricity for ethanol synthesis, and more heat for District Heating. The findings for road transport include Not Fuel Cells fuelled by Hydrogen, but Hybrid engines fuelled by Ethanol. This last could be home-grown bio-ethanol, ethanol synthesised in a carbon-neutral fashion, and imported ethanol. These findings are based on extensive evidence from Europe, America, and Japan.

The UK energy system in 2050 was modelled with the most effective options, and a Linear Programming method used to find optimum solutions. These suggest that the 60% carbon reduction target could be met, and with scope for flexibility, by varying the amounts of biomass and wind energy. Along with an overall demand reduction of 30 %, the Final to Primary energy fraction could increase from 0.69 at present to around 0.80, and the Renewable to Primary energy fraction from 0.01 at present to around 0.30. Some solutions could even reduce oil and gas consumption below the levels permitted by the carbon target. Such solutions would increase energy security, environmental quality and sustainability, and reduce fuel poverty.

In Part II, the case is developed for a new operating regime in UK energy markets. Having satisfied itself and others that there are energy technology solutions that can meet their carbon emission targets, the Government could invite energy service companies to take up franchises for these markets. These would each have sales of around a billion pounds a year, and be accompanied by Carbon Reduction Obligations, which would directly reflect those of the Government itself. With their knowledge of the field, experience in big projects, and access to low cost, long term financing, these companies could implement energy saving and efficiency, and renewable energy supply options, symmetrically with fossil energy supply - in order to meet their Carbon Reduction Obligations.

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1 Introduction

Following the Kyoto Protocol, the UK Government has committed itself to a 12.5 % reduction in greenhouse gas emissions from the 1990 baseline level during 2008-2012. It has also set a national target of a 20 % reduction in carbon dioxide emissions by 2010. Moreover, the Royal Commission on Environmental Pollution recommended that the UK move towards sustainability, by reducing the total UK greenhouse gas emissions by 60 % by 2050 and 80 % by 2100. [1] For this report, the base year was taken as 1997, when the UK total carbon emissions on the IPCC basis were 155 MtC. [2] The carbon emission target for 2050 is thus 62 MtC/y. These quantities are summarised in Table 1 and Fig. 1. [The GHG and carbon emission values have been lumped together to illustrate the trend]. Moreover, the production of oil is expected to peak around 2005, and gas around 2015, followed by steep increases in prices. [3] This inevitability is arriving faster than climate change, and may be an even greater spur to carbon reduction.

The driving objective of UK energy policy is therefore carbon reduction – primarily due to climate change, but also due to the exhaustion of oil and gas. Other objectives of UK energy policy are maintaining security of energy service and the relief of fuel poverty.

There are 24 million households in the UK. Assuming each had a 10 kWth boiler, this would be a total domestic heat load of 240 GWth (before diversity). For comparison, the total electric capacity of the large power stations is about 80 GWe. There are 24 million cars in the UK, accounting for a large part of the consumption of transport fuel. In all, the UK consumed purchased primary energy of about 243 mtoe in 2001. However, there are 24 million hectares of land in the UK. This receives solar energy equal to about 20 thousand mtoe each year, with more available from the winds and the seas. Even within the limits of biology and technology, the problem should be soluble with the right choices.

1.1 Energy Quality

Energy has a simple thermal dimension, and also a 'thermodynamic' dimension. Equal amounts of the various forms of energy may differ in quality – i.e. their ability to do work (= mechanical power x time). This quality of energy is known as 'exergy', and is low for hot water, medium for fuels, and high for electricity, which can drive a motor, and produce mechanical work. However, for both thermodynamic and practical reasons, and because electricity generating plant is expensive, exergy has to be paid for – both in higher conversion costs, and in the marketplace – where the price of domestic electricity is about five times the price of heat (or gas in the UK). It follows that – to minimise the waste of exergy and energy - the energy quality of the carrier should be matched to that of the load - i.e. low temperature heat for space and water heating, portable fuels as sources of energy (e.g. in vehicles), and electricity for light and mechanical work.

Fortunately, an exergy analysis of the UK energy system has been published fairly recently. [4] This determined the scope for improvement, both in total and for four end-use sectors. The total scope is about 30 % - and has been for over three decades. It is much the greatest in the supply of heat to the domestic, services, and industrial sectors, and secondarily in the conversion of fuel to mechanical power in electricity generation and in transport vehicles. Thus, in the domestic and services sectors, the Thermodynamic Improvement Potential in space and water heating is 28.2 + 10.5 = 38.7 mtoe/y, and that in road transport is 22 mtoe/y. They account for about 17 % and 9 % = 26 %. Recognition of these priorities is absolutely crucial to achieving the maximum energy and carbon savings, and thus the present objective. The above paper was cited in the DEFRA Energy Efficiency Strategy that was included in the PIU Energy Review Working Papers. [5] However, I am not aware of any recent study that directly addresses these potentials. Therefore the purpose of the present study is to explore the options which do (amongst others).

1.2 Criteria for Choosing the Options.

The present study uses energy technology options available today to provide for the future up to 2050. By basing the choices on 'sound science' (exergy analysis), the technological limits are recognised, but the choices are tested against an ideal. They have already proved highly effective in other European countries, Japan, and America. Moreover, the options chosen have been shown (in the following analysis) to deliver substantial savings in exergy, energy, and carbon for the UK, and are therefore very likely still to be optimal in 2050. This approach is thus 'evidence-based' through both the actual installations in place (e.g. in Denmark, Germany, and elsewhere), and the following analysis. The options chosen are thus assured of a future and, as mature - but state of the art - shipping products, they can be costed with confidence, and are attractive to investors.

The present study thus differs from the MARKAL study that has informed the IAG and PIU reports. [6] [7] Not only does it reduce the range of options by testing them directly against the principal objective - carbon reduction - but it also avoids assuming technology advances which may or may not be realised. Moreover, some assumed in the MARKAL study may not be realisable due to expense. Others may be hardly relevant while the large exergy potentials remain untapped.

Other countries, such as Denmark and Germany, have also considered exergy in choosing their energy technology options, and have found that appropriate choices can offer great rewards:
- meeting their international commitments and national targets on carbon emissions.
- reducing fuel poverty and increasing sustainability.
- securing a higher degree of energy self-sufficiency.
- attaining an improved environment, with lower noxious emissions.
- reducing expenditure on imported fuel.
- providing attractive opportunities to investors on the necessary scale.
- providing employment.
- affording scope for new and popular exports.

1.3 Summary of the Approach

First several major options for energy saving and supply are discussed, both qualitatively and quantitatively. To facilitate checking, references are given for (almost) every statement, equation, and data value. Then, recognising that the greatest opportunities lay in heating and transport:

A spreadsheet model is used to compare options for the supply of heat (and some electricity).

A spreadsheet model is used to compare the production of biofuels for transport.

Finally, a spreadsheet model is used, which starts with a breakdown of final energy by sector and the principal end-uses for 2001, and embodies the chosen options for heat, electricity and transport fuels, to seek solutions for the 60 % carbon reduction target for 2050.

The models used are engineering, rather than econometric. The latter are often particularly wanting in their use of extrapolation. Hubbert and Campbell have shown that the resources of oil and gas are finite, which is a fundamental discontinuity. This makes future prices quite unpredictable. Also, as engineering systems, energy technology options cannot be improved without limit without violating the physical laws, such as the First and Second Laws of Thermodynamics. The latter gives rise to the maximum theoretical efficiency of conversion from heat (e.g. from fuels) to work. This is known as the Carnot efficiency, and is a function of the top and bottom temperatures. (See below). Moreover, higher efficiency usually costs disproportionately more - e.g. in costly materials - so it is often better to do something else instead. For example, rather than striving for ever-higher electricity efficiency of power plant, it is better to harness the reject heat, via Combined Heat and Power. This is particularly so since the demand for heat is much larger than the demand for electricity.

1.3 Data

In the UK, the data on energy production and use is collected by the DTI, and published as the Digest of UK Energy Statistics (DUKES). [8] However, the data on the associated emissions is collected by/for the DEFRA, and published as NETCEN. [9] Unfortunately, they are broken down differently. This makes it difficult to determine the emissions consequences of any change in energy production and use (analysis), or the energy production and use needed to achieve a given emissions outcome (synthesis).

In the UK, data on energy production and use is also available in less detail - by fuel, and by end-use sector, usually domestic, services, industrial, and transport. As well as the original primary form - coal, oil, gas - it is usually given in terms of so-called final energy. This means the refined or converted form - heating oil, gas, electricity, and transport fuels - in which it is sold to the final end user. (For Continental readers, very little heat is sold as such in the UK). The forms of final energy in the UK in 2000 were approximately: heating fuels 48 %, electricity 18 %, and transport fuels 34 %. [10] Final energy is then converted - by e.g. boilers and engines - to energy services – heat, mechanical power, and electricity for lighting and electronics, and motion in vehicles. Fortunately, data on energy consumption in the UK, broken down by fuel, sector, and the main types of end use, has been published fairly recently. [11]

For stationary plant (e.g. boilers and engines), there is some published data on the conversion efficiency at full load. However, there is much less data published in the UK on the part load efficiency and almost none on the annual average efficiency of these conversions. This makes it difficult to determine the scope for improvement. For the large fossil-fuelled electricity generating plant, both input fuel quantities and output energies are published, along with the annual average efficiencies for the different plant types - e.g. in DUKES. [12] For road transport vehicles, data obtained during emissions testing may be used to determine the thermal efficiency of the engine and transmission. However, this only reaches the open literature via occasional professional society papers.

In line with UK practice, in this document the energy content (calorific value) of fuels, and the thermal efficiencies, are generally quoted on the Gross Calorific Value (GCV) or Higher Heat Value (HHV) basis. Exceptions - quoted on the Net Calorific Value (NCV) or Lower Heat Value (LHV) basis - are noted.

In UK energy data, much use is made of the non-SI units of energy - toe and mtoe.
1 tonne oil equivalent = 41.868 GJ. 1 million tonnes oil equivalent = 11.63 TWh.

Energy quality can usefully be implied when using the units of power and energy - Watts (W) and Joules (J). Thus Wth can be used to imply thermal heat, Wfuel to imply fuel, and We to imply electricity.

2 Energy Technology Options

In addition to quantifying the scope for improvement, it is necessary to consider the various energy technology options that could help meet the targets. There are two main end-use sectors - (stationary) heat and electricity, and (mobile) transport - and three ways of reducing carbon emissions – energy saving (via both demand reduction and energy efficiency increase), renewable energy supply, and fuel switching.

2.1 For Heat and Electricity

Examples of energy saving options are:
- Insulating buildings to save heat.
- Heat pumps for heating
- Micro-CHP and hydrogen for heating
- DH-CHP for heating.
- Electricity saving in appliances and lighting.

Examples of renewable energy supply options are:
- Biomass for heat and electricity.

- Large-scale solar heat.
- Wind electricity.

Examples of fuel switching options are:
- Replacing coal and oil with natural gas.
- Replacing coal with ‘clean coal’ – i.e. coal with CO_2 capture and sequestration.
- Replacing fossil fuels with nuclear fission.

2.2 For Transport

Examples of energy saving options are:
- Smaller road vehicles.
- Hybrid engines in road vehicles.

Examples of renewable energy supply options are:
- Biomass liquids (bio-fuels) for transport fuels.

Examples of fuel switching options are:
- Replacing petroleum-based transport fuels with synthetic low carbon or carbon-neutral fuels.

3 Heat - Energy Saving

To evaluate options for saving energy and carbon emissions for space and water heating in buildings, it is necessary to know the average annual efficiency of the present stock of conversion equipment - here mainly gas boilers. Unfortunately, very little work has been done on this in the UK, and even that was many years ago, before gas and electricity supply was privatized, and such end-use R and D ceased. Now it seems to be nobody's responsibility, despite the evident importance for energy policy planning. Not only is the cost of gas some £ 5 billion a year for the domestic sector alone, but it will soon have to be imported again. [13] Meanwhile, for the average annual efficiency of domestic gas boilers, the PIU has used 0.65 or 65 %. [14]

3.1 Insulation and Advanced Windows

For new and existing buildings, there is considerable scope for saving heat by insulation. When applied to cavity walls, it is invisible, but solid walls may be insulated either internally or externally, which can still look good, and this is widespread in Denmark and Germany. Another option, with both cavity and solid walls, is to fit advanced windows. These typically use special coatings on the glass of double-glazed units, in frames specially designed for high thermal performance. [15] They are far more effective thermally than conventional double-glazed windows - never mind the single-glazed windows still widespread in the UK. The benefit is far greater than their area, since thermally windows are the weakest parts of the building envelope. If the original windows are old, new ones will also reduce ventilation heat losses. Denmark is the first country to develop an energy-labelling scheme for the advanced windows available in Denmark. [16] In a single-family house under Danish conditions, the best windows give a positive net energy gain of more than 20 kWh/m2 per year. [17] If the appearance is critical, as in 'heritage' buildings, then visible insulation measures may not be permissible and reliance must be placed on other options, such as DH-CHP.

3.2 Zero Heat Buildings

It is possible to build new, detached houses in the UK that require little or no energy for space heating. Instead of using passive or active solar heating and thermal storage (as in earlier attempts), this was done successfully with very high levels of insulation. Moreover, this was without any loss of function or significant additional cost, and within current building codes. [18] Since 'zero heat' is possible for a single house, then - due to the 'square-cube law' - it should be even easier for larger buildings, such as blocks of flats or offices. This should therefore become the norm for new buildings, which are usually sited at the edge of existing cities and towns, or in the countryside. Zero heat design is especially desirable when the buildings are far from any gas or district heating network.

3.3 Thermodynamic Heating

Given demands for electricity and low temperature heat, the best ways of using the exergy in the fuel, and reducing the energy required for heating, all involve ‘thermodynamic’ heating. Rather than supplying all the heat from fuel, this means upgrading the temperature of another source of heat by doing work on it. Although termed an 'efficiency', that of thermodynamic heating can exceed one. Nevertheless, for the present study, the term 'thermodynamic heating efficiency' (THE) is used. The options capable of 'thermodynamic heating' include individual electric heat pumps, gas-fired heat pumps, and Micro-Combined Heat and Power (Micro-CHP) units, and District Heating from large central CHP plant (DH-CHP). For any form of CHP, the heat-related fuel consumption and carbon emissions are those of the CHP unit, generating heat and power, minus those for equal amounts of electricity from central generators.

3.4 Heat Pumps

Heat pumps require a source of low temperature heat (usually outside air or water), which is upgraded in temperature – e.g. for space heating. However, both electric heat pumps (after allowing for the efficiency of electricity generation), and gas-fired heat pumps, offer THEs no greater than about 1.3, and present many installation problems. The outside air or water may have temperatures of e.g. 20 C in summer, and 0 C or lower in winter, and hence heat pumps often have problems with freezing of water on or around the source coil in winter. This - along with the high specific cost of heat pumps - means that they usually require a separate fuel-fired or even electrical heater for high heat loads. This imposes undesirable peak loads on the supply and distribution system, and reduces the annual average THE, and they are not considered further.

3.5 CHP Energy Input Conventions in the UK

In UK energy statistics, CHP has been treated according to several different conventions. [19] Paragraph 6.32 says in part "In order to provide a comprehensive picture of electricity generation in the UK and the fuels used to generate that electricity, the energy input to CHP schemes has to be allocated between heat and electricity production. This allocation is notional and not determinate. The present [usual] convention is that CHP plant displaces Heat-Only Boiler plant with an overall efficiency of 75 per cent. The fuel that would be consumed in the Heat-Only Boiler plant to produce the same amount of heat - - - is subtracted from the CHP scheme's fuel consumption. The balance is the amount of fuel assumed to be used for electricity generation". [Thus all the benefit is allocated to electricity generation, and this completely conceals the advantage of thermodynamic heating].

