Tyndall°Centre
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Evaluating the options for carbon sequestration

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This is the final report from Tyndall research project IT1.22 (Carbon sequestration: a pilot stage multi-criteria evaluation of biological and physio-chemical approaches). The following researchers worked on this project:

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Introduction

The term carbon sequestration refers to any means of locking up CO_2 over very long periods in order to mitigate against the effects of anthropogenic climate change. There are three broad types of carbon sequestration:

1. Biological sequestration describes the carbon stored in soils or forests; this approach has been much debated in connection with the Kyoto Protocol and allows land use or forestry schemes to be offset against emission reduction targets;
2. Geological / physical carbon sequestration involves injecting CO_2 gas into large physical structures (such as disused oil fields or other geological formations) where it should be secure over the long term.
3. Ocean sequestration – the oceans represent a large natural sink for CO_2 and this approach has been proposed to accelerate the process through which atmospheric CO_2 would reach equilibrium with the oceans. The two main approaches to direct ocean storage are a) direct dissolution of gaseous CO_2 over large areas and b) injection of CO_2 at depths greater than 1000m at which an impermeable hydrate seal should form, preventing dissolution of the CO_2. Other approaches that exploit the ocean include accelerated carbonate dissolution (Caldeira and Rau, 2000) in which CO_2 in flue gases is reacted with sea water to produce carbonic acid, which is then reacted with limestone, this produces bicarbonate in solution which may be dissolved in the ocean. Ocean fertilisation has also been proposed as a route for carbon sequestration. This involves seeding the ocean with iron to promote growth of carbon fixing plankton; although this has received some attention in recent years it is not likely to be considered as a policy option.

In this study we have looked at the first two of these approaches – biological and geological (or physio-chemical) sequestration. The third approach, ocean sequestration has been excluded from the study as it was considered unlikely that it will become a significant mitigation option for the UK in the near to medium term. Research expertise in this area is currently centred in the US and in Japan.

The structure of the report reflects the methodological organisation of the project. We have analysed and documented the two key forms of carbon sequestration, biological and physio-chemical, independently. This is considered to be the most appropriate approach for this study for the following reasons:

i) the two technologies are at very different stages of their development: biological carbon sequestration is well established on the policy agenda, for example it is included within the Kyoto Protocol; geological carbon storage is a relatively new technology only beginning to be understood beyond narrow expert technical communities;

ii) the overall mitigation potential is expressed on very different scales (in the UK the realistic potential for biological potential is estimated to be around 0.5 GTC; the potential capacity for geological storage could be 100 times that figure (Holloway *et al.,* 1996).

iii) geographical scope: biological sequestration has been analysed here at global, European and national scales; we have considered geological carbon sequestration only on a UK national scale;

iv) although both describe approaches through which carbon dioxide is locked up such that it does not enter the atmosphere, biological and geological carbon sequestration reflect fundamentally different processes and have very different technical, economic, environmental and socio-political implications.

Biological sequestration exploits the natural process through which plants and biomass accumulate CO_2 directly from the atmosphere, whereas geological sequestration involves the capture of CO_2 from large scale industrial processes (such as power generation) and its subsequent transport to a suitable storage location.

Thus Sections A and B of the report describe the methods and results evaluating biological and geological carbon sequestration respectively. In Section C, we attempt to draw together these two strands of analysis and summarise the main conclusions of the project.

Section A. Biological Carbon Sequestration

Biological carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK

Introduction

This paper summarizes and reviews global, European and UK estimates of the amount of carbon that could be sequestered in biomass (plants and soils) during the coming 50-100 years, and the amount of carbon emitted by burning fossil fuels that could be avoided by growing biomass for energy.

The literature on these two aspects is extensive, but it is scattered and bedevilled with different interpretations of what is 'potential' and what is actually achievable. In this review, estimates are given of the range of values for:

- *theoretical potential capacity*, meaning some or all practical constraints have been ignored,

- *realistic potential capacity,* meaning account has been taken of most constraints, but some optimistic assumptions are made about land availability, socio-economic and policy drivers,

- *conservative, achievable capacity,* meaning a cautious prognosis, based on current trends, with few optimistic assumptions.

Each section is prefaced with a likely range of values, in italics, followed by a review of the literature and calculations upon which the range of values is based.

1. Carbon Sequestration

The estimates given here are the amounts of carbon that can be stored in vegetation and soils as a direct result of man's activities over the next 50-100 years – additional to the carbon sink that exists 'naturally', most of which is essentially free. This net 'natural' terrestrial carbon sink was 1.5 ∀ 0.7 GtC/yr in the 1990s, the net result of a sink of 3.2 GtC/yr and an emission due to deforestation of 1.5 GtC/yr. Thus, about 23% of the 6.4 GtC/yr emitted from fossil fuels is being taken up by the land without any change in current practices (Royal Society of London, 2001).

This 'natural' sink of 3.2 GtC/yr can be attributed to two factors. First, forest and soil carbon stores are naturally recovering from past depletion. Thus, the present distributions of age classes in the forests of US, Canada, Europe and parts of Russia are not in a quasi-equilibrium state – they are aggrading. The living biomass in forests is increasing by 0.17 GtC/yr in US and 0.11GtC/yr in W Europe (Houghton, 2001). Some of this sink is due to man's activities or decisions to conserve forests, prevent fires and not to harvest as much timber each year as grows, but much of it can be regarded as 'natural'. Second, the sink is due to a global acceleration of photosynthesis by increasing atmospheric CO_2 levels and, in some areas, nitrogen deposition.

Recent estimates would place 0.88 GtC/yr of this 3.2 GtC/yr global sink in temperate and boreal regions (Metz et al., 2001) and 0.3-0.6 GtC/yr in the US (Pacala et al., 2001).

1.1 World

Current global fossil fuel emissions were 6.4 ∀ 0.4 GtC/yr in the 1990s (Prentice *et al*., 2001). The total amount of carbon emitted from fossil fuels plus land use change up to 2000 was about 420 GtC. Projections of the amount of carbon emitted from 2000 to 2100 range from 690 following IPCC scenario IS92c, 1430 GtC following IS92a (approximately business-as-usual) to 2090 GtC following IS92c (Lenton and Cannell, 2001).

Theoretical potential capacity

Likely range 100-200 GtC; 2 to 4 GtC/yr for 50 years

It could be argued that an upper boundary on the amount of carbon that could be added to the store of carbon on land is roughly equal to the amount that has been lost historically as a result of man's activities. That is, all vegetation and soil carbon pools could be brought back to quasi-equilibrium with the climate – all naturally forested land restored to forest and so on. This boundary condition would be achieved by a mixture of current 'natural' processes and new activities. The amount of carbon that has been lost from global soils and vegetation (principally forests) in the period 1700-1985 is estimated to be about 170 GtC (41 GtC from soils) (Houghton and Skole, 1990; Houghton 1999). Assuming some loss prior to 1700, the total loss is about 200 GtC. Some would argue that the upper boundary is higher than this because of elevated CO_2 and climate change, combined with the use of fertilizers and irrigation – but those factors are uncertain and/or carry fossil fuel costs.

Optimistic estimates of the land area available to store carbon in trees (afforestation, regeneration, agroforestry) and agricultural soils (restoration, set-aside, minimal tillage) and of the amount of carbon stored over about 50 years, give totals of 76-147 GtC. This is made up from 52-104 GtC in trees and 24-43 GtC in agricultural soils (Winjum *et al.*, 1992; Paustain *et al.*, 1998). These estimates assume that 300-600 Mha of land in the tropics is converted to forests or agroforests and that soils are restored in 10-50% of the 1200 Mha of tropical degraded lands. Also, over half of the carbon lost historically from agricultural soils would be restored.

All of these estimates of potential carbon storage violate or ignore the ideals of sustainable development, encompassing economic, social and environmental goals.

Realistic potential capacity

Likely range 50-100 GtC; 1 to 2 GtC/yr for 50 years

Estimates have been made of the amount of carbon that could be stored by (i) planting new forest and agroforest plantations, (ii) managing existing forests, and (iii) managing croplands - taking into account competing demands on land and the timescale of tree planting or cropland management. These three estimates are expanded below. However, all assume no adverse climate change and an aggressive policy to support carbon sequestration, requiring the commitment of considerable financial resources.

(i) The best estimates of sequestration in new forests/agroforests are still those of Nilsson and Schopfhauser (1995) and Trexler and Haugen (1994), used in the IPCC Second Assessment (Brown *et al.*, 1996). The existing global plantation forest area of 80-120 Mha (about 40 Mha in the tropics) could be expanded by an additional 275 Mha, plus 70 Mha of agroforests from 1995 to 2050, by planting at rates consistent with national forestry objectives (8.5 Mha/yr globally for plantations, which is reasonable when compared with 3.9 Mha/yr in China alone in the 1980s). They assumed that all technically suitable lands at mid- and high-latitudes are used (215 Mha) but only 6% of technically suitable lands at low latitudes (130 Mha) because of demands for food and other constraints. By 2050, a total of 38 GtC would be sequestered in planted forests and agroforests, plus a less certain 12-29 GtC as a result of regeneration on degraded tropical lands, giving a total of 50-67 GtC. Estimates of carbon emissions prevented by slowing deforestation are ignored in this analysis.

(ii) Existing forests can be managed to raise the carbon store in trees and forest soils, by lengthening rotations, preventing fires and insect pest outbreaks, applying fertilizers and so on. These actions could potentially increase the sink in existing forests to 0.7GtC/yr by 2040 (Sampson *et al.*, 2000). However, this assumes that half of the forest area is managed with carbon storage as an objective, it includes activities that will occur anyway and ignores adverse effects on, for instance, biodiversity, fire hazard and water quantity.

(iii) Lal and Bruce (1999) estimated the potential carbon storage in croplands (essentially in soils) over 20-50 years to be somewhere in the range 10-30 GtC. This is equivalent to 0.4-0.6 GtC/yr for 20-50 years, achieved by accumulating 0.08-0.12GtC/yr by erosion control, 0.02-0.03 GtC/yr by restoration of degraded soils, 0.02-0.04 GtC/yr by reclamation of salt-affected soils, 0.15-0.175 GtC/yr by conservation tillage and crop residue management, and 0.18-0.24 GtC/yr by improved cropping systems (see also, Metz *et al*., 2001). In a separate estimate, Keller and Goldstein (1998) considered that 0.8 GtC/yr could be sequestered by restoring drylands (woodland, grass and semi-desert), which if continued over 20 years would accumulate 16 GtC (partly in vegetation, partly in soils).

Overall, the IPCC Special Report on land use, land use change and forestry concluded that, by 2040, the potential sequestration rate by managing lands (cropland, grazing, forest management, urban etc) could be 0.8 GtC/yr in Annex I countries and 0.7 GtC/yr in non-Annex I countries, totalling 1.5GtC/yr. In addition a further 0.6 GtC/yr could be sequestered by the adoption of agroforestry in unproductive croplands and grasslands (Watson *et al*., 2000).

Mention may also be made of the pool of carbon in forests products. Globally, this pool is estimated to be 10-20 GtC , increasing by 0.139 GtC/yr – thus representing a small sink (Sampson *et al* 1993, Winjum *et al* 1998).

Conservative, achievable capacity

Likely range 10-50 GtC; 0.2 to 1.0 GtC/yr for 50 years

Current policies and trends make it very likely that many direct human actions and decisions will, indeed, be made that will enhance the 'natural' terrestrial carbon sink in the coming decades. These actions are driven by goals other than carbon sequestration.

(i) Global timber models predict that, as a result of increased demand, global forests will become a sink of 0.11- 0.25 GtC/yr between 1995 and 2045 (at least half in tropical/subtropical countries). This is a result of increased demand for timber and normal market activity (Sohngen and Sedjo 2000). (ii) Conservation tillage (minimum and no-till), which saves 40% of tractor fuel and lessens soil organic matter decomposition, is increasing in the US and Canada (Gerbhardt *et al*., 1985; Dumanski *et al*., 1998) – although the primary motives are to lessen production, reduce costs, conserve water, reduce erosion and enhance biodiversity. (iii) Some countries are vigorously pursuing policies to increase their forest cover, notably China and India, in order to lessen erosion and provide fuelwood, while others are promoting agroforestry and many developed countries place greater emphasis on forest conservation. There is a growth in the area of forest plantations worldwide, led by Asia; half of all plantations in the world are less than 15 years old (FAO, 2001).

The IPCC Special Report on land use, land use change and forestry, estimated that, globally, with an ambitious policy agenda, new afforestation/reforestation could sequester 0.20-0.58 GtC/yr by 2008-2012, and 'additional activities' (forest, cropland and grassland management, agroforestry and cropland to grass conversion) may lead to sequestration of about 1.0 GtC (0.4 GtC/yr from agroforestry alone). These estimates total 1.2-1.6 GtC/yr by 2008-2012 (Watson *et al*., 2000). By contrast, new afforestation and reforestation since 1990 in Annex I countries is likely to sequester only 0.007- 0.046 GtC/yr in 2012.

There are, however, good reasons to be cautious. In the absence of financial incentives, carbon sequestration is likely to remain incidental to the main gaols of land managers. All ten of the existing major forestry projects in tropical countries designed specifically to sequester carbon or avoid emissions (by lessening deforestation) will save only about 0.05 GtC over their lifetime (covering 2.9 Mha, Watson *et al*., 2000). This estimate assumes no negative leakage - the displacement of activities which release carbon elsewhere - and does not take account of the fossil fuel cost of implementation. Any large-scale global afforestation programme to sequester carbon would result in an oversupply of wood, undermining incentives for current afforestation – causing negative leakage (Sedjo and Solomon, 1989). Account must also be taken of the effect of land use change on the sources and sinks of N_2O and CH_4, and of the risk of climate change itself adversely affecting forests, notably by increasing the risk of fire (Stocks *et al*., 1998).

Even with financial incentives, there are formidable constraints to increasing forest cover in many parts of the tropics. These are the same forces that are driving deforestation, namely, the demand for cropland, fuelwood and, in Latin America, grazing land - fuelled by insecure tenure, landless people, land speculation, external debt and migration. Sathaye and Ravindranath (1998) estimated that, in tropical and temperate Asia, less than half of the potential sequestration of 26 GtC is likely to be feasible, and that is probably optimistic.

1.2 Europe

In 2000, anthropogenic emissions from the EU15 totalled about 0.94 GtC/yr (Eurostat website). Because of underharvesting, increased growth rates, conservation and new planting, forests in EU15 countries are estimated to be net carbon sinks, totalling 63 MtC/yr in 1995 (about 14 MtC/yr in Germany, 11 MtC/yr in Sweden, 10 MtC/yr in France and 7 MtC/yr in Finland) (Liski *et al*., 2000). Thus, the current forest sink takes up about 7% of emissions.

The EU15 countries have about 116 Mha of forest and 142 Mha of agricultural land, of which 72 Mha is arable and 35 Mha is cropped with cereals. The estimates of potential sequestration depend primarily on judgements of the areas that can be converted from agriculture to forest and from arable to pasture as well as changes in cropland management.

Theoretical potential capacity

Likely range 20 - 30 GtC; 200 to 500 MtC/yr for 50 to 100 years

If all of the 142 Mha of agricultural land were afforested, and accumulated 100-150 tC/ha over 50 to100 years (200-300 t/ha dry biomass, Cannell 1982), this would store 14- 21 GtC in biomass, plus possibly an additional 5 GtC in the soils on previously arable land, totalling 19-26 GtC, averaging a sequestration rate of 0.38-0.52 GtC/yr over 50 years or 0.19-0.26 GtC/yr over 100 years. This gives some notion of the upper boundary for carbon sequestration, representing 20-55% of current EU15 emissions. Scurlock *et al.* (1993) made similar back-of-envelope calculations, showing that 40-120% of the total land area of Europe would need to be devoted to new forests to absorb all Europe's emissions.

Realistic potential capacity

Likely range 5-10 GtC; 50 to100 MtC/yr for 100 years

More credible estimates of potential carbon storage in the EU15 countries were made by Smith *et al.* (1997). They estimated that afforesting 20 % of current arable land (ie 14 Mha) would sequester about 5 GtC over 100 years in biomass and soils, and incorporating straw, manures and sewage sludge into agricultural soils would sequester another 2-3 GtC over 100 years.

Alternatively, if all EU15 arable land were converted to no-till farming, this would sequester about 23 MC/yr (Smith *et al*., 1998). In addition, we should attribute some fraction of the current European forest sink to management practices that will continue within the existing forest area.

In a further study, Smith *et al.* (2000) considered the carbon sequestration and biofuel offset consequences of a number of policy options for the use of 10% surplus arable land in the EU15 (ca. 7 Mha) and management of the remaining arable land. In their optimal scenario, 50% of the surplus land is used for bioenergy, 50% for woodland and the remaining arable land is managed with a high rate of organic matter incorporation into soils. This optimal scenario produced a carbon mitigation potential of 105 MtC/yr.

These estimates suggest that a realistic potential sequestration capacity resulting from all types of land use change and management might lie in the range 5-10 GtC, giving a sequestration rate of 50-100 MtC/yr for 100 years. However, Smith *et al.* (1997, 1998) stressed that these are potentials and do not consider all the constraints.

Conservative, achievable capacity

Likely range 2-5 GtC; 20 to 50 MtC/yr for 100 years

Actual land use change in Europe in the past 50 years has been slow relative to the potential changes considered above. If historic constraints on land use change persist, future change might be slow and potential rates of carbon sequestration will not be achieved. At present, it seems unlikely that carbon sequestration will feature strongly in changes in the Common Agricultural Policy or incentives for forestry, although Solberg (1997) has argued that the net value of carbon sequestered in forests is greater than the net value of the timber. History suggests that any large expansion in plantation forestry is likely to meet local objections, especially in southern Europe where water supplies may become increasingly critical.

The European Forest Institute scenario model suggests that, in a business-as-usual scenario, the growing stock of carbon in 27 European countries will increase by 74 MtC/yr between 1990 and 2050, mainly due to continued increase in the biomass of existing forests. In an alternative scenario, which includes forest expansion of 4 Mha and conservation forestry on 4 Mha, the increase in carbon was 94 MtC/yr from 1990 to 2050 (Nabuurs *et al*., 2001). However, much of this carbon storage is the legacy of past actions.

There is no objective way of estimating the level of carbon sequestration that might actually be achieved by new forest planting in the EU15, but a conservative range would be 2-5 GtC, or 20-50 MtC/yr for 100 years, offsetting the equivalent of 2-5% of current EU15 emissions.

1.3 United Kingdom

In 2000, the UK emitted 147 MtC/yr by burning fossil fuels. A further 4 MtC/yr were emitted as a result of past land use change (primarily from soils), partially offset by about 3 MtC/yr absorbed by forests (DEFRA, 2001). The forest sink is the legacy of expansion in the area of forest since the 1950s. A detailed breakdown of UK carbon sources and sinks in 1990 - due to changes in the stores of carbon in soils and vegetation - is given by Cannell *et al*. (1999).

The UK has about 11.4 Mha of agricultural (about 5.3 Mha of which is arable cropland and 6.1 Mha grassland), 6.6 Mha of semi-natural vegetation (mostly in the uplands) and 2.6 Mha of forest.

Theoretical potential capacity

Likely range 2.5-3.5 GtC; 30 -70 MtC/yr for 50 to100 years

If all the non-forest land in the UK (18 Mha) were afforested instantly and accumulated 150-200 tC/ha over the next 50 to 100 years, it would store 2.7 - 3.6 GtC, equivalent to 54-72 MtC/yr over 50 years or 27-36 MtC/yr over 100 years, equal to 18-49% of current emissions.

Realistic potential capacity

Likely range 0.3- 0.5 GtC; 3-5 MtC/yr over 50 to 100 years

The maximum rate at which the forest area expanded in UK during the 20^{th} century was about 40 Kha/yr in the early 1970s, mainly in the uplands (Cannell and Dewar, 1995). From 1950 to 1990 the average rate of forest expansion was about 25 kha/yr. The eventual establishment of about 1.3 Mha of mainly conifer forests during the 20th century met with considerable objection, because of its impacts on the landscape, acidification, water resources, wildlife and recreation.

Even with an aggressive carbon sequestration policy, it seems unlikely that the rate of forest expansion could exceed 50 kha/yr. Furthermore, it would be unrealistic to imagine that this rate of expansion could be maintained for much more than 50 years, which would give an additional 2.5 Mha of forest, approximately doubling the existing forest area in the UK.

If that aggressive planting programme were implemented, another 0.38-0.50 GtC would eventually be stored in forests (assuming all felled forests were replanted) with a sink averaging 3- 5 MtC/yr over 50 to 100 years (Cannell and Dewar, 1995) equivalent to 2-4% of current emissions.

Conservative, achievable capacity

Likely range 0.05-0.10 GtC; initially 1-2MtC/yr, then falling to zero over 50-100 years

The actual forest sink in the UK was estimated to be 2.9 MtC/yr in the year 2000, (DEFRA, 2001). If the area of new forest continues to expand at the 1997 rate of 7 kha/yr of conifers and 10 kha of broadleaved woodland (assuming, additionally, that all existing clearfelled forests are replanted) the UK forest sink will be about 2.7 MtC in 2020 (Milne, 2001). This is the business-as-usual scenario.

Alternatively, if forest area expansion occurred at a higher rate of 10 kha/yr of conifers and 20 kha/yr of broadleaved woodland, the forest sink would be 3.1 MtC/yr in 2020, storing an extra 50 MtC by 2020 (DEFRA, 2001; Milne, 2001). By 2020, approximately a further 0.2 Mha of upland conifer forest would be created and 0.4 Mha of woodland on land mainly taken out of farming. This is realistically achievable, but possibly not on a 20-year timescale. Also, the planting rate of 30 kha/yr is unlikely to be sustained much beyond 2020 as forestry would then encroach on land that is in demand for other purposes. When the forest expansion rate declines, as it must inevitably, the forest sink will diminish towards zero about 40 years later (Cannell and Dewar, 1995).

A conservative, achievable storage capacity, taking into account the constraints on land use change in the UK, might be somewhere in the range 50-100 MtC over the next 100 years, sustaining a sink of 1-2 MtC/yr for a few decades but then falling to zero. Sequestration of 1-2 MtC/yr is equivalent to 0.7-1.3% of current UK carbon emissions.

Meanwhile, estimates of emissions of carbon from agricultural soils as a result of past land use change (excluding the forest sink) will change from 4.0 - 4.7 GtC/yr in 2000 to anywhere in the range 0.0 - 6.3 GtC/yr in 2020 (DEFRA, 2001) and would be expected to diminish towards zero if some agricultural land was afforested and other land was managed less intensively (eg with minimal tillage).

Conclusions

Table 1 summarizes the ranges of carbon sequestration capacities and rates concluded from this review. In all cases, a realistic assessment of the potential is about an order of magnitude less than the theoretical potential, and a conservative estimate of what may be achievable is about half of the realistic potential. Clearly, what is achievable is based largely on informed subjective judgement, but it nevertheless signals reasons for caution in the use of potential estimates.

In reality, sequestration rates following afforestation and land use change will change over time, eventually falling to a time-average of zero as the vegetation-soil system reaches a new equilibrium. Thus, the estimates given of sequestration rates are approximate time-averages.

Globally, land management to enhance carbon sequestration could add another 200-1000 MtC/yr to the ‘natural’ terrestrial carbon sinks. Most of this could be achieved by enhancing current good land management practices, such as afforestation for erosion control and wood supply, agroforestry and minimal tillage. This is a substantial contribution, representing 3-15% of current emissions of 6400 MtC/yr.

Within the EU15, readily achievable carbon sequestration may be only 20-50 MtC/yr (additional to the natural sinks), 2-5% of current EU emissions of 940 MtC/yr. In the UK, only 1-2% of current emissions of 147 MtC/yr can readily be offset by carbon sequestration activities (1-2 MtC/yr). More than this is clearly possible, but would require a major shift in land use policies and public perception of priorities.

Table 1. Biological carbon sequestration estimates for the world, the EU15 countries and the UK.

	Theoretical potential	Realistic potential	Conservative achievable
	Carbon storage capacity (GtC)		
World	100-200	50-100	10-50
Europe	20-30	5-10	2-5
UK	2.5-3.5	0.3-0.5	0.05-0.10
	Carbon sequestration rates for 50-100 years (MtC/yr)		
World	2000-4000	1000-2000	200-1000
Europe	200-500	50-100	20-50
UK	30-70	3-5	1-2

2. Biomass Energy Substitution

In any discussion of biomass energy potential, and the extent to which it offsets carbon emissions from fossil fuels, it is first necessary to define the terms and conversion factors being used. There are many options, which are not always clear in the literature.

2.1 Definitions

Energy units

The energy units used here are Joules, the quantity of energy, rather than Watts, the rate of energy supply or consumption. Conversion factors are given in Appendix A.

Biomass energy

The energy considered here is that coming from ‘modern’ biomass, which is either produced from energy crops and plantations or recovered from industrial forest residues. These may be used to produce electricity, combined heat and power or liquid fuels. We are not concerned with ‘traditional’ biomass energy, from dung, charcoal and fuelwood collected by households. Furthermore, we should be clear that biomass energy is only one component of all biofuels, which includes energy from waste and landfill gas.

Carbon content of fuels

Various conversion factors have been used in the literature for the amount of carbon emitted per unit of energy for different fuels. The conversion factors used here are 27 kgC/GJ for biomass and coal, 21 kgC/GJ for oil and 15 kgC/GJ for natural gas, which equate to 37 GJ/tC for biomass and coal, 48 GJ/tC for oil and 66 GJ/tC for gas (Blundell, 2000, Royal Commission on Environmental Pollution; Marland, 1983)[1].

Biomass fuel carbon displacement of coal, oil and gas

Calculation of the amount of carbon *not* emitted to the atmosphere as a result of using energy from biomass rather than fossil fuels is potentially complex, primarily because, (i) fossil fuel carbon is emitted during the cultivation and transport of biomass (and in alternative land management systems) and is also emitted during the mining and transport fossil fuels, and (ii) substitution (displacement) values can obtained based on the ‘primary energy’ content of fuels as supplied to the primary user (power station or conversion plant) or the electrical or liquid fuel energy supplied to the end user. Complete life cycle analyses of biomass and fossil fuel emissions have led to a range of substitution values, depending, for instance, on what operations/processes are included, the choice of fuel mix, the reference land use system, the energy costs and valuation by-products, and the effects of non-CO2 gases emitted. It is beyond the scope of this study to cover all of these aspects.

In this review, the substitution values used are that:

- 1 tonne of dry biomass used to generate electricity prevents 0.50 tC being emitted to the atmosphere from coal, 0.44 tC from oil or 0.28 tC from natural gas, using the primary energy contents of biomass, coal, oil and gas before electricity generation; and
- in the UK and the rest of Europe, biomass used to produce liquid fuels prevents 0.2-2.0 tC being emitted to the atmosphere for every hectare planted with energy crops, based on complete fuel cycle analyses of Kaltschmitt *et al* (1997) and Bauen (2002).

The justification for using these conversion factors is given below.

Electricity generation

Consider the simplified diagrams in Figure 1 of carbon and energy flow from the production of biomass, coal and gas to electricity generation.

One tonne of dry biomass from energy crops contains about 500 kg of carbon, which is fixed by photosynthesis from the atmosphere. One tonne of biomass, delivered to produce electricity (by combustion, pyrolysis or gasification), contains about 18.5 GJ of energy (37 GJ/tC, Table 1). The production of biomass involves the use of fossil energy (for cultivation, fertilizers, transport and so on), typically with an emission of 0.5-2.0 kgC per GJ of primary biomass energy delivered to a power plant – the emission factor (Turhollow and Perlack, 1991; Matthews and Robertson, 2002). This means that the cultivation and production of 500 kgC of biomass emits about 10-40 kgC (approximately 18.5x1.5 to 18.5x2.0) and so consumes about 0.5-1.5 GJ, assuming the that the fossil fuels used in cultivation and transport emit an average of about 25 kgC/GJ. This 10-40 kgC is the net cost to the atmosphere of producing biomass fuel, because the 500 kgC fixed by photosynthesis is assumed to be returned to the atmosphere during electricity generation[2]. If we take the scheme to electricity generation, then only about 40% of the 18.5 GJ is recovered as electrical energy[3].

Note that, in this simplified scheme, the ratio of energy input (0.5-1.5 GJ) to primary energy output (18.5 GJ) is in the range 12-37, in accord with published values for wood production systems of about

[1] Values used in the Oak Ridge National Laboratory are 25.4 , 19.9 and 14.4 kgC/GJ for coal, oil and gas, respectively.
[2] A small additional amount of the carbon in biomass may be returned to the atmosphere by respiration and decay before it is used for electricity generation (Matthews and Robertson, 2002).
[3] The efficiency of converting biomass energy to electrical energy by pyrolysis and gasification (integrated gasification combined cycle) is about 44% for energy crops and 31% for agricultural and forestry waste (or municipal solid waste) (Blundell, 2000). The ARBRE biomass plant in the UK has achieved efficiencies of 43-53%, depending on the gasifier perating pressure and plant capacity. By contrast, the energy conversion efficiency of CHP plants is commonly 70% (heat efficiency 52%, electrical efficiency 19% with a heat:power ratio of 2.6) and can be up to 80%.

25 (Matthews and Robertson, 2002) while the ratio of electrical energy output (7.4 GJ) to energy input is 5-15, or 9-26 if the biomass is used to produce combined heat and power (CHP). In this scheme (Fig. 1) the 'emission factor' for electricity generation (10-40 kgC divided by 7.4 GJ) is 1.4- 5.4, at the lower end of the range in the literature (1.6-14.7 kgC/GJ, equivalent to 22-193 gCO_2/kWh of electricity (Matthews and Robertson, 2002).

If we now compare the biomass fuel chain with that for 500 kg of coal, we see a similar picture (Fig. A1). Coal is carbonised biomass, so it is not surprising that 500 kg coal also contains about 18.5 GJ. Furthermore, the energy required to mine coal and deliver it to a power station is similar to that required to produce biomass, per unit of carbon or energy content (in Fig. A1, given as 0.5-2.0 GJ, emitting 10-50 kgC, to produce 500 kg coal). Furthermore, the conversion efficiency of coal to electricity is also around 40% [4]. Consequently, for electricity generation, biomass and coal are approximate energy equivalents. The only substantial difference in Figure 1 is that coal emits 500 kgC to the atmosphere whereas energy crops recycle it. Consequently, to a reasonable approximation, 1.0 dry tonne of biomass displaces 0.5 tC from coal both as a primary fuel and when used to generate electricity. This analysis is consistent with Bauen (2002) who estimated that short rotation coppice yielding about 10 t/ha/yr in the UK displaces 5.4 tC/ha from coal used to produce electricity. In the terms used by Schlamadinger and Marland (2001), it is assumed that the 'displacement factor' of biomass relative to coal used to generate electricity is one (ie the efficiency of the energy systems and C emissions per Joule are the same).

For natural gas, the situation is different, because gas contains more energy per unit of carbon emitted (15 kgC/GJ, Table 1) and is converted to electricity more efficiently[5] (Fig. A1). In terms of primary energy, 1 tonne of biomass (500 kgC) displaces 280 kgC of gas (500 x 18.5/33). In terms of electrical energy, assuming 50% conversion efficiency for gas, 500 kg biomass displaces 224 kgC from gas (500 x7.4/16.5)[6]. It may be noted that the 'emissions factors' for coal and gas in Figure 1 for electricity generation are 69-74 kgC/GJ and 31-33 kgC/GJ, respectively, at the lower end of the range in the literature (73-98 kgC/GJ for coal and 31-39 kgC/GJ for gas, Matthews and Robertson, 2002).

Oil contains about 21 kgC/GJ, so the equivalent calculation for oil is that 1 tonne of biomass (500 kgC) displaces 440 kgC of oil (500 x 18.5/21).