Paragraph 6.32 mentions that in the iron and steel sector, the above convention can give negative fuel inputs for electricity generation, or inputs that are less than the energy production. [i.e. electricity and total efficiencies of over 100 per cent]. Therefore an additional [alternative] assumption has been made for iron and steel that the fuel input for electricity was equivalent to that required to generate the electricity at an efficiency of 85 per cent. [It is surprising that this did not give some engineers pause for thought].

There is a fuller discussion of the allocation of fuel use between electricity generated and heat supplied in "Savings in Carbon Emissions from Combined Heat and Power". [20] Three conventions are discussed.

The first - as the first above - of all the fuel and emissions savings being allocated to electricity generation - is used by the EU, and hence by the UK for annual energy statistics.
The second - of electricity generated with the best available comparator (in this case taken as the carbon content of the average on the grid), with the remainder allocated to heat supply. This is used for the UK Standard Assessment Procedure (SAP) for the Energy Cost calculations for dwellings. [21]
The third is a convention midway between the other two - and relates the split to the (notional) relative efficiency of heat and electricity supply - or more specifically: two units of fuel allocated to electricity, and one unit of fuel allocated to heat. This has been adopted for the DETR Guidelines for Company reporting of Greenhouse Gas Emissions, and for Negotiated Agreements as part of the Climate Change Levy. [22]

3.6 CHP Working Principles

3.6.1 Basics

All Combined Heat and Power units contain an engine and a 'virtual heat pump'. (See Fig. 2). A particular advantage of the CHP 'virtual heat pump' is that it has no apparent physical manifestation, including the working fluid. For a device capable of delivering up to hundreds of MegaWatts of heat, this seems remarkable. In fact, both are effectively shared with the 'power cycle' hardware - the engine or turbine. In effect, the prime mover (engine or turbine) embodies two thermodynamic cycles. One - the 'power cycle' - provides the major amount of mechanical (then - via a generator - electrical) power and the other - the 'heat pump cycle' - uses a minor amount of power to upgrade a source of low temperature heat to a more useful temperature. For the 'virtual heat pump', the 'work' input is manifest as a modest reduction in the potential electricity output of the engine, the source of low temperature heat is the water returning from the central or district heating, and the heat output is carried in the water flowing to the central or district heating.

To assess CHP correctly requires allocating fuel and carbon costs between the useful heat and electricity generated, and determining the true heating efficiency. Several authors recommend that fuel costs be allocated according to the 'exergy method'. [23] This means according to the ability of the two energy outputs to do work. When this is done, the true efficiency of 'thermodynamic heating' becomes apparent. [24]

Consider a CHP plant which:
- in Back-Pressure mode has a Heat Efficiency of ηh, an Electricity Efficiency of ηe, and a Total Efficiency of $\eta h + \eta e$,
- and in Condensing mode has a Heat Efficiency of 0, an Electricity Efficiency of ηc, and a Total Efficiency of ηc.

Then the appropriate ratio Fuel to Electricity/Fuel to Heat = $\eta e/(\eta c - \eta e)$
This allocation of fuel use not only avoids the confusing variety of different conventions, but it reveals the true efficiency of thermodynamic heating from CHP.

If the Electrical Efficiency of the Generator is 1, the Thermal Efficiency = the Electricity Efficiency, ηe.

A CHP plant has a 'Virtual Heat Pump' with a Coefficient of Performance (COP) = $\eta h/(\eta c - \eta e)$

Then the Thermodynamic Heating Efficiency (THE) = Thermal Efficiency x COP = $\eta e \times \eta h/(\eta c - \eta e)$

Some may be concerned that the THE often has values greater than 1 (or 100 %). However, no other term seems to have gained wide acceptance. Some might be tempted to call it a COP, but this is only part of the THE. Frutschi calls it the 'Heat Potential', but it is actually available. The term THE is used in the present study.

Referring to Fig. 2, the thermal efficiency of the engine is about 0.5, and the COP for the electric heat pump is about 3, which gives a THE of about 1.5. However, for CHP, the thermal efficiency of the engine is still about 0.5, but the COP of the 'virtual heat pump' is about 8, which gives a THE of about 4 or 400 %. Hence for the same amount of heating, the motor power for the electric heat pump would have to be about 4/1.5 =

2.7 times as much as the effective motor power of the 'virtual heat pump' of CHP. Moreover, while an electric heat pump of comparable output would be expensive, the 'virtual heat pump' of CHP capability adds little or nothing to the cost of a turbine-generating set. (It contains the same number of components, and actually fewer rows of turbine blades).

3.6.2 More Advanced

More advanced consideration becomes necessary when data for the above parameters is not available, and must therefore be estimated. A CHP unit can be analysed by considering the two 'cycles' as ideal Carnot cycle machines in the first instance. The Carnot cycle is the 'ideal' for all heat engines and all heat pumps, and their efficiencies depend on the highest (top) temperature, T1, and lowest (bottom) temperature, T2, in the cycle. These temperatures must be expressed relative to 'absolute zero', -273 C, and such temperatures use the Kelvin scale, degrees K. The Carnot 'power cycle' thermal efficiency (a ratio of work to heat) is equal to (T1-T2)/T1, and the corresponding 'heat pump cycle' efficiency is T1/(T1-T2). (This is for the case when the 'product' is heat. When the 'product' is cold, as for a refrigerator, the ideal efficiency is T2/(T1-T2)). Since the heat pump efficiency (a ratio of heat to work) may be greater than one, it is often termed a Coefficient of Performance (COP). Real machines can never achieve the Carnot efficiencies, but they can approach them. Most importantly, the performance and efficiency of real machines are proportional to those of the ideal machines - notably in respect of changes in the top and bottom temperatures.

Thus the efficiencies of real machines change according to the above formulae, multiplied by simple factors which are substantially constant over the temperature ranges of interest. They may be termed 'Carnot factors', and are always less than one for real machines. Typical values for the 'Carnot factor' are 0.66 or more for a large power plant, and 0.5 for a small one, with 0.5 for a large 'virtual heat pump', and 0.33 for a small one. [25] They vary because large machines can afford to be more complex (in the interests of efficiency) than small ones, and due to scale effects. Where possible, the Carnot factors should be deduced from available data, using the above formulae. Hence the efficiencies at other temperatures may be calculated by the ‘delta-power’ method. For example, given data for either the back-pressure or condensing mode, that for the other may be calculated.

In some cases no engine thermal efficiency data is available. For any engine, the top temperature experienced by the working fluid of the 'power cycle' may be estimated. For an internal combustion engine, such as a gas turbine or a piston engine, it may be taken as the flame temperature - perhaps 1000 C. For an external combustion engine, such as a steam turbine or Stirling engine, it will be limited by the metal of the wall between the flame and the working fluid - to perhaps 600 C. When generating only electricity in 'condensing' mode, the outside air or water used as a sink for the reject heat, giving a bottom temperature of perhaps 10 to 20 C. CHP involves raising the bottom temperature of the 'power cycle' to that of the water returning from the central or district heating - perhaps 40 to 50 C. This is called 'back-pressure' mode. Using the above formulae and factors, the thermal efficiencies in back-pressure and condensing modes may be estimated by the ‘cycle’ method.

By assuming that the total efficiency of the CHP unit is say 0.8, and subtracting the thermal efficiency in back-pressure mode, the heat efficiency may be estimated. Hence the thermal efficiency in back-pressure mode of the 'power cycle', and the COP of the 'virtual heat pump cycle' may be calculated. Multiplying the two together gives the 'thermodynamic heating efficiency' (THE) of the CHP unit.

Absolute clarity is now essential in the energy field, in order to take well-informed decisions. Yet multiple conventions must lead to endless conflicts and misunderstandings. Therefore, to avoid these - and anybody thinking that any of the conventions is true - the thermodynamically correct analysis of CHP should be adopted. This is all the more important, since it can best address the largest single Thermodynamic Improvement Potential in the UK energy system, amounting to 39.7 mtoe in 1999 - i.e. about 17 % of the national purchased primary energy consumption. This thermodynamically correct analysis of CHP has been used for the modelling of Micro-CHP, District Heating-CHP, and Industrial-CHP that follow.

3.7 Micro-CHP

Micro-CHP units usually consist of a small engine driving a generator, and produce heat and electricity. Unlike boilers, ordinary small internal combustion (piston) engines are not intended to run thousands of hours a year. Hence most Micro-CHP units use external combustion Stirling engines. These engines are expensive. (See Fig. 3). [26] Hence they are usually sized for only part of the load, and include a supplementary burner or boiler for higher heat loads. The typical cost of a Micro-CHP installation is £ 2800 for a unit of 3 kWe and 9 kWth. [27] Moreover, since one is needed for each dwelling, Micro-CHP units do not benefit from the 'diversity factor' of e.g. 0.7 of large networks. From the national perspective, this increases the total cost of the option. Furthermore, because they are nevertheless built down to a price, the frequency and cost of maintenance (parts and labour) will probably still be high.

All CHP plant works by upgrading the temperature of the water returning from the central heating, which avoids many of the installation problems. The 'virtual heat pump' has source temperatures of e.g. 30 C in summer and 40 to 50 C in winter – and hence no problem with freezing. Micro-CHP units may have an electricity efficiency of 0.15, and a total efficiency of 0.9. [28] Hence, Micro-CHP units may have a THE of only about 0.86 – and after allowing for the effect of the supplementary boiler needed for higher heat loads, the annual average THE for supplying heat may be still only 0.86. This is no better than a condensing boiler.

Micro-CHP units could also be based on fuel cells. These avoid the Carnot cycle limit on conversion efficiency that applies to heat engines, and may have a higher electricity efficiency, but the case would not be much improved. They convert hydrogen (plus oxygen from the air) to heat and electricity, but when supplied with natural gas, they need a reformer to extract the hydrogen. This would be expensive and incur energy losses – not least because the carbon content is discarded as CO_2. Although, unlike an engine, they have no reciprocating parts, fuel cells have at least a compressor and an expander for air, and a pump for exhaust water – so are certainly not simple or silent. Also, they usually contain some platinum metals for catalysis – which makes them expensive.

See also Appendix

Some have proposed the production of hydrogen, to be fed through the gas network, and burnt in boilers or Micro-CHP units. [29] In principle, this could be done using renewable energy or nuclear power. Hydrogen networks make more sense for supplying fuel cell Micro-CHP units, since this would avoid the need for a local reformer. However, by far the cheapest way of making hydrogen is by reforming natural gas, incurring losses. Hence, hydrogen incurs an energy penalty, and increased carbon emissions. Moreover, both natural gas and hydrogen have high exergy. Thus using either would still involve a gross exergy mismatch with space and water heating, and the heat rejected in central electricity generation would still not be harnessed.

See also Appendix.

3.8 District Heating

An alternative to a hydrogen network is a hydrogen oxide (i.e. hot water) network for District Heating. This consists of pairs of insulated pipes laid in the street, carrying hot water, to which each building is connected.

- This is the perfect match (not least in exergy terms) for space and water heating in buildings.
- Having a much larger molecule, water is far less prone to leak. Also, being a liquid, it is visible.
- Even if it does leak, the energy loss is much less, and hot water is not (very) dangerous.
- Because it is neither flammable nor potentially explosive, hot water would attract no unwanted attention from terrorists.
- This is the only energy network option that allows the harnessing of heat from CHP, waste and biomass combustion, and solar heat collectors, and hence is by far the most sustainable option.
- Hot water networks have a fifty-year track record of success, so are easy and inexpensive to finance.

A common impression in the UK is that DH networks suffer from high heat losses. However, this is based on experience of old systems, which were built on the cheap, and then neglected. Moreover, the heat used was almost never metered or properly controlled, so encouraging waste - such as opening windows to deal with over-heating. Existing DH networks that are properly designed and built have overall heat losses of about 13 %. [30] New DH networks may have overall heat losses of only 7 %. [31] This may be compared with the transmission and distribution losses for centrally generated electricity of 7.4 % [32] and for natural gas of 5 %. [33] Moreover, modern DH installations include metering, which helps in fault-finding, and encourages proper economy in use. Furthermore, they provide primary temperature control over the year, with outside temperature compensation. Thus the water flow temperature is higher in winter and lower in summer, which reduces losses. Also, in most countries where DH is widespread, every radiator must be fitted with a thermostatic valve of approved quality and function. These provide individual room control, and also take maximum advantage of incidental gains, from occupants, sunlight, lights and appliances - thus avoiding over-heating, and saving energy. Finally, correct design of the space and water heating systems should ensure low return temperatures - e.g. 40 to 50 C - which also reduces losses.

DH originated with group or community heating schemes with heat-only boilers. This was because the larger boilers could burn heavy oil, which was much less expensive than the light oil needed for individual boilers. However, heat has come increasingly from CHP plant, giving much greater savings - especially of energy. (See below). Nevertheless, DH networks are not limited to delivering heat from fossil or even renewable fuels (e.g. biomass). Sooner or later, they may be used to deliver heat from large solar arrays, and including inter-seasonal heat storage. Several prototype installations already exist. (See below).

3.9 District Heating with Combined Heat and Power (DH-CHP)

Most conversion of fuel to electricity is done in large, stationary power plants. The conversion losses take the form of heat which is usually rejected to the ambient - either rivers or the sea where possible, or atmospheric air, via large cooling towers (all too numerous in the UK). In the UK, the total heat thus rejected is comparable in amount to the total electricity produced, and to the total demand for space and water heating in the domestic, services, and industrial sectors. This suggests a solution, known as co-generation or combined heat and power (CHP), together with District Heating (DH) double-pipe networks to take the heat to the buildings. This increases the exergy efficiency of building heating (mainly by displacing heat from gas boilers), and has been widely adopted over the last fifty years - especially on the Continent. CHP plants can be located near their heat loads, rather than e.g. near the sea. Moreover, the heat is generated ‘thermodynamically’ at very high efficiency, and can be sold profitably, which improves the economics of the complete system.

Nowadays, most new large electric power plants (e.g. 100 MWe and above) are fuelled with natural gas, and use a Combined Cycle, consisting of a Gas Turbine, coupled with a Steam Turbine (GTCC). This offers high conversion efficiency and low emissions, along with low specific capital cost - e.g. £ 270/kWe. [34] Such GTCC plant is especially suitable for CHP operation. Although the electrical efficiency is high, at around 0.5 (on the Gross Calorific Value or Higher Heat Value basis), the reject heat is still appreciable. For District Heating, the flow temperature may be up to say 90 C, but an annual average of say 70 C, and the return temperature may be say 50 C, rather than say 10 to 20 C for condensing operation. However, due to the high top temperature of the GTCC plant, DH may be supplied with only a small drop in the notional electrical output. For example, with modern GTCC plant, the heat supplied at 90 C divided by the drop in notional electrical output (i.e. the COP) is 8.2. With an electricity efficiency in back-pressure mode of 0.514, the THE is therefore 8.2 x 0.514 = 4.18. [35] Hence the ‘efficiency’ of thermodynamic heating for such CHP plant is 418 %.

A complete District Heating system always includes fuel-fired heat-only boilers, that are intended for emergencies, and while the heating load is being built up. Thus they are used to supply buildings as they are connected to the network, and before connection of another CHP plant. Moreover, the heat-only boilers are also used to supply e.g. 5 to 10 % of the annual heat energy in helping meet peak loads, which may halve the maximum demand on the CHP plant, and thus lowers the overall cost.