Equivalence between sequestration and electrical energy substitution

Assuming an average yield of oven dry biomass from temperate short rotation woody plantations of 10 t/ha/yr (Cannell and Smith, 1980), every 100 Mha of land yields approximately 18.5 EJ of primary energy and offsets 0.50 GtC from coal or 0.28 GtC from gas. By comparison, 100Mha might have the capacity to sequester 100-200 tC/ha (200-400 t dry matter/ha) totalling 10-20 GtC, offsetting 0.2-0.4 GtC/yr over 50 years or 0.1-0.2 GtC/yr over 100 years. Thus, over a 50-100 year timescale, the carbon offset benefit derived from biomass grown for energy is roughly comparable to that derived from growing it to sequester carbon. This equivalence is the direct result of the carbon-energy equivalence between biomass and coal. Within the growing lifetime of forests (when they are sequestering carbon) it may make little difference whether their biomass is left as a carbon store or used as an energy substitute for coal (Scurlock *et al*., 1993).

Liquid fuel production

Liquid biofuels derived from biomass (ethanol, methanol, biodeisel etc.) have approximately the same energy content as diesel and petroleum (19-22 kgC/GJ, 45- 53 GJ/tC). However, the energy costs of

[4] Conventional coal fired power stations have a conversion efficiency of about 38%, whereas coal 'integrated gasification combined cycle' plants and those with pulverised fluid bed combustion have efficiencies of about 46%.
[5] Combined cycle gas turbines have a conversion efficiency of 53%, with new designs reaching 60 % (Shao and Golomb, 1996).
[6] Stated differently, 18.5 GJ (500 kgC) of biomass displaces 500 kgC of coal or 280 kgC gas, so that 1 GJ of biomass displaces 27 kgC coal or 15 kgC gas, or 1 EJ displaces 0.027 GtC coal or 0.015 GtC gas.

production are high compared with the energy costs of producing bio-electricity and a limited number of studies have been made of the complete energy or fuel chain.

Brazilian ethanol from sugar cane (with bagasse) probably has the highest efficiency, with only 30-40% of the fuel energy being used in production – ie with energy output/input ratios of 2.5-3.5 (Giampietro et al., 1997). Estimates of this ratio for ethanol from maize, taking account of total energy costs of production are 1.01-1.13 in the USA (Marland and Tuhollow, 1991; Shapouri et al., 1995), 1.02 in France (CCPCS, 1991) and only 0.6 in Italy, or 1.36 when residues are used to provide energy for the process and some energy credit is given for byproducts (Ulgiati, 2001). Matthews and Robertson (2002) reviewed the literature and concluded that the likely range was 2-15, but noted large variation in reported energy ratios due in part to variation in accounting procedures.

Overall, it is clear that, in non-tropical countries, biomass used to produce liquid fuel offsets much less fossil carbon than biomass used to generate electricity, and, in the worst case, the energy balance of liquid fuel production in non-tropical regions may be questionable (Ulgiati, 2001). Only in some tropical situations will the carbon offset be appreciable. Ethanol production from sugar cane in Brazil has been estimated to replace about 2 tC/ha/yr relative to petrol, but excluding the emissions involved in the production of petrol (Kheshgi et al., 2001).

Given the uncertainty, this review comments only on the potential for carbon offsets using liquid biofuels in the EU15 and UK, based on the most comprehensive fuel chain analyses of Kaltschmitt *et al*., (1997), Ulgiati (2001) and Bauen (2002). Their analyses of a range of crops growing on agricultural land (cereals, oilseed rape, short rotation coppice and Miscanthus) and a range of liquid fuels and processes, suggest that the potential for fossil diesel substitution lies in the range 0.2-2.0 tC per hectare of land.

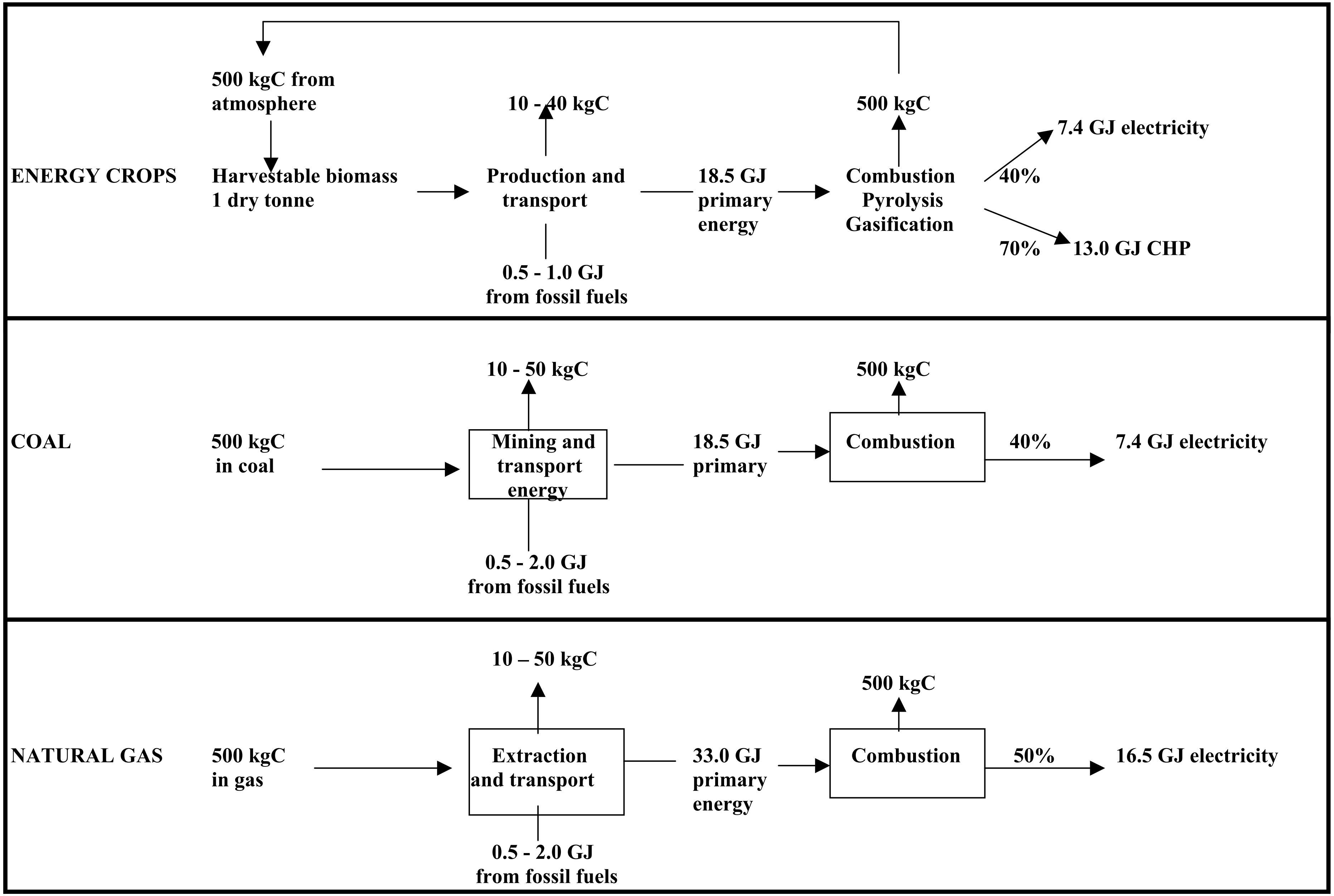


Figure 1. Simplified schemes of the flows of energy and carbon when generating electricity from biomass, coal or natural gas. (CHP is 'combined heat and power'.)

2.2 World

Current global emissions of 6.4 GtC/yr are associated with the generation of about 400 EJ of primary energy per year. By 2100, global primary energy use may be 1400 EJ per year in a business-as-usual scenario, or 700 EJ in a low demand scenario (Leemans *et al*., 1996).

Whereas forests planted for carbon storage can be planted on poor land, biofuel plantations of trees or annual crops require productive land to sustain high yields (Marland and Schlamadinger, 1997). The current global cropland area is about 1450 Mha.

Theoretical potential capacity

Likely range of fossil fuel offset: 2-5 GtC/yr by 2050-2100

The physical upper boundary for biomass energy production is set by global annual net primary production of biomass. Global NPP is about 100 Gt dry biomass/yr, or 50 GtC/yr (Cramer *et al*., 1999), which contains about 1850 EJ, equal to the energy in 50 GtC/yr in coal or 28 GtC/yr in gas. But, clearly, this is not a helpful potential figure, as it assumes no other uses for land. It is better to consider the theoretical potential in terms of maximum potential land use for energy crops.

The most extreme estimates of the area of land that could be used worldwide for biomass energy are 800 Mha by 2100 (Leemans *et al*., 1996) and 600 Mha by 2050 (Hall, 1991; Hall *et al*, 1991; Rosillo-Calle and Hall, 1992, Hall *et al*., 2000). The former is equivalent to 55% of the current cropland area (although made up in large part from degraded lands) while the latter assumes that 40% of the current cropland area is used, plus 15% of the current forest area (Hall *et al*., 1991).

Assuming an average yield of 10 dry t/ha, 800 Mha would give 148 EJ/yr of biomass energy and displace 4.0 GtC/yr coal or 2.2 GtC/yr gas, while 600 Mha would give 111 EJ/yr of energy and displace 3.0 GtC/yr coal or 1.7 GtC/yr gas. A further 0.9 GtC/yr coal offset might potentially be obtained by 2050 by using biomass residues (wood and straw) and 0.9 GtC/yr by generating electricity form sugar cane and kraft pulp (Hall, 1991).

With assumptions of high yields (>10 t/ha/yr of biomass) and high conversion efficiencies, estimates have been made of over 300 EJ/yr being derived from biomass by 2100, equivalent to a coal offset of 8.1 GtCyr or gas offset of 4.5 GtC/yr, but not all of this is 'modern' biomass (Hall and Scrase, 1998; Nakivcenovic *et al*., 1998). In the IPCC Special Report on Land Use, Land Use Change and Forestry (Watson *et al*., 2000, Fact Sheet 4.21) an extreme scenario is given of 250 Mha devoted to energy crops by 2020 and 500 Mha in 2100, which, with yields rising from 10 to 25 t/ha/yr, could produce about 300 EJ/yr by 2050.

Bearing in mind that biomass primary energy may offset a mix of fossil fuels, most of these optimistic estimates suggest that modern biomass could potentially produced anything in the range of 150-300EJ by 2050-2100, displacing perhaps 2-5 GtC/yr, similar to the theoretical global potential for carbon sequestration. However, these estimates violate or ignore the constraints of sustainable development.

Realistic potential capacity

Likely range of fossil fuel offset: 1-2 GtC/yr by 2050-2100

The area of high quality land available for energy crops will be constrained by the need for increased food production as world population increases from about 6 to 10 billion. The relationships between land availability, land quality and development needs should not be oversimplified. Locally, the tradeoffs between energy, food and water security may be resolved in different ways. The notion that half of the current cropland could be devoted to energy crops is highly questionable.

Even in the USA, there is a two-fold difference in the more optimistic estimates of biomass energy potential. Thus, optimistic projections by Wright and Hughes (1993) suggest that 20% of current US emissions could be met by 2030, requiring 28 Mha of land, to be planted at a rate of 1 Mha /yr, with yield increases of 1.5%/yr (to over 22 t/ha/yr) and the installation of 500 MW new capacity each year. A more realistic, yet still optimistic, assumption is that 14 Mha could be used for energy crops, displacing 3-6% of current US emissions (Graham *et al*., 1992; Haroon *et al*., 2000).

In developing countries, the difference between optimistic and realistic potential land availability is likely to be greater than in the USA, because of faster population growth and demand for food and water. Also, degraded lands, which are included in many theoretical calculations, may require too large an investment of energy and capital to be viable for energy cropping.

Rather than 500-800 Mha being devoted to energy crops worldwide by 2050-2100, a more reasonable potential land area, suggested by some authors, is 200-400 Mha (14-28% of current cropland area) (Johannson *et al*., 1993; Haroon *et al*., 2000). Assuming, again, an average biomass yield of 10 dry t/ha, this area could produce 37-74 EJ/yr, offsetting 1-2 GtC from coal or 0.6-1.1 GtC from gas.

Conservative, achievable capacity

Likely range of fossil fuel offset: 0.2-1.0 GtC/yr

The main reasons for caution in projecting a large role for biomass energy crops worldwide are as follows.

(i) Most developing countries are facing continuous or periodic food and water shortages, as well as shortages of traditional biofuels. Increasing populations, combined with shifts in the patterns or reliability of rainfall as a result of climate change, will make matters worse. Global food production kept pace with global population doubling during the 20^{th} century largely by increasing yields per hectare. This increase has been possible by increased use of fertilizers and breeding to increase the ‘harvest index’. In future, a larger fraction of increased food demand may have to be met by increasing the cropland area. Competition for land is bound to intensify to simultaneously achieve food, energy and water security and a quality of life. It is worth recalling the concern that water use by eucalyptus plantations has caused in India and SE Asia and that food shortages in Brazil have been linked to the ProAlcohol Program.

(ii) Substantial economic and policy obstacles must be overcome to allow biomass energy to penetrate the energy market. Fossil fuel energy costs must approximately double, or biomass energy costs halve. Changes would be required not only in energy policies, but also in policies on agriculture, forestry, conservation and transport. Biomass is used most efficiently in small local generator plants, with combined heat and power, requiring a restructuring of energy consumption patterns. Such radical change is not likely to occur quickly.

(iii) The environmental costs of woody biomass energy crops may be greater than those of annual crops. Water use will be greater (owing to greater rainfall interception), landscapes will change and the harvesting and transport of bulky material will create nuisance, while adverse impacts on biodiversity and freshwater eutrophication may remain.

(iv) As mentioned, the total life cycle energy balance of energy crops for liquid fuel is questionable in non-tropical countries unless residues are used as a fuel in the process and co-products are credited as outputs. Ulgiati (2001) calculated that, in Italy, it would take 37% of all crop and pasture land, and 22% of available water, to produce 5% of the current total energy used in transport. The Brazilian ProAlcohol Program succeeds because 4 Mha are available in an area with a small population (20 persons/km^2)

where sugar cane yield 50-60 t/ha/yr. However, it supplies only about 4% of Brazil's total country energy in the transport sector (Ulgiati, 2001). The fossil energy used in production means that, even here, only 29% of the energy in the cane is captured – likely to be the maximum for any crop in the world.

(v) The total greenhouse gas benefit of biomass energy plantations way be less if N fertilizers lead to increased N_2O emissions and if plantations are planted on organically rich soils (eg former forest or natural land) which may then lose carbon to the atmosphere.

In a recent study, Yamamoto *et al*. (2000) took into account the carbon emitted when converting forests to short rotation plantations, and derived an achievable global fuelwood programme that would offset only 2-7% of the accumulated global fossil emission of 1260 GtC from 1990 to 2100 (slightly below IS92a). Bauen and Kaltschmitt (2001) gave a conservative estimate of 150 Mha of land potentially available for energy crops – based on current FAO agricultural and forestry statistics and regional assessments of land suitability and future cropland demand. Finally, the World Energy Council's estimate of the carbon offset that could realistically be achieved in 2020 by global deployment of modern biomass is in the range 0.12- 0.28 GtC/year with current policies and 0.30- 0.65 GtC/year with 'ecologically driven' policies (WEC, 1993).

Overall, a conservative global estimate of energy cropland by 2050-2100 might lie anywhere in the range 50-200 Mha, producing 9- 37 EJ, displacing 0.24-1.00 GtC/yr from coal or 0.14-0.56 GtC from gas.

2.3 Europe

In 2000, the EU15 had a primary energy use of 59 EJ (1442 Mtoe; 41% from oil, 23% gas, 15% nuclear, 15% coal, 6% renewables) of which 3.7% was from biomass (mostly in France and Scandinavia) (Eurostat website). This energy use equates to the emission of about 0.51 GtC from oil, 0.20 GtC from gas and 0.23 GtC from coal, totalling 0.94 GtC/yr.

As mentioned above, there are 142 Mha of agricultural and 72 Mha of arable land in the EU. In 2000, about 3.9 Mha of agricultural land was set aside.

Theoretical potential capacity

Likely range of fossil fuel offset: 0.6-0.9 GtC/yr

If all of the 142 Mha of agricultural land in the EU15 were devoted to energy crops yielding 10 t/ha/yr biomass with 18.5 GJ/t, this would capture about 26.3 EJ per year, 44% of the total primary energy consumption in 2000 (or 52% excluding nuclear).

If this 26.3 EJ/yr of biomass energy were used to offset all of the coal energy (8.6 EJ) and the remaining 17.7 EJ/yr (26.3-8.6) were used to offset oil consumption (it could offset 73% of the 24.4 EJ/yr of oil consumption in the EU15), it would displace about 0.65 GtC/yr (0.23 GtC from coal and 0.42 GtC from oil), 69% of the EU15 total emission in 2000. A further 0.2-0.3 GtC/yr may be displaced by making full use of forest residues. There would be no agricultural residues in this scenario.

Thus, if all agricultural land were converted to energy crops and forest residues were fully exploited - and with the most carbon-saving fuel substitution - the total carbon displacement would be 0.8-0.9 GtC/yr, similar to the EU15 emission of 0.94 GtC/yr in 2000. With less optimum energy substitution (substituting some natural gas use) the theoretical potential is likely to lie in the range 0.6- 0.8 GtC/yr.

This estimate of theoretical carbon displacement by energy substitution is greater than the theoretical calculation made above of 0.19-0.52 GtC/yr sequestered in biomass and soils for 50 to 100 years if all 142 Mha of agricultural land were afforested.

Realistic potential capacity

Likely range of fossil fuel offset: 200-300 MtC/yr

A more realistic potential substitution scenario might involve the use of, say 30-40 Mha for energy crops, substituting 150-200 MtC from coal plus the fuller use of forest and agricultural residues, to make a total offset in the range 200-300 MtC/yr, 21-32% of EU15 carbon emissions in 2000.

In a realistic analysis of the potential use of short-rotation woody crops and forest residues for fuel, Schwaiger and Schlamadinger (1998) concluded that up to 30% of the current EU15 carbon emissions (about 0.3 GtC/yr) could be displaced – mainly by the proliferation of small generating plants, combined heat and power, and individual or district house heating. Small-scale cogeneration for district heating is currently an attractive alternative to gas-based systems, based on costs and efficiency as well as emissions (Ossebaard *et al*., 1997).

Conservative, achievable capacity

Likely range of fossil fuel offset: 100-200 MtC/yr by 2050

The reality is that, in the EU15, biomass energy crops are being promoted as part of the policies contained in the Renewables Directive (12% of primary energy consumption by 2010), Biofuels Directive (5% by 2010) and Combined Heat and Power Directive (18% by 2010) as well as the Kyoto agreement to reduce emissions by 8% below 1990 levels by 2008-2012. These pressures accompany changes to improve air quality (Large Combustion Plant Directive) and reform the Common Agricultural Policy (Agenda 2000).

Sweden is leading the way in the use of biofuels in Europe. Currently, 15% of Swedish energy is currently supplied from biomass and the potential is over 20% (Gustavsson, 1994, 1997). However, Sweden has a low population density, a large forest area, consumes only 3.5% of the EU15 total energy demand and, in fact, produces only 14% of the EU15 biomass fuel.

The European Commission's White Paper on Renewables proposes a target of doubling the contribution of renewables from 6% to 12% of the EU's total primary energy needs by 2010 involving a capital investment of 165 billion Euros. The subsidiary target for all biofuels by 2010 is 5.6 EJ/yr (135 Mtoe) (DTI, 2001). It is assumed that energy crops will contribute 1.85 EJ/yr, requiring 10 Mha and that agricultural and forest residues will contribute 1.23 EJ/yr. The 1.85 EJ/yr of energy crops will offset about 50 MtC of coal (28 MtC of gas) and the residues will offset about 33 MtC/yr of coal (or 18 MtC/yr of gas), making a total target offset of 83 MtC/yr of coal (or 46 MtC/yr of gas) by 2010.

In addition, liquid biofuels will make a small contribution. In 1998, about 0.4 Mha of set-aside land in the EU15 were dedicated to liquid fuels, supplying about 0.3% of liquid fuel demand. This production gives an offset of fossil liquid fuels in the range 0.09-0.88 MtC/yr (0.2-2.0 tC/ha, see above). If it were assumed that this area increased by a factor of 2-5 by 2010, the offset would be in the range 0.2-4.4 MtC/yr. However, at current oil prices, the production cost of liquid biofuels (about 0.5 Euros/litre) is twice that of diesel.

Thus, the EU15 target carbon offset in 2010 is around 83- 87 MtC/yr of coal or 46- 50 MtC/yr of gas, representing about 9% of current EU15 carbon emissions for coal substitution and 5% for gas substitution.

Looking ahead to 2050, a reasonable guess might be that an offset in the range 100-200 MtC/yr is achievable with continued expansion in land areas, improvements in yields, use of heat and power and improved conversion technologies.

2.4 United Kingdom

In 2000, UK primary energy consumption was 9.5 EJ/yr (232 Mtoe; 36% oil, 35% oil, 16% coal, 11 % nuclear). All renewables contributed only 0.12 EJ/yr , 1.3% of primary energy consumption, which can be divided into hydro (14%), all forms of biofuels (82 %) and 'other' (4%, including wind and geothermal). The biggest contributors to biofuels were landfill gas (0.030 EJ/yr), refuse combustion (0.026 EJ/yr) and wood for industrial and domestic use (0.021 EJ/yr). Straw combustion for heat contributed 0.003 EJ/yr and a similarly small contribution was made from a total of about 2000 ha of energy crops (mostly for the ARBRE power plant).

The consumption of 9.5 EJ/yr was accompanied by the emission of 147 GtC/yr, mostly from liquid fuels and gas.

There are 11.4 Mha of farmland in the UK. The current set-aside area is about 0.5 Mha. The UK has about 2.7 Mha of forest. Annual removals of timber are about 7 M green tonnes per year.

Theoretical potential capacity

Likely range of fossil fuel offset: 40-60 MtC/yr

If all of the 11.4 Mha of farmland in the UK were devoted to energy crops yielding 10 t/ha/yr, this would capture 2.1 EJ/yr, 22% of the total primary energy consumption of the UK in 2000 (or 25% excluding nuclear). If this biomass energy were used to offset all of the coal energy (1.5 EJ/yr) and the remainder used to offset oil energy it would displace 57 MtC/yr (41 MtC/yr from coal and 16 MtC/yr from oil), 39% of current emissions.

The forest residues available for energy production are about 15% of the timber removals, approximately 0.5 M dry tonnes of wood. Not all of this could be removed without depleting soil organic carbon. If 70% were removed (0.35 Mt dry wood) this would offset only 0.18 MtC/yr from coal. In this scenario, no residues would be available from farmland.

Thus the theoretical offset in the UK is about 50-60 MtC/yr, but involving the disappearance of virtually all farming activities. This estimate may be compared with the calculation made above of 30-70 MtC/yr sequestered in biomass and soils for 50 to 100 years if all 11.4 Mha of farmland were afforested.

Realistic potential capacity

Likely range of fossil fuel offset: 5-20 MtC/yr

Clearly, a more realistic potential offset capacity would involve the transfer of large areas of farmland to energy cropping, but not all. There will be the following constraints.

- It is unlikely that the UK will abandon home production of agricultural produce. Even if agricultural subsidies were reduced, the economic benefits of non-agricultural alternative land uses, including wind farms, may be greater than those of energy crops in many areas.

- Given the strength of public resistance to afforestation of about 1.3 Mha of UK uplands from 1920 to 2000, it is unlikely that millions of agricultural land, closer to human habitation, will be acceptable without large benefits or incentives. Large scale energy cropping could be resisted because of its impacts on water quality, wildlife, recreation, landscape, transport use and noise[7].

- Short rotation coppice is likely to be economic only in areas where yields of about 10 t/ha yr (dry wood) can be sustained. Poplar and willow coppice transpire about 1 kg water for every 3.5 g of stemwood produced, so 10t/ha/yr is equivalent to 286 mm of rainfall (Allen *et al*., 1997). Transpiration

[7] Note that 1 Mha yielding 10 Mt dry wood per year with a 5 year rotation means that 200,000 ha are clearfelled each year in different regions and that about 20 Mt of green material in transported each year.

constitutes only about 65% of total evaporation, even assuming no groundwater recharge. Thus, water use may be a constraint on extensive cropping with short rotation coppice in much of southern and eastern England, especially in areas dependent on groundwater resources (Hall and Allen, 1997).

- The greatest energy and economic benefits are obtained from small-scale combined heat and power units, located close to energy users. Only certain localities may be geographically suitable.

There is no objective basis upon which to set a realistic 'potential' land area for energy crops, except that it will less than 11.4 Mha and probably greater than the existing set-aside area of 0.5 Mha. A reasonable guess might would be in the range 1- 4 Mha, giving an offset of 5-20 MtC/yr from coal.

Conservative, achievable capacity

Likely range of fossil fuel offset: 1-6MtC/yr by 2050

The current policy drivers for biomass energy in the UK are the (i) Non-Fossil Fuel Obligation (NFFO) – to generate 10% of electricity form renewable sources by 2010, (ii) post-Kyoto target to obtain a 20% reduction in greenhouse gas emissions compared to 1990 by 2010, and (iii) Green Fuels Challenge, which provides a 20% tax rebate for biodiesel. Achieving the 10% NFFO is thought to be feasible provided Government subsidies enable the electricity to be sold at 3.5p/kWh (cf 2.6p/kWh in 1998). However 3.5 p/kWh is currently too low to promote significant investment in biomass energy schemes, other than those using low cost wastes as fuels - but energy analysts agree that, to meet the Renewables Obligation, energy crops will be required as well as greater use of waste and wind.

Bauen (2002) suggested that up to 125,000 ha of energy crops will be required by 2010 to meet the 10% Renewables Obligation. At 10 t/ha/yr, this area would produce 0.23 EJ/yr and offset 0.625 MtC/yr from coal. If we project forward to 2050, this area could conceivably be multiplied by 2-10, with an offset of around 1-6 MtC/yr from coal.

The current reality is that energy crops are only just beginning to be introduced. The UK's first significant power plant to be fuelled by energy crops is the ARBRE project at Eggborough in North Yorkshire. It will generate 8 MW of electricity from an annual input of 43500 dry tonnes of wood, initially from forest residues and in time from willow coppice. It is supported by an NFFO grant, Forestry planting grants and the EU-THERMIE programme. Meanwhile, in Northern Ireland, B9 Energy Biomass Limited has set up a combined heat and power plant (200 kW) at Blackwater Valley Museum in County Armargh.

These pioneering projects suggest that, in the longer term, the costs could become competitive. However, the UK Department of Trade and Industry (2001) states: 'at present, competing agricultural activities receive financial support and it is unrealistic to expect the farming industry to switch to an untested crop for which there is no equivalent financial support. It will therefore be necessary to extend equivalent financial support at least temporarily to energy crops to pump prime the industry if it is to progress.' To this end, in 2001 the UK Government allocated £29m to encourage planting of up to 6000 ha of energy crops and £33m for power generation technologies.

The Green Fuels Challenge tax rebate seems to be insufficient to make biodeisel competitive with diesel, except when produced from recycled vegetable oil (Bauen, 2002). There is, nevertheless, a vigorous lobby for biodiesel, although the carbon offset is likely to be small (0.2-2.0 tC/ha).

Conclusions

Table 2 summarizes the carbon substitution values that are possible using modern biomass and industrial residues, derived in this review. As for carbon sequestration, achievable levels of substitution are well below potential levels.

Table 2. Estimates of carbon substitution using energy crops for the world, the EU15 and the UK. (MtC/yr).

	Theoretical potential	**Realistic potential**	**Conservative achievable**
World	2000-5000	1000-2000	200-1000
Europe	600-900	200-300	100-200
UK	40-60	5-20	1-6

3. Discussion

The ranges of sequestration and substitution values derived here are shown in relation to each other and to current fossil carbon emissions in Figures 2a (world), 2b (EU15) and 2c (UK).

Although the theoretical potential offsets are high, when critical consideration is given to the constraints, especially land use, the realistic and likely achievable offsets are more modest. Expressed as a percentage of current fossil carbon emissions, the 'realistic potential' offsets were estimated to be in the range 16-31% globally, 5-32% in the EU15 and 2-14% in the UK, while the 'conservative achievable' estimates were 3-15% globally, 2-21% in the EU15 and 1-4% in the UK. Thus, biological carbon sequestration and energy substitution can play a significant, but not a dominant, role in mitigating carbon emissions. Clearly, the percentage contribution is smallest in countries and regions with large populations and high fossil carbon emissions per unit area of land available for carbon management.

In the EU15 and the UK, the estimates of carbon offset by energy substitution are greater than those by sequestration, when considering realistic and achievable offsets (fig 2b and c). Thus, in the EU15, the 'realistic potential' and 'conservative achievable' estimates for energy crop substitution were 21-32% and 11-21% of current emissions, respectively, compared with 5-11% and 2-5% for carbon sequestration. This difference is due, in part, to the fact that sequestration was averaged over 100 years – in reality, sequestration rates rise to a peak following a land use change and then fall towards zero. A more rigorous comparison between sequestration and energy substitution can be made using an equivalence factor, based on radiative forcing reduction over time (Moura Costa and Wilson, 2000; 1 tCO_2 sequestered for one year is equivalent to about 0.018 tCO_2 emitted). Inevitably, energy substitution becomes more advantageous over long time periods, because it can be sustained indefinitely (Schlamadinger and Marland, 1996).

Using land to sequester carbon in trees and soils, rather than to produce bioenergy, is the best option only when forest productivity is low (on poor quality land) and/or the costs of harvesting and utilization for energy are high. However, carbon storage in forests has the problem of 'permanence', ie sequestration is revered if the forest is destroyed. Energy crops avoid this problem, while providing some carbon sequestration during the first rotation (20-40 tC/ha in short rotation coppice) and possibly in soils. However, energy crops require good quality land, can have environmental disbenefits, involve the transport of a bulky product, involve multiple stakeholders (compared with other renewables), and may be economically advantageous only in certain localities.

The optimum offset policies will be those which (i) provide win-win solutions, meeting other needs on the same land area, such as soil conservation, biodiversity enhancement and water conservation, and (ii) link short-term sequestration with long term substitution. Read (1999) showed that high, sustained carbon substitution can be obtained by planting forests for sequestration which are subsequently harvested for fuel. As mentioned, the longer the time horizon, the greater the likelihood that harvesting forests for energy will give the greatest carbon offset.

Figure 2a. Global carbon sequestration and energy substitution capacity in the next 50-100 years shown in relation to fossil fuel emissions in the 1990s.