With any large system supplying water, heat, gas, or electricity, the peak system load is less than the sum of the individual loads, due to 'diversity'. This is because – at any one time - some buildings are less than fully occupied. For a large system (e.g. 100s of buildings or dwellings) the 'diversity factor' can be as low as 0.7. In the case of District Heating, the peaks of demand are further eased by the heat stored in the pipe network, which can cover an hour or two. This can be extended with thermal stores (large tanks of hot water) - to e.g. 8 or 10 hours. By allowing the heat generated to be greater (when charging) or less (when discharging) than the current heat demand, such stores increase the flexibility for meeting both the heat and electricity demands at high efficiency.

Even after allowing for the effect of a small amount of heat from heat-only boiler plant at higher heat loads, and for the heat distribution losses, the annual average THE can still be about 3.3 or 330 %. Since the efficiency of domestic gas boilers may be only 0.65, such thermodynamic heating can deliver savings in fuel for heating of about (1/0.65 - 1/3.3)/(1/0.65) = (1 - 0.65/3.3) = 0.80 or 80 %.

3.10 Fuel Use and Carbon Emissions (for heat and electricity generation)

Several different heat supply options, such as Micro-CHP and DH-CHP, have been analysed and compared. For a given useful heat load, the amounts of cogenerated electricity differ, and hence the matching electricity, and the net fuel required for heat. The calculations of the energy and carbon savings are shown in Table 2 and the results summarised in Table 3.

The UK space and water heating demand by sector in 1998 was domestic 69 %, services 25 %, and industrial 6 %. [36] To allow a direct comparison to be made between Micro-CHP and DH-CHP, only the heat demand for the domestic sector was considered at first, since the services and industrial sectors are comprised of larger buildings, which would be unlikely to use Micro-CHP units. Furthermore, the heat demand considered was taken as only the domestic heating demand that is currently met by gas. In principle, Micro-CHP and DH-CHP could serve the whole domestic space and water heating demand. However, all networks (electricity, gas, and hot water) become less economic at lower load densities. So the remainder - largely rural domestic dwellings - may continue to be heated by other means (e.g. electricity, oil, LPG, biogas or wood). For 2000, the final gas energy for space heating was 21.652 mtoe and for water heating was 8.608 mtoe, giving a total of 30.26 mtoe. [37] With a domestic gas boiler efficiency of 0.65, the corresponding useful heat is 30.36 x 0.65 = 19.67 mtoe = 229 TWh.

The carbon saving depends on the type or mix of fuel displaced. The carbon intensity for primary gas is 51.8 gC/kWh fuel. With a transmission and distribution loss of 5 %, this becomes 54.5 gC/kWh fuel. With an electricity generation efficiency of 0.5, it becomes 109 gC/kWhe. The carbon emissions from UK power stations in 1999 was 38.5 MtC. [38] The electricity sent out by the major power producers in 1999 was 317 TWh. [39] Hence the average carbon intensity for the fuel mix used in 1999 was 121.3 gC/kWhe.

Proponents of Micro-CHP put the UK potential at 13 million units - 8 million x 1 kWe and 5 million x 3 kWe. [40] At an average installed cost of £ 2800 each, this would be £ 26 billion. [41] With an average electrical capacity of 1.77 kWe each, this is a specific cost of £ 1582/kWe. Compared with that of a GTCC plant with an electricity efficiency of 0.5, at £ 270/kWe, this is nearly six times as much. Yet Micro-CHP units may have an electricity efficiency of 0.15, and a total efficiency of 0.9. [42] When heat is cogenerated with electricity, the carbon saving for heating can be considerable. Compared with gas boilers with an efficiency of 0.65 and large central 'mix'-fired electricity generators, for a heat load of 229 TWh/y, Micro-CHP could give a carbon saving of 8.2 MtC/y, or 42.9 %, and with gas-fired generators, 7.3 MtC/y, or 37.9 %. (See Tables 2 and 3). The variation of the Specific Carbon Savings per unit of heat with the electricity efficiency of the Micro-CHP units is shown in Figs. 4 and 5.

The energy efficiency of producing hydrogen from natural gas may be 0.65 to 0.75. (Producing hydrogen by Steam Methane Reforming with carbon capture is only about 0.5). [43] Another source gives the efficiency as 0.85. [44] For the present calculations, a value of 0.7 was assumed. As a result, compared with gas-fired boilers and gas-fired electricity generators, Hydrogen for Heating Boilers and Hydrogen with Micro-CHP units increases the carbon emissions. Moreover, Hydrogen even with Fuel Cells offers only a small carbon saving.

(See Tables 2 and 3). (For this comparison, it is not valid to assume that the hydrogen would come from renewable sources - such as biomass or wind. If these were available, due to the losses in the production of hydrogen, they would save more carbon if used directly to displace fossil generated heat and - more so - electricity).

With modern Gas Turbine Combined Cycle (GTCC) CHP plants, the electricity is cogenerated in back-pressure mode at efficiencies very little lower than for GTCC electricity-only, condensing-mode plants, so the specific carbon savings per unit of heat are large. (See Figs. 6 and 7). Moreover, they become very large when all the suitable heat loads - here taken as 78.6 % of the domestic heat load - are connected. Provided that all the cogenerated electricity can be used, with gas firing of DH-CHP relative to the present domestic boilers fuelled by gas, and electricity generated by the current fuel mix, it would be 24.7 MtC/y, or 128.6 %. (This exceeds 100 % because the higher-carbon 'mix' is replaced with the lower-carbon gas). Likewise, with gas firing of DH-CHP relative to boilers fuelled by gas, and electricity generated by gas, it would be 14.6 MtC/y, or 76.1 %. (See Tables 2 and 3).

The results for the several heating options are summarised in Table 3, and in Figs. 8 and 9. The fuel and carbon saving advantages of DH-CHP over Micro-CHP and hydrogen for heating are fundamental and cannot be reversed by R and D. The reasons include:

- Micro-CHP units usually use external combustion (such as Stirling) engines, which have a solid wall between the flame and the working fluid. This is necessary for the containment of the working fluid (usually helium or hydrogen). Material and price considerations limit the top temperature of the working fluid, and thus the thermodynamic, or so-called 'thermal' efficiency. However, the best modern electricity and CHP plant (GTCC) use internal combustion engines (such as gas turbines) for the high temperature part, with steam turbines for the low temperature part. Medium-sized CHP plant uses internal combustion piston engines. This means that large and medium CHP plant can make better use of any given flame temperature, and this has a crucial effect on the efficiency of conversion of fuel heat to work, and thus (via the generator) to electricity.

- Compared with those in central power stations, Micro-CHP units are vastly smaller in output, by a factor of e.g. 100,000, and cannot feasibly incorporate the same level of design refinements. There are also scale effects in various components, such as burners, turbines and generators, for which the losses are proportionately larger in small plant.

In practice, Micro-CHP is not likely to be widely adopted because there are too many decision-makers, and they would be difficult to persuade to invest in such expensive devices. (The take up of even condensing boilers has been low and slow in the UK). Moreover, to improve their economics, any users of Micro-CHP units would want to sell their surplus cogenerated electricity. Yet the big electricity suppliers would not want to buy it because it would lower the load factor on their own large plant – and hence their economic return. In any case, several severe practical problems would prevent either Micro-CHP units or Hydrogen for Heating from being deployed widely. (See Appendix).

DH-CHP would also replace some of the electricity at present used for space and water heating. Even off-peak electrical storage heating has its price in carbon emissions - especially after the closure of the nuclear power plants. In the UK, electric heating was used by 9 % of households in 2000. [45] The efficiency of heating with electricity from present gas-fired electricity plant might be 0.5 at best, but - after allowing for the effects of heat and electricity distribution losses, and for heat-only boilers supplying 0.1 of the heat - the 'thermodynamic heating efficiency' of DH from GTCC CHP plant is about 3.3 or 330 %. Hence replacing electric heating by DH-CHP would reduce the fuel consumption and carbon emissions to less than one-sixth - a saving of 85 %. Clearly the phasing out of all electric heating should be encouraged - even with incentives, as in Denmark. [46]

3.11 The Combined Heat and Power Quality Assurance Scheme

All types of power generating plant can be converted to - or purchased ready for - CHP operation. However, to maximise the net carbon savings, it should have high electricity and heat efficiencies. For outputs of e.g. 100s of MWe, modern GTCC plant has electricity efficiencies of about 0.5 (on the GCV basis). This already forms much of the high merit electricity generating capacity in the UK. For outputs of e.g. 300 kWe to 3 MWe, large gas (piston) engines have good electricity efficiencies of 0.35 to 0.38 (on the GCV basis), and good heat efficiencies. (See Fig. 10). [47]

In the UK, CHP is quite often used in industry and the service sector - both of which are now subject to the Climate Change Levy. This is a carbon tax, but at different rates for each fuel. (See Part II). For CHP plants that meet certain quality criteria, the fuel input and electricity output are at present exempted from the Climate Change Levy. The above model of CHP can also be used to estimate fuel use and carbon emissions for such industrial CHP - with some parameter changes. Since the heat and electricity loads are local, their distribution efficiencies are taken as 1. Moreover, all the heat cogenerated with electricity is assumed to be used, and the heat-only boiler fraction is taken as 0. The efficiency of the industrial boilers displaced is taken as 0.8, and the central electricity generators are currently 'mix' fired, but are likely to be increasingly gas-fired, with an efficiency of over 0.5. The results are shown in Table 4.

The Government target is 10 GWe of 'Good Quality' CHP by 2010. The criteria for the CHP Quality Assurance scheme are given in Guidance Note 10. [48] The present criteria in effect require electricity efficiencies of from 0.11 to 0.37, depending on unit size. Assuming a total efficiency (GCV) of 0.8, for the most favourable (and hopefully common) case of all the cogenerated heat being used, the expressions for the different electricity outputs may be represented by a single curve. (See Fig. 13). However, these criteria, with the electricity efficiency varying with electrical output, do not fully reflect the policy objective – which is carbon saving. Only the largest sizes of CHP units (above 50 to 100 MWe) achieve the 'maximum' carbon savings. (See below).

Industrial CHP has been specially analysed, since it is largely responsible for the present perception of CHP in the UK. Also, if DH-CHP is widely adopted, it will be important for industry and the service sector to see how it fits into a low carbon future. For the UK to enjoy the highest carbon saving, large central CHP units should take over from smaller industrial CHP units with lower electricity efficiencies. (This has been assumed for the industrial and service sector heat loads when modelling the UK energy system. See below). Of course, industry and the service sector could still own and operate such larger plant. However, they may find that their existing CHP plant is no longer allowed full relief from the CCL, and choose to buy heat and power from large central CHP stations.

3.12 Proposed New Criteria for the CHP QA Scheme

The nature of the Climate Change Levy (CCL) is considered below. (See Part II). However, the above calculations show that relief from the Levy should be:

- independent of the CHP unit capacity (usually quoted as electrical output power).

- zero at a CHP electricity efficiency, and hence carbon savings, of zero.

- maximum at the carbon saving equal to the boiler fuel carbon intensity divided by the boiler efficiency. For gas-fired Industrial CHP, this is 54.5 gC/kWh gas divided by 0.8, which equals 68 gC/kWh heat. A specific carbon saving of 68 gC/kWh heat on the 'gas plus mix' curve corresponds to an electricity efficiency of 0.42. (See Fig. 11). A specific carbon saving of 68 gC/kWh heat on the 'all-gas' curve corresponds to an electricity efficiency of 0.50. (See Fig. 12). The efficiency at the maximum carbon saving is lower with mix-fired generation, because for the electricity that it displaces, that generated by gas-fired CHP plant incurs lower carbon emissions. Different curves would apply for displaced boiler fuels other than natural gas, and for the (say annual) change of the electricity generation fuel mix. Corrections would be needed where the total efficiency (of utilized energy - heat and electricity) of the CHP unit was other than 0.8, as assumed here.

- determined by the net carbon saving resulting from moving from a boiler with an efficiency of e.g. 0.8, and central electricity generation efficiency of e.g. 0.44 or 0.51, to the CHP scheme. The relief from the CCL would depend on the electricity efficiency of the (existing or proposed) CHP plant, and thus the specific carbon saving. For the immediate future, while the present fuel mix is used for central electricity generators, the curve in Fig. 11 should be used to estimate the net carbon saving. The relief would then be calculated as a proportion of the maximum specific carbon saving of 68 gC/kWh heat. If the central generators were all fired by gas, the curve in Fig. 12 should be used, and relief determined as a proportion of the maximum specific carbon saving of 68 gC/kWh heat. If the electricity efficiency were higher than that earning the maximum relief, then the maximum relief would be allowable. The CCL relief for the two cases may be plotted against the electricity efficiency of the CHP unit on a single chart. (See Fig. 14).

Hence the carbon savings are proportional to the electricity efficiency of the CHP units. For the 'maximum' carbon savings, certain electricity efficiencies should be met - i.e. 0.42 or 0.50. (See above). Most of the CHP units of below 50 to 100 MWe that meet the existing criteria would not qualify. (See Fig. 13). The upper sloping line shows the 'state of the art'. (The efficiency varies with CHP unit output capacity, but this is merely an expression of engineering realities, such as scale effects, as discussed above in respect of Micro-CHP). When displacing electricity generated with the present fuel mix, only the best CHP units of above 50 MWe achieve 0.42 or more. When displacing electricity generated with gas, only the best CHP units of above 100 MWe achieve 0.50 or more. Since only these can achieve the 'maximum' carbon savings, only they should be eligible for full relief from the CCL. The owners of CHP units with lower electricity efficiencies would not be obliged to replace them, but they should not enjoy full relief from the CCL.

3.13 Potential Heat Demands and Carbon Savings

To maximise the national carbon savings, DH-CHP should be used for as much as possible of the space and water heating demand - including those of the services and industrial sectors. Indeed, for maximum flexibility and economy, the domestic, services, and industrial heat loads should all be connected to the same (local) DH networks. While the gas-fuelled domestic useful heat demand for 2000 is 20.4 x 0.69 = 14.1 mtoe, adding the services and industrial (including low temperature process heat) demand, gives 38.5 mtoe. (See Table 11). Incidentally, an excellent impression of the distribution of these heat loads across the UK is given by the satellite photograph on the front cover of the RCEP Report No. 22. For this larger case, essentially all space and water heat (save that for rural dwellings) would be cogenerated with electricity, or reject heat from ethanol synthesis plants - thus minimising the exergy loss incurred by the present heating systems (mostly gas-fired boilers).

The paradox is that the big energy losses occur in power generation, but the big exergy losses occur in humble gas boilers - now so prevalent in the UK. Enhancing the power stations to produce CHP solves the first problem, while using the resulting heat to displace that supplied by the gas boilers solves the second problem. This is a truly elegant 'win-win' solution, and addresses the Thermodynamic Improvement Potential in space and water heating of 38.7 mtoe/y identified by Hammond et al. [49]

For comparison with the Government target of 10 GWe of 'good quality' CHP by 2010, the above DH-CHP case may be expressed on an electrical capacity basis. With the overall demand reduction of 30 % assumed for 2050, the electricity demand could be 170 TWhe/y. If this was all generated from CHP plant, with an annual load factor of say 0.5 (because of following the heat and electricity demands), the plant capacity would be about 170/(8760 x 0.5) = 39 GWe. Hence the scope for CHP in 2050 could be four times the present target for 2010 of 10 GWe. However, with GTCC CHP plant, the cogenerated heat would only suffice for a District Heating fraction of 0.28. (See Table 12).