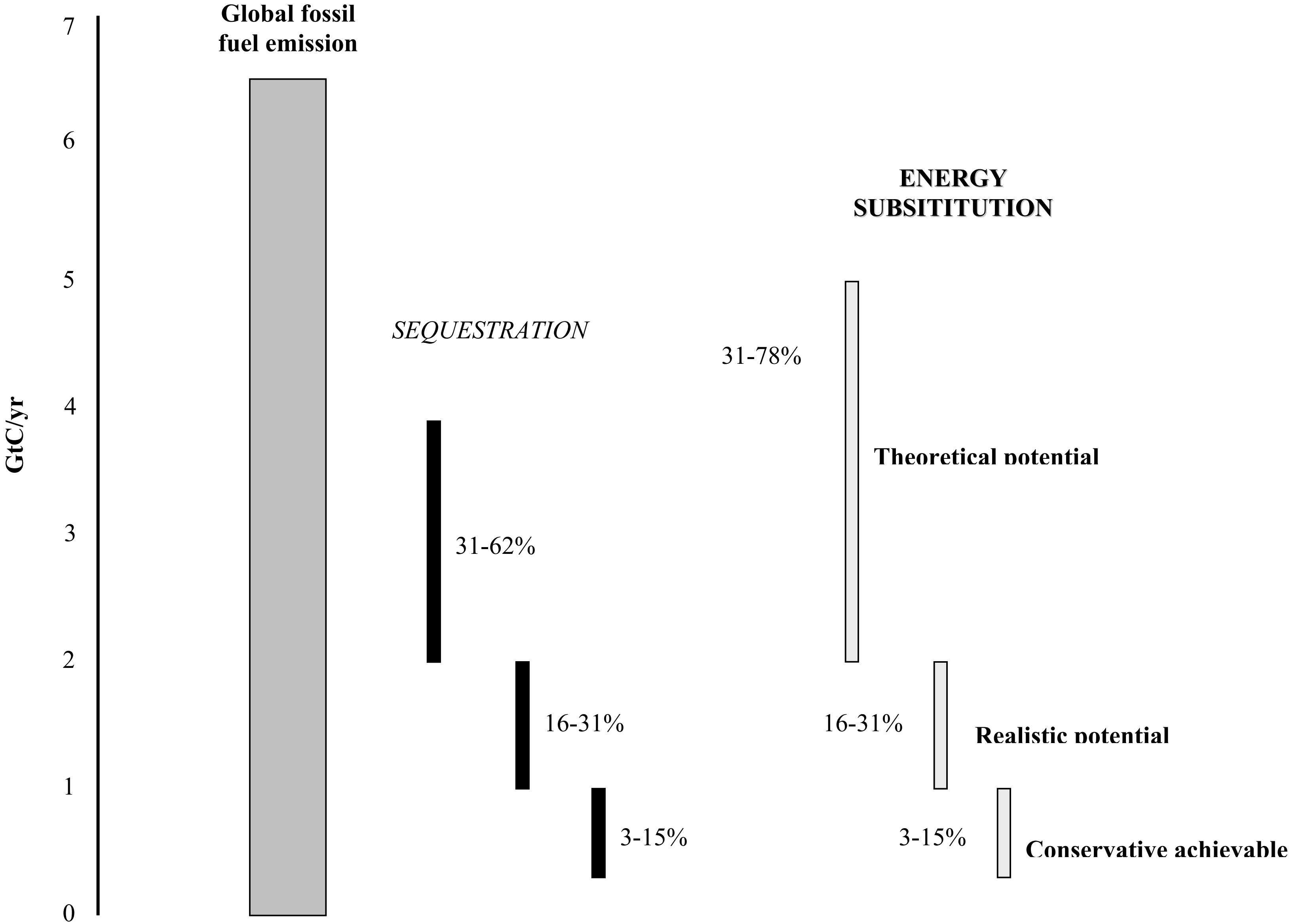


Figure 2b. Carbon sequestration and energy substitution capacity in the next 50-100 years in the EU15, shown in relation to fossil fuel emissions in 2000

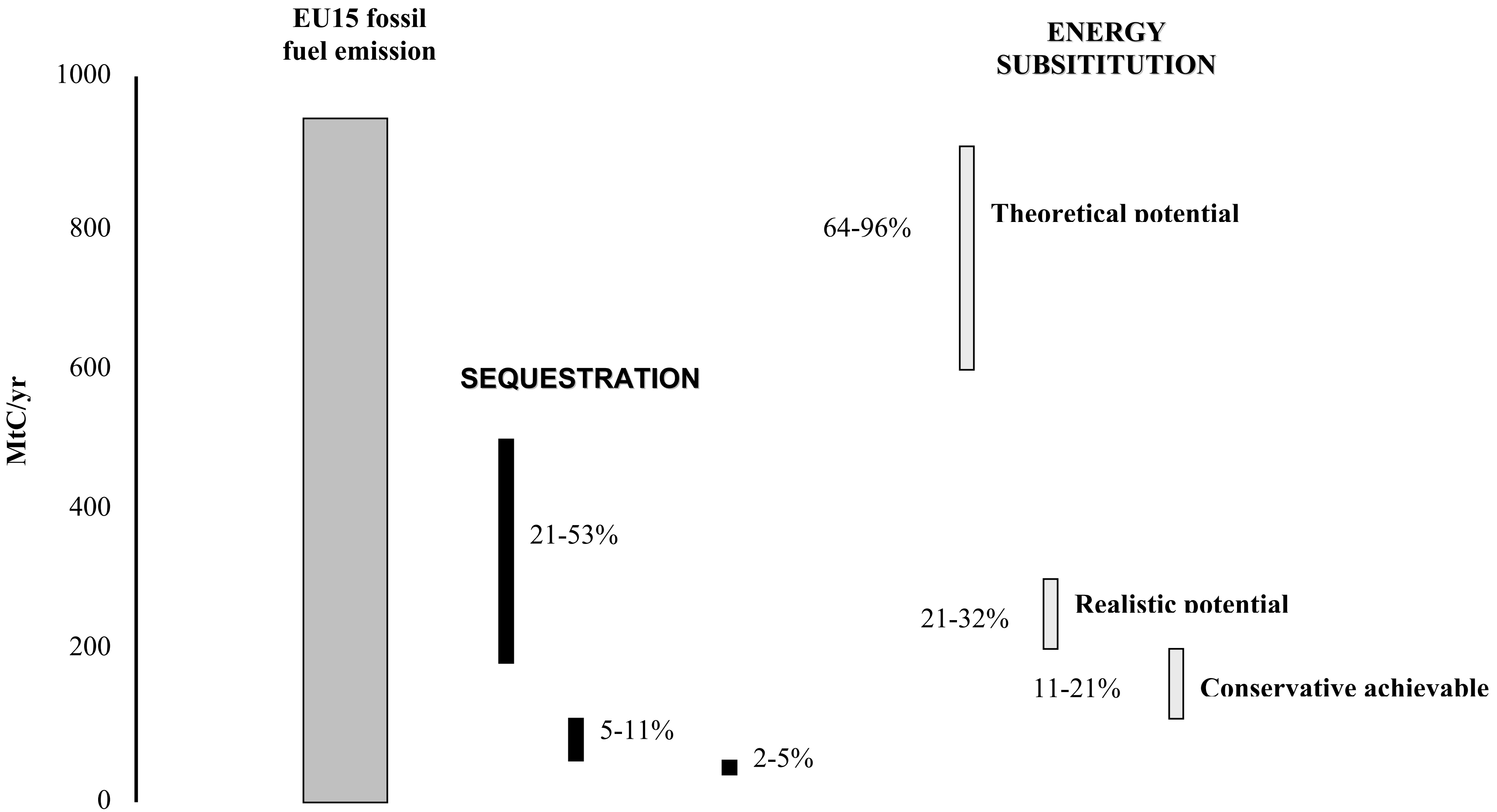
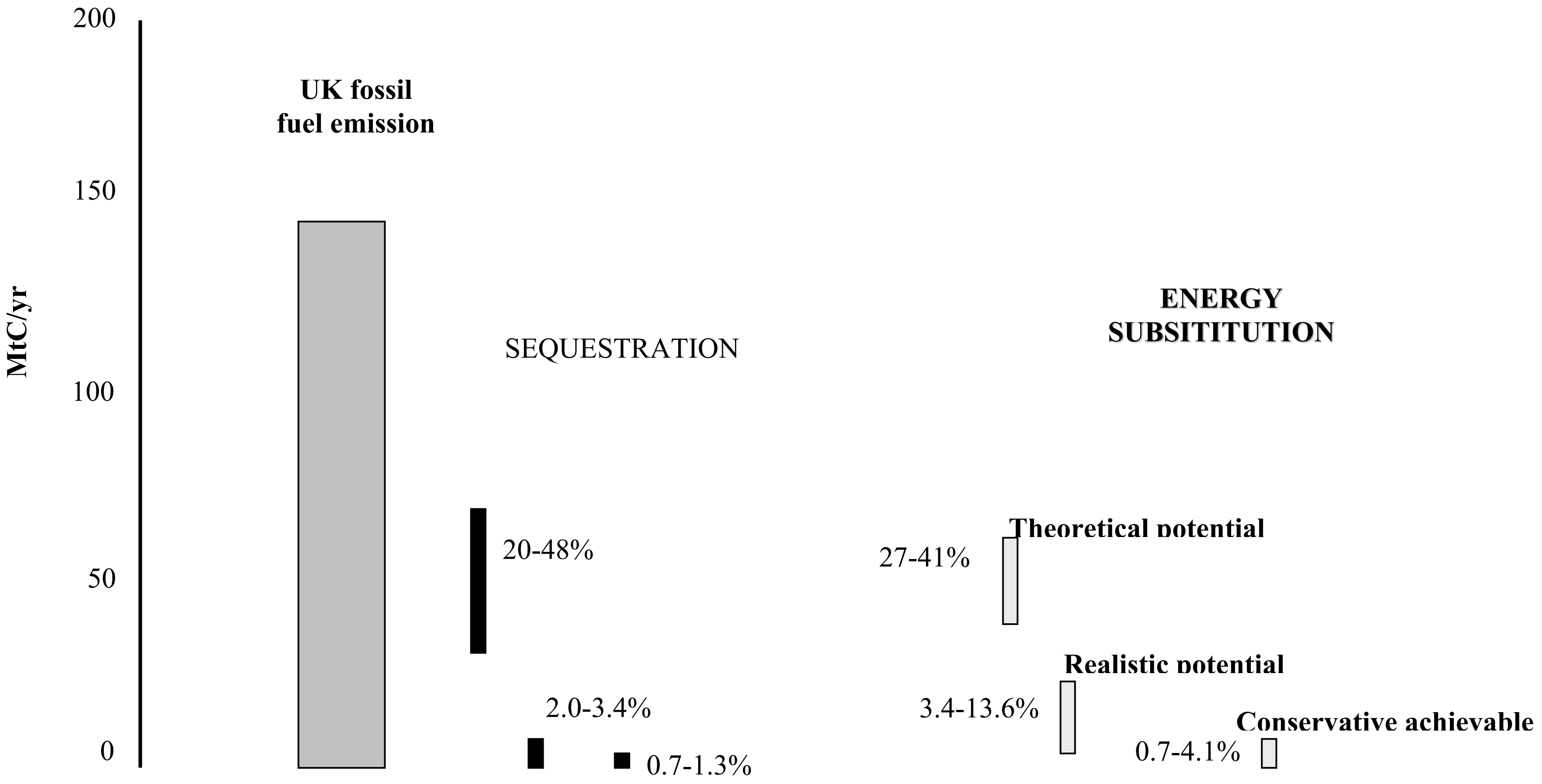


Figure 2c. Carbon sequestration and energy substitution capacity in the next 50-100 years in the UK, shown in relation to fossil fuel emissions in 2000.



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Section B. Geological Carbon Sequestration

The concept of removing CO_2 from the flue gases of fossil fuelled power stations for long term storage was first referred to in the literature by Marchetti (1977). It is in the last five to ten years however that significant attention has been paid to the associated technologies. The seminal text on the subject is the final report of a study from the JOULE II programme funded by the European Commission (Holloway *et al.*, 1996); this text provides a comprehensive review of the potential for underground storage of CO2 in Europe, taking into account the technical and economic factors associated with capture and storage, the storage capacity, safety and stability of storage from geological and geochemical point of view. We refer to this text widely throughout this report, citing individual authored chapters where applicable. More recently it has reached the agenda of governments and policy makers around the world – in the US, for example, the Department of Energy has recently dedicated substantial sums to sequestration R&D. In the UK, the influential Energy Review produced earlier this year (PIU, 2002) calls for more detailed assessment of carbon capture and storage as part of a low carbon future; this is echoed in a recent review on clean coal technologies by the DTI (DTI, 2001). The aim of this study is to initiate that analysis on the UK by:

i) identifying key options and issues that require further assessment;
ii) developing a set of scenarios through which those options may be explored in the context of other carbon mitigation approaches;
iii) developing and implementing a pilot application of a Multi-Criteria Assessment (MCA) framework to explore different perceptions of the potential for geological carbon sequestration in the UK.

The structure of this Section of the report reflects these three key activities. The scenario development and MCA were conducted in consultation with stakeholders, all professionally engaged in a relevant field. In addition to the views of these stakeholders we conducted two preliminary Focus Groups with lay citizens – these Focus Group sessions are described separately in Appendix F. As this is a pilot study, designed to make a preliminary assessment of carbon sequestration, the consultation process, both with stakeholders and citizens, has been limited to a small number of carefully selected organisations and individuals. A full representative survey of opinion is beyond the scope of this study; the consultation has instead been designed to test the methodology and the tools used, to explore initial responses to the technology and to identify key issues that require more detailed consideration. The forthcoming follow-up study (Tyndall code T2/2i) will build on the information and experience developed during the current pilot study to conduct a more extensive assessment of carbon storage.

1. Key options and Issues

1.1 Carbon capture and recovery

A more extensive analysis of the costs of carbon capture and storage will be conducted in the follow-up study. Existing published cost estimates do not lend themselves to direct comparison - they are expressed in different currencies, involve different assumptions about fuel prices and discount rates, and include different elements of overall costs (for example capture, compression, transport and storage). A large component of the overall costs of geological carbon sequestration is the cost of CO_2 capture and considerable industrial R&D effort is currently focused on reducing these costs (for example see the CO_2 capture project, www.co2captureproject.org/). A detailed review of costs is beyond the scope of this study; as a guide estimates of average costs are shown in Table 1. The various cost estimates that are available for carbon capture are particularly difficult to compare as they include many assumptions relating to plant type, discounts rates, fuel prices and are expressed in different currencies. The follow up study should address the costs of carbon capture in greater detail.

Table 1. Overview of estimates of costs

Capture costs	Electricity costs with capture	Reference
30-40 \$/tCO2 (capture only)		IEA, 2000
10-50 Euro/tCO_2 (incl. Disposal)		Hendriks *et al.* 2000
30- 60 \$/t CO_2 (capture and disposal)		Haugen and Eide, 1996
24-90 \$/t CO_2 (capture and disposal)		Herzog quoted in Grimston *et al*. (2001)
	3-7 c/kWh (capture only)	Audus, 2000
	3.0–4.5 p/KWh (capture and storage)[1]	PIU 2002

The processes described below all deliver around 90% CO_2 capture, which equates to a CO_2 avoidance of about 80% of the emissions of an equivalent plant without CO_2 capture, once parasitic energy losses (i.e. the energy used in the capture process itself) are taken in to account. This energy use is generally expressed in terms of the reduction in energy efficiency of the plant, for a NGCC plant, carbon capture implies a reduction in efficiency from 55% without capture to around 45-48% with carbon capture; for a modern coal fired plant, efficiency drops from 46% to 30-36% with carbon capture (Lozza and Chiesa, 2000a, 2000b; Reimer *et al.*, 1999). In addition to processes to remove CO_2 from fossil fuel combustion or power generation processes, this recovered CO_2 must be compressed prior to transport and storage. CO_2 compressed to a supercritical state occupies a greatly reduced volume than in the gas phase and improves transportation efficiency (this state is maintained if ultimate storage is at correct conditions of temperature and pressure).

Post Combustion Capture

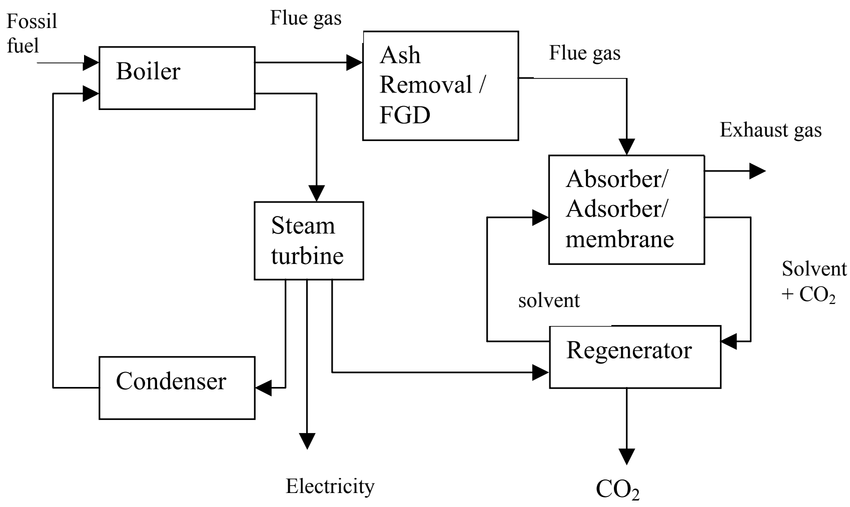
Post-combustion capture refers to technologies which operate on conventional power stations to recover CO_2 from the flue gases; a generic post combustion capture system is illustrated in Figure 1. The concentration of CO_2 in flue gases ranges from about 4% for a Natural Gas Combined Cycle (NGCC) plant to about 14% for a coal plant (IEA 2000), implying that large volumes of flue gas must be treated.

Physical and Chemical Absorption

- Chemical solvents such as amines (the most commonly used is Monoethanolamine (MEA), but other possibilities include Diethanolamine (DEA), Methyldiethanolamine (MDEA)). This type of carbon capture is commonly referred to as amine or flue gas scrubbing
- Regeneration of the solvents is by steam stripping and is very energy intensive (accounting for 80% of the energy requirements of CO_2 capture by this technology)
- It can be used with low CO_2 concentration in the flue gases but other pretreatment to remove contaminants such as SO_2, NO_x and particulates will be necessary to avoid solvent contamination
- This is a fully proven technology, offering the greatest potential in the short term on the basis of cost and efficiency
- Bi-products of decomposed amines (which form a sludge) and some solvents escaping to the flue gas could lead to secondary environmental problems
- This process is associated with a loss of plant efficiency of about 15% (natural gas) to 30% (coal)
- Physical absorption is an alternative route (using Selexol (dimethyl ether of polyethylene glycol) or Rectisol (cold methanol)) at high pressure – but this is less economical
- Hybrid physical and chemical solvents have also been developed
- The technology can be applied to all fossil fuel plant, post combustion
- Yields streams of high purity CO_2 at source pressures

See Audus, 2000; IEA 2000; Riemer *et al* 1999, Chakma 1997, USDOE 1999

[1] this figure is about double the cost of onshore wind generation in the UK (PIU, 2002)



Adapted from : Doherty and R. Harrison (1996)

Figure 1. post combustion capture of carbon dioxide.

Physical and Chemical Adsorption

- Adsorption refers to the concentration of one substance on the surface of another - e.g. gas molecules on the surface of a solid. Here, selective separation of CO_2 is achieved by physical adsorption onto high surface area solids (e.g. zeolite[2] molecular sieves)
- Adsorption may operate in pressure (PSA), thermal or temperature swing adsorption (TSA) modes. PSA: gases are adsorbed at high pressures, then 'desorbed' by lowering the pressure (variant of PSA is vacuum swing adsorption); TSA: gases are adsorbed at low temperatures then desorbed by heating. The swing adsorption technology refers to method of regenerating the adsorbent bed
- PSA currently offers greater potential than TSA since it requires less energy (by about 2-3 times) and the plants are considerably smaller
- It is energy intensive and expensive – might be applicable at large point sources but it can double power costs
- Adsorption technology is currently widely used to separate CO_2 in Hydrogen production from natural gas; the CO_2 from these processes is generally vented to atmosphere in current applications.

Refs: Riemer at al. 1999, USDOE 1999

Gas separation / absorption membranes

- Technology based on differential reactions between components of input gas and the membrane material
- Viewed as having high potential by the US DOE, although limited experience exists
- *Polymeric membranes* - gas is dissolved in the membrane and diffuses through the membrane – these are the closest to commercial development
- *Palladium membranes* – degraded by sulphur, expensive but with long life times and can be used in conditions not suitable for polymer membranes (e.g. high temperatures and pressures, corrosive environments)

[2] Zeolites are a large class of aluminosilicates used for adsorbents / ion exchange. They may be natural or synthetic.

- Palladium membranes could be used in hydrogen production from reformed hydrocarbon fuels with the resulting hydrogen to be used in fuel cells or advanced turbine power systems.
- *Porous inorganic membranes* (metallic or ceramic) – much greater porosity than polymeric membranes but high cost, smaller membrane area to module volume ratio implies net costs comparable. Inorganic membranes have long life cycles and can operate at high temperatures and pressures and in corrosive environments.
- *Molecular sieves* (e.g. zeolite type materials) - currently insufficient permeability and high production costs but generating considerable R&D interest
- *Gas absorption membranes* – membranes for contacting devices between a gas flow and a liquid flow - a solvent on one side of the membrane selectively removes compounds from the gas stream. These are approaching commercial introduction.
- Not currently used for CO_2 separation but shows great potential - notably when used in conjunction with scrubbing solvents, whereby membranes are used to remove most of the CO_2 followed by use of solvents to remove trace residues.

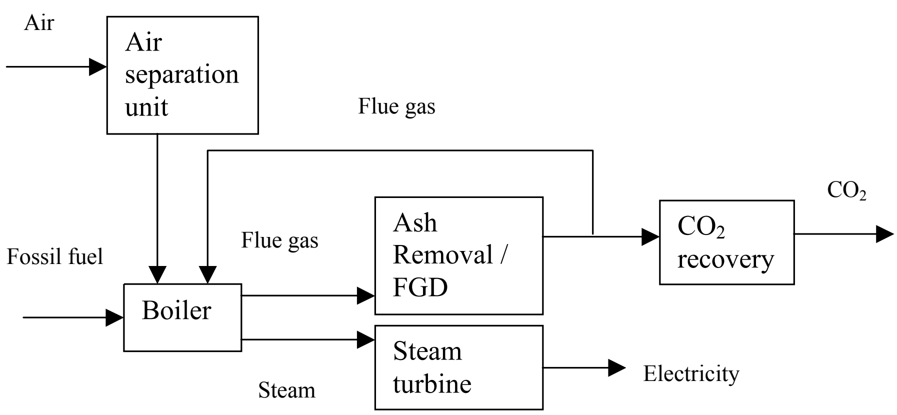
References: IEA 2000, USDOE 1999

Boiler redesign

Flue Gas Recycling / Oxyfuel Boiler

- Instead of burning fuel in air, as occurs in conventional fossil fuel power plant, combustion occurs in pure / highly enriched oxygen, producing flue gases containing only water and CO_2; the water can easily be condensed leaving pure CO_2 as the key bi-product
- The process requires the recycling of flue gases in order to reduce high temperatures resulting from combustion in oxygen (which would present a problem to conventional boiler / turbine materials)
- The process can be fuelled by any fossil fuel (incl. Syngas, a.k.a. synthesis gas, a mix of CO and H_2)
- Plant can be operated in "cogeneration mode" as CHP
- Components are all commercially available
- Thermal efficiency NG – 45% (c.f. 54% without capture); coal gasification plant – 37% (c.f. 48% without capture)
- Existing boilers can be converted to oxyfuel, the technology is at the demonstration stage but is expensive in both economic and energy terms. The most expensive part of the process is the Air Separation Unit (ASU) which splits air into oxygen, nitrogen and Argon
- An example of a possible configuration of an oxyfuel system is shown in Figure 2

References: Shao and Golomb ,1996; IEA 2000; Wilkinson et al. 2001



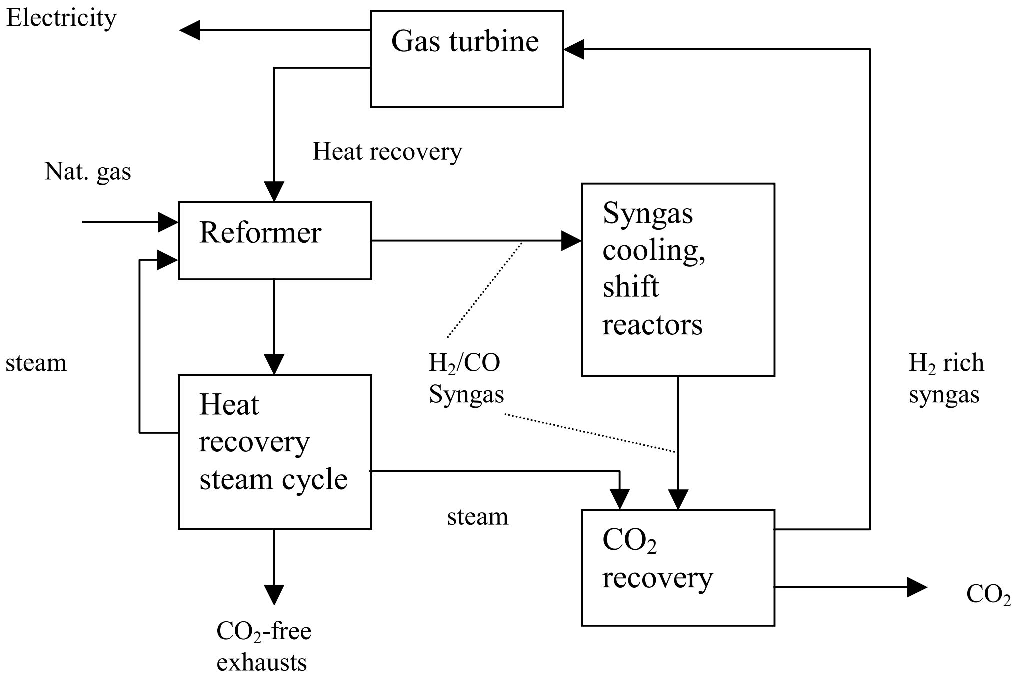
Adapted from : Doherty and R. Harrison (1996)

Figure 2. Oxyfuel / flue gas recycling

Precombustion capture

- This involves treating the fuel before combustion - generally to deliver CO or CO_2 and Hydrogen which is then used as the power generating fuel – either in an existing gas turbine or in a fuel cell
- The CO is removed from this "synthesis gas" using techniques such as physical absorption, cryogenics, membranes etc.
- In principle, this decarbonised synthesis gas can be used to fuel an existing gas turbine (see for example Lozza, 2000a) but this is not a proven technology
- Although the gas reformation process is well proven in certain industrial processes, the technology for subsequent power generation is not currently at commercial scale of development.
- *Natural gas partial oxidation* – exothermic, oxygen-poor combustion producing CO and H_2; the CO is converted to CO_2 and removed by physical or chemical absorption. Efficiency of 48.5% (compared to 56%) possible with removal efficiency of 90%. It can be applied to existing NGCCs with limited modification
- *Steam methane reforming*: requires high temperature and low pressure (endothermic reaction so more energy intensive than partial oxidation), chemical absorption is required (as physical absorption is not suitable under low pressures) to separate the CO_2, again H_2 is used as the turbine fuel.

References: Audus, 2000; IEA 2000; Lozza and Chiesa, 200a; Riemer et al 1999



Adapted from Lozza and Chiesa (2000)

Figure 3. Precombustion capture of carbon dioxide

Cryogenics

- Most likely to be applied pre-combustion or to oxyfuel processes, producing streams of high concentration CO_2
- Low temperature physical approach – CO_2 is separated directly by condensation or via a solvent
- Energy intensive refrigeration required
- Enables direct production of liquid CO_2 (suitable for transport by tanker)

References: IEA 2000, Riemer et al. 1999

Potential Novel technologies

- CO_2 containing gases dissolved in water, converted to CO_2 hydrates (clathrates[3])
- Electric Swing Adsoption (ESA) using activate carbon fibres – avoids the problems of PSA / TSA and requires only low voltage current, should be energy efficient and economical. Pilot stage in 3 years.
- Chemical-looping combustion / sorbent energy transfer: fossil fuel (gasified coal or methane) used to reduce metal oxide producing steam (to power steam turbine) and high pressure CO_2 (no extra energy needed for CO_2 compression); the metal is then re-oxidised in air – exothermic reaction from which the energy is used to raise the temperature of high pressure steam and drive gas turbine.

References: USDOE 1999

1.2 Transport of CO_2

Once recovered from large point sources, the CO_2 must be transported to the storage location – this is most likely to be via pipeline and/or tankers. The most efficient means of CO_2 transport is by pipeline. Onshore pipelines in the US are already being used for CO_2 transport over 100s of km. It may be possible to use existing gas pipelines for CO_2 transport but CO_2 is corrosive when wet, so this would require a change in the material used for seals.

Cost of building a new pipeline is estimated to be within the range \$1-10/tonne CO_2/100miles (Bergman *et al.*, 1997; USDOE, 1999; Doctor et al. 2000; Hendriks *et al.*, 2000); cost estimates depend on pipe width, length, terrain crossed etc.

1.3 Storage in geological formations

Essentially geological carbon sequestration involves storing CO_2 in large natural reservoirs – reservoirs that currently contain saltwater (saline aquifers), gas, oil or coal (hydrocarbon fields) or salt (salt caverns) for example. The methods and issues associated with exploiting each of these reservoir types for carbon storage are quite different. In this section we consider a range of potential storage reservoirs, explaining the key features of each and the rationale for whether or not they have been included in the subsequent analytical part of the study. The information described below is drawn both from available published literature and from discussions with relevant experts – in particular Sam Holloway at British Geological Survey. An additional interview to those directed at developing the scenarios, criteria and Multi Criteria Assessment was also conducted with a representative of Aquila Energy (who operate natural gas storage facilities) to discuss the potential for using salt caverns for CO2 storage.

Saline Aquifers

A saline aquifer is a geological formation in the rock below the seabed or below ground (the "deep subsurface"); in general we refer to offshore saline aquifers in the context of carbon sequestration but there are also similar formations at onshore locations which could be used. A saline aquifer consists of a layer of porous rock; the pores are filled by salt water and hence it is sometimes referred to as reservoir. This water is held in the pores between grains in the rock (see Figure 4 for a schematic diagram of a saline aquifer). The rock between the seabed and the saline aquifer is not porous and hence is impermeable to the water contained in the aquifer – creating a seal preventing movement of fluids out of the reservoir – this layer is referred to as 'cap rock'. Although most aquifers do eventually connect to the seafloor - and hence are linked to the deep ocean - there is little mixing between the water contained in the aquifer and the open sea; these extend over very large areas (for example several hundreds of

[3] Clathrates are ice-like crystalline solids in which molecules of another compound, e.g. CO_2, is trapped

square kilometres) and are protected by a cap rock ceiling The water contained in the aquifers has remained there over geological time scales. The cap rock prevents vertical migration of the stored CO_2 - i.e. movement towards the surface. Where there are traps within the aquifer (see Figure 4), the CO_2 is stored within a dome-like formation within reservoir; following injection it will float to the ceiling of the dome (because CO_2 is less dense than the water in the aquifer) and will remain within it, prevented from any horizontal or lateral migration by the walls of the dome (cap rock).

Long term secure storage in aquifers outside these trapped domes is also feasible. As CO_2 is injected, it slowly migrates through the aquifer pores, displacing the saline water as it goes; the time it will take for the CO_2 to reach the edge of the aquifer will depend on the injection rate, the speed with which it moves through the aquifer (sweep efficiency) and how far it has to travel - thus it will be different at each site (Elewaut *et al.*, 1996). However, providing that CO_2 is injected in the central area of the aquifer – distant from the edges it should not reach the surface (of the seabed) for 1000s of years.

The understanding of these processes is drawn from detailed studies of natural CO_2 reservoirs (naturally occurring areas where large quantities of CO_2 are found in underground formations) and from comprehensive understanding of gas fields (migration of natural gas is known to be similar to CO_2). Only those aquifers that are not in communication with other formations, (such as formations containing freshwater), or that are completely sealed off or sealed by a cap rock over a very large area are considered to be suitable sites for potential CO_2 storage. Thus, although the behaviour of injected CO2 is fairly well understood, the reliability of extrapolating these assumptions depends on a sufficient knowledge of the formation in which the COP2 is to be stored – and in particular that the impermeable cap rock layer extends uninterrupted across the entire formation.

There are three mechanisms through which CO_2 may become sequestered in a saline aquifer (Elewaut *et al*., 1996; USDOE, 1999):

i) the most significant is *hydrodynamic trapping* whereby the CO_2 is held in the pore space, as free CO_2, displacing saltwater as described above;
ii) *solubility trapping* whereby CO_2 dissolves in the water in the aquifer, thought to be a very slow process;
iii) *mineral trapping* – a slow (and not well understood) process) whereby CO_2 reacts with minerals and organic matter within the formation to form a solid mineral structure (for example calcium, magnesium or iron carbonates)

According to the above description – the terminology used throughout this document is as follows:

Traps in aquifers – this refers to a domed space within an aquifer, within which the CO_2 is sealed as if within an upturned cup.

Aquifers outside traps – this refers to storage in regions of aquifers other than the traps. In these cases the aquifer formation is sealed by impervious layers of cap rock and generally extend over very large areas (several hundreds of kilometres).

Estimates of the potential capacity for storage in an aquifer are calculated from estimates of the first type of sequestration, displacement of water by CO_2. The term used to describe this displacement of water in the aquifer by CO_2 is volumetric sweep efficiency – it is expressed as a percentage, indicating the proportion of fluids displaced and estimates are based on modelled simulations of reservoirs[4]. It determines the amount of CO_2 that can potentially be stored within a reservoir and corresponds to the percentage of the pore volume that can be occupied by CO_2. This tends to be low (generally though to be between 1 and 6%) because, as described above, CO_2 rises to aquifer ceiling from where it spreads in channels. The pore volume that can be used for CO_2 storage is reservoir specific and will depend on

[4] Such simulations have been carried out by van der Meer (1995) and Lindeberg (referred to in Elewaut *et al.*, 1996), producing compatible results. The estimates of volumetric sweep efficiency are based on these simulations of generic formations.

factors such as injection rate, relative permeability, density and mobility of the fluids, rock heterogeneity *inter alia*. Very little of this information is currently available for the majority of potential storage reservoirs. Consequently, estimates of potential storage capacities at a national level are based on modelled average values and hence remain a source of uncertainty (Elewaut *et al.*, 1996; van der Meer, 1995). These modelled estimates may provide an indication of average potential but the actual potential storage volume will be highly site specific.

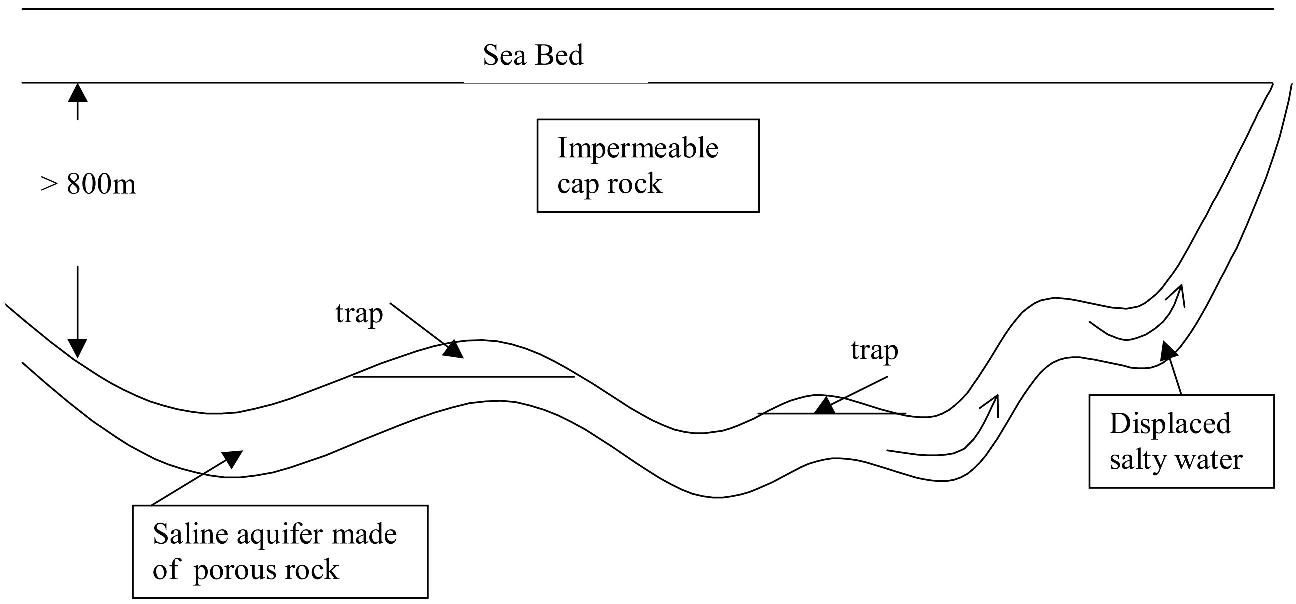


Figure 4. A saline aquifer with traps (ref. Holloway, *pers. comm*)

Carbon Storage at Sleipner

CO_2 storage is currently underway at an industrial scale in the North Sea at the Norwegian Sleipner gas field, operated by Statoil. Since 1996 approximately 1 million tonnes of CO_2 per year has been injected into the Utsira aquifer formation (a layer of sandstone filled with saltwater) almost 1km below the sea bed. This represents about 3% of Norway's CO_2 emissions and is the first example of commercial CO_2 storage in the world.

The natural gas at the field has a CO_2 content of 9%, which, under Norwegian law, must be reduced to no more than 2.5% for the gas to be used commercially. A carbon tax of $50 per tonne CO_2 in Norway (reduced to $38 in 2000) motivated Statoil to develop the storage potential at this site, storing the CO_2 recovered from the gas extracted rather than venting to the atmosphere (as would normally be the case) (Herzog *et al.*, 2000).

The SACS (Saline Aquifer CO_2 Storage) Project, funded by the European Commission ENERGIE programme and involving a consortium of 19 collaborating institutions representing industry, academic and government organisations, is closely monitoring, modelling and assessing the facility to build experience that can be applied to other similar ventures in the future. As part of the monitoring in SACS, seismic surveys have been carried out across the site - one before storage commenced, another in 1999 and a third survey in 2001. These provide a 3 dimensional image of the CO_2 "bubble" within the aquifer at each time interval.

Risks and challenges

- Borehole integrity – further analysis of potential leakage around the injection point over very long timescales is needed
- Pressure build up - the CO_2 injected into the formation may lead to a pressure build up as it displaces water (although this has not been experienced at Sleipner to date, the elapsed storage time is very short - about 5 years, compared to 100s or 1000s of years required storage times). If there is an eventual outlet for the water, risks associated with such a pressure should be low. However if significant pressure should build up it could affect cap rock integrity, land surface deformation (particularly important at on shore sites) or induce seismicity (USDOE, 1999)
- The presence of unidentified faults may provide pathways through which CO_2 could migrate to the surface; storage security depends on the confidence that can be placed in the cap rock, which will require extensive surveying across the area of the aquifer
- Goechemistry: slow chemical reactions with sandstone and carbonate formations of the reservoir could affect storage characteristics / integrity of the formation, little is known about this effect.
- Onshore sites – if leaked CO_2 were to accumulate, by dense CO_2 leaking into a confined space or into a bowl/crater formation at the surface, it causes asphyxiation at relatively low concentrations (see Holloway, 1997).

Hydrocarbon Fields

The oil and gas exploration and extraction industry has developed a wide experience and understanding of the characteristics of oil and gas fields. These are effectively natural underground traps and have stored oil and gas over geological time scales; there is also considerable existing infrastructure around the sites which could be exploited for future CO_2 storage purposes.

Enhanced Oil Recovery / Enhanced Gas Recovery

As oil fields approach the end of their commercial life, CO_2 can be used to increase oil production and maximise the extraction of the oil that remains in the field, this is known as Enhanced Oil Recovery (EOR). EOR is routinely practised at on-shore oil fields (in the US producing 190,000 b/d oil, Stevens & Gale, 2000), a practice driven by the economic benefits of EOR rather than CO_2 emission reductions. There are no examples of offshore EOR to date. EOR works in two ways: i) through displacement of oil and saltwater in the field and ii) CO_2 dissolves, lowering the viscosity and increasing the volume of oil allowing it to flow more easily to surface (USDOE, 1999). Any CO_2 dissolving in this way will eventually reappear at the surface as the oil is extracted, this is recovered and re-injected into the well; however, this factor has prompted some debate over the actual efficacy of this EOR for carbon storage.

In theory, EOR could also be used at off-shore sites – although this has not been carried out as yet, it is currently under consideration by major oil companies. Suitability of potential sites for EOR also depends on depth – deeper reservoirs are at higher pressure which implies a greater miscibility between oil and CO_2 and hence greater EOR efficiency – minimum depth to achieve these conditions at onshore sites is 2500 ft (Bergman at al. 1997). Once oil is no longer being extracted, the remaining infrastructure could be used to continue injecting CO_2 to the field for long term storage. Although EOR may not deliver the amount of CO_2 storage that is possible within a saline aquifer, because there are economic benefits of greater oil extraction it could represent an important pathway through which future geological carbon storage is established; initial estimates even suggest that by offsetting costs of CO_2 capture with oil sales from EOR (providing this displaces oil that would otherwise be produced elsewhere and does not imply increased oil sales) could deliver CO_2 avoidance at zero costs (Doherty and Harrison, 1996). BP have identified the Forties field as having potential for development as a CO_2 storage hub based on EOR using CO_2 the Grangemouth refinery and petrochemical complex, supplying 2-4 MT CO_2/yr (Espie, 2000).

The prospect of Enhanced Gas Recovery is more uncertain and it has not been tested. However, disused gas fields do offer significant potential for CO_2 storage. Once gas has been extracted, the pressure within a field is reduced, providing an opportunity to inject CO_2, replacing the gas that has been extracted and maintaining pressure. (USDOE, 1999).

Risks and challenges

- Years of exploitation has left numerous well holes at these sites, these must be located and sealed effectively; abandoned wells may affect the integrity of the fields and further research is required in this area.
- There may be different geochemical effects resulting from CO_2 compared to oil or gas storage at these sites.
- Corrosion at injection wells and where abandoned wells meet underground formation used for storage; this can be avoided by use of gas drying techniques suggesting this should be an economic rather than a technical challenge (Bergman *et al.*, 1997)
- CO_2 injection will lead to pressure increases within the field which could have secondary effects such as creation of new pathways, to the surface and to adjacent formations, fracturing of the reservoir at wells and leaks around the wells (USDOE, 1999)

Enhanced Coal Bed Methane (ECBM)

At some coal seams, methane is naturally adsorbed to the surface of coal micropores. CO_2 has a greater affinity to the coal than methane, so injecting CO_2 should release the methane and lock the CO_2 to the coal (two molecules of CO_2 are adsorbed for every molecule of methane released). It may be possible to directly inject flue gas (containing a mix of primarily CO_2 and N_2); this would avoid the costs of separating CO_2 from flue gases but balanced against reduced efficiency of the methane recovery (compared to using a pure stream of CO_2) (Holloway, 2002; Gunter *et al.*, 1997). In each case there would also be economic benefits to be derived from selling this released 'coal bed methane' but if the CO_2 is to remain in long term storage this implies that coal could not be extracted from the site at a later date.

ECBM (sometimes also known as Enhanced Gas Recovery for coal bed methane) has been field tested at small scales using CO_2 in the US but most of the information concerning this approach derives from modelling results. The greatest potential for the technology is in countries which have an abundant coal reserve but which do not have reserves of Natural Gas (for example China, Australia, India *inter alia*) (Wong, *et al.* 2000).

Risks and challenges

- Any future requirements to mine remaining coal would lead to a release of stored CO_2
- Leakage from onshore coal seams presents risks to human health
- The nature of overlying and adjacent strata must be suitable to ensure security of both CO_2 in the time between injection and adsorption and the methane subsequently released before it is extracted.

Salt Caverns

Although this has not yet been implemented, potentially CO_2 could be stored in salt caverns – either natural or man-made. Storage caverns can be created, where suitable rock salt formations occur, by injecting water to dissolve the rock, producing brine and a cavity. The brine produced by this process could either be used in appropriate industrial applications or, in the case of a coastal site, released into the sea. Caverns formed in this way are currently used for storage of natural gas but could, in principle, be similarly used to store CO_2 (for example from neighbouring industrial installations). The pressure and temperature conditions of typical salt caverns imply that they could be used to store liquid CO_2 without the need for surface compressors. Although in absolute terms, the potential volumes of CO_2 storage offered by these reservoirs is not huge, their location in the UK, for example, in areas such as Cheshire where there is a high density of chemical and industrial activity suggest some potential. Salt caverns have been used for natural gas storage (for example, in Germany as well as the UK) and this could provide relevant knowledge for similar utilisation of mined salt caverns for CO_2 storage.

Risks and challenges

- Structural stability - are the rock pillars between cavities sufficiently strong to avoid collapse? This is especially pertinent for utilisation of existing salt caverns. Bespoke salt caverns for CO2 storage could be designed appropriately to reduce this hazard.
- Proximity of possible sites to inhabited areas
- Local disputes and opposition over creation of salt caverns for natural gas storage in Cheshire creating problems in getting planning permission
- Limited capacity
- High cost, given that the storage costs alone would be significantly higher given the limited capacity
- Leakage – if water could enter the cavern it would force out the stored CO_2

Selection of Storage Reservoirs

The following Section of this report documents the analytical component of the study, for which we explore the potential application of geological carbon storage within UK climate change policy. We have not included all of the formations described above, only those that we consider offer sufficient potential, are likely to feature in decisions to be made in the next 10 years and about which respondents are likely to have a reasonable understanding. For these reasons we have included storage in saline aquifers (within and outside traps), hydrocarbon fields (including EOR) but not enhanced coal bed methane or salt caverns. It is assumed that the majority of these sites will be off-shore and we have added an additional category of 'onshore sites' for which it is assumed that the onshore location will hold a greater bearing on their acceptability than the specific formation in question.

2. Long-term Scenarios for Carbon Storage

Scenarios are a tool for exploring the long term implications of near term policy choices. A set of long-range scenarios have been developed in order to explore the different contexts within which carbon storage might be adopted in the UK. The aim of the scenarios is to provide credible alternative pathways which expose the main tradeoffs associated with different climate change mitigation strategies in general and carbon storage in particular. They are not predictions or representations of what we think will happen. At this stage in our research, these are more like energy storylines, rather than full scenarios, for which the carbon storage dimensions have been elaborated in more detail. The scenarios will then be evaluated in the subsequent Multi Criteria Assessment, in which they will be scored against a set of criteria to assess how they are received in environmental, socio-political, technical and economic terms by a variety of stakeholders.

2.1 Scenario methodology

The scenarios have been developed by the researchers initially, with subsequent review and revisions in consultation with stakeholders (referred to here as 'round one interviews'). The starting point for the scenarios is a set of progressive national CO_2 emission reduction targets between 2010 and 2100 (see Table 2). The four basic scenarios describe ways in which these targets can be achieved have been designed, each placing different levels of dependence on geological carbon sequestration as a means of reaching the targets. The design of the scenarios ensures that they have different characteristics in terms of capacity and location of CO_2 storage sites exploited.

Provisional versions of the scenarios were distributed to a small group of stakeholders prior to discussion in one-to-one interviews. This enabled the scenarios to be refined through a process of iteration, to deliver the final scenarios described here and used subsequently in the Multi Criteria Assessment. At this stage, eight individuals were interviewed, covering expertise in relevant areas of geology, energy technology, carbon capture and storage and process integration (see Appendix D for list of participants).

2.2 The scenarios

Each scenario consists of a description of the key features of alternative energy supply and demand pathways; these are mostly qualitative but contain some quantitative descriptions of the carbon storage options. The basic assumptions of each scenario are detailed below. In addition to the four basic scenarios, we have added an additional scenario – a variation from one of the original scenarios – in response to suggestions made during the stakeholder interviews. Fuller descriptions of the scenarios can be found in Appendix B.

In any of these scenarios the nature of energy supply can vary hugely – we have, however intentionally kept the descriptions as general as possible; the aim of this initial research is to explore reactions to alternative carbon storage options and not, for example, to evaluate alternative renewable energy strategies within those scenarios. It is important that the levels of energy provision by the various sources is credible within the scenarios but at this stage we feel that precise elaboration will divert the focus away from the carbon storage issue. Similarly, social and political factors have not been addressed in the scenarios at this stage.

Each scenario is described over a time period 2010 – 2100. Note that in all scenarios the same CO_2 emission reductions are met - expressed as percentage reductions relative to the base year, 1990 (emissions = 168 Mt C) as follows:

Table 2. Target emission reductions

Year	Reduction relative to 1990	Emission target (MTC / yr)	Rationale
2010	20%	134	UK target (UK Climate change programme)
2020	30%	118	Incremental decrease in emissions (equivalent to power generation contribution to total emissions)
2050	60%	67	Emission reductions required to maintain atmospheric CO_2 concentration below 550 ppmv (RCEP, 2000)
2100	80%	34	Emission reductions required to maintain atmospheric CO_2 concentration below 550 ppmv (RCEP, 2000)

A brief summary of the scenarios is shown below in Table 3. Note that none of the scenarios include a reduction in energy use – the reason for this is not that we exclude this possibility but that it would not produce a sufficiently challenging backdrop for our study at this stage. Energy use in the scenarios is considered to grow at a rate of 0.5% p.a, (the mean rate of growth over the last 40 years, RCEP (2000)); although the energy demand figures are not used directly in the current scenarios, they provide useful contextual information and will be used as a basis for subsequent quantification of the scenarios. As we are assuming significant emission reduction targets common to all of the scenarios, we have not identified explicit factors that might drive such a climate change policy in each scenario. Further elaboration of the scenarios can be found in Appendix B.

Table 3. Summary of scenarios

		Carbon storage	
		Low	**High**
Energy Use	**Growth (0.5% pa)**	*Nuclear Renaissance* Carbon storage is adopted as an interim measure to enable emission reduction targets to be met during a gradual transition to a high nuclear energy future	*Fossilwise* Carbon storage is adopted as the major component of the emission reduction strategy, allowing the UK to continue its dependence on fossil fuels
	No growth (from 1998)	*Renewable generation* Carbon storage is seen as necessary to achieve emission reductions as the UK moves towards a renewables based hydrogen economy, enabling nuclear power to be abandoned	*Spreading the load* High levels of carbon storage adopted within a diverse energy regime, large centralised power stations (with CO_2 capture if fossil fuelled) coexist with more decentralised networks of new and renewable energy technologies

All of the scenarios are assumed to meet the CO_2 emission reduction targets; the three 'caricature' scenarios describe the dominant energy source used to supply energy. Thus, the 'Fossilwise' scenario features the greatest reliance on carbon capture and storage throughout the scenario. In 'Nuclear Renaissance' a gradual build up in the nuclear generating capacity allows targets to be met with the least dependence on carbon storage – although storage is only phased out at the very end of the period. 'Renewable Generation' initially sees carbon storage employed as a bridging technology to ensure that targets are met as sufficient renewable generation and the associated infrastructure is installed; here storage peaks around 2050 after which it is phased out by 2070. In the 'Spreading the Load' scenarios, the aim was to explore the feasibility of a more mixed approach in which no single energy source dominates, with the coexistence of centralised and distributed generation. The key features of the scenarios are summarised in Table 4. These scenarios are preliminary sketches which provide an indication of possible energy regimes which could deliver significant reductions in CO_2 emissions. They are considered to provide credible descriptions and this has been backed up during all of the interviews conducted for the present study. However, a more detailed quantification of the implied energy balances would enable a more realistic evaluation. This would, for example, enable us to present figures for different types of generating capacity and fuel mixes that are consistent across the scenarios. Inevitably, such an exercise implies huge assumptions in estimating emission factors and sectoral demand across these timescales, but we feel that a greater level of quantification than has been presented here would be useful for this and other Tyndall projects.

The amount of geological carbon storage assumed in each scenario is presented as annual rates in Figure 5 and as total accumulated storage in Figure 6. An initial judgement was made about the likely annual carbon storage under each of the scenarios at each time interval, these figures were then extrapolated across the whole time period and the total accumulated storage levels calculated from the annual rates. Thus an incremental rate of change is also assumed for each scenario. The implications of these estimates of carbon storage were subsequently matched to capacity of different reservoirs in the UK, referring to Elewaut *et al.* (1996). Thus, given the target emissions and assumed carbon storage we have defined energy supply scenarios which we consider will deliver the assumed demand for energy whilst satisfying the emission targets.

The scenarios were chosen in order to encourage stakeholders to consider the tradeoffs associated with different broad approaches to CO_2 reduction, during the assessment process they are asked to consider how they view the relative performance of the options across a range of criteria.

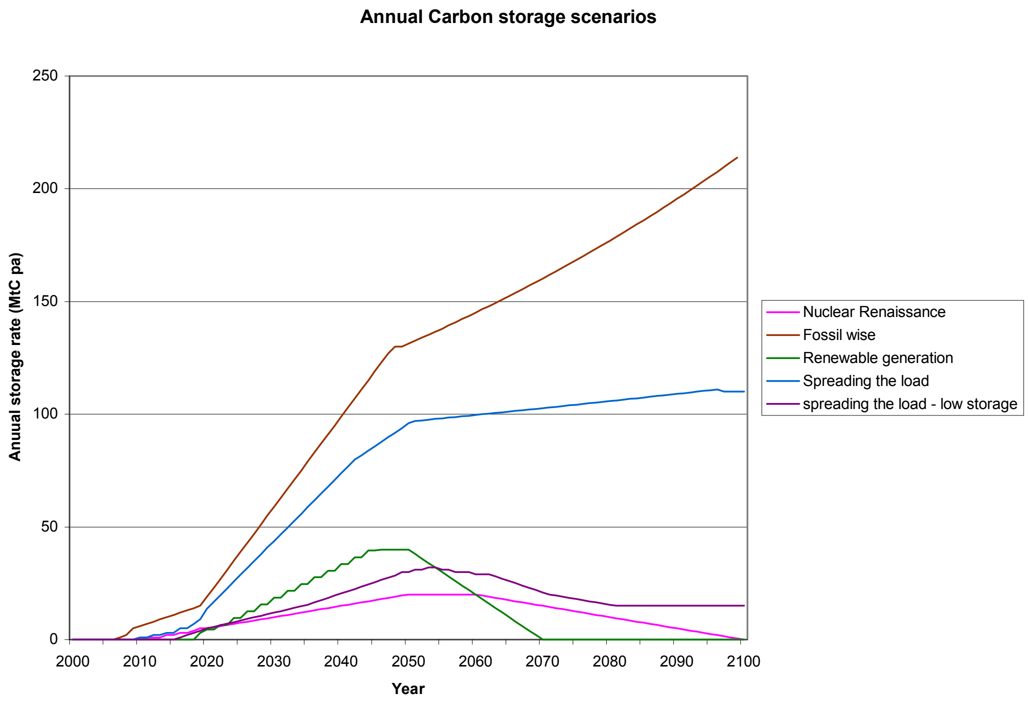


Figure 5. Annual carbon storage in each scenario

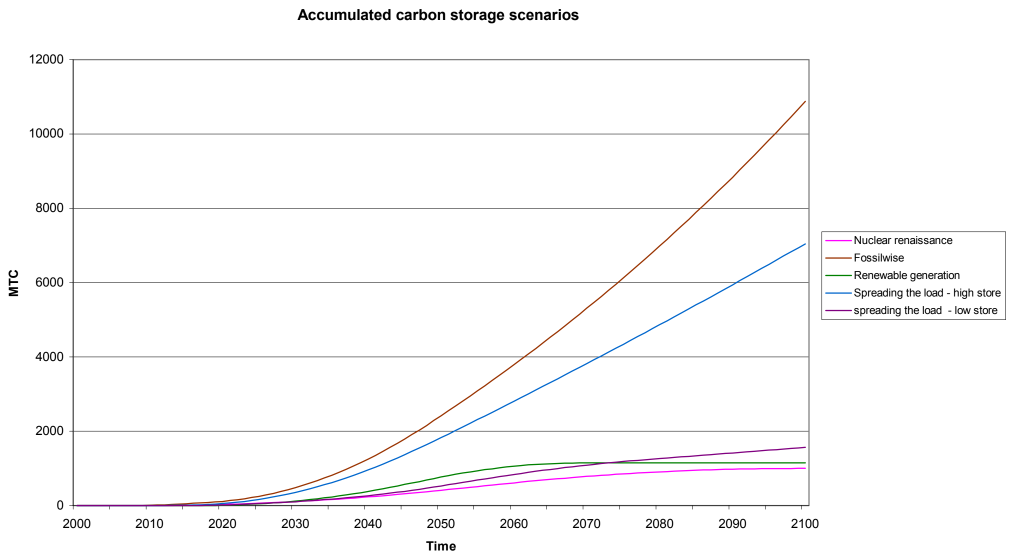


Figure 6. Total accumulated carbon storage in each scenario

Stakeholder interviews

A total of eight individuals (see Appendix D for list) were interviewed during Autumn 2001. Participants were supplied with a brief description of the project and rationale behind the scenarios, together with the four basic scenarios (earlier versions of the scenarios described above). The format was the same for each interview - following an introduction to the aims and methods of the project and opportunity for the participant to pose general questions, each scenario was discussed in detail. The aim of the discussions was to establish which features of the scenarios were seen as being more or less credible, to expand details of the scenarios according to the specific knowledge of the individual and to provide an opportunity for participants to propose additional scenarios or variations. The second part of the interview focused on the discussion of assessment criteria, and is described in Section 3.

In general there was a good level of acceptance of the scenarios, which were seen as useful descriptions of alternative pathways for carbon storage regimes in the UK. The interview process yielded specific information based on the judgement of individuals in particular relating to:

- Suitable storage locations
- Assessment of the order in which various reservoir types are likely to be exploited
- Timing of market penetration of different energy technologies, such as fuel cells
- Key issues associated with particular energy technologies, for example, mode of hydrogen generation for mobile sources
- Comments on the wording used in the scenarios - improving accuracy and limiting biased representations
- Addition of a fifth scenario based on a variation of the original ‘spreading the load’ scenario

Where there were strong differences of opinion between participants (generally relating to the feasibility of different technologies), we tried to capture the range opinion across the different scenarios.

Thus these interviews provided the following functions within the study:

i) expert review of the scenarios, providing an indication that the scenarios do provide valid descriptions of plausible pathways;

ii) additional information on particular areas covered by the scenarios, based on the knowledge of experts; this enabled us to benefit from both the judgement of the interviewees and their understanding of latest developments in their area of expertise. A straightforward literature review would not deliver this type of information.

Table 4. Overview of carbon storage scenarios

	Nuclear Renaissance	***Fossilwise***	***Renewable Generation***	***Spreading the load – high storage***	***Spreading the load – low storage***
Capture	• Amine scrubbers • Slow development • Post combustion Pressure Swing Adsorption by 2020	• Amine scrubbers • Fast pace development • ESA / radical new tech	• Precombustion route towards H_2 economy	• Post combustion; Pressure Swing Adsorption by 2012 • Moderate pace of development • Precombustion by 2030	• Scrubbers and membranes • Slow pace of development. • Precombustion by 2050
Storage	• Enhanced Oil Recovery (EOR) • Forties storage hub • Economics driven • Phased out	• Hydrocarbon fields and aquifers • Driven by maintaining the status quo	• EOR missed – disused oil fields using old infrastructure • Avoid controversy • Phased out	• Storage in saline aquifers (off- & on-shore sites)	• Storage begins 2020 -in aquifer traps
Energy Regime	• Gradual transition to greater reliance on nuclear energy • Carbon storage as bridging strategy • Hydrogen limited to mobile applications	• Continued dependence on fossil fuels as main energy source • H_2 via steam reformation of methane	• Renewables – based hydrogen economy (H_2 via electrolysis) • Nuclear power phased out	• No single clear strategy evolves • Locally generated hydrogen based on small scale electrolysis using off-peak electricity – no centralised hydrogen production	• No single clear strategy evolves– diverse regime • No hydrogen economy – natural gas in the domestic sector • Gas and electricity grid remain – with micro CHP • H_2 enriched natural gas

3. Multi Criteria Assessment

The scenarios described above have been designed to expose some of the key challenges to the energy supply system when strict CO_2 reduction targets are introduced. In this phase of the project, we aim to explore how these scenarios, and the various carbon storage regimes included within them, are viewed by a variety of stakeholders. To do this, we have developed a methodology based on Multi Criteria Assessment (MCA).

MCA covers a variety of non-monetary evaluation techniques sharing a basic framework under which a number of alternatives can be scored against a series of defined criteria and to which users attach weights reflecting the relative importance of each criterion. It provides a systematic means of representing different perspectives in an assessment process, MCA allows stakeholders the flexibility to explore options with their own criteria, weightings and scores. The method is easily understandable, flexible, transparent and does not depend on the technical expertise of the participants, allowing the incorporation of a broad range of perspectives in the assessment. Further background to the MCA methodology can be found in Dodgson *et al.* (2001); Keeney and Raiffa, (1993).

The way in which we are using the MCA approach bears many similarities to Multi Criteria Mapping developed by Stirling and Mayer (2001). Although the ultimate product of the MCA procedure is a ranking of options, the methodology delivers a much richer profile of the views and preferences of participants and thus enables us to begin to 'map' the key issues that will affect the prospects for implementation of carbon storage. We are thus interested in the process-oriented heuristic functions of the methodology rather than looking for an outcome-oriented 'analytical fix' to defining a 'best' option (Brown *et al.*, 2001; Stirling and Mayer, 2001). Figure 7 illustrates how we have implemented this approach during two rounds of stakeholder interviews.

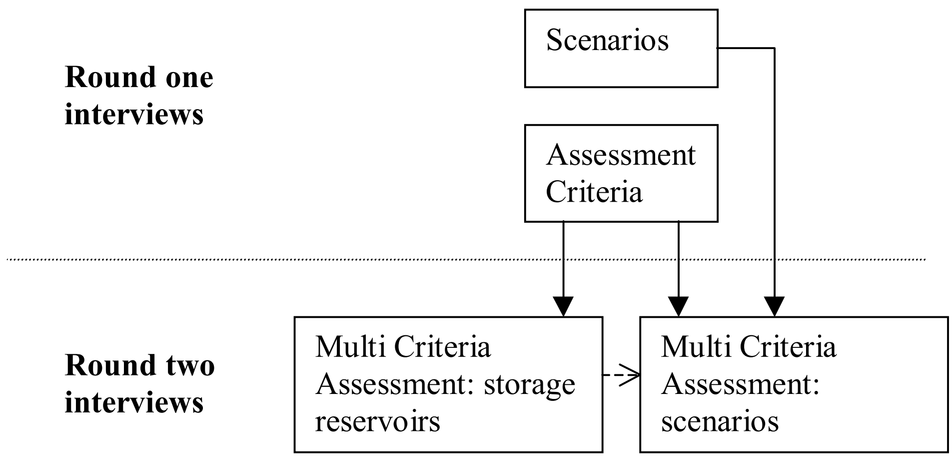


Figure 7. Interview methodology

3.1 Defining Assessment Criteria

The first stage in the MCA process is the definition of a set of criteria against which the carbon storage options within the scenarios will be assessed. This list was drawn up through a process of iteration. Prior to the consultation phase, the research team drew up a long list of possible criteria, grouped into the following broad sections: technical/engineering, environmental, economic, socio-political, legal. At this stage, no attempt was made to satisfy the criteria requirements described below – the aim was to identify as many factors as possible relating to viability, efficacy and acceptability of approaches to carbon storage and the different ways that these issues might be expressed. This long list was presented to participants in the first round interviews for comment and addition of further criteria. It has been found that people will readily comment on and add to a list of possible criteria presented to them, but that they find it difficult to spontaneously propose criteria from scratch. During a second round of interviews, the final scenarios were scored under a set of appraisal criteria, selected by the analysts from the full list of criteria resulting from the first round of interviews. Interviewees were also given the opportunity to define a small number of their own evaluation criteria to this final list during the assessment process; this provides those not included in the first interviews with the opportunity to define criteria and provides a final check on the analysts' selection.

It was thus possible to define a set of operational criteria such that that was considered to reflect the issues raised during the interviews, such that certain conditions were satisfied:

1. the number of criteria is kept manageable, typically somewhere in the range 6-20 criteria is considered appropriate;
2. criteria are mutually independent and there are no redundant criteria; if the score assigned to one criterion depends on knowledge of the score for another then the two are not independent;
3. it is possible to judge the performance of options against the criteria, i.e. the criteria must be expressed clearly and unambiguously;
4. the list covers all the major areas of importance - ensuring that criteria from each of the 5 groups from the initial long list helps to check for such completeness.