Also renewable electricity from existing hydro-electric plant and wind turbines should be available at low cost. However, some believe that the demand for electricity will rise, even though that for heat may fall. Nevertheless, to maximise the carbon saving, all significant fuel-fired generation should be CHP. Any 'spare' electricity could be used to displace fossil fuels (e.g. oil or LPG) from the heating of rural dwellings, and for the synthesis of transport fuels - thus reducing imports. (See below). Harnessing say 0.8 of the reject heat from ethanol synthesis plants for district heating would provide additional heat for DH fractions up to 1.

The savings in carbon emissions from CHP have been considered by ETSU. [50] Firstly, since carbon emissions are proportional to energy, they should be related to energy, rather than to power or capacity. Secondly, CHP is mainly about supplying heat at very high efficiency, rather than about electricity. Hence, my comparison is on a heat energy basis. ETSU put it at 3.29 MtC for 54.1 TWh heat and 20.2 TWh electricity. This is a specific carbon saving of 0.0593 MtC per TWh heat, or 0.69 MtC/mtoe. My figure (displacing gas heat and mix electricity) is 24.7 MtC for 229 TWh heat, which is 0.108 MtC per TWh heat, or 1.25 MtC/mtoe - about 82 % more. However, the ETSU figure is based on the existing industrial CHP plant (mostly steam turbines), with low electricity efficiencies. (See Fig. 13). Hence, the carbon saving for the cogenerated heat is offset to a considerable degree by a carbon penalty for the cogenerated electricity. Conversely, mine is based on new central GTCC CHP plant, with high electricity efficiency. Hence the carbon saving for the cogenerated heat is reduced only slightly due to the difference in carbon emissions for the cogenerated electricity, versus that separately generated. Clearly, with the high electricity efficiency of the best modern CHP plant, the performance of existing CHP plant is not a good guide for policy.

3.14 Fuel Poverty and Sustainability

The old centres of cities and towns are often where there is the greatest incidence of fuel poverty. However, by including the service sector, they usually have the highest heat load densities (in MWth/km2), and are where DH-CHP is best first deployed. Wherever it was installed, DH-CHP would require much (e.g. 76 %) less fuel for heat (see above). Hence it becomes possible to supply heat (rather than cash grants) without incurring excessive cost or wasting energy – especially as the heat would be properly controlled, and metered to encourage careful use. The large fuel saving would also increase security of supply, and help towards sustainability. These would also be greatly increased by the ability of large central CHP plant to burn almost any fuel - including industrial and municipal wastes, biogas and biomass. (See below).

One might wonder why the UK has not deployed CHP more widely, including District Heating (the largest heat load). The main reason appears to be that, on nationalization in 1947, the electricity industry was required to maximise the efficiency of electricity generation. This means discarding the reject heat at the lowest possible temperature, so there are now a great many cooling towers – as well as many households in fuel poverty.

The merits of DH-CHP are fully appreciated in many other European countries – notably Austria, Denmark, Germany, and the Netherlands – with 25 to 50 % of their electricity coming from CHP stations, compared with 5.6 % in the UK. Indeed, in Denmark 50% of the electricity comes from CHP stations and all new power stations must supply heat as well as electricity. [51] [52] This has helped these same countries to progress further towards sustainability than has the UK.

For the present study, it was assumed that deploying DH to the full extent, and building or modifying the power stations for CHP, would be possible by 2050. The feasibility of this could be confirmed by asking those who have done, and are continuing, to do both, such as Denmark, the Netherlands, Finland, Austria, and Germany.

4 Electricity - Energy Saving

4.1 Low Energy Appliances and Lighting

The UK Government is encouraging energy saving in appliances, lighting, and industry via the Market Transformation Programme. [53] Most appliances and lighting use only electric energy, which is particularly easy to measure and record. Moreover, in the UK most electricity is generated by thermodynamic conversion of fuels at about 30 to 50 %, and it is the most expensive (non-transport) form of energy. Indeed, UK households spend £ 5.3 billion a year on electricity. [54] This means that there is strong incentive to save it. It is now recognized that there is considerable scope for energy saving in domestic (and office) appliances. The greatest electricity energy saving (for a given power) comes from those appliances that are on continuously, or for a large part of the year. Particular attention is being given internationally to 'stand-by' power levels - e.g. for TVs and videos - and manufacturers are responding with low power solutions. [55]

There has also been considerable success in reducing the electricity used by each 'cold' appliance - refrigerator, freezer, and fridge-freezer. These account for about 16 % of domestic electricity consumption. Energy labelling has been adopted (A to G), and the higher energy designs (D to G) have been phased out. However, even lower energy designs, such as the Energy Plus range of fridge-freezers, are already in production. [56] A typical European fridge-freezer, with a total net volume of 257 litres, uses 590 kWh/y. However, a comparable A-rated unit has an Energy Efficiency Index (EEI) of 0.55, and uses 325 kWh/y. Moreover, an Energy Plus unit has an EEI of 0.42, and uses only 248 kWh/y. Yet even this Energy Plus standard can be bettered, and refrigerators with an Energy Efficiency Index of 0.2 are under discussion. [57]

If every household in the UK had a typical fridge-freezer, and replaced it with an Energy Plus unit, they would save about 342 kWh/y, worth say £ 24/y. With some 24 million households, this would amount to 8.2 TWh/y, worth - at say £ 0.07/kWhe - about £ 580 million/y. Compared with the UK electricity consumption of 334 TWh/y in 2001, this electricity saving is 2.5 %. [58] Moreover, with generators fired by the present fuel mix, electricity has a carbon intensity of 121.3 gC/kWhe, and the carbon savings would be about 1 MtC/y.

This electricity saving would also save generating capacity of about 1 GWe. GTCC generating plant has the lowest specific capital cost of about £ 270/kWe, implying a total cost of at least £ 270 million. At £ 13.5 per household, this could well cover the additional cost of an Energy Plus fridge-freezer and bring a national carbon saving. There would also be savings in fuel and carbon over the lifetime. Over even only 10 years, and at an electricity cost (to the supplier) of say £ 0.02/kWh, the value of the fuel saving would be say 342 x 10 x 0.02 = £ 68.4. Likewise, the carbon saving could be 342 kWhe/y x 121.3 gC/kWhe = 41.5 kgC/y. At the Carbon Trading price of £ 53/t, this would be worth £ 2.2/y, and £ 22 over 10 years. [59] Taken with the saving in power station capacity of £ 13.5, this gives a total of £ 13.5 + 68.4 + 22 = £ 104 each, which must far exceed any additional cost for an Energy Plus fridge-freezer. If the operating regime encouraged it, the Energy Service Companies may well prefer to make this (and similar) investments. (See below, Part II).

According to a Europe-wide study, the scope for energy saving in 'wet' domestic appliances - for washing and drying clothes etc. and dishes etc. - is more than one in four units of electricity. [60] Indeed, significant energy savings have been achieved in recent 'wet' appliances.

Lighting accounts for about 16 % of domestic electricity consumption. [61] Compared with incandescent lamps, Compact Fluorescent Lamps (CFLs) offer electric power and energy savings of up to 80 %, and lifetimes of up to 12,000 hours, versus 1000 hours or less. The economic case for CFLs can be made from two perspectives - that of the electricity supplier, and that of the householder. Assuming that each household has one '100 Watt' (equivalent) lamp on for 1000 hours a year, for the evenings, then with 24 million households, this would amount to 1.8 GWe for 1000 h/y without diversity, or say 1 GWe with diversity. As even the lowest cost generation capacity (GTCC) costs £ 270/kWe, this is equivalent to £ 11.25 per lamp. Fuel and carbon savings could be worth a further £ 2 a year per lamp to the electricity supplier. Since CFLs cost less than £ 5 each in volume, it would be cheaper for the supplier to provide every household with one or more CFLs. For the householder, a '100 Watt' equivalent CFL may save 75 %, last 12,000 hours, and cost £ 10 retail. Over its lifetime, it would save 75 x 12,000/1000 = 900 kWh. Hence the unit cost of the 'saved' electricity is only £ 10/900 = £ 0.011/kWhe. In other words, if the householder normally pays £ 0.07 per kWhe, the saving is £ 63. In addition, the price of 12 incandescent lamps, each lasting only about 1000 h, would be saved. Either way, it represents extraordinary value.

Domestic electric lighting required 1.5 mtoe of electricity in 2000. [62] All the incandescent lamps that are on for appreciable periods (hours in the year) could be replaced with CFLs. Assuming (conservatively) that the saving is 70 % (across all sizes), and that only 10 % of the potential has so far been realised, this amounts to 1.5 x 11.63 x 0.7 x 0.9 = 11 TWhe/y. With electricity having a carbon intensity for the present fuel mix of 121.3 gC/kWhe, this corresponds to a carbon saving of 1.3 MtC/y.

4.2 Industry

A considerable part of the electricity used in industry is for mechanical drives. [63] Hence there is scope for saving electricity by upgrading these with variable speed drives. These have become increasingly economic with the development of power electronics. Much of the potential saving is because the demand for heat and cold, for buildings and processes, varies considerably over the day and the year. The savings can be substantial, since many industrial drives are for fans and pumps, and the power taken by these varies as the cube of the speed in theory. This means that halving the speed reduces the power to one-eighth - or slightly more in practice.

It seems that in the UK the ownership of most appliances has saturated, so that migration to low energy designs should result in a declining demand for electricity. [64] However, the rates of deployment of new energy-efficient appliances may vary, and new types of appliances may appear in future. Hence possible transitions towards sustainability should be modelled, with various mixes of options. (See below).

5 Heat and Electricity - Renewable Energy Supply

Complete energy saving is impossible. For example, it would take many decades to replace the building stock, and a significant proportion are 'heritage' buildings. Also, even the best plant and equipment suffers losses, especially in energy conversion. Hence renewable energy supply will be needed for sustainability.

5.1 Biomass Wastes for Heat and Electricity

Renewable fuels, such as solid biomass, gasified biomass, and biogas, can be used in central heat-only boilers and CHP plant. By displacing fossil fuels, such as coal and gas, they reduce carbon emissions and increase sustainability. Biogas may be produced by anaerobic digesters (usually fed with wet wastes), from landfills, or by gasification of solid biomass. These may come from agricultural and forestry wastes, domestic and industrial wastes, and from energy crops.

As well as in boilers, biogas can also be used in engines for small-scale CHP of 10 to 100 kWe, 10 to 100 kWth. This also addresses the issue of the biogas resource exceeding the demand, since the heat and some electricity may be used locally, and the balance of the electricity exported to the grid. The biogas may require some cleaning but does not have to be of pipeline quality, or have a standard calorific value. Instead, the CHP or boiler plant can be adapted to suit, thus reducing the overall cost. [65] However, deployment of such rural CHP would require an adequate local infrastructure for digesting wastes and producing biogas.

Landfill gas comes from 'mining' old biomass wastes, and is therefore not a sustainable resource. However, landfills would otherwise release methane (a greenhouse gas even more powerful than carbon dioxide) to the atmosphere. Again, to make the best use of the high exergy of biogas, it should be used in CHP plant. However, landfill is increasingly discouraged, and landfill gas is a small resource, and should be exhausted by 2050, so was not considered when modelling the UK energy system (see below).

Unlike energy crops, biomass wastes arise with no separate requirement for land. There are wastes and trimmings from the 24 % of the UK land area that is not occupied by agriculture - including forests. In agriculture, occupying 76 % of the land area, there are wastes from the inedible parts of food crops, such as straw, and from animal wastes. Additional biomass wastes arise from imported food and animal feed (before and after it has been eaten). Substantial biomass wastes also arise in industry (especially wood and food processing), and from households. Because they are often expensive to dispose of in other ways, such wastes are often available at low cost. For example, the infrastructure for collecting straw is fully developed in Denmark and upgrading from boilers to CHP units is now in progress. [66] Although modest in national terms, this is a further useful contribution to renewable energy supply.

Cereal (food) crops account for only about 4 million ha. [67] For winter wheat, about 43 % of the energy is in the grain and 57 % in the straw. [68] If this is typical, about half the (above ground) biomass of any crop may be wastes. With a solar income of about 920 kWh/m2,y, and a biomass collection efficiency of say 0.5 %, this implies that the wastes available from food crops alone may be about 7.9 mtoe/y - and could well be more. Moreover, a later ETSU study put the Municipal (domestic and industrial) Solid Waste resource as 5.8 mtoe/y as fuel. [69]

5.2 Energy Crops

Crops may be grown for solid fuels, which may be used for generating heat and electricity in CHP plants. For example, winter wheat and its straw (less the energy required for fertilisers etc., and farming), has a net energy yield of 103 GJ/ha,y = 2.46 toe/ha,y. Grown on 20 % of the UK land area, this could produce 8.7 mtoe/y. (See Table 5). If this displaced the 1999 fuel mix in electric power stations, the carbon saving would be 8.7 x 11.63 x 121.3/1000 = 12.3 MtC/y.

There are other energy crops, with higher yields - and therefore giving more energy for a given area of land. These include 'Miscanthus' and Short Rotation Coppicing of Willow and Poplar. Energy crops suitable for the UK are compared in Table 6. Miscanthus is a so-called 'C4' plant, which can convert the solar energy very efficiently (for biomass) - even in the UK. A typical net yield is 5.3 toe/ha,y. SRC is already receiving a lot of attention in the UK, and features in some Non Fossil Fuel Obligation (NFFO) schemes for electricity generation. [70] Both are under active development by DEFRA. [71] [72]

UK-grown energy crops and biofuels would make demands on UK land area. However, the area not used for agriculture amounts to only 24 %, and that for human food crops only about 17 %. Although some of the remaining 59 % is used for growing animal feed, and for grazing, there is in principle plenty left for such an important and valuable crop as bio-energy, when oil and gas are depleting rapidly. "The Department of Land Economy at Cambridge University estimates that 1 to 1.5 million ha may become surplus to requirements for food production by 2000 - - rising to 5.5 million by 2010". [73] This is 22.5 % of the UK land area.

The total energy from biofuels for 1997 was only 1.89 mtoe. [74] However, it has been estimated that biomass could supply up to 19 % of UK energy demand by 2025. [75] Even so, this may have considered only electricity generation - as in the NFFO schemes - so CHP generation may be able to supply two or three times as much final energy as heat and electricity.

Moreover, biogas and solid biomass may be used alongside fossil fuels (whether by co-firing or in separate plant), thus allowing for variations in availability over the year, and progressive adoption, year by year. Furthermore, biomass (wastes, energy crops, and biofuels) saves foreign currency and creates jobs at home. It also increases fuel diversity and security of supply.

5.2.1 Land Use Change

Land use change arises through construction, farming, and forestry, and causes carbon emissions. This amounted to approximately 4 MtC in 1990. The growing of energy crops, such as Miscanthus and the Short Rotation Coppicing of willow, is seen as a possible countermeasure. [76] The value of 4 MtC/y has been assumed for the modelling. It was held constant even when the energy demands were reduced.