(Dodgson *et al*., 2001)

During the process of drawing up a final list of criteria to be used in the assessment, it was decided to conduct the multi criteria evaluation of carbon sequestration in two stages:

1. The first stage explores in detail the various carbon storage reservoirs included in the study; a set of evaluation criteria to assess the alternative storage reservoirs independently of the scenarios was defined for this purpose;
2. In the second stage scenarios are assessed using a set of criteria relating specifically to the scenarios.

The process was split into these two stages for two reasons. Firstly, it enabled us to explore the issues surrounding the different storage reservoirs in much greater detail during the first stage, in conjunction with a more superficial analysis of the broader trade-offs covered in the scenarios. It would not have possible to incorporate a sufficient number of criteria relating specifically to carbon storage in a single assessment of scenarios. Secondly, because the scoring in the reservoir assessment depends on a certain level of technical expertise, separating it into two phases facilitated the involvement of non-experts in the process.

A link between these two stages allows the results of stage one (the reservoirs assessment), to carry over to the scenario assessment. This is achieved by calculating an aggregate score from stage one, according to the scores and weights of participants and the relative use of each reservoir type in each scenario. This approach allows us to identify the key issues associated with and make a more detailed assessment of the different reservoir types and then to explore the use of carbon sequestration in the context of other climate mitigation strategies and the tradeoffs associated with these different pathways.

Stage One - Reservoir Specific Criteria

- Rate of leakage of CO_2
- Storage timescale
- Potential storage capacity
- Proven storage security
- Monitoring / verification
- Public opposition
- Planning or legal barriers

- Costs
- Adverse impacts - human health
- Adverse impacts - ecosystems

Stage Two - Scenario specific Criteria

- Reservoir performance (within each scenario, calculated from results of step one)
- Costs- energy supply and use
- Infrastructure change
- Lifestyle changes
- Security of energy supply (resource security and reliability)
- Environmental impact
- Credibility

Care was taken to ensure, as far as possible, that criteria were independent. To some extent it is possible to identify linkages between some of the criteria, suggesting partial dependence between them. For example, the scenario criterion 'credibility' caused some problems, as it was felt that the credibility of a scenario depended on its performance against the other criteria. The criteria set used is nevertheless considered to be valid, given that each criterion is influenced by many factors beyond those relating to the other criterion in question.

3.2 The Multi-criteria Assessment Process

The number of criteria for each stage is restricted to a maximum of sixteen. Scoring is based on the information provided within the scenarios and the expertise and opinions of the respondents; it provides an indication of the relative performance of the various options against each criterion. Once the scenarios have been scored, the criteria must be weighted. Participants are asked to weight the criteria according to their views of what is desirable - rather than what they consider to be most likely or politically acceptable. It is important to be clear about how the scoring and weighting is being approached by each participant.

A spreadsheet tool (see Appendix E) was developed to facilitate the process; this enabled participants to enter scores and weightings directly onto the spreadsheet, which keeps tally of total points for each criterion and automatically calculates the final scoring and ranking from the performance matrix. The assessment process was implemented through interviews lasting about 1 to 1.5 hours[1]. So far, seven individuals (see Appendix D) have been interviewed; the process will continue to include additional stakeholders, for example no representatives from industry have been involved in the assessment to date. At each stage, participants were presented with the basic list of criteria, with the option of specifying additional criteria. As this assessment represents an initial scoping exercise – mapping out possible trade-offs and issues associated with carbon sequestration - and given the uncertainty associated with many of the parameters, these criteria were all evaluated on a relative scale by allocating 100 points to each criterion across the options. For all criteria the scoring operates on the basis of high scores indicating a good performance (so, for example, a high score for costs indicates that an option is *not* expensive, compared to the other options). Since many of the reservoir criteria are currently not known or not measurable, the choice of a relative scoring system reflects the level of uncertainty and novelty associated with carbon storage technologies. The second stage of the assessment adopts a set of non-quantifiable criteria applied to descriptive and generalised scenarios for which only a relative scale is appropriate. Prior to the interviews, each participant was presented with a scenario pack, explaining the

[1] Intermittent problems with the tape recording of interviews mean that acccurate transcripts were not produced for all of the interviews; although a record of the final scores are saved on the spreadsheets, notes on the supporting discussions are incomplete for some of the interviews.

rationale behind the scenarios, the scenarios themselves and summary table for reference during the MCA, and an explanation of the criteria (see Appendix C) and how to score them.

It was apparent that, even using the relative scoring system, scoring the reservoir criteria in the first stage requires a knowledge of geological storage issues far beyond that of the majority of our stakeholders. We thus decided to include a set of 'default' scores which could be used should participants not feel comfortable assigning scores themselves. To define these default scores we consulted colleagues at British Geological Survey (BGS); three individuals were consulted. Initially, each geologist assigned his own reservoir scores; these were compared and default values agreed during a detailed discussion for each criterion. Once the default scores had been agreed, the geologists proceeded individually with the assessment – defining weights to the reservoir criteria and weighting and scoring the scenarios. This set of default scores for the reservoir criteria was then made available to all participants enabling non-experts to engage in the reservoir assessment.

There are a number of methods that can be used in order to determine the ranking for the alternatives (reservoirs or scenarios), see for example Stirling and Mayer, (1999); Dodgson *et al.*., (2001). We have used a simple linear additive weighting model; here, an overall score for each option is calculated by simply multiplying the criteria scores and weights and summing these weighted scores. Since the purpose of the MCA has been to map the views of the participants rather than deliver a 'final' ranking or 'best' option, the transparency of the procedure is considered to be vital. Whilst more complex mathematical models are available for calculating final rankings it would not be appropriate to introduce this level of complexity within this exploratory study, with its qualitative scenarios and criteria. We consider that such methods would reduce transparency and detract from the heuristic benefits of the process.

3. Results from the pilot assessment

In this section, we present the results from the second round of interviews, using the MCA tool. Since we have only interviewed a very small number of stakeholders in this pilot study, it is not appropriate to draw firm conclusions regarding chosen strategies. Consequently a formal sensitivity analysis has not been applied to the results at this stage.

We begin with some comments interviewees made about geological carbon sequestration in general, then proceed with a review of the default scores and the subsequent scoring and weighting process. Before embarking on the MCA process, there was some brief discussion during which interviewees had the opportunity to raise questions or general comments relating to carbon storage. The views of the geologists are discussed later in relation to the definition of default scores; however, because of the time spent working on the default scores, the scenario assessment stage was rather rushed in the geologists' interview – all felt that they would have liked more time to think about this part of the process.

Both of the NGOs were very sceptical about carbon sequestration but considered that, as a "last resort" short term bridging strategy, and if it was demonstrated that alternative options such as renewable energy and reduced consumption / greater efficiency could not deliver sufficient reductions, limited carbon storage might be acceptable. The view is that mitigation should be focused on emissions reductions, which a carbon sequestration strategy is not considered to do.

The concern that pursuing carbon storage will divert significant R & D funds away from alternatives comes across from both of the NGOs interviewed and also in previous personal communications with other NGOs. This argument applies particularly to public sector investment. For private sector investment, it may be less straightforward; as a way of maintaining their fossil fuel markets, while satisfying CO_2 targets, carbon sequestration could be an important technology for oil companies, many of whom also have interests in renewable energy. However, both NGOs did consider that sequestration might be preferable to nuclear power as a means of achieving significant early reductions in atmospheric release of CO2, *if* it became clear that even with greater commitment to renewables and energy efficiency sufficient reductions would not be made:

NGO2: "we're not going to go 100% renewable within the next 20 years , its just not feasible. (…) 10% by 2010 is great, and we're pushing for at least 20% by 2020 in the UK, globally it's a different matter. If you really want to be serious about substantial CO_2 reductions , you might have to look at some kind of alternative interim solution, and for us the biggest question is , with our position towards nuclear, what would we rather have..lets say our priority is to get emissions down a lot further than Kyoto, would we rather have nuclear or sequestration? (…) can we actually go far enough fast enough if we don't want nuclear, and we won't change on that, we do not want any new nuclear, and then it may come down to some sequestration"

Although the responses of the two individuals that we spoke to are in general agreement, these represent the views of those individuals and do not reflect an 'official' view from either of their respective organisations. Within WWF, the debate is still active, with views ranging from absolute opposition to geological sequestration to slightly more pragmatic but still sceptical; resources have not been directed to developing a 'consensus view' from the organisation (beyond a clear opposition to ocean sequestration). Similarly carbon sequestration does not currently feature within the FoE climate change campaign material, although a similarly sceptical reaction can be expected. It is unlikely that either of these NGOs would support carbon capture and storage as anything other than a minor component of a future energy system. As the NGO community is typically very tightly resourced and geological sequestration is not seen as a priority issue for them, the notion of diverting resources away from alternatives applies equally to themselves - to the extent that currently they do not have the capacity to play an active role in the debate. Whether one is opposed to or in favour of carbon sequestration this is disadvantageous; it is crucial that a wide variety of stakeholders engage in the debate if a robust strategy to its application is to be achieved.

In contrast to the NGO view, the RDA representative was attracted to the idea of carbon sequestration as a way of satisfying both energy needs and ambitious greenhouse gas reduction targets. It was thought that carbon sequestration is likely to gain support within that region as a clean coal technology; with 6000 jobs in the coal industry within the region the social benefits would be significant.

The academic was not familiar with the approach of carbon storage and had few general comments about the technology.

The following section documents the results of the formal application of the MCA methodology.

3.1 Stage One: Reservoir Assessment

Reservoir classifications

The first version of the assessment tool classified alternative storage reservoirs into 5 categories: oil and gas fields, traps in aquifers, closed aquifers outside traps, open aquifers outside traps and onshore sites. The distinction of aquifer types reflects the classifications described in the Joule II study (Holloway 1996); closed or confined aquifers are completely sealed form any neighbouring formations, unconfined aquifers were also identified as suitable potential storage sites within very large sedimentary basins – these are sealed vertically by a layer of cap rock but may not be completely closed structures (these were considered appropriate if the injection point was sufficiently distant from the margins of the basin). During the consultation with the geologists, this classification clearly caused problems and discussion repeatedly turned to the definitions of the structures as the criteria were considered.

At the time of the Joule study, aquifers were distinguished in this way to facilitate the estimation of potential CO_2 storage capacity, which was assumed to be limited by pressure. In closed structures it was assumed that, with no outlet for the displaced water, build up of pressure as CO_2 is injected would be the main limiting factor for capacity. In unconfined aquifers, no such pressure build up is assumed as the displaced water can migrate out of the storage formation. Thus, estimates were based on 2% of the pore volume in confined aquifers and on a pore volume of 6% in unconfined aquifers, allowing for displacement of water which would not occur in a confined structure. The Joule report represents the first comprehensive assessment of geological sequestration and aimed to give a first approximate indication of potential capacity. Thus classifications were made in order to facilitate this process. However, discussions during the present study reveal that it may not be as straightforward as this classification implies; the characterisation of the reservoirs is highly context specific and the terminology is too ambiguous, subject to different interpretations by different branches of geology. For the purposes of this study it was decided that it would be more accurate to distinguish only between traps within aquifers (which are clearly identified structures) and all other aquifers outside traps. We will explore this issue further in the forthcoming study.

Default scores

The second round interview with the geologists took a slightly different format to the other second round interviews. Rather than being held one to one, we talked to the three representatives together in order to derive some default scores for the reservoir criteria. This was done by initially asking for individuals to assign their own scores independently without discussion. These scores were then compared and the group agreed on a single consensus score for each criterion. This proved to be a highly informative process, revealing uncertainties and further understanding that may not have been explicit otherwise. For some of the criteria, just explaining their thinking led an individual to revise the score, in other cases discussions revealed greater uncertainties surrounding the criteria. The individual and default scores are illustrated in Figures 8-12. Once agreement on the default scores was reached the group continued with the assessment process, each individual defining weights for the reservoir criteria and scores and weights for the scenarios.

See over for Figs 9-12

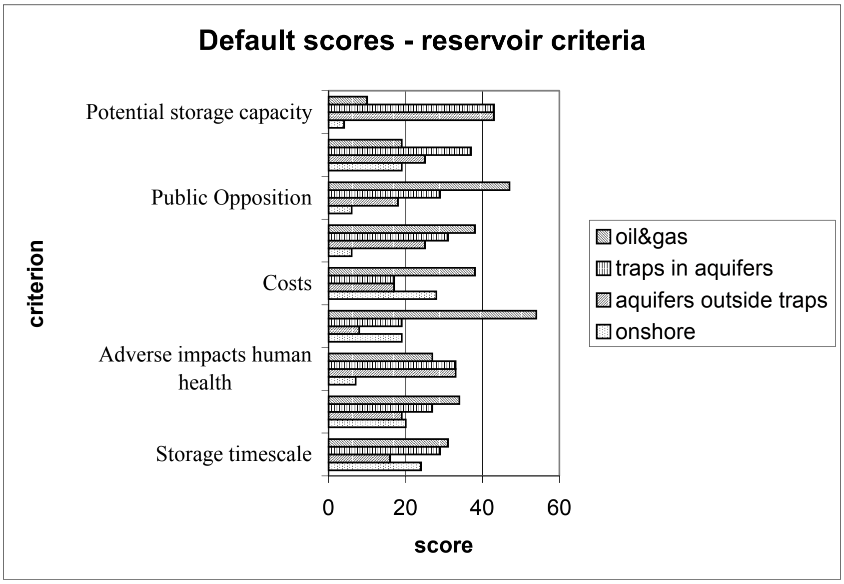


Figure 8. Default reservoir scores

Rate of leakage of CO_2

This criterion was originally included to provide an indication of the slow leakage rates from a reservoir, from around the injection point, or any other region of the reservoir boundary. However, during the criteria scoring process it was apparent that there were problems with the independence of this criterion and another two: storage timescale and environmental impacts. It was felt that the leakage potential would be adequately captured in these other two criteria and "rate of leakage" was removed from the criteria list.

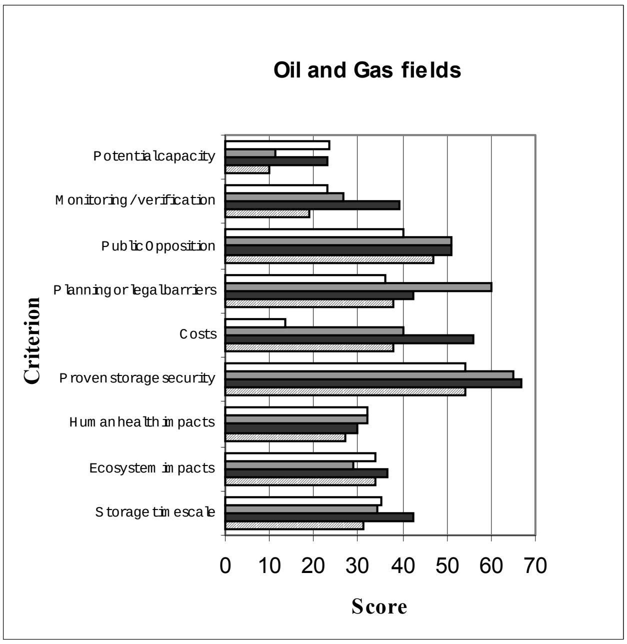


Figure 9

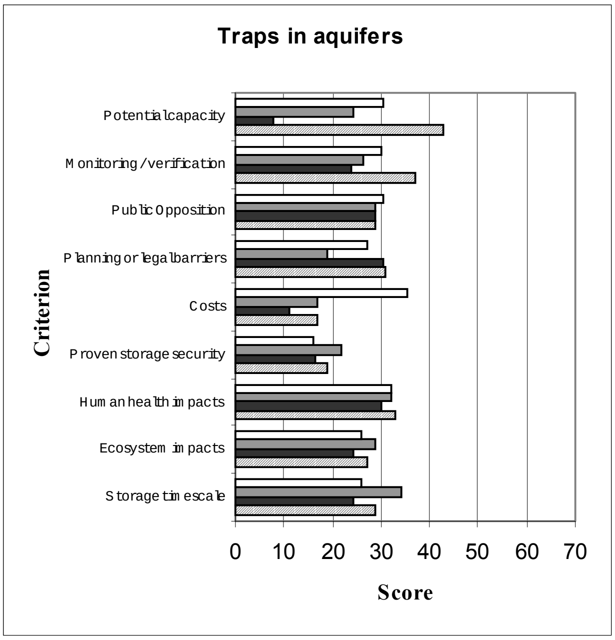


Figure 10

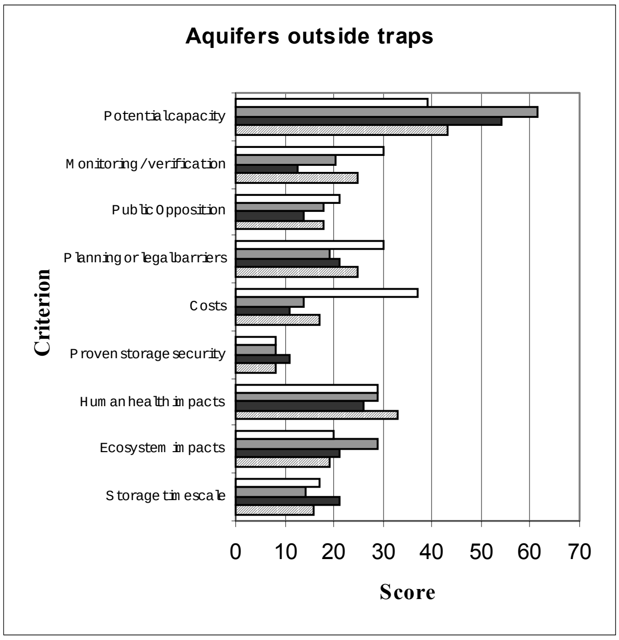


Figure 11

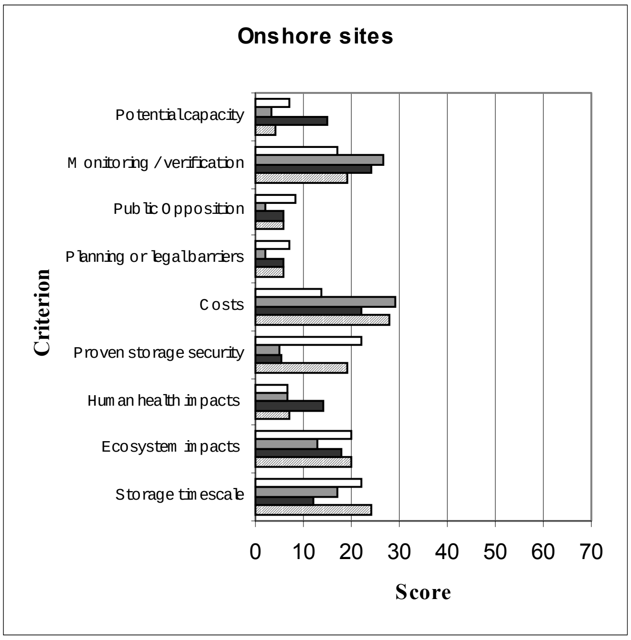


Figure 12

Legend

- ☐ Geologist A
- Geologist B (grey)
- Geologist C (black)
- Default (hatched)

Storage Timescale

Oil and gas fields were awarded the highest score, indicating a high level of confidence in their performance for long term storage. This score subsequently was reduced to account for the possible reduction in integrity caused by large numbers of bore holes through the cap rock surface. However, it was considered that if these had been abandoned adequately this should not cause problems, and that fast remedial action could be taken against such leaks – provided their detection and repair occurs rapidly.

Traps in aquifers came close behind oil and gas fields; CO_2 injection would occur to the side of the trap, from where it will migrate into the trap without the need to bore through the caprock. Aquifers outside traps scored slightly lower, since there is the possibility that CO_2 could migrate to a poorly understood region of the aquifer (where there is a gap in the caprock), over a timescale of only 10s to 100s of years.

Since the onshore category includes all of the previous categories, it was thought that, theoretically, the storage timescale should be an average of the other three categories. However, the group considered that a lack of "classic" structures onshore in the UK, as there are offshore, and the fact that onshore sites are likely to be shallower and closer to the rock outcrops the score was reduced a little. At the time the group was not asked to clarify their interpretation of the term "classic" structures – which may reflect certain presumptions that are being made about the offshore formations concerning their geological structure.

Potential storage capacity

Compared to original estimates made for the Joule report, the scoring for this criterion reflects advances in understanding of potential storage capacity. Even though they represent only a proportion of total aquifer volume and hence a smaller absolute volume, the consensus was to score traps in aquifers the same. For the Joule report, estimates of storage capacity assumed the same percentage of the pore volume could be filled (1%); it is now thought that a much greater volume of the pore space of a trap can be filled.

Proven Storage Security

This criterion reflects the extent to which either equivalent or analogous formations have been observed to provide a secure gaseous seal. For example, storage may be in a structure that has previously contained gaseous or liquid compounds over long periods or there may be evidence of secure storage at analogous formations considered to be structurally similar. The scores were in broad agreement on this criterion, with the exception of onshore sites. Here, an optimistic position was taken with respect to onshore sites, which were awarded a similar score to traps in aquifers, reflecting the range of formations covered by this category.

Monitoring/verification

There was quite a lengthy discussion surrounding this criterion, coming to the conclusion that oil fields would not be as straightforward to monitor as commonly assumed. 'Geologist A' held the most experience in this area and lead the discussion concerning the default scores. Offshore aquifers scored highest because they are shallow, structurally uniform and easy to monitor. Geologically, aquifers are simpler structures than oil and gas fields which tend to be deeper, more structured and often located within geologically complex areas, making their monitoring more complex. Out of use oil wells are not relevant for use in monitoring as they would be sealed off. Onshore seismic surveying is more expensive than offshore but it would be possible to use gravity methods at onshore sites (a technique using gravity data to indicate porosity and density of rock formations).

Public Opposition

There was general agreement on scoring within the group although there was some discussion regarding how low onshore sites should be scored. Many of the potential onshore sites occur in areas with high landscape and amenity value that would be likely to spark high opposition (such as the Worcester Basin beneath the Cotswolds). However, it was felt by this group, that if an onshore storage were to be linked to a particular existing industrial installation it might be received more positively. Our own research suggest that this situation might produce the opposite effect of greater opposition to local disposal of industrial waste; for example, a recent proposal to develop a gas storage facility at a salt cavern in Cheshire, supplying local industrial processes, provoked a strong local opposition campaign.

Planning / Legal Barriers

As oil and gas fields are already seen as industrial sites they are considered to present the least challenge to planning or legal processes and were initially given a very high score by 'Geologist B'. This was reduced somewhat since it was felt that a distinction could be made between Enhanced Oil Recovery (EOR) and storage at a disused field. Technically, EOR could be considered to be part of the oil extraction process, whereas storage at a disused site could be seen as 'dumping' and objections under the OSPAR and London Conventions would apply. The fact that aquifer storage is already occurring (at Sleipner) also brought the scores closer.

Costs

Although the results show a reasonable variation between the individual scores, this criterion did not prompt a lengthy discussion. The default scores were awarded on the following basis: oil and gas score highly because of the potential economic returns from EOR and the opportunity to use existing infrastructure; onshore score quite highly, as this is seen to be the main motivation for choosing an onshore site; aquifers score slightly lower as they would incur the additional costs associated with being offshore but without the benefits of EOR. Individually, 'Geologist A' gave aquifers a much higher score on the grounds that, being shallower than oil fields, the costs of the two reservoir options would be closer but subsequently revised this score deciding that additional depth would not significantly increase drilling costs.

Adverse Impacts – human health

There was broad agreement on the scoring for this criterion. It was felt that oil and gas fields should score lower (indicating a worse performance against this criterion) than the other offshore sites as they would be associated with a higher level of human activity (associated with extraction) than the others. The low score for onshore sites reflects the possibility of leaks occurring in populated areas, which by definition must be greater than at offshore sites.

Adverse Impacts – ecosystems

As described earlier, it was agreed to remove the criterion "rate of leakage" since it was assumed that any assessment of adverse impacts would include an indication of the probability of a leak occurring. Once this had been agreed, this changed the basis on which this criterion should be scored for some individuals.

There was some discussion surrounding the probability of a leak from an oil or gas field. It was felt that these are the least likely to develop a leak (because a high level of confidence could be attached to a secure geological seal), any leak would be most likely to occur through a well, which, although could be large, could be quickly sealed with cement. Sealing a leak originating at a fault would present a much greater challenge.

There was some discussion around the effect on any microorganisms that might inhabit a reservoir formation, although very little is known about this. It was thought that oil and gas activity would already have either damaged such ecosystems or that adaptation would have occurred; it was considered that any impacts to the 'pristine' ecosystems within an aquifer would be less acceptable than to an 'industrial' site.

Although potential impacts near an onshore site could be significant, these were not given the lowest score on the grounds that only sites at which there was a very high level of confidence in security would be used. In addition any leaks would be likely to be contained within a small area (due to the relative density of CO_2 in air), a leak to the ocean would result in an acid plume which could have a large effect on the sensitive marine environment.

Summary

The following general observations can be made in relation to the scoring of reservoir criteria:

- traps in aquifers are awarded mid to high scores consistently across all criteria
- onshore sites are given low scores across all criteria (with exception of costs, although they are still considered more costly than oil and gas fields)
- oil and gas fields generally score highest for the 'socio-economic' criteria
- aquifers outside traps score very poorly for 'socio-economic' criteria
- the uncertainty concerning discussion of scoring for onshore sites is generally a product of the classification, which covers a range of geological formations with an onshore location, than any additional inherent uncertainty associated with being onshore.

As there was some variation between the individual scores from the geologists, in addition to the default scores we also included scores representing 'cautious' (Geologist B) and 'confident' (Geologist A) outlooks.

Reservoir Assessment

With one exception, all of the remaining interviewees were happy to adopt the default scores and apply their own weightings to the assessment of the reservoir types – these are illustrated in Figure 13. One of the environmental NGO representatives (NGO2) did not want to engage in the reservoir assessment process on the grounds that the relative assessment of the reservoirs implied an acceptance of the principle of carbon storage; instead the issues surrounding storage were discussed prior to continuing with the scenario assessment. None of the interviewees felt able to assign scores to the reservoir criteria themselves.

Most of the interviewees opted for the straight default scores. The NGO representative that did engage in the reservoir assessment selected the scores labelled as 'cautious', No-one wanted to amend or discuss these default scores.

The RDA representative considered security, storage timescale and impact on ecosystems to be the most important criteria. Public opposition was not ranked highly on the grounds that opposition could be avoided if public information was produced early on in the process of introducing the technology. Providing clear and accessible information to the public would enable them to visualise the process and reach their own conclusions regarding the safety of the technology. This interviewee considered that carbon storage would only be likely to proceed if the other criteria were satisfied and in which case levels of public opposition should be low. This argument implies that public opposition is not independent of the other criteria, this concern was also expressed by NGO1, albeit recognising that this criterion is so contingent on unpredictable factors that it is very difficult to score – referring to it as a "wild card".

> *RDA: "(...) less weighting, ironically (...), would go on public perception. Mainly because usually those things can be overcome if they're built in… my working assumption would be that this would be a less important factor as you would work to get the information out earlier on."*

Similar discussion between the geologists, one ranked storage timescale very highly - as a necessary factor in public acceptance, whereas another ranked public opposition high as one of the key deciding factors (with costs) – both were arguing along similar lines but with quite different interpretations to the weightings.

> *Geologist C: "(...) that's why I put opposition down higher than storage because really everything will come down to cost and public opposition"*

Geologist A: "I've done it the other way round - if you can demonstrate that its safe then the public opposition hopefully will not be severe. Same argument but you end up with completely different weightings."

Costs were also not ranked highly by the RDA representative, who considered that they were trying to view things in terms of value rather than cost. This interviewee also did not consider impacts on human health as separate to ecosystem impacts – considering humans to be part of the same system and assigned the human health criteria a low weight. This interviewee described her weightings overall as 'technocratic' – prioritising the measures of effectiveness and performance of the carbon storage options.

The assessment process has thus revealed the different attitudes to the policy process and how it relates to the introduction of a new technology such as carbon storage. For example, Geologist A and the RDA representative are assuming a rational process:

1. demonstrate that the technology is safe
2. develop an effective communicate strategy to present the case for the technology
3. the technology will be accepted.

The NGOs and Geologist C see the process as being much more contingent on other factors – the wild card effect of public opinion – through which steps 2 and 3 above cannot necessarily be inferred from step 1.

There was considerable variation in the weightings assigned by the geologists. Geologist A considered that the two overriding criteria would be storage timescale and capacity, without which he considered a reservoir would not be used. In contrast Geologist C considered storage timescales to be the least important of the criteria – on the grounds that for a reservoir even to be considered it must be secure for 100s of years - any variations above this time scale being insignificant. This raises a point over how the assessment is being viewed – whether it is being seen as a check to see whether a reservoir should be used or as means of choosing between reservoirs that have already been selected as potential sites. This ambiguity is, to some extent, a result of the way in which we are using MCA - heuristically, as a means of mapping the issues rather than as a decision tool.

Storage capacity was not seen as being important by the NGO representative – this would only be important in the context of significant CO_2 storage, and since he didn't consider this desirable, capacity becomes less relevant.

Additional Criteria

Several of the interviewees suggested additional criteria, described below; this demonstrates a good level of engagement in the assessment process despite limited knowledge of geological storage approaches.

Degree of reversibility: this criterion was proposed by two of the interviewees. It was incorporated into the assessment tool by one, the academic to indicate the extent to which CO_2 could be retrieved from a storage reservoir should new evidence reveal major disadvantages or detrimental effects or should a more effective means of CO_2 disposal be discovered. This criterion was also proposed by NGO1 to indicate the potential effect of a lock-in and how easy it would be to move to a new approach once carbon storage was established.

Robustness to uncertainty: concern was expressed by the academic regarding potential large-scale earth system effects, for example, concern that changes in the balance or weight distribution between ice caps and the oceans, resulting from increased global temperatures, could affect the geology.