5.3 Central Solar Heat

Only DH allows the harnessing of solar heat on a large scale. (The same applies to harnessing geothermal heat and large central heat pumps - which could be powered by renewable electricity). With individual solar water heaters, the best collection potential may arise just when the household is away on holiday. However heat from large-scale solar systems is much less expensive, since the specific capital cost is lower, and all the output from all the collectors can be utilised. For such systems, the solar collector areas are typically of thousands of square meters, and can make a significant contribution to the annual total heat demand of e.g. a small town. This is so especially in summer, when the heat load would be low, and losses from the DH network may be proportionately high. Such solar heat may also allow the fuelled plant to be shut down for annual maintenance. Solar heat collectors can have an energy yield per unit of land area that is twenty five to fifty times as high as biomass energy crops, and large arrays can be built in say one year, rather than taking e.g. up to five to seven years to reach production. With short-term thermal storage (e.g. 12 to 18 hours), solar heat can supply say 10-15 % of the annual heat. Many large solar collector arrays are in use - in Denmark, Germany, the Netherlands, and Sweden. Feasibility has been amply demonstrated, and the cost of heat is approaching competitive in certain cases. One of the largest systems in the world is in Denmark, and long had a collector area of some 9000 m2, which has since been doubled. [77]

Rather than being stored chemically, as in biomass, solar energy can be stored as heat in large water reservoirs. Such thermal stores can have volumes of thousands of cubic meters, holding thousands of tonnes of water, enabling solar heat to supply up to say 90 % of the annual total energy. (The remainder would be fuel for boilers used for peak heat loads, and electricity for pumping). District Heating with large thermal stores make very resilient, predictable, and secure systems, with very high sustainability. Many solar heating systems with large thermal stores are already in use – notably in Sweden, and Germany. Feasibility has been demonstrated, but the cost of heat - while falling - is still high. However, due to the effects of the learning curve, and of the 'square-cube' law, this will improve as more and larger thermal stores are built. [78]

5.4 Wind Electricity

Wind turbines are increasingly recognised as delivering electricity at competitive cost. [79] Unlike photo-voltaic arrays, they operate night and day, and the output is higher in winter. Although wind turbines may cause visual intrusion when on-shore, and are subject to planning constraints, this is much less so when placed offshore. However, perceptions about on-shore wind turbines should change as fossil fuel prices rise.

Even for wind farms of many MWe-class turbines, the construction times are only about a year. Moreover, an analysis of a 600 kWe wind turbine found that the embodied energy, including installation, 20 years Operation and Maintenance, and decommissioning, would be repaid in just 3-4 months of operation. [80] This means that even rapidly growing wind turbine programmes do not lead to excessive negative energy flows during the construction period.

Some claim that the output from wind turbines is too variable for them to constitute more than 30 % of the total electricity system capacity. However, this overlooks the characteristics of a national or larger interconnected system that is geographically large, with turbines at many widely separated locations. Also, modern methods allow their output to be forecast within 10 % up to 36 hours ahead. [81] Moreover, given that some of the best wind resources are on the west of the UK, and most of the hydro-electric capacity is in Wales and Scotland, it should be possible to operate much of the wind capacity in conjunction with the hydro capacity – and so increase its ‘firmness’. Thus wind electricity would act as an 'extender' of even 'free-fall' hydro. Furthermore, more of the hydro capacity could be converted to pumped storage operation (like Dinorwic) at relatively low cost. To that extent, the UK is better off than Denmark - which has no mountains, but is nevertheless planning on generating 50 % of its electricity from wind. [82] Doubtless this will be helped by their electricity grid being connected to large hydro capacity in Sweden and Norway. Another possibility for medium scale electricity storage is the regenerative fuel cell - e.g. Regenesys - developed in the UK. [83] This acts as a free-standing storage system, without the need to produce and distribute hydrogen. As might be expected, as well as in the UK, this is being tested in Denmark. [84]

Widespread deployment of District Heating would allow another way of handling the varying output of wind electricity – especially as its contribution grows. If the other main source of electricity is from CHP plant, then - to achieve the full savings from cogeneration - the heat demand more or less determines the electricity output. While the wind electricity output was less than the remaining demand, it would be used to the full, and any difference made up by varying the heat to power ratio of the CHP plants, and from stored electricity. However, whenever the wind electricity output exceeded the remaining demand, CHP output of electricity and heat could be reduced, and the excess wind electricity used to heat the DH system. This could reduce any remaining fossil fuel use in CHP plant, or conserve the biomass fuel normally used. Although there is an exergy mismatch, the electricity is renewable, and DH is a very efficient way of supplying high heating loads. The equipment at the central CHP station is inexpensive, and it requires no expensive reinforcement of the electricity distribution system. At the end of the day, it is justified if it helps in the achievement of the carbon reduction objective. In Sweden, excess hydro electricity available at certain times of the year is used in DH.

The Danish energy research centre at Risoe is responsible for testing and type-approval of Danish wind turbine designs. However, it has clearly made a substantial contribution to the evolution of design. The Danish Windpower Industry has identified 15 recent technological improvements leading to productivity gains. [85] A PIU Working Paper has used Danish and other data in a 'learning curve' analysis to project continued falls in the cost of electricity from wind - both on- and off-shore. [86]

In Denmark, the total turnover in wind turbines was DKK 15 billion in 2000, and is growing at 20 % per year. [87] At DKK 10 = £ 1, this is about £ 1.5 billion. Moreover, the employment in wind turbine manufacture 2001 was 16,000, with component supplies and installations of Danish wind turbines accounting for an additional 8000 world-wide. [88] Denmark is exporting wind turbines worldwide. Wind turbines are ideal for export, since they are modular, with capacities (kWe to MWe) convenient for the target markets, and which allow series production. Also, they generate electricity with very low operation and maintenance costs, and without carbon emissions. The manufacture of wind turbines has also created over 20,000 jobs in Germany. [89] However, as a latecomer, the prospects for the UK might be less favourable unless there was a large home market. Two Danish companies - Vestas and NEG Micon - have already set up subsidiaries in the UK. [90]

The UK wind power resource has been estimated as 114 TWh/y onshore and 80.2 TWh/y offshore, or up to 100 TWh/y offshore. [91] Compared with the total UK electricity (energy - as opposed to power) demand of 355 TWh for 2000 [92], this would be up to 60 %. At a typical load factor of 0.38 for offshore turbines, 200 TWh/y would imply a total capacity of 60 GWe. However, the European Wind Energy Association 1997 Targets were for 100 GWe by 2020. [93] It was assumed in the modelling that wind turbines to capture this could be fully deployed by 2050. This could be confirmed by asking e.g. Denmark, the Netherlands, Spain, and Germany.

6 Heat and Electricity - Fuel Switching

6.1 Conventional Coal

For heat and electricity generation, carbon savings can be effected by switching from coal to gas. As a fuel, coal has a high carbon intensity - about 1.06 MtC/mtoe fuel - and contains sulphur, which burns to SO2 – a major cause of acid rain. While it is possible to reduce the latter with Flue Gas Cleaning, this raises both capital and running costs. When burnt in conventional steam turbine power stations, the electricity efficiency is about 0.36 (on the GCV basis). [94] This also limits the thermodynamic efficiency of the cogenerated heat in CHP plant. Moreover, the carbon intensity of the resulting electricity becomes 2.95 MtC/mtoe electricity or 254 gC/kWhe.

6.2 'Clean Coal'

An alternative would be to continue to burn gas and/or coal, but with capture and sequestration (long term storage) of the carbon dioxide. The leading technology allowing the use of coal with carbon capture is Integrated Gasification Combined Cycle (IGCC) plant. However, there are only a few such plants in existence, and they are very much more expensive than GTCC plant. For example, the cost of IGCC has been cited as £ 1232/kWe, versus GTCC at £ 270/kWe. [95] Moreover, carbon capture (and sequestration of the CO2 ?) may reduce the electrical output by 10 %, and increase the cost of electricity by up to 50 % for gas-fired plant, and up to 80 % for coal-fired plant. [96]

6.3 Nuclear Fission Electricity

6.3.1 Nuclear Risks

Nuclear power is subject to two unquantifiable risks, each with enormous consequences. The first is the risk of a radioactive release – leading to injury and death of potentially many thousands. Thus nuclear power facilities are uninsurable. Indeed, the very concept of insurance is implausible, when even the insurers may be wiped out, and there may be no-one left to receive any redress. Also, there is a growing realisation of the infinite cost of storing the inevitable nuclear waste for ever. Hence nuclear power can only continue to operate because some Governments (including that of the UK) allow it special exemptions.

The second unquantifiable risk is financial. There are still some 400 nuclear plants world-wide. Since almost none have been built for the last 25 years, they are all reaching the end of their design lives. Another major accident will result in demands for all existing plants to be shut down and any new construction to cease – regardless of the money (and energy) already spent. This would result in vast ‘stranded assets’. Hence the private sector will not finance new nuclear power stations. Nor would it purchase British Nuclear Fuels Limited (BNFL), which therefore remains in Government ownership.

Nuclear power plants are not normally considered for CHP operation. Although large potential sources of heat, the electricity efficiencies are low and hence the thermodynamic heating efficiencies are also low. Moreover, due to the risk of radioactive release, they are usually located distant from major towns and cities – so transmission costs and losses would be relatively high. There is also a risk of the water pumped into homes becoming radioactive.

Also, all nuclear facilities will always be potential targets for terrorists – whether seeking to cause a radioactive release, or stealing radioactive material for later use or blackmail.

See also Appendix.

6.3.2 Possible Financial and Energy Costs

There has been talk of a new nuclear power programme of perhaps 15 stations. [97] These are usually taken to be each of 1 GWe output. The proponents of nuclear power suggest a specific capital cost (for series production) of 1995 £ 1500/kWe. [98] This would imply nuclear programme costs of over £ 22.5 billion. However, with the record of the UK in building nuclear power stations, and the fact that there is only one supplier (BNFL) for both the reactor and the initial fuel charge, the cost and time might easily overrun by 50 % or more. Also, the assets may become 'stranded' at any time. It is not difficult to imagine that almost all other 'carbon saving' options would be less expensive, and certainly less risky. Even so, the greatest cost would be the opportunity cost. Attempting a large new nuclear power programme would mean that the UK could less afford any other major option.

Even worse than the cash flow would be the energy flow. During the construction of a series of nuclear power plants, the UK energy system would have to supply most (and pay for all) of the energy embodied in the plant and for refining and manufacturing the initial fuel charge. A nuclear power plant may take six or more years to build, and then at least two years of continuous operation to repay this embodied energy. Even building several at once, and to time, a programme of 15 stations could take beyond 2050. Over the whole period, the UK would be 'investing' energy, most coming from fast-declining supplies of fossil fuels. Then there is the fact that the demand for electricity is smaller than that for heat and transport fuels - for which nuclear power is quite unsuited. Hence a new nuclear power programme, despite pre-empting most other investments, cannot possibly enable the UK to meet the target of 60 % carbon reduction by 2050. Taken with the unquantifiable risks mentioned above, attempting a new nuclear programme could only be described as perverse.

6.4 Nuclear Fusion

Some advocate nuclear fusion as a potential source of 'unlimited power' – provided that someone else pays for it. Yet with global warming, the last thing we need is 'unlimited power'. Even if it ever worked on earth, we could not use it. The Sun is the only nuclear fusion reactor that we need. Therefore all publicly funded R and D on nuclear fusion should cease forthwith.

The cost of R and D on nuclear fusion is not limited to the financial. Even more important is the 'opportunity cost'. This means that working on fusion means we are not working on something else, which may be far more relevant. This is especially important for the UK, since our technical resource is now severely depleted, as is publicly-funded R and D, and compares unfavourably with our principal competitors. It is noticeable that those countries - Denmark, the Netherlands, Sweden, and Germany - which are furthest along the road to sustainability, have the least interest in fusion. Indeed, it could be argued that the reason why we are so far behind - both economically and in sustainability - is exactly because we have for so long misspent much of our limited technical resource.

7 Transport - Energy Saving

All forms of powered transport should contribute to the reduction of UK carbon emissions. The growth in the 'volume' of transport should be checked, and then reversed - notably by better town planning, with homes closer to places of work, and by encouraging remote working (tele-commuting) via the Internet. For this last, as a major employer, the Government could give a lead.

7.1 Modal Switching

In his presentation 'The Imminent Peak of World Oil Production' at the House of Commons in July 1999, [99] Colin Campbell said, "The global market will come to an end because of the high transport costs". It follows that air transport will cease to grow around 2005 simply because it will become obvious - especially if aviation fuel is still untaxed - that it is 'stealing' from other uses of oil. For high-speed transport, energy use could be reduced by modal switching from aircraft (with ~ 5.5 MJ/passenger-km) to trains (with ~ 0.7). [100] This would have major implications for air travel - as it already has for Concorde, which used about ten times as much fuel per Revenue Passenger Kilometer as the best subsonic jets. [101] Also, with the higher cost of air transport fuel, building any additional runways at Heathrow, or elsewhere in the UK, are likely to prove expensive mistakes - because the additional traffic will not be there.

Land transport energy use could also be reduced by encouraging 'modal switching' - from cars (with ~ 1.5 MJ/passenger-km), to buses (with ~ 1.1), trams, and trains (with ~ 0.7), cycling, and walking. [102] However, this could only come about after delivery of an integrated transport policy that made these alternative transport modes more attractive. Average car usage is 10,557 miles (about 17,000 km) a year in the UK, but only 7776 (about 12,500 km) in Germany, and very similar in other European countries, most of which are both larger and more prosperous. [103] Not only are places of work often closer to homes, but there are effective integrated systems of public transport.

7.2 Smaller Vehicles and More Efficient Conventional Engines

The association of European automobile makers has undertaken to reduce the average new car fuel consumption from the 1998 level of 186 g CO_2/km to 140 g CO_2/km - i.e. by 25 % - by 2008. [104] By historic standards, the present level of fuel efficiency is high, and already about three-quarters of the new cars sold are no larger than a Ford Focus, VW Golf, or Toyota Corolla. Hence this is a demanding target, and likely to require further reduction of the average size of new vehicles. The VW Lupo 3L has an official fuel consumption of diesel fuel of 3 l/100 km, 94 mpg, and CO_2 emissions of 82 g/km. This can seat four and shows what can be done in this direction. [105]

7.3 Hybrid Vehicles

As noted above, the conversion of fuel to mechanical work or power is always accompanied by significant losses. In vehicle engines, these take the form of heat at medium temperature (e.g. 500 C) as exhaust gases, and low temperature (e.g. 100 C) as cooling air. In a moving vehicle, it is impractical to harness this heat - other than for heating the interior. This however is a significant load - up to 5 to 10 kWth - and always a problem for battery-electric vehicles. Nevertheless, the efficiency of converting the fuel energy to work can still be increased.

One way is by adopting petrol- or diesel-electric hybrid propulsion. This results in the engine running not at part-throttle (and inefficiently) almost all of the time, but at full throttle (and efficiently) for less time. The rest of the time it is driven by a large electric motor powered from a small battery. This is a proven solution and gives a fuel and carbon saving of about 25 to 50 % on the US driving cycle. [106] The actual saving depends upon the vehicle usage, being greater at lower speeds.

Toyota and Honda are already selling hybrid passenger cars, with others expected shortly. The Toyota Prius has a weight of 1265 kg, and an official EU fuel consumption of petrol of 57.6 mpg, 4.9 l/100 km, with CO2 emissions of 120 g/km. [107] This car has plenty of room for five occupants, and has automatic transmission and climate control as standard. At 20.4 km/l, the fuel economy on the European driving cycle is about 70 % more than the average for petrol cars, and is equal to the best of the diesel cars of the same weight. [108] However, compared with petrol, diesel fuel has about 1.12 times as much energy per litre (on the NCV basis). Hence for the Prius, both the fuel consumption on an energy basis (GJ/km) and CO2 emissions (g/km) are some 12 % lower than the best diesel cars of the same weight.

In the paper by Hammond et al [109], the thermal efficiency of road vehicles is shown as 17 %, while those of other transport modes are around 27 %. Published data on the Toyota Prius shows the maximum thermal efficiency of the special petrol engine as 36.4 % (on the NCV basis), and that the hybrid transmission keeps all engine operation as near to this as possible. [110] [111]

In Fig. 13 of the present paper, the 'peaky' curve on the left is the thermal efficiency of the special Prius engine, as measured independently in the USA. [112] (It is only 'peaky' because of the logarithmic scale). For comparison, these data have been converted to the GCV basis, giving efficiencies of over 32 % from 5 to 40 kW, with a best of 34.6 %. Thus the efficiency is about twice that of conventional engines - and over a wide speed and load range. (This is necessary in a vehicle engine, whereas on a power or CHP system, as the load falls, some stations can simply be taken off line - leaving the rest to run at near their full load and best efficiency). Moreover, this is extended to the lowest speeds by electric traction - helped by regenerative braking. Thus this special car engine is nearly as efficient as the big Jenbacher gas engines of around 1000 kW. Of course, the Prius engine - like any car engine - does not have to run for 10s of thousands of hours between overhauls, so Toyota push the materials somewhat harder than Jenbacher. Nevertheless, it is a striking demonstration of how well hybrid vehicles already address the Thermodynamic Improvement Potential in road transport of 22 mtoe/y (i.e. 9 % of the total) identified by Hammond et al.

8 Transport - Renewable Fuels

Nowadays, most high-speed trains - like the French TGV and German ICE - are electric, in order to provide the high power required. Furthermore, with long distance and high-speed trains, the 'feeder' journeys are often by public transport. Conversely, with air trips, due to the rural location of most major airports, the 'feeder' journeys are often by car. Likewise, suburban trains and urban trams are always electric. Hence, with trains and trams, both main and 'feeder' journeys could use renewable electricity directly, rather than portable fuels.

Renewable electricity could be used to recharge battery-electric road vehicles. However, they suffer from the inefficiency of moving a heavy battery around, short range, and - if numerous - would require a strengthened electricity infrastructure. Hence for road vehicles, a portable fuel is preferable.

8.1 Choice of a Low Carbon Transport Fuel

The requirement is for a transport fuel that is at least carbon-neutral. It should be efficient to produce and use, and convenient to handle when refuelling. Solids have been deemed impractical since the days of coal-fired steam vehicles. Hence it comes down to gases or liquids. Moreover, such a fuel should preferably be suitable for use in existing vehicles (or with minimal modification). A possible Index of Merit might be the Carbon Intensity divided by the (Net) Calorific Value. (See Table 7). Within transport, the Net Calorific Value is usually used, but national statistics use the Gross Calorific Value for consistency with other data.

Although hydrogen has zero carbon intensity at the point of use, there are severe problems with leakage, danger, and limited range. Moreover, it is gaseous at normal temperatures and pressures. To liquefy hydrogen costs effectively one third of its energy. [113] Storage must then be at extremely low temperatures - below -252 C - and is subject to 'boil-off' losses of as much as 3 to 4 % a day. [114] Furthermore, it is 'rocket science', and would require a completely new infrastructure for production and distribution. UK road transport consumes about 1 million barrels of oil a day. [115] The cost of a hydrogen infrastructure for 1 million barrels a day may be $ 100 billion. [116] Some might say that, to reject hydrogen would be to favour heat engines over fuel cells. However, petrol and diesel engines are mature, can be made at low cost, and are well understood for service. Also, engine-electric hybrids give major fuel savings. Fuel cells are still under development, and very complex and expensive.

Furthermore, the costs of an additional completely new hydrogen infrastructure would be most unwelcome for developed countries (such as Denmark) which do not manufacture road vehicles, and so would not even gain from accelerated renewal of the vehicle fleet. This would be all the more so for developing countries - for which hydrogen is certainly not a valid option. Yet one of the criteria for the UK energy technology options is supposed to be their suitability for export.

Fuels that are liquid at normal temperatures are far easier to handle and to store in the vehicle. Of these, methanol has the lowest carbon intensity. However, it is poisonous, has a calorific value only about half that of petrol, and attracts water - making it difficult to blend with petrol. Petrol is familiar, and is fully compatible with existing vehicles, but synthesis by the Fischer Tropsch process may have an efficiency of only 0.5. [117] With a limited biomass resource as feedstock, inefficient synthesis of petrol means a reduced yield.

Of the liquids, ethanol has almost the lowest carbon intensity at the point of use. This means almost the maximum energy in portable fuel for the limited amount of carbon that is easy to capture (e.g. from power station flues). Moreover, it is non-poisonous (in moderation), and blends easily with petrol. The presence of the carbon increases the energy density and enables the hydrogen to be carried conveniently. Indeed, for ethanol, the energy density per unit volume is 2.34 times that of liquid hydrogen. Furthermore, ethanol is already widely used in motor fuel. For many years, much of the motor spirit sold in Brazil has been a blend of 22 to 24 % ethanol (made from sugar cane). Also in the USA, some 1.4 billion gallons of ethanol a year (made from corn/maize) is used in motor spirit. Moreover, since it can be used in existing vehicles (in blends of up to 10 to 20 %), and with the existing infrastructure, it could be adopted much sooner - for a faster impact on carbon emissions, Hence ethanol seems to be by far the best candidate.

8.2 Use of Low Carbon Fuel

Ethanol requires no separate infrastructure for distribution - except for separate tanks, as used for grades of petrol and diesel. Since it is a solvent, some upgrading of seals and finishes may be required. Ethanol has the advantage of flexibility. Most existing petrol vehicles can use up to 10 % ethanol, known as E10. Indeed, ethanol is an ‘oxygenate’, the use of which is mandated in certain U.S. states (including California), since it reduces regulated (noxious) emissions. E10 would satisfy this requirement. In Brazil, all the motor spirit contains about 23 % bioethanol. Therefore all the major manufacturers in Brazil sell suitable vehicles. The maximum blend is usually 85 % ethanol, with 15 % petrol to help with cold starting - known as E85. New 'petrol' vehicles may be designed to handle blends of anything between 0 and 85 % ethanol. Thus if no ethanol blend is available, users can still fill up with petrol. In the USA, such Flexible Fuel Vehicles (FFVs) are available from all the major manufacturers, and they sell for the same price as standard vehicles. Unlike LPG vehicles, FFVs have almost no disadvantages. There is no loss of luggage space or spare wheel to a second fuel tank. Instead, in FFVs, a single tank suffices. There is a sensor in the fuel line that detects the presence of ethanol, and causes the engine management computer to make the appropriate changes to the fuelling and ignition. The regulated emissions from spark ignition (petrol) engines running on E85 are reduced by 20 to 30 %. [118] As yet only a few models of FFVs are available, but the principle is well established. The US FFV fleet is already about two million, with Federal and State Governments being notable buyers and users. [119]

The Swedish test fleet for vehicles operating on ethanol includes about 300 buses, 7 trucks, and 100 Flexible Fuel Vehicles. [120] Also Ford has recently supplied the first Flexible Fuel Focus to Sweden. In 2001 production was 400, and in 2002 they delivered 2500 to 3000 to the Swedish market. Ford claim that they reduce CO2 output by 80 %. [121]

Diesel vehicles with only minor modifications can use up to 95 % ethanol. Where continued supply of high blends is assured, modifications may be made to increase engine efficiency. [122] Moreover, ‘diesel’ vehicles require only minimal changes in order to use biodiesel (95 % Rape Methyl Ester). Biodiesel is sold in Germany and France, and all VW diesel engines can use it as standard. A modest reduction in fuel tax on biodiesel of £ 0.20/litre has recently been announced in the UK, but none is yet on general sale.

Ethanol has only about two-thirds the energy per litre of petrol or diesel fuel. (See Table 8). With E85, the power is increased by 3 to 5 %, and the fuel economy by about 5 %, so the range is reduced to about 72 % of that with petrol. [123] However, this is hardly critical - especially in densely populated countries. Moreover, the range is still far better than with LPG, battery-electric or even hydrogen-fuelled fuel-cell vehicles - or going nowhere at all, through fuel shortage. Furthermore, new flexible-fuel vehicles are usually fitted with larger tanks. Biodiesel has about 6 % less energy per litre than petro-diesel - so performance and range are little affected. [124]

Biofuels and synthetic ethanol do not require radical changes in the fuelling infrastructure or vehicle fleet (as would hydrogen and fuel cells). Instead, they can be adopted incrementally, using the existing fuelling infrastructure, and the present and foreseeable future vehicle fleet (which has an average life of about 15 years). Also, the introduction of biofuels and ethanol still allows other options, such as smaller vehicles, and hybrid engines. With on-board reformers, ethanol could be used even in fuel cell vehicles, if they prove feasible and competitive with heat engine vehicles.

Once the fuel storage tanks and vehicles were upgraded to handle ethanol, petrol and ethanol could be distributed in any proportions. Thus, it would be easy to migrate from petrol to ethanol as the carbon emission limits decline, and the supply of petrol decreases and that of ethanol - home-produced bio, imported bio, or synthesised - increases.

Most developed and developing countries could produce their own biofuels - so saving themselves foreign exchange, and reducing the world net carbon emissions. If the UK were to manufacture Flexible Fuel Vehicles, they should find ready markets at home and overseas.

8.3 Biofuel Production

World production of ethanol in 1998 was 33.3 billion litres. 91 per cent was bioethanol, produced by fermentation, and 9 per cent synthesised, by the indirect or direct hydration of ethylene. About 68 per cent was used for fuel, 21 per cent for industrial purposes, and 11 per cent for beverages. [125]

In the USA, bioethanol production in 2000 was 1.4 billion U.S. gallons a year - mostly from corn/maize. This is about 1.1 % of U.S. gasoline consumption. [126] However, most was used as an oxygenate, and only 3.3 million gallons gasoline equivalent of E85 were used in 2000. Compared with a projected highway use of petrol and diesel of 164 billion gallons for 2001, this is only 0.002 %. [127] The price of E85 is still higher than that of gasoline before tax, but a tax concession reduces it to about the same price per gallon. However, due to the lower energy per gallon, the cost per mile is still higher. Both Government and industry laboratories are actively developing more efficient methods of producing bioethanol, which promise to save both energy and cost. They should also make much better use of the available biomass resource. [128]

In Brazil, bioethanol production was 16.1 billion litres in 1998. Blends of up to 22 per cent anhydrous (water free) ethanol with gasoline may be used in 'standard' engines, and hydrous ethanol (including 5 per cent water) may be used 'neat' in suitably modified engines. [129]

In Sweden, ethanol production was 79 million litres (of 80 per cent minimum concentration) in 1995. More than 70 per cent was made from wheat starch, and the rest from sulphite liquor. Forest wastes of about 46 million m3/y could be used to produce roughly 1 billion litres of ethanol annually. The Swedish government has a target to produce 15 per cent of transport fuel from biomass by 2010. This would imply about 1.35 billion litres/y. [130] A plant for producing ethanol from grain, using biomass as process fuel, is under construction, with a capacity of 50 million litres/y. [131]

In the 1930s and 50s, Cleveland 'Discol' was available in the UK, which was a blend of ethanol (made from molasses) and petrol. Much more recently, Shell has purchased a stake in Iogen of Canada, who are developing improved methods of bioethanol production. [132]

Growing energy crops capture their own CO2 from the low concentration in the atmosphere. Since the available land area limits the biomass resource, it is interesting to compare the yield of different biofuels. A recent detailed study carried out in the UK has shown that both bioethanol made from winter wheat, and biodiesel made from oil seed rape are carbon-neutral, indeed carbon-negative, with net energy surpluses after allowing for fertilisers etc., farming, and processing energies. However, in terms of the biofuel and straw energy, the yield of the former is about 50 % higher than that of the latter. (See Table 6). [133] Since land is limited, bio-ethanol is preferable to bio-diesel. Ethanol can be used in both 'petrol' (spark-ignition) and 'diesel' (compression-ignition) engines.

When bioethanol is produced, there is an energy surplus (after allowing for processing energy) from the associated straw. The total energy saving for bioethanol is thus that of the fossil fuel (petrol and diesel) displaced, plus the energy surplus, which may be used to displace fossil fuel in CHP plants etc.

Assuming that 20 % of the UK land area could be used for biofuels, winter wheat could produce 8.7 mtoe/y of bioethanol. (See Table 6). Compared with the UK road transport energy consumption in 2001 of 41.4 mtoe, this is 0.21. The carbon intensity for petrol and diesel fuels is about 855 kgC/t fuel. [134] Hence the carbon saving for transport fuel would be 8.7 x 0.855 = 7.4 MtC/y. The energy surplus biomass (wheat straw) is 3.4 mtoe/y = 39.8 TWh/y fuel. (See Table 5). If this displaced gas in electric power stations, for which the carbon intensity is 54.5 gC/kWh fuel, the carbon saving would be 39.8 x 54.5/1000 = 2.2 MtC/y. Hence the total carbon saving from this energy crop could be 7.4 + 2.2 = 9.6 MtC/y. Crops for biofuels for transport are shown in Table 8. Another possible biofuel crop for the UK is sweet sorghum. This is a 'C4' plant, with a high yield.

Such biofuel would also be very valuable in displacing (or replacing) oil - the price of which will rise due to scarcity. For example, $ 20/barrel is $ 145 per toe, and $ 35/barrel is $ 253 per toe. At the former price, 8.7 mtoe/y would imply a potential income of $ 1.26 billion/y, or about £ 0.84 billion/y, and at the latter price, about $ 2.2 billion/y, or about £ 1.5 billion/y. Moreover, due to its carbon-neutral status, bio-ethanol is likely to command a premium over oil. At the UK Carbon Trading price of £ 53/tC, this could amount to 8.7 x 0.855 x 53 = £ 394 million/y.

There is an EU draft directive on the use of biofuels for road transport, with a target of 5.75 % by 2010. In addition, there is an EU proposal for 20 % alternative fuels, largely from biofuels, by 2020. [135]

According to the US National Renewable Energy Laboratory (NREL), biofuels reduce oil imports, reduce the trade deficit, create jobs (at home), improve the economy, revitalize agriculture and industry, improve global competitiveness, provide energy security, and diversity and promote energy competition. They also improve the environment by improving urban air quality and by reducing the threat of global warming. [136] These advantages would also apply to ethanol synthesised in a carbon-neutral fashion. Furthermore, as for all forms of renewable energy, accessing it is not a 'zero-sum' game. However much is harnessed (as opposed to used) in the UK, there is still the same left for everyone else. Indeed, the better we are at doing so, the more others could gain through technology transfer.

8.4 Importing Low Carbon Fuels

If enough fuel cannot be grown or made in the UK, it may be necessary to import renewable fuels. After all, the UK will soon again become a net importer of petroleum. For the present study, bio-ethanol is chosen, to give the maximum flexibility in supplying fuels for both petrol and diesel engines. Moreover, the sources of bioethanol are likely to be more numerous than the 30-odd major oil and gas provinces in the world, since they are limited only by land and climate, rather than by geology. The potential annual world production of bioethanol from starch-sugar crops is roughly 500 mtoe, of which 67 mtoe is in the EU. Production from lignocellulosic biomass is under very active R and D. If this succeeds, the potential would be 1300 mtoe. This would be equivalent to 37 % of world petroleum production in 1998. However, it is not necessary to replace all petroleum with liquid biofuels – only the 20 % that is used for transport. [137] Hence, the potential annual production of bioethanol is (in energy terms) almost twice that of all the petroleum currently used for transport.

As a liquid with a high energy density, ethanol has many attractions as a tradable fuel. (See Table 9). Moreover, unlike crude oil and some oil products, ethanol has no heavy, tarry components. Hence in the event of a spill (at sea or on land), it should be easily dissipated, and is also bio-degradable.