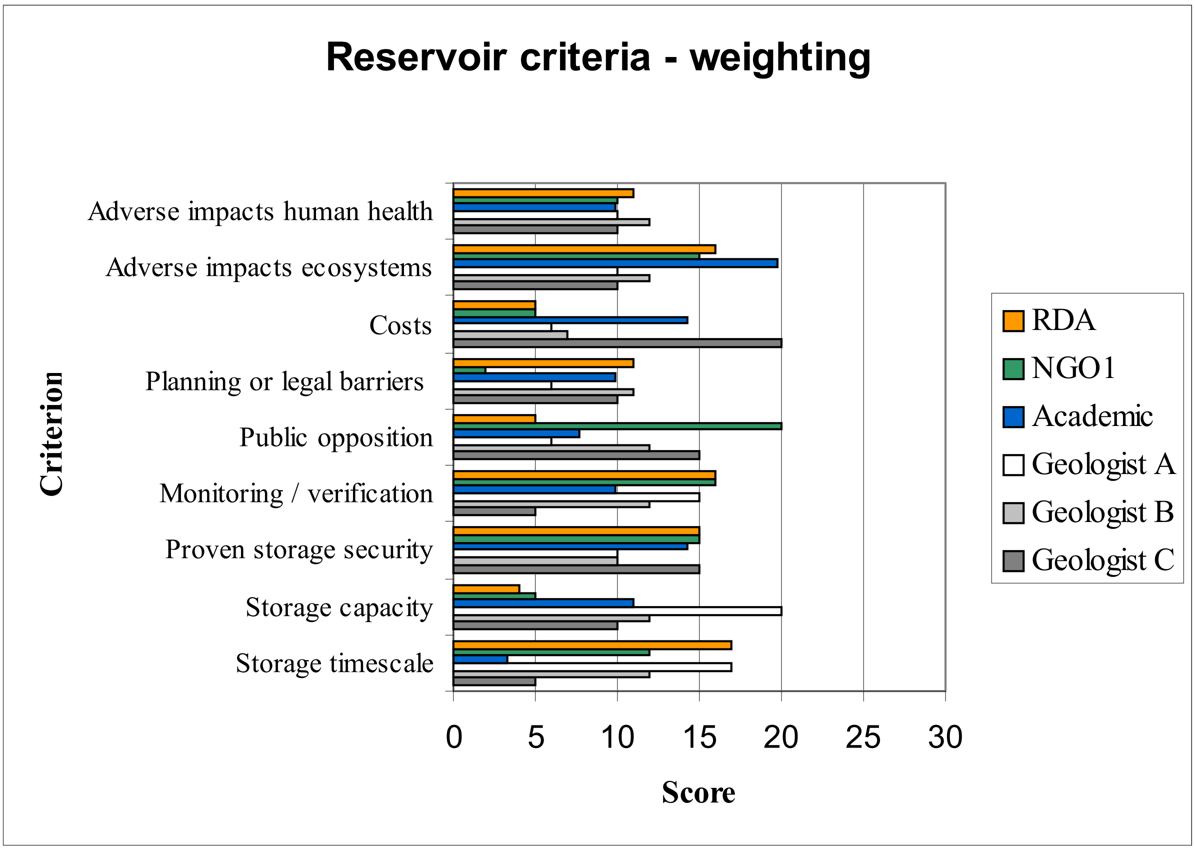


Figure 13. Reservoir criteria weights

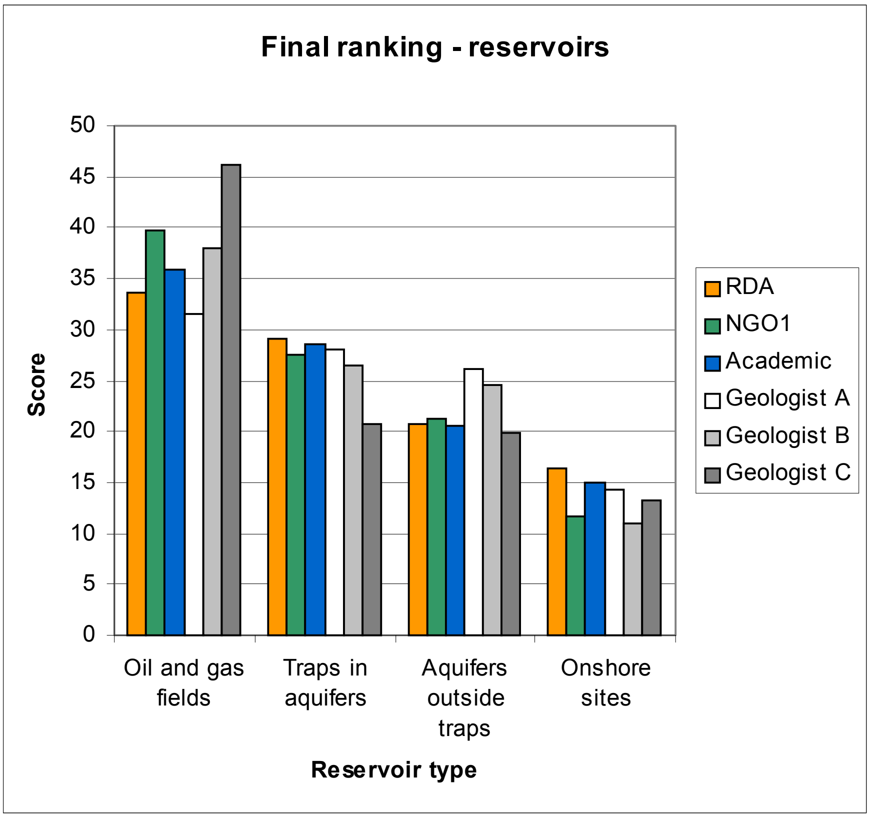


Figure 14. Reservoir Assessment – final ranking

Energy penalty: this criterion, suggested by NGO2, would be most relevant applied to the carbon capture stage. In the current version of the assessment, different capture approaches and their implications are not explicitly included (although they are referred to in the scenarios these are not expressed in sufficient detail to assess energy losses explicitly).

Research and Development: both of the NGOs raised concerns over the diversion of investment away from alternative solutions – making the transition less likely (hence also leading to lock-in). Such a criterion would require careful wording to avoid imposing a bias to the criteria.

Final Ranking of reservoirs

In general, the relative preferences for reservoir types was consistent across all users, this is illustrated in Figure 14; these results are based on individual scores for the three geologists and on the default sores for all other stakeholders. The order of preference is: oil and gas fields, traps in aquifers, aquifers outside traps, onshore sites. Oil and gas fields score higher than the other reservoirs on all criteria except monitoring and storage potential (capacity), for which aquifers score more highly; these criteria do not dominate the results under any of the weightings. Onshore sites score more highly than offshore aquifers for costs but score poorly on all other criteria. Since default scores were used for this assessment, care should be taken not to place too much emphasis on the final ranking for each stakeholder. Although the definition of the default scores generated lively debate, reflecting the underlying uncertainty in characterising the storage reservoirs, this ranking still applies when geologists' individual scores are used; this can be seen to indicate a degree of robustness in the *relative* performance of the different reservoir types.

This result is also consistent with the intuitive assessment of NGO1. Without running through the MCA of the reservoirs, this interviewee thought that the existing experience with oil and gas fields, since they are already industrial sites, gave these sites the most potential. However, concerns about impacts on marine ecosystems implied that offshore sites would not necessarily be viewed any more favourably than onshore sites.

3.2 Stage Two: Scenario Assessment

All participants were comfortable with scoring and weighting the scenarios. Those who had not been involved in the scenario development process of the first round made some general comments.

Although it was explained that none of the scenarios considered an overall reduction in energy demand one of the NGO reps wanted to see energy efficiency and demand reduction included in the scenarios, although the RDA rep thought that even with improved energy conservation measures a growth in the regional energy use is still expected. The Hydrogen economy was generally popular amongst our respondents although did not spark much debate. The RDA was very keen to promote this in her region, ultimately hoping see hydrogen generation by renewables based electrolysis.

Scenario Criteria

Because we are not aiming at a final 'decision' over the best option or scenario we have avoided 'overdefining' the criteria. For example by asking participants to give a score for the effect on lifestyle we are also aiming to identify what *sorts* of impacts they think a scenario will have on lifestyle; this yielded some varied responses, illustrated in the following examples:

> *NGO1: "the current levels of consumerism that we have reached are having negative impacts on lifestyles and are bringing us to environmental and resource depletion limits - a change is needed"*

This respondent thus scored any scenario thought to deliver such changes highly; he also considered that this criterion should incorporate society and community issues and social cohesion. A similar approach was taken by the RDA representative:

RDA: "Renewable generation does require massive changes but it's a good thing; my starting point is that a distributed power supply makes more sense for handling variable load, local accountability for energy use, reducing network losses etc."

whereas another included even broader notions of lifestyle:

NGO2: "I give a low score to nuclear because I think there will be so much opposition, I think people are a lot more concerned about nuclear than carbon storage, (...) if people are scared about health issues then that is negative in terms of lifestyles"

The credibility criterion also prompted some discussion over how the scoring should be approached:

Geologist C: "(...) I wasn't thinking of my own credibility, I was thinking of the credibility to the general public"

Geologist A: "again this is why I wasn't sure what to put with credibility"

Interviewer: "do you think that this scenario describes a pathway that could happen?"

Geologist A: "so its your own personal credibility, because again the nuclear in general I think has got low credibility to lots of people, although from my point of view I think its an extremely credible way of going ahead "

Geologist B: "I've marked it for myself - I've put it down as high credibility, nuclear because I think it could happen, it could work, whereas I think that renewables can't work under any circumstances because there just aren't enough of them and they turn off at night and when the weather's nice. So I've put nuclear down as very credible."

As this debate arose during the first of the multi criteria interviews, the interviewer made a point of explaining that scoring should be done on the basis with a participants own personal set of values and perceptions; this problem was thus avoided in the remaining the interviews.

Several participants proposed additional criteria for the scenarios scoring:

Although public concern was included as a criterion in the reservoir assessment stage (as public opposition), there was no separate criterion to capture this in the scenario assessment. Hence, NGO2, for example, explicitly incorporated public concern issues into her scoring of the lifestyle and credibility criteria. In future assessments it may be better to include a public concern / public opposition criterion in place of the credibility criterion used here.

Risk of major disasters – this criterion was proposed by the academic to characterise the risk of something "going wrong" within the scenario – Fossilwise and Renewable Generation were given high scores for this criterion and nuclear was given a very low score. Related to this, one of the NGOs thought that Vulnerability to terrorist acts was a crucial criterion

International effects / Distributional issues - one of the NGOs added this criterion to capture the social and environmental impacts of the scenarios to other countries. This was felt to be very important:

NGO1: "Part of the reason we have the problem of climate change in the first place is because we have ignored the distributional issues of our behaviour – so ignoring it again in the carbon sequestration / fossil fuel energy pathway is simply perpetuating that problem and continuing with the same erroneous outlook"

Other respondents also raised this issue – considering both the positive and negative effects on other parties that a scenario might have.

Scoring (scenarios)

The scores given for the scenario criteria are illustrated in Figures 15-21.

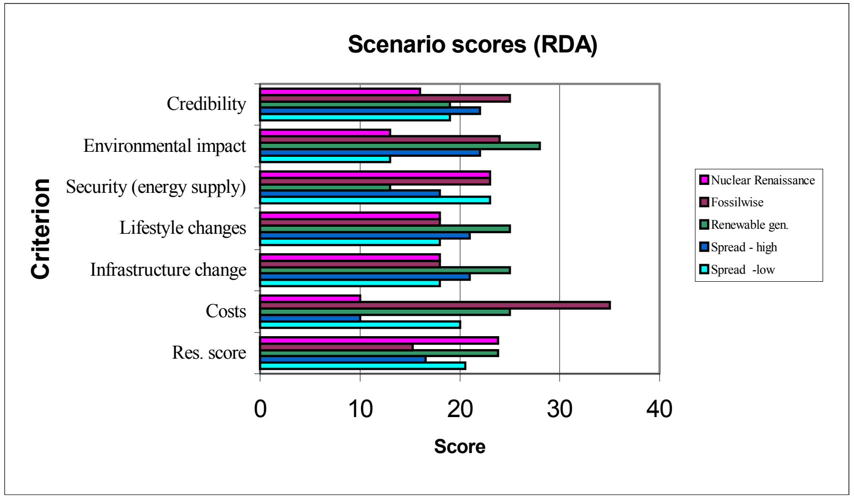


Figure 15. Scenario Scores: RDA Representative

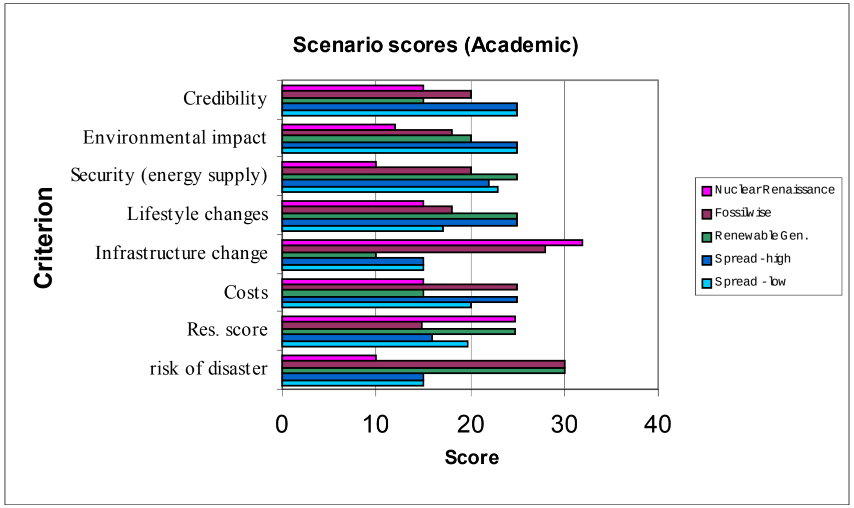


Figure 16. Scenario Scores: Academic

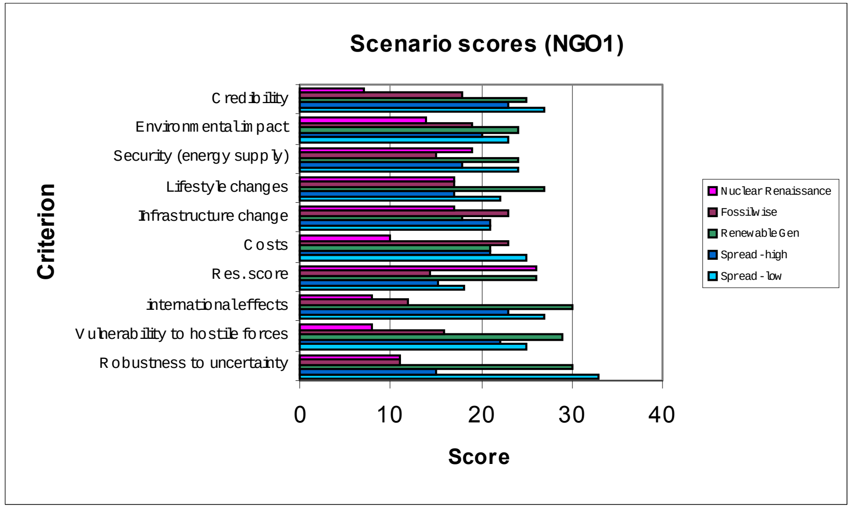


Figure 17. Scenario Scores: NGO1

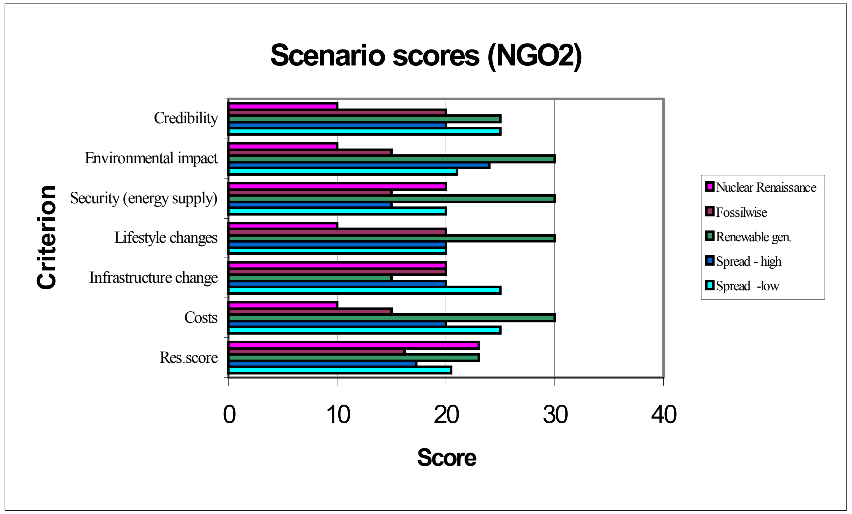


Figure 18. Scenario Scores: NGO2

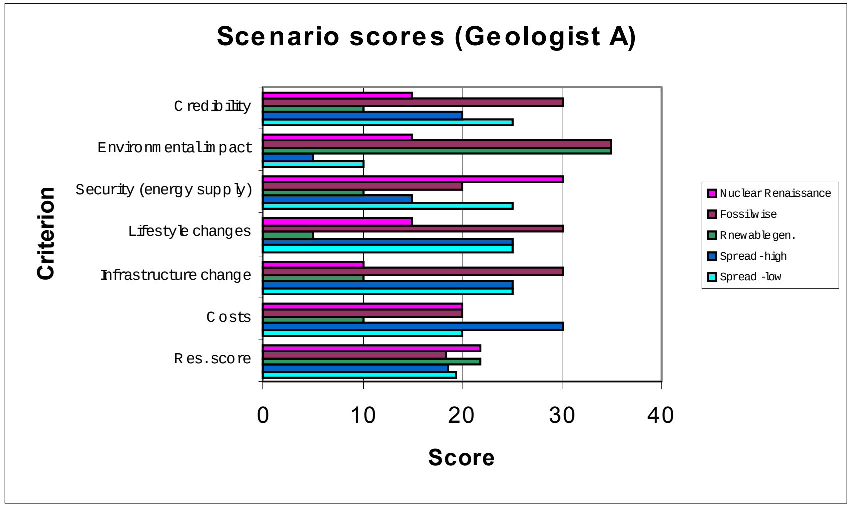


Figure 19. Scenario Scores: Geologist A

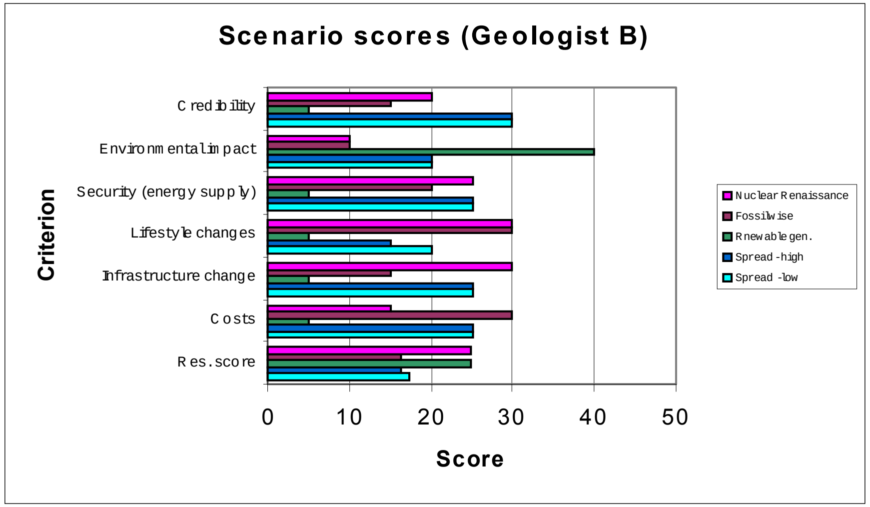


Figure 20. Scenario Scores: Geologist

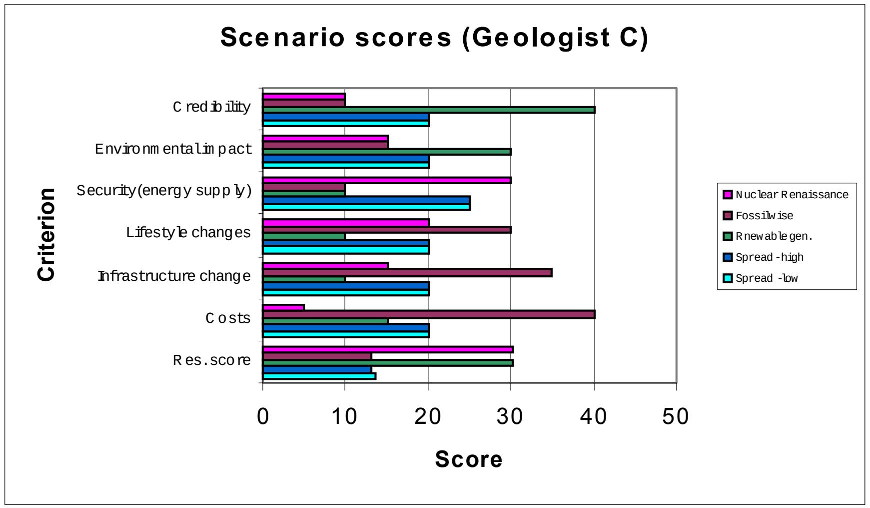


Figure 21. Scenario Scores: Geologist C

Fossilwise:

Fossilwise always gets a low score on reservoir performance as it exploits the maximum storage capacity of all the scenarios, extensively using a range of available reservoir types, including the less preferred sites as well as the preferred sites. All respondents, except NGO2, scored the Fossilwise scenario consistently highly for costs. It is also generally considered to be a credible scenario by all except Geologist C who was responding to his perception of stronger societal drives towards more mixed energy regimes and particularly a desire for more renewables. The credibility score given by NGO2 was also a little lower than Renewables and the low storage Spreading the Load scenario, reflecting her doubts about significant reliance on carbon storage.

Although the three geologists all scored this scenario high for the lifestyle change criterion, surprisingly this was not the case with the other respondents. The criterion is open to broad interpretation, as described earlier and this is reflected in the range of scores awarded.

The RDA rep scored Fossilwise fairly high for all criteria, its lowest score being for infrastructure and lifestyle change. She viewed a UK dependence on fossil fuels positively, as a highly credible possibility. Social and economic benefits could be made in this scenario, without environmental compromise if fossil fuels are used as efficiently as possible; this does not necessarily imply a reliance on imported gas (which in turn would export the economic benefits) since there were opportunities for clean coal technologies with domestic supplies. The NGOs both also picked up on the international effects of future reliance on fossil fuels, focusing on the export of environmental problems associated with exploration.

Nuclear Renaissance:

The nuclear scenario adopts only modest levels of carbon storage enabling it to store only in oil and gas fields – consequently it scores highly for the reservoir performance criterion. It is considered to provide the most secure energy supply of all the scenarios by Geologists A and C, and by the RDA representative as being equally as secure as Fossilwise and the low storage Spreading the Load. The academic and Geologist A give it a high score for infrastructure change but otherwise it is scored consistently low for all other criteria – particularly costs (decommissioning, capital and infrastructure) and (long term) environmental effects. Overall, from a regional perspective it was seen as very different matter to introduce new capacity to a region that does not already have any nuclear compared to expanding existing capacity in a region – primarily because of the need to confront waste disposal as new issue for a region.

The credibility score of this scenario was strongly linked to views of public opinion - even if a respondent personally was positive about a significant use of nuclear power all considered that strong public opposition would make this scenario unlikely.

NGO2 felt that this was the only scenario to have a significant (negative) impact on lifestyle, incorporating public opposition within this criterion but also reflecting health concerns. Since none of the scenarios imply overall reductions in energy use they were considered to have minimal lifestyle impacts – for example in the transport sector, moving to a hydrogen economy would change the types of vehicles driven rather than lead to a change in mode or demand.

Renewable Generation

Generally, participants scored this scenario either low (geologists) or high (others) across most criteria – indicating strong feelings about renewable energy.

The RDA rep considered that overall this scenario was closest to the current thinking within her region but raised some comments about the details, in particular the balance between fossil fuels and renewables. In her view there is no reason for current tensions between the two sectors to persist – since both have an important role to play together in reducing greenhouse gases. For example, carbon storage is assumed to be phased out in the scenario, her view is that in the long term all fossil fuel energy will be associated with carbon capture. The international dimension was also seen as important – with increasing regional autonomy it is as likely that energy partnerships will occur with other European countries as with other UK region – making the import of Hydrogen from Iceland described in this scenario highly feasible in her opinion.

There was a marked split in the scoring for renewable generation between the Geologists and the other stakeholders, with the academic somewhere in between. All respondents scored this scenario highest on the environmental performance, except the academic who scored it below the spreading the load scenarios for environmental impact. Although most acknowledged that there are visual impacts to the landscape to be considered with this scenario, these were widely dismissed as not being so important in the long term; one (the RDA rep) went so far as to say that the cultural values influencing reactions to such effects may alter drastically over the next century.

The NGOs gave this scenario the highest score for just about all the criteria – the only exception being NGO1, who scored it slightly lower than Fossilwise and Spreading the Load (low storage) on costs. For its impact on lifestyle, it was either considered to be the best of the scenarios (NGOs, RDA, Academic) or the worst (Geologists).

A similar picture appears for the credibility of this scenario – scored most credible (NGOs, Geologist C) or least credible (Geologists A and B, Academic). The RDA representative thought the scenario to be highly credible to those "versed in the issues" but gave it a slightly lower score to account for barriers created by the inertia of the current system – considering it to require a shift in attitudes amongst relevant institutions and industry to 'sign up' to environmental and social goals.

Spreading the Load

Having two spreading the load scenarios did force the participants to consider the scenario descriptions a little more. In order to make the distinction between the two, it was less easy to rely on a mental caricature view of these scenarios and participants had to refer to the supporting material more than for the other scenarios – making the scoring a little more challenging. These generally were awarded average scores for most criteria (with the low storage scenario generally scoring better than high storage), although this may reflect the participants' lack of a preconceived idea about these scenarios.

These were identified as being quite credible scenarios (particularly the low storage version):

> *Geologist B: most likely - a bit of everything – highest credibility*

> *RDA: good because it mixes its distribution network. I think it's entirely reasonable that energy policy will develop in this type of* ad hoc *way.*

There was some difference of opinion about the cost implications of these scenarios:

> *RDA: my perception is that one of the spreading the load is highest cost – mainly because doing something* ad hoc *always costs you twice as much as planning it in advance and given that there's locally generated hydrolysis - that's going to be expensive to get going, although hopefully it will be cheap once the technology is proven*

> *NGO2: Spreading the load (low storage) – that will be cheap as it's almost Business as Usual*

Weighting (scenario criteria)

The scenario weightings are illustrated in Figure 22.

The effect of adding further criteria is to reduce the range of weights applied by spreading the same 100 points across more criteria - so to display the weights these have been adjusted so that direct comparison can be made (effectively increasing the total number of points) – this enables the weight for each criterion to be compared across all the participants in the charts. In the actual spreadsheet calculations, this adjustment is not necessary since internal consistency is maintained within the evaluation for each participant.

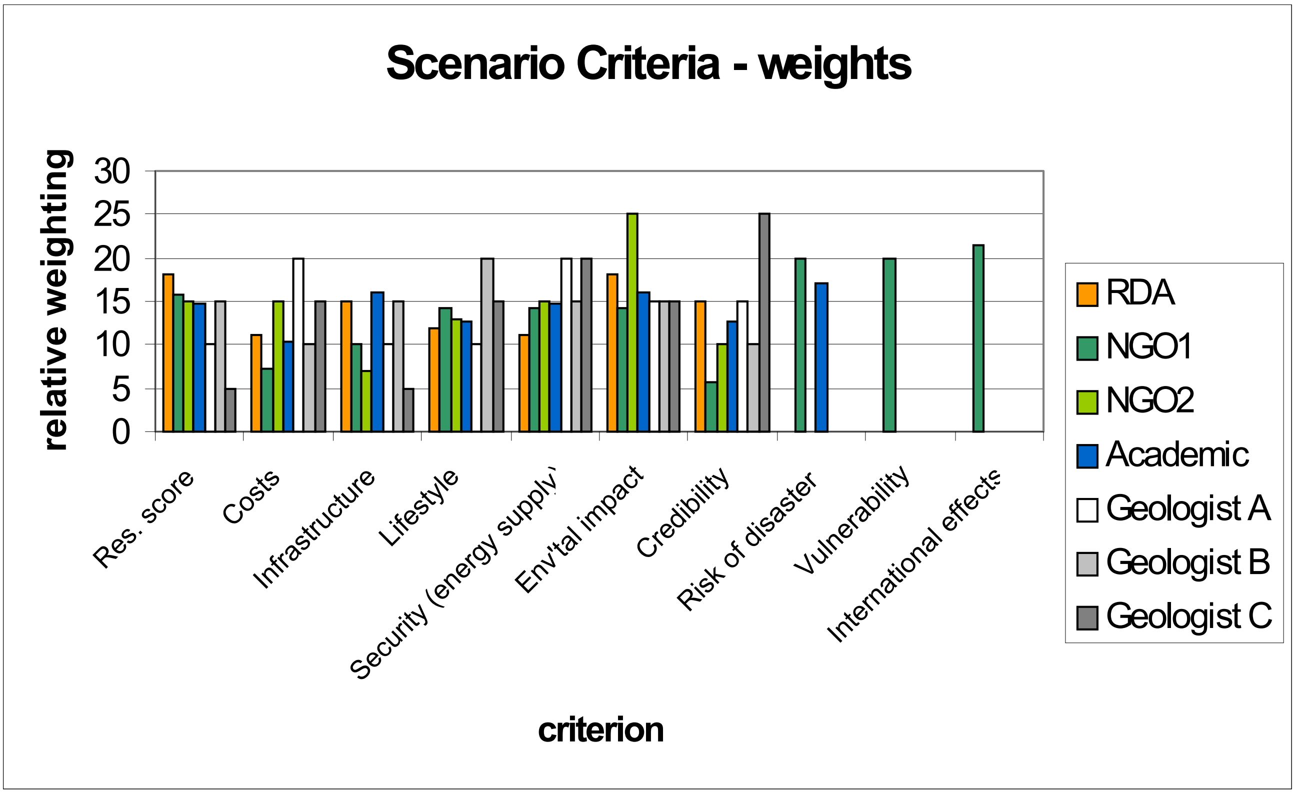


Figure 22. Weights applied to scenario criteria

The weighting revealed some problems of dependence between the criteria as discussed earlier and below.

Reservoir performance (within scenario): Geologists A and C gave this lowest weighting, unfortunately there was not time to discuss the weightings in details with the geologists. This possibly reflects their underlying confidence in the use of carbon storage?. The RDA representative considered this criterion to be linked to credibility - unless there is a convincing case for the performance of the reservoirs used, it is unlikely to be adopted.

Costs- energy supply and use: Cost was not considered to be the most important criterion by any of the respondents except Geologist A. This could reflect the narrow spectrum of interviewees as one would expect this to be seen as a key factor by some.

Infrastructure change: There is some problem of the independence of this from the costs as recognized by NGO1. This was given the lowest weighting by several of the participants.

Lifestyle changes: This was seen as moderately important by most – although the RDA representative thought it might be less significant as market mechanisms could be used to drive lifestyle changes.

Security of energy supply: This was identified as being reasonably important by most, although the RDA gave it a low weighting as resources would be considered from an international context.

Environmental impact: This criterion was given a high weight by all respondents.

Credibility: Credibility was often identified as being of low importance – since the credibility of a scenario will be governed by its performance against the other criteria.

Those that defined additional criteria all gave their own criteria the highest weights.

Final ranking

The final ranking of the scenarios is illustrated in Figure 23.

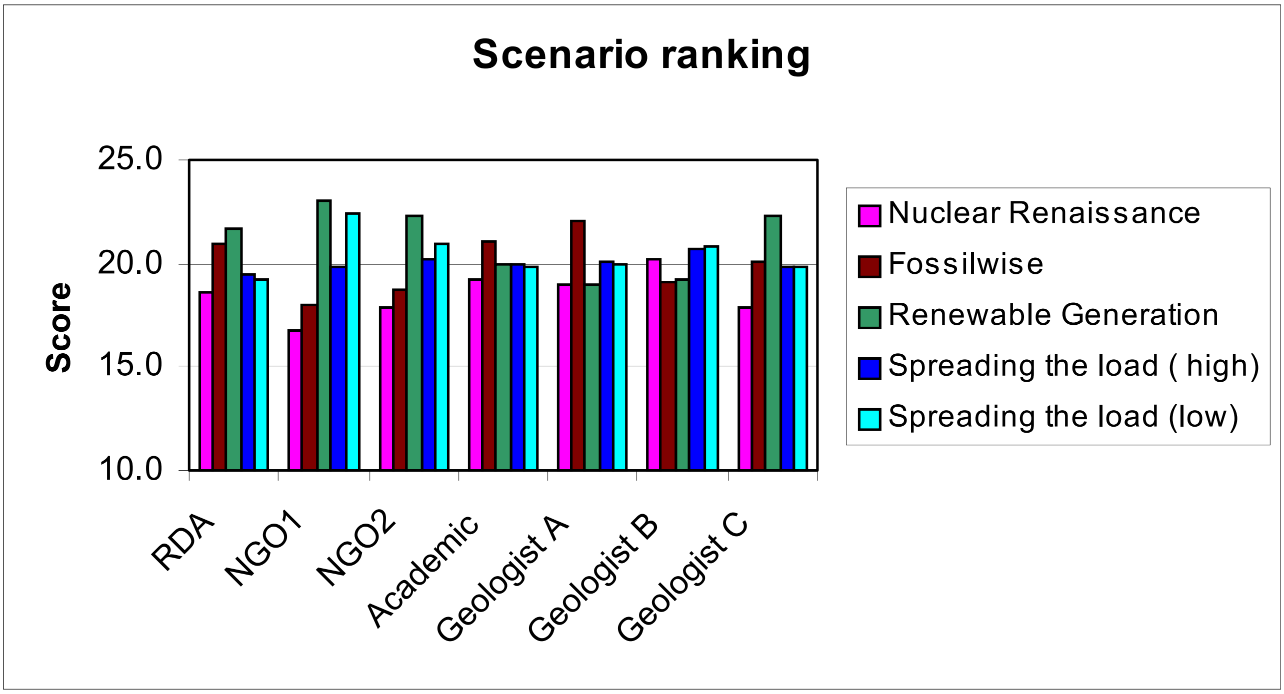


Figure 23. Final ranking: scenarios

Renewable Generation is ranked highest by four of the participants (NGO1, NGO2, RDA, Geologist C); Geologists A and B give this scenario a very low ranking.