9 Transport - Fuel Switching

If energy saving, and renewable energy supply (home-grown and imported) will not meet the near-term carbon emissions target, it may be necessary to switch fuels - e.g. by synthesising low carbon or carbon-neutral fuels. However, an entire new fuel industry cannot be built, and ready in time, by starting only when indicated by economic models. There are many social, financial, and engineering realities - all of which take time to overcome. Also, financial incentives or differential tax rates may be needed to ensure that sufficient capacity is established in time. (See below, Part II).

For aircraft, other fuels, such as ethanol or hydrogen, are possible, but would make aviation much more expensive. This is largely because the aircraft would be much more expensive, partly due to the increased R and D, and partly because the reduced energy density of the new fuels would reduce aircraft payloads, and hence increase their operating costs. Ethanol is lower on both a mass and a volume basis, which would require larger tanks. While hydrogen is higher on a mass basis, it is far lower on a volume basis as a gas, which may imply heavy cryogenic tanks, to hold it in liquid form (at below -252 C).

9.1 Synthetic Fuel Production

The amount of fuel of biological origin is ultimately limited by land area - whether in the UK or abroad. However, fuels may also be synthesised, from suitable chemicals and energy, while requiring very little land area. Using electricity to synthesise a portable fuel is acceptable in exergy terms, since both are high. For hydrogen, the requirements are only water and electricity. The energy required to produce hydrogen by electrolysis is 3.9 kWh/Nm3 (at module level). [138] Compared with a calorific value of 3.0 kWh/Nm3, this is an efficiency of 0.77. [139] However, in many transport applications, it must be liquefied, at an efficiency of about 0.66. [140] This gives an overall efficiency for liquid hydrogen of 0.51. Even this would not be delivered in practice, due to 'boil-off' losses from the stored liquid, and leakage losses when turned into a gas for use.

Ethanol could be synthesised with carbon dioxide from the atmosphere, and using renewable electricity to produce the hydrogen, and complete the process. Although CO2 would be released again on combustion, such ethanol would be carbon-neutral. [141] This and other references by the same authors suggest that the synthesis of ethanol requires about 13.1 x electricity, and 2.8 x heat, corresponding to an energy efficiency of only 6.6 %. However, the efficiency of bio-ethanol production is only about 0.22 % of the solar income. (See Table 5). Hence ethanol synthesis is already some 30 times higher, and the process has not yet been optimised (e.g. by process integration). Also ethanol synthesis is the subject of considerable R and D, notably seeking suitable catalysts, and especially in Japan. Moreover, ethanol produced by synthesis is not constrained by land area, and the reject heat from the process could be used in District Heating. (See above).

9.1.1 Carbon for Ethanol Synthesis

CO2 could be captured from the high concentrations available in the boiler flues and gas turbine exhausts of CHP plants, fuelled by gas or biomass. There may be a small loss of electricity output and efficiency due to such capture. However, this would be a small price to pay to avoid the need for a hydrogen 'economy' (which is certainly a misnomer). Also, any reduction in electricity output could be made up with renewable electricity. Moreover, CO2 capture (and sequestration) is already envisaged by those who propose the 'clean coal' option. [142] When burning biomass, the CO2 captured would be sustainable. Furthermore, fuelling the CHP plants with biomass would avoid the need for permanent sequestration and verification of the CO2, which are both difficult and expensive. The calorific value of biomass averages 20.3 GJ/t Dry Matter, while the carbon content is about 0.445 by mass. Hence the carbon intensity is about 0.445 x 3600/20.3 = 79 gC/kWh fuel or 0.918 tC/toe. [143]

Synthesising ethanol in this fashion would avoid the need to capture CO2 after burning the ethanol in the vehicle, which would be impractical. Also, it would make use of all the R and D work that is going into carbon and CO2 capture. Moreover, if the carbon capture and ethanol synthesis processes are close-coupled, the effectiveness of capture could be demonstrated and verified by the production of ethanol.

9.1.2 Energy for Ethanol Synthesis

Such synthesis plant would probably be best located near to the supplies of captured CO2. It is convenient that the CHP generators (gas or biomass fuelled) that provide the CO2 are also (by definition) well connected to the electricity grid. If required, they could also provide heat - e.g. for distillation. Ethanol could therefore be synthesised using hydrogen produced at the CHP plants with renewable electricity - e.g. from wind turbines. Wind, water current, and wave energy collectors can reach out beyond the UK land area, and the available resources are vast. (See above). The renewable electricity could be both firm and non-firm (i.e. surplus to its use as electricity elsewhere). Also, using renewable electricity largely to synthesise ethanol deals outright with the 'storage problem'. Indeed, this should result in more complete use of the renewable resource, since 'none need be turned away'. Production is not time-critical, so can proceed whenever carbon dioxide, electricity and heat are available, while the resultant ethanol can be stored inexpensively - e.g. in 'oil' tanks. Moreover, as a clean fuel, the same ethanol may be used in road transport and in high efficiency CHP plants, using internal combustion, such as GTCC and piston engines - thus affording both operational flexibility and energy security.

9.2 Energy storage

Repeated mention has been made in the recent reports of the importance of energy storage (usually meaning electricity), and often proposing hydrogen. [144] However, the UK consumes more heat and transport fuels, than electricity. Conversion of electricity into hydrogen and then into these energy forms would incur considerable losses, and should be limited to the synthesis of ethanol. Rather than storing and distributing hydrogen, energy should be stored in hot water, biomass, hydro-electric potential, and in ethanol. These match the exergy of the end uses, and so minimise conversion losses. (See Table 10).

10 Seeking Solutions by Modelling

The UK energy system for 2050 was modelled, with the primary objective of achieving exactly the reduced carbon emission target of 62 MtC/y. The solutions are built on three main options: DH-CHP, Biomass, and Wind, plus a certain amount of oil and gas (limited by the carbon emission target). Because of the nature of the energy technologies chosen, they also address the energy security, fuel poverty, and 'towards sustainability' objectives.

10.1 Energy Saving

No changes in the pattern of energy demand from 2001 were assumed, as they were deemed beyond the scope of the present study. (Further work could include seeking solutions for e.g. the four scenarios first defined under the Foresight programme). However, all energy demands were assumed to be reduced by 30 % by 2050. The text above includes qualitative descriptions and quantitative estimates of a number of major and proven energy savings options. These include super-insulation and advanced windows in buildings, low energy appliances and lighting, and lower power motor drives in industry. Savings in road transport energy should come from the ACEA commitment (of 25 % reduction by 2008), and the increasing adoption of hybrid electric-internal combustion engine propulsion (that have already demonstrated fuel savings of 25 to 50 %). Air transport energy is likely to decline, due both to higher aircraft fuel efficiency and to the increasing shortage of petroleum-based aviation fuel after 2005, when world oil production is expected to peak. However, aircraft and marine fuels were assumed to be still oil-based in 2050.

10.2 Energy Efficiency

For DH-CHP, the possible heat load comprises three separate tranches. The first is all of industry and the services sector. The second is urban domestic electric heating (such as may be suffering fuel poverty - and is already being addressed by the DEFRA Community Heating Programme). The third is the urban domestic gas-heating load. In the model, the extent of domestic electric heating (except in rural areas) is represented as a fraction between 0 and 1. The extent of District Heating is also represented as a fraction between 0 and 1. The model was free to optimise the values of each when seeking solutions.

The total capacity of the CHP plants, supplying heat and electricity, was constrained only loosely, to confirm feasibility. 100 GWe is not out of the question in view of their doubled (heat and electricity) function, for little if any more cost per unit. Also, there should be enough units to supply heat to every town and city in the UK with District Heating without unduly long pipelines, yet they should generally be of 300 MWe each to achieve the best electricity and thermodynamic heating efficiencies. Based on a published analysis of a production GTCC CHP unit from ABB, the 'thermodynamic heating efficiency' was taken as 4.179, the electricity to heat ratio (alpha) as 1.976, and the electricity efficiency as 0.514. (See Table 2). [145] It was assumed that deploying DH to the full extent foreseen, and building or modifying the power stations for CHP, would be possible by 2050.

DH could also distribute otherwise wasted heat from industry. In particular, the present model utilises (80 % of) the heat rejected by the ethanol synthesis plants. These would be co-located with the CHP plants, for access to electricity and carbon dioxide from flue gasses - as well as allowing the reject heat to be harnessed.

10.3 Energy Supply

Final Gas does not include Fuel for Centrals (CHP plants and Heat-Only Boilers for DH) etc. Final Gas is used in the UK as a supply for (mostly) low temperature heat. Conversely, Fuel for Centrals is the higher exergy fuel needed for CHP (and the small amount for Heat-Only Boilers), and High Temperature Process Heat (taken as above 100 C, but could be up to 1000 C).

The Sent Out Energies are higher than the Final (or Useful) Energies due to transmission and distribution losses. These were taken as 0.13 for District Heating, 0.074 for electricity, 0.05 for gas, 0 for petroleum fuels, and 0 for ethanol (although the last two would require some transport energy for delivery). However, petroleum-based fuels are also subject to a refining overhead - of about 0.05 for diesel, and 0.15 for petrol. Hence Bought In (Primary) energies have been taken as higher than Final energies by 0.10 for all petroleum. After primary purchase, ethanol needs no processing, but only blending for use in transport vehicles.

10.3.1 Coal

Conventional coal was ruled out due to the high carbon intensity, and the potential for other emissions, such as Sulphur Oxides. 'Clean coal', including carbon capture and sequestration, was ruled out as unproven, and too expensive.

10.3.2 Oil

In the model, if the carbon emission limit permits, oil can be used for transport fuels, for firing CHP stations, and as rural heating fuel. (In reality, due to its higher price and higher carbon intensity, oil would only be used outside transport in the event of short-term gas shortage). Motor fuels are assumed to be blends of ethanol, averaging 90 %, with petrol and diesel oil. Assuming that demand is reduced 30 % by 2050, the oil consumption to supply all aviation and marine fuel, and 10 % of the road transport fuel would be 11.75 mtoe/y, some 17 % of present. This is the technical minimum, at least with current aircraft technology. The oil consumption was usually constrained to this - on the assumption that by 2050 it would be scarce and expensive.

10.3.3 Gas

The remaining world gas resource is larger than that of oil but the supply of gas will also soon be in decline. In using the model, the gas consumption was not constrained directly, but by the carbon emissions target.

10.4 Renewable Energy Supply

10.4.1 Wastes for Rural Heat

Rural Domestic Heating is assumed to be fuelled by biogas or other biomass from agricultural and forestry wastes. The resource has been assumed to be 10 mtoe/y by 2050. However, assuming a demand reduction of 30 % by 2050, rural heating would be only 3.8 mtoe/y. In future, the biogas yield could well be higher and the excess could be piped into the gas network, and used in large, central CHP units.

10.4.2 Energy Crops - UK Grown

The energy crop for use in the CHP stations and Heat Only Boilers for DH was taken as Miscanthus, with a yield of 5.3 toe/ha,y. This is modest compared with those measured during trials in the UK. [146] The carbon emitted on combustion may be captured for use in the synthesis of ethanol. The intensity was taken as 0.918 MtC/mtoe (see above). However, having come from an energy crop, it was not included in the UK total of carbon emitted.

10.4.3 Land Use Change

The value of 4 MtC/y has been assumed for the modelling. It was held constant even when the energy demands were reduced.

10.4.4 Bio-ethanol - UK Grown

To produce bio-ethanol, the crop assumed was winter wheat, with a yield of bio-ethanol of 1.77 toe/ha, y. After allowing for all farming inputs, the straw provides all the process energy - with a significant surplus of 3.4/8.7 = 0.394 toe per toe of bio-ethanol. (See Table 5). The energy surplus straw is assumed to be used (perhaps after gasification) in CHP plants - displacing gas and thus reducing carbon emissions.

For the fraction of the UK land area devoted to energy crops and bio-ethanol, the limit is ultimately a judgement on the nation's priorities, but at least 0.225 should be possible. (See above). It was assumed that such bio-energy crops could be established as required up to 2050.

In the model, the total of UK land used for bio-energy (energy crops and bio-ethanol) was usually constrained - e.g. to fractions of 0 to 0.2, when looking at 'trade-offs'.

10.4.5 Renewable Electricity

For renewable electricity, the wind energy resource of the UK - onshore and offshore together - is up to 200 TWh/y. (see above). It was assumed that wind turbines to capture this could be fully deployed by 2050.

The model omits hydro-electricity, even though it would help in integrating wind electricity. However, electricity is less important (numerically) than heat and transport fuels, and hydro-electricity is small and cannot be much increased in the UK. If solutions can be found without hydro-electricity, they also exist with it.

In the model, the renewable electricity was usually constrained - e.g. to 0 to 100 TWh/y, when looking at trade-offs.

10.4.6 Electricity for District Heating

In the model, if renewable electricity is available, it may be used directly in District Heating networks. This avoids the nonsense of it being used to synthesise ethanol, which is then burnt in CHP stations. The use of electricity for heating may seem paradoxical, after the emphasis above on exergy matching. However, this may be attractive with a large proportion of renewable electricity, and allows increased flexibility to the energy supplier in operating the DH-CHP system over the day, and over the year.

10.4.7 Electricity for Rural Heat

All rural dwellings are assumed connected to 'mains' electricity - although the connection may not be 'strong' enough for the heating loads. However, this was considered an option that might enable renewable or efficiently cogenerated electricity to replace e.g. heating oil or Liquefied Petroleum Gas.

10.4.8 Electricity and Heat for Synthetic Ethanol

Synthesising ethanol requires carbon (as carbon dioxide), and hydrogen (e.g. from the electrolysis of water). In the model, a check is made that the available carbon emitted from the flues of the CHP plants is sufficient (assuming that 0.9 of this could be captured). The electricity includes any surplus cogenerated with heat at the CHP plants (another operational flexibility), as well as that from renewable resources, taken as wind turbines. Ethanol synthesis was assumed to require 13.1 x electricity and 2.8 x heat, which limits the amount produced. The heat was assumed to be high temperature, produced from gas at an efficiency of 0.8. Moreover, 0.8 of the 14.9 x reject heat was assumed to be used in DH networks. (See above).

10.4.9 Bio-ethanol - Imported

Compared with gas, oil is more expensive - even though it has a higher carbon intensity - because it is nearer exhaustion, is easier to transport, and is a source of portable fuels for transport. Likewise, compared with oil, ethanol should be more expensive - even though it is renewable - because it is carbon-neutral, is equally easy to transport, and is a portable fuel suitable for transport. Indeed, once the carbon emission target has been reached, any additional fuel must be carbon-neutral. Hence the marginal fuel is assumed to be ethanol.

In the model, if carbon-neutral ethanol - home-grown, synthesised, or imported - is available, it can be used in road transport fuel, for firing CHP stations, and - if necessary - as rural heating fuel. It was assumed that imported bioethanol is just carbon neutral, and the energy surplus due to the straw is retained by the country in which it is grown.

The usual objective was to minimise the amount of imported ethanol, subject to the several constraints. UK imports of up to 50 mtoe/y were considered plausible relative to potential resources of 67 mtoe/y in the EU, and 500 mtoe/y worldwide. (See above).

10.5 Finding the Solutions

The spreadsheet model may be 'driven' as a Linear Programming model, in order to find solutions that meet the objective within the constraints. This capability is available in Microsoft Excel 97, via the Solver add-in. This requires the choice of one variable as the target, usually to be minimised or maximised. Other variables are chosen to be manipulated, and several of these and others may be subject to constraints. These often include only positive values, and values less than certain limits, such as annual energy flows and carbon emissions. As implemented in Excel 97 and Solver, this model allows the determination - almost instantaneously - of e.g. the minimum imported ethanol possible within a given set of circumstances.

While it is valuable to find individual solutions, it is also instructive to examine the 'trade-offs' or interactions between key variables. In Excel with Solver, each 'Scenario' may be saved, and the variables plotted against each other, usually as an 'XY scatter' chart. This enables insights into the UK energy system, at least as modelled. (See Table 12 and Fig. 15).

11 Results and Discussion

11.1 Results

Solutions have been found which meet the key carbon emissions target, using significant amounts of DH-CHP, bio-energy (energy crops and biofuels) and renewable electricity (from wind turbines), along with the other 'minor' options. Biomass and Wind are renewables that are carbon-free and sustainable, and can replace much of the oil and gas, which are nearing exhaustion, increasingly expensive, and not sustainable. After oil and gas are constrained by the carbon emission target, farm wastes exploited, any land used to grow bio-ethanol and energy crops, and any renewable electricity used to synthesise ethanol and supply reject heat, imported ethanol is the balancing item. An example of the results is shown in Table 11, and they are summarized in Table 12 and Fig. 15.

With a 30 % reduction in overall energy demand, and an oil ratio of 0.17 of present, a gas ratio of 0.83 of present is the maximum permitted by the carbon target of 62 MtC/y in 2050. This would generate large financial savings. However, the solutions show that the UK would have to import carbon-neutral fuel, such as ethanol. The solutions offer choices between annual running costs and capital expenditure. Thus the UK could choose to invest the minimum, and import more ethanol. Or the UK could invest in deploying DH, growing biofuels on UK land, and in wind turbines - both on- and off-shore - and so import less ethanol.

The solution for Land = 0 and Renewable Electricity = 0 is the limit case. When oil and gas have taken up the carbon limit, the additional fuel for road transport and the CHP plants must be carbon-neutral. In this case, the UK would have to import all of the 26.1 mtoe/y of ethanol needed for road transport fuel, plus about 4.5 mtoe/y for use in the CHP plants. When RE = 0, the DH fraction is limited by the demand for electricity, and by the high value of the electricity to heat ratio (alpha) of the GTCC CHP plant. After the assumed demand reduction of 30 %, the electricity demand is 16.8 mtoe/y, and the useful heat demand is 31.4 mtoe/y. With the demand for electricity only about half that for heat, and an alpha value of almost two, the cogenerated heat is only 8 mtoe/y. Hence the DH fraction is only about 0.28. However, this is more than enough to displace all (urban) electric heating - and so help to relieve fuel poverty.

There is a trade-off with land use. (See Fig. 15). These solutions suggest that growing wheat for bio-ethanol and the straw (rather than energy crops) on 0.2 of UK land would save imported ethanol of up to 30.6 - 17.8 = 12.8 mtoe/y. Assuming that the yield is maintained, this should continue indefinitely. This is with a yield from winter wheat of bio-ethanol of 1.77 toe/ha,y, plus straw of 0.394 toe/toe ethanol, and from energy crops of Miscanthus of 5.3 toe/ha, y. Higher yields would increase the saving of imported ethanol.

There is also a trade-off with renewable electricity capacity. These solutions suggest that installing wind turbines for 100 TWh/y would save imported ethanol of up to 30.6 - 25.2 = 5.4 mtoe/y. Since wind turbines should last about 20 years (and - with refurbishment - another 20 years), capacity for 100 TWh/y should save up to 20 x 5.4 mtoe = 108 mtoe over 20 years. This is with ethanol synthesis requiring 13.1 x electricity. However, the high reject heat enables solutions with RE of 100 TWh/y to give DH fractions of up to 0.76, which improves the return on investment in wind turbines. Moreover, renewable electricity of from 100 to 200 TWh/y could enable DH fractions of up to 1.0 and gas consumption to be less than that allowed by the carbon target. (See Table 12). This could be a good insurance against future 'gas shocks'.

The 'trade-offs' or 'sensitivities' are sometimes called 'shadow prices'. Given a value for imported ethanol (see above), they can be used to quantify the benefits of capital investments - especially in the three main options of DH-CHP, Bio-energy, and Renewable Electricity. If adopted soon enough, all the renewable fuels (including the synthetic ethanol, made with captured carbon dioxide and renewable electricity) would extend the life of the UK oil and gas reserves. Although the carbon emission target would enforce the much smaller use (later imports) of oil, and the use (later imports) of gas, the financial savings would help fund the capital investments in energy technology options and offset the cost of imported ethanol.

11.2 Discussion

The model has shown that the chosen energy technology options are together capable of solutions that meet the carbon emissions target of -60 % - i.e. 62 MtC/y for 2050. However, this assumes that sufficient quantities of both oil and gas are to be had. Oil is already being consumed at four times the rate of discovery, and could start to 'run out' around 2005. The present profligate use of oil will no longer be possible - never mind permissible. Certainly both oil and gas will be much more expensive - because the rest of the world will want their share. This might be decided by the market and the ability to pay (as under WTO rules, which favour the USA), or by the fair allocation of an equal amount per capita (through contraction and convergence). However, unless the USA has changed its habits by 2005, the UK and other countries might find it difficult and expensive to obtain supplies.

In addition, there could be further tightening of the carbon emissions targets due to new signs of climate change, shortfalls in demand reduction, or even increases in demand - e.g. for transport. For example, under the Kyoto Protocol, the UK share of international air transport fuel is not at present included in the IPCC/UNECE target. Instead, it is referred to as 'Non-Sectoral', and is large and growing fast. Depending on the rate of reduction in the carbon intensity, it could add carbon emissions of between 14 and 21 MtC/y. [147] Hence, in the terms of the present study, solutions would have to be found within a carbon emissions target of 62 - 14 or 21 = 48 or 41 MtC/y.

Further reductions in fossil fuel use would require more use of advanced energy technologies, such as super-insulated buildings, energy crops, and heat from large central heat pumps and large-scale solar collector arrays - both of which are less expensive and more efficient than small ones. These last would be distributed by more extensive DH networks, which provide the flexibility to meet such changing circumstances.

The implications of such circumstances could of course be explored very quickly with the present model, or simple extensions thereof.

11.3 Further Work

The above model is about the simplest possible for comparing the major energy technology options, and assessing how they could meet the carbon reduction objective. Possible tasks for future work are:

- to assemble some indicative costs and financial benefits for the major energy technology options.

- to track from now to then for e.g. each of the scenarios first defined under the Foresight Programme - to see how the chosen energy technologies could be deployed to meet the intermediate carbon emissions targets up to 2050. It could also be extended further towards sustainability - say 2100 - to confirm their validity in the longer term.

- to increase the level of detail – both spatially and temporally. Thus for DH-CHP, an outline could be developed for matching major existing power stations to suitable heat loads – i.e. the nearest cities or towns.

Where the heat loads and CHP plants (perhaps with multiple units) are large (e.g. GWth in scale), it can be economic to run heating pipes for tens of kilometers or miles, if necessary. Also, the interplay of the demands for heat and electricity could be modelled for typical summer and winter days.

12 Conclusions to Part I

1) This study has tested various energy technology options against the principal objective - carbon reduction. In particular, it has addressed the two largest Thermodynamic Improvement Potentials identified by an exergy analysis of the UK energy system. These are due to losses in conversion, transmission and distribution, and amount to about a quarter of the primary energy consumption. Whereas the UK energy system in 1999 (as in the previous 30 years) had a Final to Primary Fraction of 0.69, the solutions found for 2050 give values of 0.74 to 0.80. Thus the conversion losses could be reduced by about one-third. This is a measure of the Thermodynamic Improvement in matching the exergy of energy carrier and end-use, resulting in loss reduction or increased energy efficiency (as distinct from demand reduction or energy saving).

2) A new analysis of Combined Heat and Power, based on thermodynamics, has been used for this study. Absolute clarity is now essential in the energy field, in order to take well-informed decisions. Yet in the UK there are multiple conventions in use for allocating the energy inputs for CHP systems between heat and electricity. This must lead to endless conflicts and misunderstandings. They also obscure the high efficiency of 'Thermodynamic Heating' from CHP, which can give fuel and carbon savings of 76 % or more. Therefore - to avoid these, and anybody thinking that any of the conventions is true - the thermodynamically correct analysis of CHP should be adopted.

3) This new analysis has been used to evaluate several options, including Micro-CHP, District Heating from central CHP stations, and industrial CHP. Fuelled by Natural Gas, Micro-CHP could give useful carbon savings, but fuelled by Hydrogen, Micro-CHP or Fuel Cells would give little or none. However, only DH-CHP (including Industrial-CHP) could largely achieve the largest Thermodynamic Improvement Potential in the present UK energy system, amounting to some 36.7 mtoe in 1999. It has been in production for decades and offers the largest carbon savings. Also DH-CHP can use almost any fuel, including wastes and biomass.

4) For CHP in the industrial and service sectors, the present CHP QA criteria do not ensure the maximum carbon savings, and hence merit full relief from the Climate Change Levy. New criteria, embodied in a simple chart, are proposed.

5) The largest Thermodynamic Improvement Potential in the UK energy system can be addressed by replacing heating by gas boilers with DH from cogenerated heat from CHP plants, and reject heat from ethanol synthesis plants. The model solutions suggest that this could reduce the loss by 0.10 out of a possible 0.17. Moreover, co-locating the CHP and ethanol synthesis plants integrates two of the energy technology options - DH-CHP for heat, and ethanol for road transport fuel. Although neither was employed in the solutions of the recent MARKAL study, CHP and biomass generally has been identified in Denmark (Energi 21), and CHP and (methanol and) ethanol specifically in Sweden (e.g. 'Energilaget ar 2050') - so they are quite mainstream.

6) The second largest thermodynamic Improvement Potential is that in road transport, amounting to 22 mtoe in 1999. This can be addressed by vehicles with hybrid engine-electric propulsion, such as are already in production and offer a large carbon saving. From the published data available, these should reduce the conversion loss by at least 0.03 to 0.04 out of a possible 0.09.

7) Whereas for the present energy system, the Renewable to Primary Fraction is about 0.01, the model solutions for 2050 give values of 0.28 to 0.31. These are significantly higher than the targets commonly cited - admittedly for earlier dates such as 2010 to 2030 - and are for the whole energy system (as opposed to only electricity). This is a measure of the sustainability, which would be greatly increased. To the extent that the renewable energy is collected in the UK, it is also a measure of the energy security. This is due to replacing coal, oil and gas with biomass and wind for heat, electricity, and transport fuels. Thanks to the

assumed overall demand reduction of 30 % by 2050, and these replacements, the oil ratio is only 0.17, and the gas ratio is only 0.83 or less. Even with nuclear and coal phased out completely, this should also increase energy security.

8) The main options chosen (DH-CHP, Biomass, and Wind) best meet the demanding carbon reduction objective and are being implemented elsewhere in Europe, Japan, and America. The additional options (Super-insulated buildings, low energy appliances, hybrid vehicles, ethanol) necessary to meet this objective have been chosen to be compatible, and again because of European, Japanese, and American precedents.

9) The study has used simple spreadsheet models, so that all equations and data used are explicit and can be checked (or changed). For example, the effects of different assumptions for energy savings, or for biomass yields, can be explored. Qualitative and quantitative analyses such as the above allow proposed energy options to be evaluated quickly. They can also indicate where capital investments should best be made. Denmark for one has invested heavily and profitably in the options chosen above, and is continuing to do so.

10) The chosen options have been shown to be together capable of meeting the carbon reduction objective in a variety of circumstances. They also address the objectives of reducing fuel poverty and increasing energy security and sustainability. All the chosen options are current products that can be costed. Moreover, with proven performance and low risks, they are known to be attractive to investors. In addition, they would save foreign exchange and increase UK employment.

11) Furthermore, DH, biomass, renewable electricity, and ethanol could be extended to achieve higher Renewable Fractions, for even lower carbon emissions and greater sustainability. This could be done by making more use of wastes, energy crops, biofuels, industrial waste heat, plus large-scale solar and heat pumps for DH, renewable electricity from various sources, and eventually ethanol for air and sea transport.

12) Such analyses can also indicate where R and D expenditure can best be employed. While the energy technology options chosen above are mature, there are plenty of opportunities for relevant energy R and D. These include end-use efficiency, biomass yields, ethanol synthesis efficiency, and lowering the costs of DH-CHP, wind turbines, and large scale solar heat collection and storage. Of Denmark's R and D expenditure of DKK 98 million in 1999, 85 % was in energy efficiency and renewables. [148]

Glossary

AEAT	AEA Technology (where AEA stands for the Atomic Energy Authority). Located at Harwell.
BNFL	British Nuclear Fuels Limited. The UK Government-owned nuclear industry.
CCL	The Climate Change Levy. This is a carbon tax on non-domestic energy, at different rates for each fuel.
CHP	Combined Heat and Power generation (also known as 'Cogeneration' and 'Total Energy')
CHPQA	The Combined Heat and Power Quality Assurance scheme.
DEFRA	Department of the Environment, Food, and Rural Affairs
DH	District Heating - a piped heat service to buildings. Usually supplied from CHP stations.
DTI	Department of Trade and Industry.
EST	The Energy Saving Trust. Responsible for energy and carbon saving in the domestic and transport sectors. See also TCT.
ETSU	The Energy Technology and Support Unit. Part of the (now-privatised) AEAT.
GCV	Gross Calorific Value. That which results from the hydrogen in fuels being reacted to water.
GHG	Greenhouse Gases. Mainly carbon dioxide, but also including methane and others.
GTCC	Gas Turbine Combined Cycle - the current standard for gas-fired power generation.
Ha	Hectare - 10^4 square metres. Usual measure of land area. That of the UK is 24.4 million ha.
HHV	Higher Heat Value. See GCV
IAG	The Inter-Departmental Analysts Group. Authors of a recent Government report on energy.
ICCEPT	Imperial College Centre for Energy Policy and Technology. Authors of a report to the Carbon Trust.
IGCC	Integrated Gasification Combined Cycle (proposed for 'clean coal' generation)
LF	Load Factor. Actual (e.g. annual) output divided by the theoretical output at continuous full load.
LHV	Lower Heat Value. See NCV
LPG	Liquefied Petroleum Gas.
MtC	Million Tonnes Carbon
mtoe	Million Tonnes Oil Equivalent. Taken by the DTI as equal to 11.63 TWh (TeraWatt Hours).
MTP	The Market Transformation Programme, an initiative of DEFRA to encourage the production and adoption of (mainly) appliances which use less energy, water, and other resources.
NCV	Net Calorific Value. That which results from the hydrogen in fuels being reacted to steam.
NFFO	The Non-Fossil Fuel Obligation. This was used mainly to subsidise nuclear power generation, but some renewable electricity generation was also funded.
ODT	Oven Dry Tonnes - usually of biomass, where moisture detracts from the calorific value.
PIU	The Performance and Innovation Unit (of the Cabinet Office). Authors of a recent review of energy.
RCEP	The Royal Commission on Environmental Pollution. Authors of Report No. 22 on energy.
RO	The Renewables Obligation. This has replaced the NFFO, but is still almost all electricity.
TCT	The Carbon Trust. Responsible for energy and carbon saving in the industry sector. Sponsored by the DTI and DEFRA. See also EST.
toe	Tonnes Oil Equivalent. Taken by the DTI as equal to 41.868 GJ (GigaJoules).

Metric Quantities

Watt	the Systeme International unit of power (in any form - heat, electricity, etc), 1 Joule/s.
Joule	the Systeme International unit of energy (in any form - heat, electricity etc), 1 Watt-s.

K	Kilo - 10^3 - a thousand
M	Mega - 10^6 - a million
G	Giga - 10^9 - a billion
T	Tera - 10^12 - a trillion
P	Peta - 10^15 - a quadrillion

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