Nuclear Renaissance is ranked lowest by all except Geologist B.

Fossilwise is ranked highest by the Academic and by Geologist A and lowest by Geologist B.

The Spreading the Load scenarios are preferred by Geologist B but otherwise both receive a mid-ranking by the other respondents.

The biggest range in the final scenario scores is seen in the scoring of both NGOs, indicating more polarised views of these respondents.

Most of the respondents considered the final rankings to match their prior expectations. Geologists A and C both felt renewable energy to be an impractical option and were opposed to proliferation of wind turbines and so Geologist C expressed surprise that renewables was ranked highest under his scoring and weighting, although he did feel that despite his objections it was a very likely scenario:

> *Geologist A: "I don't mind renewables I just don't think they're practical and I hate (...) windmills"*

> *Geologist C: "so do I which is why I'm surprised that it came out so high – I just think that's what's going to happen"*

It is perhaps surprising that Geologist B ranked the high storage scenarios lowest – referring to his original scores the Fossilwise scenario is given a low score for all of the criteria except costs, to which he gave a low weight. The two Spreading the Load scenarios are given similar scores for all criteria except lifestyles (a highly weighted criterion) – under which the low storage scenario is given a higher score. In the discussion of the results Geologist B, responding to surprise from the group was happy with pattern of the final ranking; although the geologists in particular felt that they had insufficient time to explore the scenario assessment stage – this was due to the focus in defining default values during that session.

Since these results represent the views of a very small sample of participants it is not appropriate to draw any general conclusions about the acceptability or popularity of these scenarios. The key value of these results is in testing the methodology - whether it is usable and delivers sensible results. The lessons learnt are documented in the subsequent section.

Summary

The MCA has proved to be a useful format for the exploration of stakeholder perceptions, with the capacity to include a number of perspectives and the divergent values and assumptions inspired by the technologies. Since information can be included in the various qualitative or quantitative formats in which it occurs, non commensurable factors are not forced into a single format; this allows the representation of the multi dimensional aspect of the problem in a flexible manner. The scoring of each option under each criterion is a simple and easily understood methodology, in particular the inclusion of a wide variety of information allows the involvement of both experts and non experts. The involvement of a variety of stakeholders ensures analytical breadth. The weighting of criteria enables the participants' perceptions and values to be incorporated into the decision making process in a systematic way. Manipulation of weightings allows the exploration of how different perspectives affect the performance of options under different criteria and serves to enhance the understanding of the problem rather than come up with a single 'best' option. The method is simple, transparent and easy to apply.

The scoring of criteria provides a framework within which we can explore the uncertainties associated with the technology – participants can see the effects of cautious or confident estimates, for example. MCA also serves to identify key factors, and through the weighting procedure, their perceived relative importance in the debate and the manner in which they relate to the viability, effectiveness and acceptability of the technology. This helps point to areas in which future research should be focused. The approach of allocating 100 points across the criteria was found to be difficult by all except the academic, who was experienced in various MCA approaches. The difficulty lay mainly in ensuring the totals always add up to 100 – even thought this was automated on the spreadsheet - this did not prove to be an intuitive task. A better approach would be to ask participants to score each criterion out of 100 and then to normalise these scores so each adds up to 100 – this would enable relative scoring to be compared between the participants but using a more intuitive approach.

The process of defining default scores for the reservoir assessment has been particularly useful for identifying areas of technical disagreement (Stirling and Mayer, 2001). This is illustrated by the lively discussion prompted by this process and the differences between the initial scores given by the geologists individually; this process appears to have exposed uncertainties that may not have been explicitly considered otherwise. However, during the discussion the group did not find difficulty in arriving at an agreed consensus. The application of a formal methodology such as the MCA process raised awareness of the uncertainties that may not have been addressed – each assuming the others shared the same opinion – and allowed those issues to be confronted explicitly.

Although the additional scenario was requested by one of the interviewees, it was generally found to be quite confusing two have two similar scenarios – Spreading the Load high and low storage – making it harder to remember the differences. Having clearly named and distinguishable scenarios made it much easier for respondents to hold a clear idea of the different scenarios as they are doing the scoring without continual need to refer to the support notes. However, a scenario characterisation that invokes an immediate mental picture of the scenario may cause a more serious problem – that the assessment is driven by the mental image rather than the scenario text provided. For example, it is not clear that the scoring of "Renewable Generation" reflects the relatively high levels of carbon storage adopted in the earlier phase of this scenario. In this way the scenarios were less effective in exposing tradeoffs than it had been hoped. This problem is confounded when participants have not read the material prior to the interview session, there is little that can be done to avoid this beyond ensuring that the amount of text circulated is kept to a minimum.

4. Conclusions

This study has treated separately the analysis of the potential for biological and geological carbon sequestration to contribute to climate change mitigation in the UK. This is necessary as they are fundamentally different approaches and occupy different positions on the political agenda. Biological sequestration is a well-developed concept and afforded formal political acceptance through its inclusion in the Kyoto Protocol. In contrast, the potential for geological sequestration is only just beginning to be recognised within political debate; there remain many technical, social and political challenges before it becomes a "mainstream" mitigation option.

This study has begun to map out some of the key issues to be addressed in relation to geological carbon storage and to test a methodology for assessing those issues. As a result we can summarise the following points that this study has revealed in relation to the methodology:

a) Different participants will interpret the scoring and weighting process differently because of different reasoning processes. This underlines just how important it is that these reasoning processes, or 'cognitive maps' are clearly understood during the qualitative interview stage. We find out more from the explanation of the scoring and weighting process than we do from the actual scores and weights provided. This is to be expected since the MCA method is being used in heuristic mode, not in providing decision-makers with the 'best' answer.

b) The MCA approach has allowed us to identify subtle differences in expert opinion, that may not otherwise have been discussed. A good example is the debate over the meaning of 'confined' and 'unconfined' aquifers, which seemed straightforward initially, but was deconstructed during expert discussions. Classifications that were helpful at the time of the JOULE II study are less useful when attempting to compare different reservoir options against the criteria.

c) A question arose over who *are* the experts and to what extent we should use expert assessments in providing default values. For instance, we relied heavily upon BGS geologists, but are they necessary representative of the wider geological science community? Are they the appropriate experts on health or ecosystem or cost issues? In the sense that they have been analysing carbon storage for a number of years and have worked closely with a number of other experts, they are well placed to hold informed opinions on these issues. But often this may be based on 'second hand' expertise. Does this matter in providing our default scores? We intend to make the process more robust in the forthcoming Round 2 Tyndall project by involving a wider range of experts across the assessment and identifying more specific experts in each area.

d) Dependency between variables emerged as an on-going challenge. Some respondents' interpretations implied a dependency between the variables, whilst others interpreted them in the same way as the research team intended. There is no definitive answer to this, as the aim of the exercise is to allow genuine stakeholder input, we cannot 'straightjacket' the respondents too much.

e) Presentation of sequestration options – although both biological and geological carbon sequestration imply locking up CO_2 in order to avoid it building up in the atmosphere, and may both be seen as 'geoengineering' approaches (Keith, 2001), they are fundamentally different. We have demonstrated also that the magnitude of CO_2 that can be sequestered through the different approaches is of a different order. For these reasons we recommend that the two approaches are not routinely grouped together, as this can be a source of confusion. Similarly ocean sequestration approaches should be clearly distinguished – not least because these are viewed very differently by many stakeholders (and also the lay public), invoking very different responses.

Next steps…

We conclude this report by considering particular areas, identified in this study, requiring further attention. The forthcoming integrated study to be conducted for the Tyndall Centre will carry out a more comprehensive, multi-disciplinary assessment of geological carbon sequestration. The following points relate specifically to the multi criteria assessment process developed here, what we've learnt during the process and associated areas which we would hope to develop further:

1. Participation of industry representatives – although we have spoken informally with industrial stakeholders it was not felt to be appropriate to trial the MCA process with them at this stage. Since a significant proportion of information and debate relating to carbon capture and storage currently comes from the industry this is not felt to be a major shortcoming of the pilot study. It was felt to be a greater priority to access the perspectives of those stakeholders that have not played such a central role in the debate so far. However, as the forthcoming study will go into the issues in much greater depth it will be essential that industrial stakeholders participate in the study. Conducting the interviews and analysing the results is a time consuming process – although the sample was not nearly broad enough to draw strong conclusions about the performance of reservoirs and scenarios, it was nevertheless highly informative in relation to both the methodology and its implementation but also to how the scenarios should be developed and presented. This will enable us to develop our future analyses more effectively.

2. NGO engagement - although there have been some efforts to engage environmental NGOs in the geological sequestration debate, there has been some reluctance on the part of the NGOs. To some extent this is due to a deep scepticism towards the technology, stemming in part from a distrust of the large energy companies promoting the technology and concern that an emphasis on carbon storage will divert resources away from developing alternative solutions. However, lack of resources within the environmental organisations themselves is also a factor – developing their understanding and knowledge of carbon sequestration takes a low priority, compared to other more high profile issues; many of the 'stakeholder' events to which NGOs are invited are not located within easy access and require considerable investment of time. As levels of interest in carbon storage are growing – within the media, academic and policy spheres – it is important that the NGOs are also involved at an early stage. Their involvement before significant political and economic efforts have been invested in the process could help to avoid a situation of high conflict in the future. One approach might be for the Tyndall Centre, as an independent organisation, to organise a half day seminar that is easy for NGOs to attend, along the lines of a kind of 'citizen panel' to which a panel of experts is available to answer questions. The purpose of this seminar would be to foster an awareness building process – to enable information exchange about the technology and to inform the sequestration community of the concerns of the NGO community. If such a process could be organised in the spirit of transparency and cooperation it may encourage a broader participation in future and identify mutually acceptable areas of opportunity for sequestration options.

3. Quantification of energy balances - basic quantification of the energy balances implied by the scenarios is required in order to demonstrate energy supply implications of the different scenarios more credibly. This should at least identify the relative capacity of types of power generation and end uses in order that the assumptions concerning energy demand and CO_2 emissions are interpreted more accurately.

4. Carbon storage vs. nuclear power – some interesting insights have been made through the study about carbon storage in relation to nuclear power. On the one hand, both can be considered to leave a legacy from today's activities onto future generations – parallels between nuclear waste disposal and carbon storage are likely to provoke strong negative reactions to carbon storage within the broader community. On the other hand, both present the possibility of achieving very large reductions in CO_2 in the near term whilst maintaining current energy demand. This pilot has demonstrated that, if it were to come to choice between nuclear power and carbon sequestration to

reach more ambitious emission targets, carbon sequestration may be seen as a popular alternative. This paradox demonstrates that the way a technology is presented can have a strong effect on the way it is perceived.

It is clear that geological carbon sequestration has the potential to make a huge contribution to the UK's climate change policy. It is also clear that there remain huge uncertainties at many levels that must be faced. Carbon storage is not a panacea that can enable us to pursue a CO_2-free fossil fuel energy economy indefinitely; inevitably, it does not prevent the production of CO_2 from energy use (neither does biological sequestration). Aside from concerns about fossil fuel resource depletion, although very large, the geological reservoirs are nevertheless of finite capacity. What it can offer, however, is the potential to minimise the interim CO_2 emissions to the atmosphere as we proceed towards a long term sustainable solution – whether that be one based on renewable energy and / or hydrogen or whatever. This study has begun to explore some of the conditions necessary to exploit that potential and some of the implications of doing so. In particular it is crucial that we engage a variety of stakeholders and the lay public as we continue to explore these options.

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Appendix A. Glossary of terms and units

Glossary of terms

Absorption of gases is the solution of gases in liquids or solids - the gas permeates the whole body of the solid or liquid (rather than just its surface)

Adsorption - is where a substance is concentrated on the surface of something - e.g. gas molecules on the surface of a solid (it also possible to distinguish between physical and chemical adsorption depending on what forces are holding them in place)

Amine scrubber - chemical solvents used in *carbon capture* such as amines (Monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA)); ammonia; hot potassium carbonate are used to neutralise the CO_2 in flue gases

Biofuels - landfill gas, energy from waste, biomass energy

Biomass energy - energy crops , forest and agricultural residues

Cap rock - the rock between the seabed and a *saline aquifer* is not porous and hence is impermeable to the water contained in the aquifer – creating a seal preventing movement of fluids out of the reservoir; this layer can extend over very large areas.

Carbon Capture – the recovery of carbon dioxide from fuel combustion processes such that it may be transported and stored or used, thus avoiding emissions to the atmosphere. Carbon capture processes may be implemented *pre- or post combustion* or may involve a modification to the combustion process.

Carbon sequestration this term refers to any means of locking up CO_2 over very long periods in order to mitigate against the effects of anthropogenic climate change

Confined *aquifers* – in these cases the entire aquifer formation is sealed by impervious layers of cap rock – and is unlinked to either other reservoir formations or to the surface, these are also sometimes referred to as 'closed' aquifers

Critical point – conditions of temperature or pressure at which the liquid and gaseous phases of a substance have the same density

EGR – Enhanced Gas recovery – in principle, CO_2 could be used to in gas extraction processes but this has not been tested.

ECBM – **Enhanced Coal Bed Methane** involves the injection of CO_2 (optionally with an inert the gas such as N_2, to push it through the system) into the coal bed, this replaces *methane* (CH_4) which is *adsorbed* onto the coal and is subsequently released. Subsequent mining of the coal would imply release of the stored CO_2

EOR - Enhanced Oil Recovery - CO_2 can be used to increase oil production and maximise the extraction of the oil that remains in a field; widely practised at on-shore oil fields in the US, commercial scale EOR at off-shore sites is currently under consideration

Final energy consumption - the energy actually consumed, taking into account the losses on conversion to electricity etc and distribution.

Geological / physical *carbon sequestration* involves injecting CO_2 gas into large physical structures (such as disused oil fields or other geological formations) where it should be secure over the long term

Gravity method - gravity data can be used to indicate density and porosity of rock formations and used as monitoring method by comparing gravity data before and after storage

Methane (CH_4) – natural gas, as used in domestic gas fuel supply

Oxyfuel Boiler - combustion occurs in pure / highly enriched oxygen rather than air, producing flue gas containing only water and CO_2

Post-combustion capture – refers to any CO_2 capture process which removes CO_2 from the flue gases after normal combustion of the fuel

Precombustion capture - the fuel is treated before combustion, generally to deliver carbon monoxide (CO) or CO_2 and Hydrogen which is then used as the power generating fuel, either in an existing gas turbine or in a fuel cell

Pressure Swing Adsorption (PSA) - a *post combustion* capture technology, the PSA process is based on the selective adsorption of gaseous compounds on a fixed bed of solid adsorbent which undergoes a repetitive cycle of adsorption and regeneration steps; gases are adsorbed at high pressures, then 'desorbed' by lowering the pressure

Primary energy production - the energy contained in fuels at the point at which they are produced (coal, oil, gas, biomass etc).

Primary energy consumption - the energy contained in fuels at the point at which they are consumed, in power stations etc.

Saline aquifer a geological formation in the rock below the seabed or below ground; in general we refer to offshore saline aquifers in the context of carbon sequestration but there are similar formations at onshore locations which could be used. A saline aquifer consists of a layer of porous rock; the pores are filled by salt water and hence it is sometimes referred to as reservoir. This water is held in the pores between grains in the rock.

Seismic survey – this is a geological method which projects sound waves from the surface and records echo responses to build up a geological picture of the sub surface – the sound waves reflect differently depending on the medium (for example salt water vs. carbon dioxide). This type of survey can be used in exploration to locate hydrocarbon deposits but has also been used successfully at Sleipner to monitor the movement of stored CO_2 within the aquifer

Sleipner – this is a gas field in the North Sea operated by the Norwegian company Statoil. CO_2 captured from the gas at Sleipner is stored in the *Utsira* formation (a *saline aquifer*). This is the first example of environmentally driven geological CO_2 storage in the world

Supercritical – describes conditions of temperature and pressure beyond the *critical point* at which the liquid and gaseous phases of a substance have the same density. CO_2 becomes a supercritical fluid at 500 – 1000m depth and occupies a greatly reduced volume (i.e. has a higher density) than as a gas at the surface

Syngas / synthesis gas is a mix of mostly carbon monoxide (CO) and Hydrogen (H_2), it is formed by steam reformation or partial combustion of coal or natural gas

Traps in *aquifers* –refers to a domed space within an aquifer, within which the CO_2 is sealed as if within an upturned cup. A high volume of the pore space within a trap can be used for CO_2 storage and they are easy to monitor

Utsira – this is the *saline aquifer* used by the operations at the *Sleipner* field. It is a layer of sandstone filled with saltwater located almost 1km below the sea bed. CO_2 has been stored within the Utsira formation at a rate of about 1 M Tonnes of CO_2 per year since 1996.

Volumetric sweep efficiency – corresponds to the fraction of the pore volume that can be filled with CO_2 before it reaches the boundaries of the reservoir – depends on injection rate, relative permeabilities densities and mobilities of the fluids, rock heterogeniety etc.

Units

Mega (M) = 10^6, giga (G) = 10^9, tera (T) = 10^{12}, peta (P) = 10^{15}, exa (E) = 10^{18}.

1Tg = 1 Mt; 1 Pg = 1 Gt; 1 Gt = 1000 Mt

To convert TJ to Mtoe or GWh multiply by 2.388×10^{-5} or 0.2778, respectively.

To convert Mtoe to TJ or GWh multiply by 4.1868×10^4 or 11630, respectively.

To convert GWh to TJ or Mtoe, multiply by 3.6 or 8.6×10^{-5}, respectively.

Appendix B. Carbon storage scenarios

"Nuclear Renaissance"

Carbon storage is adopted as an interim measure to enable emission reduction targets to be met during a gradual transition to a nuclear electricity and hydrogen future, satisfying a growth in energy consumption.

Storage

- This scenario allows the lowest dependence on carbon storage which is seen as an intermediate technology as new nuclear generation comes on line
- Storage begins around 2010 with a pipeline to the Forties field, exploiting the economic benefits of Enhanced Oil Recovery (EOR); eventually a storage hub develops around this area as storage continues once oil fields are depleted
- The sites with the maximum economic benefit are exploited – assumed to be storage in offshore hydrocarbon fields using enhanced oil and gas recovery techniques – where there is existing infrastructure and large new capital investments can be avoided
- As storage is seen as an intermediate strategy, no effort is made to exploit other potential storage sites such as saline aquifers
- Carbon storage peaks at 20MTC/yr during the 2050s and subsequently undergoes a steady decline until it is phased out around the turn of the century

Energy system

- Initially, energy policy is to 'replace nuclear with nuclear' - as old nuclear plants are retired equivalent capacity new plants are built at the same locations
- As the nuclear capacity is built up, post-combustion CO_2 capture technology (amine scrubbers) is adopted at plant in the North East – the CO_2 destined for the Forties storage hub, driven by the economic benefits of Enhanced Oil Recovery
- Capture technology develops at a fairly slow pace as R&D investment focuses on nuclear – by the 2020s Pressure Swing Adsorption is the dominant design for post-combustion capture
- Proponents of nuclear energy are effective in promoting convincing arguments toward their solution to CO_2 reduction, leading to major investment into nuclear energy technology
- Mitigation measures in other sectors, such as voluntary agreements and fiscal measures to reduce transport emissions deliver poor CO_2 reductions
- As regulatory measures are tightened fuel cells become more competitive, hydrogen is initially generated through forecourt reformation of methane at service stations
- New nuclear capacity is established as rapid improvements in the technology make nuclear power more acceptable amid fierce resistance to mitigation policies that threaten current lifestyles
- New underground nuclear waste storage facilities are developed, with access to allow future reprocessing
- Hydrogen fuel cell technology is exploited for mobile uses only – eventually based on pure H_2 generated from water electrolysis as carbon-free electricity is available from nuclear power
- Eventually, electricity becomes the main energy carrier for stationary applications, combined with NG powered microCHP installations in households
- Some fossil fuel plant remains to satisfy peak load demand – but these are highly efficient new NGCC turbines operating at least 70% efficiency by 2100 (without carbon capture)
- A small component of economically competitive renewables remain (e.g. mostly off shore some on-shore wind power, Municipal Solid Waste)
- By 2100, the majority of energy supply is from nuclear electricity in a highly centralised system, additional power generation assumed to be from highly efficient gas technology. Transport is based on fuel cells and electricity represents the dominant energy carrier for other sectors.

“Renewable Generation”

Carbon storage is seen as necessary to maintain emission reductions as the country moves towards a renewables based hydrogen economy, enabling nuclear power to be abandoned in this scenario. With an increased awareness of climate change issues, a more long term world view dominates - the emphasis is on sustainable technologies to deliver emission reductions.

Storage

- This scenario sees a cautious approach to carbon storage and so concentrates on the least controversial sites in order to meet emission reduction targets
- Carbon storage is concentrated in hydrocarbon fields – where there is existing infrastructure and potentially the least legal / political barriers to overcome
- As storage is seen as an intermediate strategy, no effort is made to establish a strategy that exploits other potential storage sites such as deep saline aquifers
- Despite energy use remaining constant at 1998 levels, this scenario requires a moderate level of storage, until a greater proportion of energy demand is met by renewable, low carbon technologies

Energy system

- This scenario is driven by the search for carbon-free energy alternatives to nuclear power, which is viewed as being unacceptable
- At the start of the century, energy efficiency measures, renewable energy and carbon sequestration are promoted as a three pillar approach to CO_2 emission reductions
- Energy efficiency measures prove effective at stabilising energy consumption but do not deliver reductions below 1998 levels – a strategy of a renewable energy driven Hydrogen economy is vigorously pursued
- Carbon storage receives a lukewarm response – given the strong negative associations with nuclear power, another technology that potentially transfers the problem to future generations is not received enthusiastically. Carbon storage is thus viewed as a ‘lesser of evils’, necessary to achieve significant reductions in CO_2 emissions within a long term strategy for renewable energy
- Major expansion is seen in wind power from the outset and marine technologies (wave and tidal) from around 2015, later followed by increased use of solar power
- Fuel cells (on board reformation of natural gas) in the transport sector are initially exploited for efficiency, gaining in market share early on in this scenario (mass production by 2008)
- Precombustion carbon capture (e.g. natural gas partial oxidation) is applied to new Natural Gas Combined Cycle turbines (NGCC) which are adapted to run on Hydrogen
- Nuclear phase out: all existing nuclear plant is closed by the 2030s
- By the 2020s, Hydrogen represents viable means of energy storage in the context of intermittent supply from renewables, the transition enabled by radical new hydrogen storage technology
- Municipal solid waste and biomass are also exploited for energy use
- CHP is aggressively exploited in the domestic sector and, during the 2030s, direct Hydrogen fuel cell CHP is becoming commonplace
- As Hydrogen replaces Natural Gas in the domestic sector, the existing NG pipeline structure can be exploited for transporting Hydrogen
- A proportion of UK’s Hydrogen demand is supplied from Iceland
- Some use of fossil fuels remains through large gas fired plant operating as baseload at existing sites (without carbon capture)
- By 2100, emission reduction targets are reached, without carbon storage, with improved renewable energy technologies and energy storage

"Spreading the load" (low storage)

As energy technology and climate policy develops in a rather *ad hoc* fashion, this scenario adopts only moderate levels of carbon storage within a diverse energy regime, large centralised power stations (which are mostly nuclear and some fossil fuel with CO_2 capture) coexist with more decentralised networks of new and renewable energy technologies.

The scenario differs from "spreading the load – high storage" through a greater dependence on nuclear power in preference to high levels of carbon storage. Hydrogen does not feature as a key energy carrier in this scenario.

Storage

- Energy use is contained at 1998 levels and a broad mix of energy technologies is employed – leading to significant storage requirements
- Traps in aquifers are viewed as the best option for storage and are exploited in favour of other reservoirs

Energy System

- A totally mixed energy system evolves - in terms of the diverse range of energy sources and types of supply networks coexisting but the Hydrogen economy fails to materialise in this scenario
- Fossil fuels remain in significant use – with a range of associated carbon capture techniques deployed; post-combustion technologies dominate (chemical scrubbers and gas separation membranes) eventually being replaced by pre-combustion technology by 2050
- Hybrid vehicles are vigorously promoted as the way to achieve maximum efficiency and performance
- This delivers moderate emission reductions in the transport sector but the challenge of achieving more significant reductions proves intractable – greater compensation in other sectors is required
- The existing model of electricity and natural gas grid networks continues
- Micro scale Combined Heat and Power (CHP) installations become widespread in the domestic sector
- Natural gas enriched with Hydrogen from CO_2 capture enables further reductions without radical changes to the supply networks
- The contribution of renewable energy is significant but only the least controversial and cost-effective options are exploited
- Significant exploitation of Nuclear power is needed, requiring new nuclear plant to meet emission targets, in conjunction with efficient natural gas plant
- As no single technology dominates, so the R&D effort is dispersed leading to only incremental improvements in the costs and range of energy technologies

"Spreading the load" (high storage)

As energy technology and climate policy develops in a rather *ad hoc* fashion, this scenario adopts high levels of carbon storage within a diverse energy regime, large centralised power stations (with CO_2 capture if fossil fuel fired) coexist with more decentralised networks of new and renewable energy technologies.

Storage

- As in the "Fossilwise" scenario, this scenario assumes an enthusiastic approach to carbon storage
- Energy use is contained at 1998 levels and a broad mix of energy technologies is employed – leading to significant storage requirements
- Traps in aquifers are viewed as the best option for storage and are exploited in favour of other storage reservoirs
- It is assumed that storage in outside traps in saline aquifers is exploited only very late on in this scenario
- Also on-shore sites are exploited - the cost advantage of shorter distances for CO_2 transport makes these sufficiently attractive in this scenario

Energy System

- A totally mixed energy system evolves - in terms of the diverse range of energy sources and types of supply networks coexisting
- Fossil fuels remain in significant use – post combustion carbon capture techniques are deployed initially and see gradual improvements in development - technologies such as Pressure Swing Adsorption (PSA) reach the commercial market by 2012
- Fuel cells are adopted in buildings first – using Hydrogen produced locally by small scale electrolysers using off-peak electricity
- Major energy efficiency drives to curb end use are linked to the use of fuel cells in both vehicles and in Combined Heat and Power (CHP) installations (Lovins' strategy)
- The contribution of renewable energy is significant but only the least controversial and most cost-effective options are exploited
- Nuclear power remains for baseload power generation (25-30% of electricity demand), requiring new plant to be built as existing plant is decommissioned
- Large centralised power stations (with CO_2 capture if fossil fuel fired) coexist with more decentralised networks of new and renewable energy technologies
- As no single technology dominates, so the R&D effort is dispersed leading to only incremental improvements in the costs and range of energy technologies
- Precombustion decarbonisation plants diffuse more slowly than in "renewable generation", becoming dominant by 2030

Appendix C. Assessment criteria – instructions for scoring

Descriptions of Assessment Criteria

The multi criteria assessment process consists of scoring options against a set of pre-defined assessment criteria and weighting these criteria according to how important *you* think that each criterion is in evaluating the various options. The process is implemented in four steps:

1. scoring reservoir criteria
2. weighting reservoir criteria
3. scoring scenario criteria
4. weighting scenario criteria.

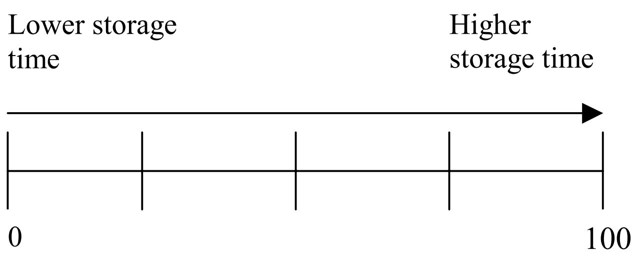
These steps and the assessment criteria are described in detail below. The purpose of the exercise is as much to gain an understanding of the reasons why different options are preferred (or not) as it is to deliver a ranking of the overall performance of the different options. You will therefore have the opportunity to explain the reasons behind the scores and weights that you assign and to revise them as the exercise progresses. We have identified a set of criteria which we feel cover the main issues associated with carbon capture and storage; however, additional criteria may be defined, scored and weighted should you feel that something is missing.

Step One: Reservoir Specific Criteria - scoring

Before considering the long term scenarios, we will assess various storage reservoirs to compare the relative performance of the reservoir types under a range of criteria. We will then use the results of this assessment, adjusted according to the relative deployment of each reservoir type within the scenarios to deliver an overall reservoir score to be used in the scenario assessment process.

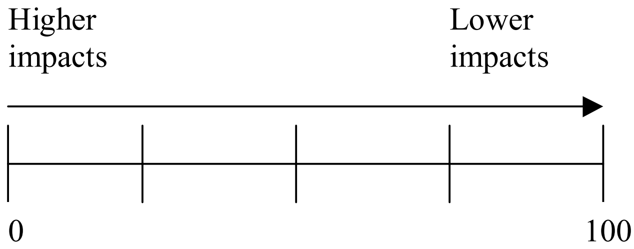
For each reservoir type, please assign a score for the following criteria by allocating 100 points across the reservoir types for each criterion as indicated. If you feel that you are unable to offer a judgement on any of the criteria a set of default values are supplied. If you feel that there is no difference between the reservoirs for a particular criterion each should be given an equal mark. Please indicate an assessment, on a scale of 1-5, your level of expertise for each criterion.

Assessment of the relative CO_2 storage time in reservoirs
This criterion provides an indication of the timescale over which large quantities of CO_2 can be stored in a reservoir; for example, this could be interpreted as the relative timescale over which 95% of the CO_2 will remain in storage. Reservoirs should be scored on a relative scale by allocating 100 points across the storage options – the most points should be allocated to the reservoir considered to provide storage over the longest period. If you wish to suggest estimates of possible storage times in years please do so.



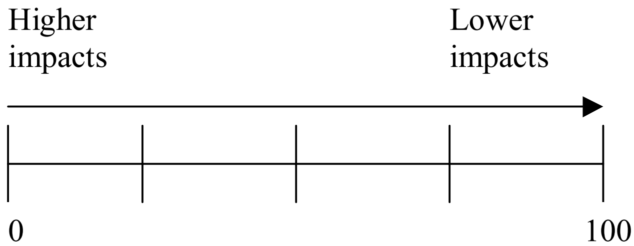
Potential adverse impacts to marine / natural ecosystems

Include any impacts such as effects of steady or sudden leaks, physical disturbance at injection site, accidents etc. and includes an indication the likelihood of such a leak occurring. A high score implies minimal impacts, a low score implies high impacts.



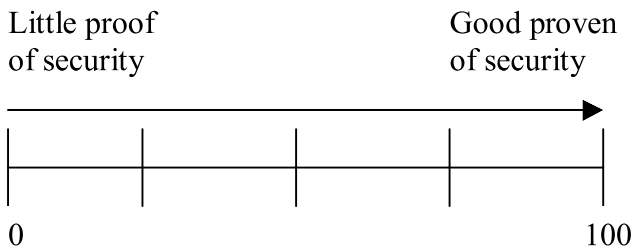
Potential adverse impacts to human health

Include any impacts such as effects of steady or sudden leaks, physical disturbance at injection site etc. A high score implies minimal impacts, a low score implies high impacts.



Proven storage security

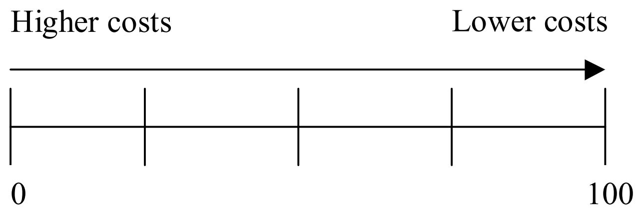
This should be given a high score if either equivalent or analogous formations have been observed to provide a secure gaseous seal; for example, storage may be in a structure that has previously contained gaseous or liquid compounds over long periods or there may be evidence of secure storage at analogous formations considered to be structurally similar. For example, a high score should indicate substantial evidence is available from the reservoir, a low score that the use of this type of reservoir is based only on theoretical evidence.



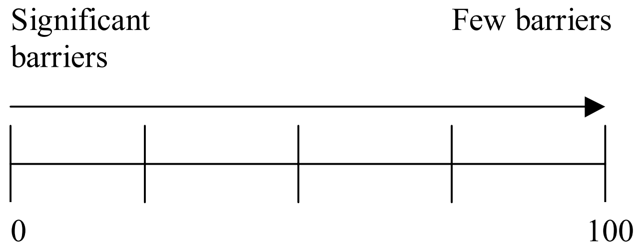
Relative Costs

Not including cost of capturing and transporting CO_2 to the reservoir, this should be used to provide a approximate indication of the *relative* costs of the different storage media; factors such as capital investment, EOR offset and operating costs should be borne in mind. This criterion reflects the cost of different storage types relative to each other and does not reflect the cost of carbon sequestration compared to other approaches to carbon reduction. At this stage this is only a crude indicator – a more realistic assessment would have to be based on an economic assessment of individual sites based on the quantity of CO_2 stored, timescale of operation, source of CO_2 etc.

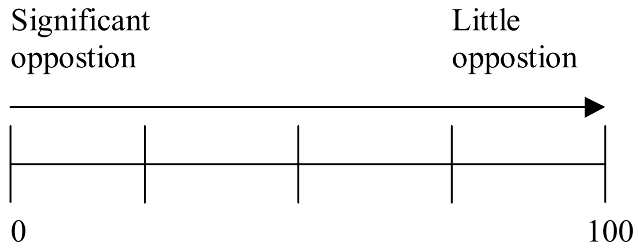
Options considered to be most expensive should be allocated lowest scores - i.e. a low cost is scored high.



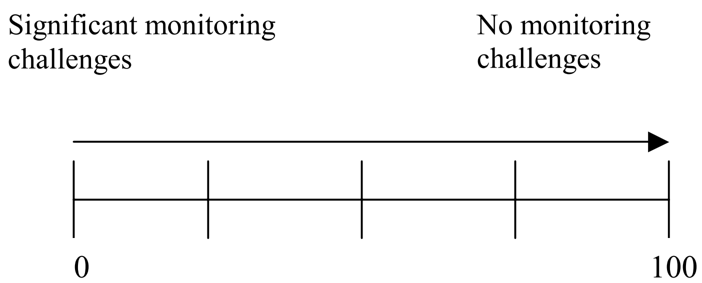
Planning or legal barriers to using reservoir for CO_2 storage
A *high* score would indicate that use of the reservoir is *not* likely to be associated with any significant legal or planning barriers to be overcome (such as the London Convention); a low score indicates that there are likely to be significant barriers of this nature.



Public opposition to using reservoir for CO_2 storage
A *high* score would indicate that use of the reservoir is *not* likely to be associated with public opposition, a *low* score indicates that there is likely to be strong public opposition.

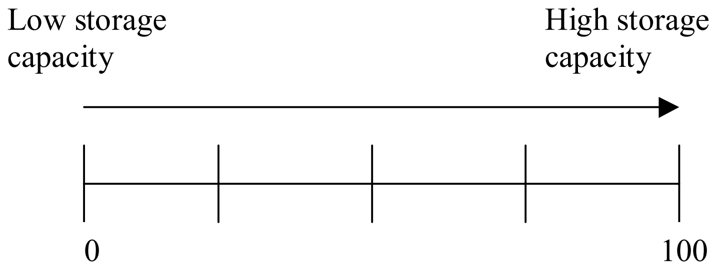


Feasibility of monitoring / verification
Do appropriate technologies exist, at reasonable cost, to monitor CO_2 levels at the reservoir for verification (compliance) purposes? A high score indicates that monitoring should not present any technical or economic problem - a low score indicates that either it would be technically difficult or prohibitively expensive to monitor the reservoir.



Storage Capacity

This criterion indicates the potential for each reservoir to store large quantities of CO_2. It should provide an indication of the relative volume of secure storage thought to exist for each reservoir type in the UK. A set of default values is available based on the estimates made in the JOULE II study.



Additional Criteria

If you wish to add any additional criteria this may be done at this stage – the new criteria should be accompanied by a brief explanation and should be scored in the same way as the previous criteria. A maximum of 3 criteria may be added. If you are satisfied with the criteria provided it is not necessary to specify further criteria.

Step Two: Weighting Of Reservoir Criteria

Once each criterion has been scored, they should be weighted according to how important they are in your overall assessment of the options. If you think that a criterion is not particularly relevant you can assign a low weight; similarly if consider a criterion to represent a crucial factor in the decision making process it should be awarded a high weight. This can be done by ranking the criteria in order of importance and allocating 100 points across all criteria (in the same way as scores were awarded). A preference ranking of the reservoir types can then be made based on your scores and the weighting that you assign to each criterion.

Aggregate Reservoir Criterion

An aggregate value for each of the reservoir-specific criteria will be calculated automatically, according to the scores and weights assigned to the reservoir criteria in Steps One and Two. The resulting values for this criterion constitute the overall ranking that you have assigned to the relative combinations of reservoirs used in the scenarios .

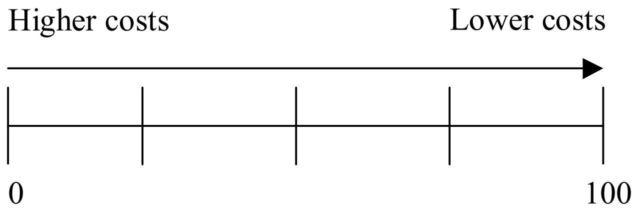
The resulting values for this aggregate criterion will be used in the next stage. A single score representing the combined performance of all of the carbon storage options described in the scenario will be calculated automatically according to the proportional use of each type assumed within each scenario.

Step Three: Assign Values To Scenario Specific Criteria

For each scenario, assign a score for the following criteria by allocating 100 points across the scenarios for each criterion as indicated.

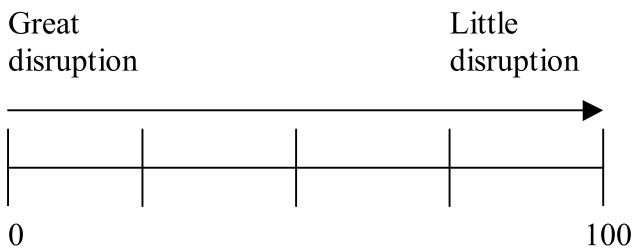
Costs of energy supply and use in the scenario

This criterion should capture the relative overall costs of energy production and transmission between the different scenarios and should reflect investment costs as well operating costs and costs to end users; it should be used to weigh up the costs of energy supply from all sources, including capture, recovery and transport of CO_2 to provide an indication of the relative energy economics of the different scenarios.



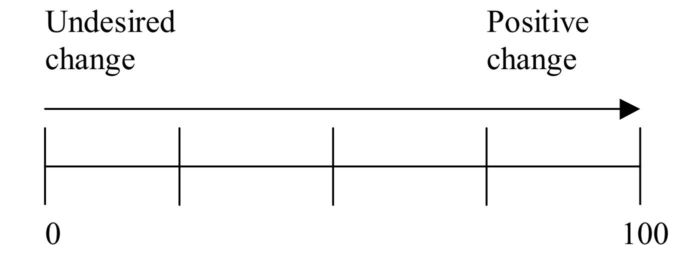
Infrastructure change

This criterion reflects the overall level of disruption to current infrastructure, reflecting perhaps large scale replacement of distribution network or other physical installations. A high score should indicate little or only gradual changes, a low score implies major disruption caused by infrastructural change.

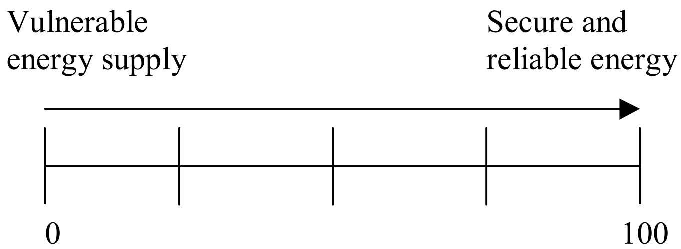


Lifestyle changes

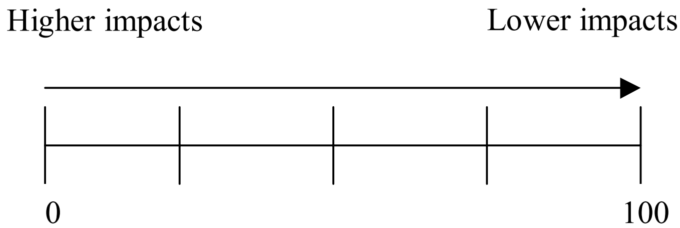
This criterion reflects how the scenario impacts on current lifestyles. A high score should indicate overall positive impacts on lifestyle, a low score implying undesirable lifestyle changes.



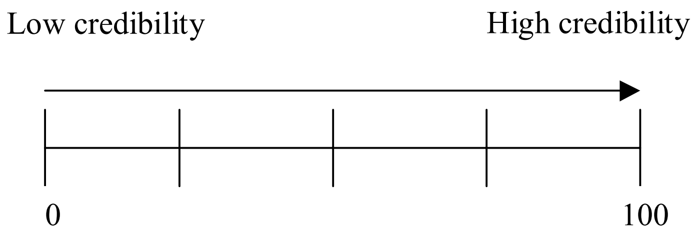
Security of energy supply
How self-sufficient is UK for its energy / how reliable will energy supply be?



Environmental impact
This criterion indicates the overall environmental performance of the scenarios, referring to all aspects of environmental quality (including air and water quality, transboundary pollution, landscape etc.).



Credibility
Do you believe that the scenario describes a credible view of a possible future to *you*? High score indicates highly credible scenario that you can imagine being realised, low score implies that you view the scenario as highly unrealistic.



Additional Criteria
If you wish to add any additional criteria this may be done at this stage – the new criteria should be accompanied by a brief explanation and should be scored in the same way as the previous criteria. A

maximum of 3 criteria may be added. If you are satisfied with the criteria provided it is not necessary to specify further criteria.

Step Four: Weighting Scenario Criteria

Returning to criteria numbers 11 onwards, these should be weighted according to how important they are in your overall assessment of the scenarios. This can be done by ranking the criteria in order of importance and allocating 100 points across all criteria (in the same way as scores were awarded). You should include the aggregate reservoir criterion in your weighting to indicate how important you consider the characteristics of the reservoirs used relative to the other scenario criteria. A preference ranking of the scenarios can then be made based on the scores and weights that you assign to each criterion.

Appendix D. Interview participants

Round One Interviews

RAL Energy technologies (academic)
IEA Greenhouse Gas T & D programme (industry)
British Geological Survey (BGS) (academic)
Department of Process Integration, UMIST – Process engineers (academic)

Round Two Interviews

"Academic", Professor of Technological Innovation and Social Change
"RDA" Yorkshire Forward – Sustainable Development Unit
"Geologists A-C" British Geological Survey
"NGO1" Friends of the Earth (environmental NGO) / Scientists for Global Responsibility
"NGO2" WWF (environmental NGO)

Appendix E. Multi Criteria Evaluation of Low Carbon Energy Technologies (spreadsheet)

ENTER SCORE FOR CRITERION FOR EACH RESERVOIR TYPE

TO STEP 2

STEP 2 ASSIGN WEIGHTS TO CRITERIA:

	Oil and gas fields (offshore)	Traps in aquifers	aquifers outside traps	Onshore sites		Total points	Criteria Weight
	25	25	25	25		100.0	11.1
Adverse impacts ecosystems*	25	25	25	25		100.0	11.1
Adverse impacts human health*	25	25	25	25		100.0	11.1
Proven storage security	25	25	25	25		100.0	11.1
Costs*	25	25	25	25		100.0	11.1
Planning or legal barriers*	25	25	25	25		100.0	11.1
Public Opposition*	25	25	25	25		100.0	11.1
Monitoring / verification	25	25	25	25		100.0	11.1
Potential storage capacity	25	25	25	25		100.0	11.1
Optional	25	25	25	25		100.0	0
Optional	25	25	25	25		100.0	0
Optional	25	25	25	25		100.0	0
Reservoir performance SCORE OUT OF 100	25.0	25.0	25.0	25.0		100	99.9

TO STEP 3

*NOTE - criteria shaded dark blue - a high score indicates a low value for the criterion

ENTER SCORE FOR CRITERION FOR EACH SCENARIO:

TO STEP 4 →

	Nuclear Renaissance	Fossilwise	Renewable Generation	Spreading the load (high storage)	Spreading the load (low storage)	Total
Reservoir performance (within scenario)	20.0	20.0	20.0	20.0	20.0	100.0
Costs- energy supply and use	20	20	20	20	20	100.0
Infrastructure change	20	20	20	20	20	100.0
Lifestyle changes	20	20	20	20	20	100.0
Security of energy supply	20	20	20	20	20	100.0
Environmental impact	20	20	20	20	20	100.0
Credibility	20	20	20	20	20	100.0
Optional	20	20	20	20	20	100.0
Optional	20	20	20	20	20	100.0
Optional	20	20	20	20	20	100.0
Scenario performance	20.00	20.00	20.00	20.00	20.00	100

STEP 4 ASSIGN WEIGHTS:

Criteria Weight	
	14.3
	14.3
	14.3
	14.3
	14.3
	14.3
	14.2
	0
	0
	0
Total (100)	100

Appendix F. Working Paper, Burying Carbon under the Sea: An Initial Exploration of Public Opinions

Burying Carbon under the Sea: An Initial Exploration of Public Opinions

Clair Gough, Ian Taylor, Simon Shackley

Abstract

Geological and ocean sequestration of carbon dioxide is a potential climate change mitigation option that is currently receiving an increasing level of attention within business, academic and policy communities. This paper presents a preliminary investigation of possible public reaction to the technologies under consideration. Using a focus group approach, we consider the similarities between carbon storage technologies and analogous technologies that have generated strong reactions with the public. Initial results suggest that, in principle, carbon capture and storage may be seen as an acceptable approach as a bridging policy while other options are developed. However, concerns were raised regarding the safety of storage and trust in the ability of the various institutions to oversee the process in the long term. This analysis forms part of an on-going study which will continue to investigate the perceptions of a range of stakeholders.

Introduction

Options to store carbon dioxide in geological formations, or in the deep ocean, are now receiving increasing attention from policy makers, industry and the scientific and engineering communities (Fujioka *et al.,* 1997; Grimston *et al.,* 2001; Herzog *et al.,* 1996; IEA GHG, 2000, 2001; Rau and Caldeira, 1999; Stevens & Gale, 2000). Attention from the NGO community is beginning to grow but the idea has barely entered the sphere of public debate (Lenstra & Engelenburg, 2000, ABC Environment News, 2001), with the exception of specific deep ocean storage projects (Johnston *et al.* 1999; CNN, 1999), including the formation of the 'Coalition against CO_2 dumping' which is campaigning against ocean storage testing in the Pacific ocean.

The underlying principle is that CO_2 can be removed from fossil fuel combustion process from where it is transported to a suitable site at which it can be stored for potentially many thousands of years, permitting continued use of fossil fuels whilst avoiding significant atmospheric CO_2 emissions. Storage sites include off-shore (and on-shore) geological reservoirs, such as depleted oil and gas fields and saline aquifers under the sea-bed; schemes to inject CO_2 directly into deep oceans are also being explored. There are some major technical hurdles to overcome before the technology becomes cost-effective, in particular, the capture of CO_2 from power station flue gases; however, the industry appears confident that technological innovation will bring down these costs (CCP, 2001).

Biological carbon sequestration (in forests and soils) – has already received considerable attention and features in the Kyoto Protocol (IPCC, 2000). Physical sequestration, despite its potential for removing vastly more CO_2 from the atmosphere than biological sequestration, has received significantly less exposure to date. A better understanding of public perceptions at an early stage, particularly before any political decisions are taken will, in our view, assist in the cultivation of a more robust public debate than has been witnessed recently for some technological changes (the introduction of Genetically Modified Organisms for example).

Methodology

A focus group methodology was used because it allows the research team to understand *why* certain viewpoints are entertained (Burgess, *et al.*, 1988, Harrison *et al.* 1996, Greenbaun, 1998, Krueger, 1998). A group discussion also allows individuals to interact and respond to one another - this is a useful feature when a new issue is being discussed because it stimulates mutual and creative information-sharing, exploration and analysis. Focus groups are a well-established research approach in the qualitative social sciences and we refer the reader to the above references for more critical information. Our focus group are not intended to be 'representative' of the public, but rather to reflect the opinions and views amongst a group of defined participants in a particular time and place. What is lost in representativeness is, however, gained in the richness and depth with which perceptions can be explored and understood. Clearly, the results from just two groups, whilst informative, must be treated as tentative findings and used to guide a larger programme of research.

We held two focus groups, the first of which consisted of 10 masters-level students from a Management School, and hence have a background in critical analysis but not in environmental studies. They were all male and mostly in their mid 20s. Some of the MSc students had a first degree in engineering, hence had some quite specific technical frameworks available for assessing carbon sequestration. The second group consisted of 9 individuals, 7 of whom were male, and mostly in their late-20s to mid-30s (range from 20 to 35). None had degrees in science subjects and their occupations were generally public service (e.g. teacher, policeman), self-employed or working in a managerial role in small firms (e.g. wholesale carpet business, video editing). Both the groups were selected 'opportunistically' through personal contacts. This was necessitated by the limited resources available to the research team but is not felt to detract from the value of the findings since two internally-cohesive groups were established. The first author (CG) provided information to the groups and observed the discussion, whilst the second author (IT) acted as the moderator.

The focus groups began with a brief discussion regarding global climate change and the role that anthropogenic carbon emissions played in these changes. The discussion moved on to debate whether carbon dioxide sequestration techniques were realistic policy options that should be explored more thoroughly. The groups analysed possible public reactions to the proposed technologies. This discussion was initiated by the introduction of examples of recent issues that have excited controversy with the aim of exploring their accuracy and relevance as potential analogues to carbon storage. The important role that the media would play in portraying and framing the issue and the consequences that this may have in determining the level of acceptance or opposition amongst the general public was also addressed.

The focus groups then discussed the individual storage and disposal options, in order to ascertain whether initial levels of support and opposition varied with regard to the various options. There was an attempt to determine why different storage solutions produced different reactions and perceptions among participants within the groups. The groups concluded by discussing some of the institutional and legal considerations that would need to be addressed in order to ensure that the integrity of sequestered CO_2 could be guaranteed for a suitable length of time.

The first focus group proved to be the most productive in terms of the range of issues raised by the participants and the resulting discussion that emerged from these initial observations. The debate was spontaneous and lively, requiring little prompting from the moderator beyond ensuring it remained relevant to the topic and broadly followed a pre-determined list of issues. The level of interest and knowledge displayed by the first group is unlikely to be reflective of the general public at large but it does provide a useful first indication of how carbon storage policies might be perceived.

The second focus group proved more challenging than the first. Possible reasons for this include that it was conducted in a less formal surrounding (in the moderator's own home), the moderator was familiar with all the participants of the group and the composition of the second group, compared to the first. Participants generally had less formal scientific training than the members of the first group, resulting in less initial familiarity with the topic. The effects of these factors were compounded by the fact that the second focus group was held the day following the terrorist attack on the World Trade Centre (11/9/01), which preoccupied the minds of many of the participants.

The combined effect of these factors was that the role of moderator was much more demanding than in the previous group - participants were less forthcoming with their opinions. This barrier was overcome by implementing more structured questioning than was necessary with the first group to ensure that a full range of issues was discussed. In addition, questions were addressed to individual participants to maintain the group discussion and to ensure that a range of views from the full complement of the group was aired.

This was a preliminary study within a broader programme of research and certain features should be born in mind when considering the results presented here. Each group met only once and, given that none of the participants were familiar with carbon sequestration, it is likely that participants either thought of new issues after the meeting had concluded, or that positions and viewpoints expressed within the groups might change after a period of reflection. However, this research was primarily concerned with initial perceptions and the identification of some of the issues relating to the social acceptability of carbon storage as a climate change mitigation approach.

Focus Group Findings

Each of the following sections is designed to convey the main opinions and perceptions of the issues that were raised and includes relevant quotations taken from the discussion groups. At the end of each section there is a brief reiteration of the major points covered.

Carbon Sequestration Viability

On the whole, both groups were in agreement that global warming is a problem and that it is at least partly due to the industrial activities of humankind over the last century and a half. Only one member of the first focus group was not convinced by these claims, contending that the earth is currently in an interglacial period and that the changes in temperature are therefore predominantly a natural phenomenon.

There was reasonable agreement that the proposals would, in principle, attract little public opposition:

Alan	On the grounds that the public can keep running their cars and get their electricity cheap it will be accepted.
Paul	It's not a contentious issue, like, to take another scientific example, GM foods; there's not the same type of animosity towards it [carbon sequestration].

(exchange in group 1)

However, concerns were raised that levels of acceptability and opposition may vary between locations:

Steve	The public in Germany are really well informed. They'll be like, 'oh no, they're dumping things in the sea'.

(exchange in group 1)

Both groups generally gave the overall impression that the potential dangers posed by anthropogenic global climate change imply that carbon storage should be investigated as a possible solution. The groups were asked about other methods that could be used to reduce carbon dioxide. One of the participants in the second group suggested a reduction in deforestation and a move towards a policy of reforestation, which was met with widespread approval within the group.

There were a number of differences between the two groups in perceptions of the viability of the process of capturing and storing CO_2. The second, less scientifically informed group, were content to accept the process was effective. The first group had a number of concerns regarding the effectiveness and potential dangers inherent in the process:

Tim	Is it pure CO_2 or does it contain pollutants. Is it safe to put those underground?
Paul	What percentage of the CO_2 will be captured in the power stations?

(exchange in group 1)

Renewable Energy and Energy Efficiency

One of the major concerns over geological or ocean storage of CO_2 is its long-term sustainability. Several participants suggested that rather than putting resources into unsustainable schemes such as this, more resources and research should directed to methods that would promote either the use of renewables or increases in energy efficiency. The consensus within the second group was that energy efficiency measures should be implemented alongside any sequestration policies that are adopted:

Sue It's a balance. You can't say we'll put the whole efficiency thing on hold and we'll just get rid of the CO_2, because people will see that we're still producing it.

(group 2)

The first group were concerned about the economic sense of building the infrastructure to support carbon sequestration technologies which were perceived as being both unsustainable in the long-term and rendered obsolete by advances in lower carbon technologies, such as clean coal technology and improved gas-fired power stations. The group was not necessarily advocating increased investment in energy efficiency R&D; rather there that technology would advance in such a way that increased energy efficiency and power stations with lower CO_2 emissions would occur 'naturally':

Alan In 30 years you would have power stations that run more efficiently, that burn better, that have filters. I'm worried about the initial outlay.

Tim Once you de-commission the old power stations, the process will occur naturally.

(exchange in group 1)

Potential problems and concerns were also identified with the costs associated not only in capturing the CO_2 but also with its storage and transport, as well as the costs relating to the long term monitoring of the potential storage sites. Particular reference was made to the difficulties and costs of transporting supercritical fluids.

A major concerns with waiting until technology progresses 'naturally' to more energy efficient technologies was alluded to by a participant in the second group:

Mark It's a case of the public seeing progress. You wouldn't see any initial progress [without intervention] because you are looking at thirty years from now and the public would say what about now?

(group 2)

Given that such a large percentage of the world's current energy needs are met by fossil fuels (approximately 75% (IEA, 2000)) and that it would not be feasible to alter this situation overnight, each group was then asked whether CO_2 sequestration should be considered as a bridging policy until greater emission reductions are achieved from energy efficiency and renewable energy. This received widespread agreement within both groups:

Sean It's something emphasis should be put on to now, to stop the escalating problem of global warming.

(group 2)

Pete Maybe that's a better perception, as a temporary fix. The primary mode of government research could be for a long-term fix of renewable resources.

(group 1)

However, there was also agreement from both groups that a CO_2 storage policy devised as a short-term solution would reduce the impetus to devise more sustainable energy policies. Corporations and governments would be satisfied that the problem had been 'solved', at least for the duration of their life span or term-of-office, and consequently would not allocate the required resources necessary to develop alternatives. The perception that adequate research into alternative energy sources would not be undertaken following an introduction of carbon storage somewhat reduced enthusiasm for CO_2 sequestration as a solution.

Relevance of Potential Analogues to Carbon Sequestration

Given that there exists only one environmentally driven geological sequestration project (Statoil's Sleipner operations in the Norwegian sector of the North Sea (Herzog *et al.*, 2000)), public awareness of such approaches to decarbonisation is low. We sought, therefore, to identify potential 'analogues' in other fields and applications, which might be regarded as indicating the shape of public perceptions to physical / chemical carbon storage. We presented two analogues to the focus groups, namely the debates over: a) nuclear power and in particular, disposal of waste (Kitschelt, 1986, Turner, 1986, Welsh, 1993, Walsh *et al.* 1993); b) the proposed disposal of the Brent Spar oil platform in the North Sea (Grove-White, 1996, Shell, 2001). Although it is recognised that there are many differences between these examples and carbon sequestration technologies, it is nevertheless possible to gain valuable insights from analysing experiences with analogous technologies (Glantz, 1995).

With reference to the Brent Spar saga, there was some agreement that there were similarities between this and proposals for carbon sequestration. Within both groups similar actors were identified as playing a major role, most notably the oil companies. There was also a general perception within each group that the Brent

Spa was an example of a large company attempting to impose a quick technical fix to a broader environmental problem. However there were differences of opinion regarding whether the general public would view proposals to store CO_2 as more or less desirable than Shell's attempt to dispose of the Brent Spar oil platform in the North Sea:

Darren	With Brent Spar, you had a big oilrig you wanted to stick in the sea. People would see it, it's visible. With this it's invisible, people won't see it.
Tim	People think of CO_2 as an evil greenhouse gas, so I don't think they will be able to get away with it. It sounds wrong.

(exchange in group 1)

On the one hand, the physical sequestration of CO_2 was seen as 'invisible' compared to Brent Spa; on the other hand, disposal of CO_2 in this way could still be seen as irresponsible. There was, however, general agreement that the dangers posed by global climate change were severe and therefore any credible policy that could alleviate the problem should be seriously considered. However the second focus group voiced some concerns relating to both the amount of CO_2 that would have to be stored in this manner and the length of time it would be required to remain *in situ* for:

Alex	The problem is a lot greater, but the scale of the amount of stuff you want to put down there is going to scare people.
Anne	It's not a one-time thing like the Brent Spar, it's something we will have to live with.

(exchange in group 2)

Both CO_2 capture & storage and nuclear power were identified with the production of waste products that would have to be effectively managed for a period of centuries. However, the nuclear industry was perceived as having an irreversibly bad reputation:

Researcher	Do you think that nuclear energy is a good analogue?
Paul	In many ways, but nuclear power already has a bad image. This is slightly different because it hasn't got an image. The concept hadn't entered my head until today.
Larry	The thing with nuclear power is that if one thing does go wrong it's a big issue.

(exchange in group 1)

At this stage the groups were asked to suggest other analogues which might provide insights into possible reactions concerning the social acceptability of CO_2 capture and storage. The second group failed to suggest any alternatives; however the first group suggested the debate over genetically modified (GM) foods as a suitable example. The example of GM foods raised a number of interesting points regarding differing levels of acceptability throughout the world:

Pete	With GM foods…in some countries they are accepted, in others they are not. It's a matter of who the public were influenced by.
Paul	I know quite a bit about that and it's a joke the way that the media has presented it.

(exchange in group 1)

Formation of Opinions

This opened the potentially crucial issue of factors that influence the formation of public opinion. One of the strongest early impressions within both groups was that people are highly suspicious of the motivations of large corporations. The active role oil companies are playing in advocating and developing CO_2 storage technologies may affect general levels of acceptance of the technologies. The oil companies were perceived by these focus groups to be motivated entirely by profit, more concerned with maintaining dependence on fossil fuels than promoting sound environmental policies:

Researcher	Do you think public perceptions may be affected due to the active role played by the oil companies in promoting these policies.
Mike	Yes, because oil companies themselves give an impression of lying to people.
Steve	In Malaysia and South East Asia, what the big oil companies say goes. They own the entire region. If the oil companies want it to go ahead down there it will go ahead because the governments eat out of their hand.

(exchange in group 1)

There was also a degree of scepticism expressed over the support and research being undertaken on behalf of the United States government regarding carbon sequestration technologies. These concerns were based on the understanding that the United States is opposed to environmental policies perceived to be detrimental to its own domestic economy. In these circumstances CO_2 capture and storage was seen as a policy devised to allow industrialised countries to continue with current economic and industrial policies.

At this point, the groups examined the influences that are important in presenting arguments to the public. A number of key actors were identified that would be involved in the framing of the issue, including the oil companies, environmental groups, national governments and the media.

The second focus group showed differences of opinion regarding the acceptability of contentious environmental policies by the general public:

Sue	The public is so ill informed. It's naturally against anything, regardless of the facts or danger.
Martin	I think it will be very much based upon…are you putting it in my back garden. No, right, I don't care.

(exchange in group 2)

The first group were more cynical about the level of interest that members of the public would have in the subject and consequently in their efforts to obtain information relevant to such proposals:

Paul	If you ask the average man on the street what Kyoto is, he wouldn't have a clue.
Darren	If you look at programmes like 'Horizon' though.
Paul	What are the audiences for these programmes though. People are not really interested. They like the idea of renewable resources, but they are not that bothered.
Alan	They're all watching 'East Enders'.

(exchange in group 1) (Note: 'Horizon' is a science documentary and 'East Enders' a soap opera, both made by the BBC).

These initial observations allowed the researchers to probe further perceptions of how information on complex issues should be conveyed to a general public insufficiently motivated to seek out information. The way that the issue is presented by the media would have a great bearing on the acceptability of any proposals, as illustrated for environmental matters in general (Gamson & Modigliani, 1990, Chapman, 1997, Social Learning Group, 2001). In the Brent Spar episode, Greenpeace was successful in convincing the media, and consequently the general public, that disposal at sea would incur unacceptable environmental risks (Grove-White, 1996). This was achieved despite scientific opinion, backed by many academics and the British government, which deemed ocean disposal to be the most environmentally benign option (Shell, 2001). The perception that the media plays an important role in determining the acceptability of environmental policies was encapsulated within the second group:

Anne	At the end of the day it's down to educating people about the subject. There are a lot of people out there who won't bother to find out and it's about how the media present it.

(group 2)

Some participants felt that CO_2 storage would be rejected by environmental groups on the grounds that it would allow the continued wide-scale use of fossil fuels in favour of an increased use of sustainable, renewable sources of energy. Others were of the impression that environment groups may be persuaded to support CO_2 storage proposals if they were presented as a bridging policy between fossil fuels and greater reliance on renewable sources.

There was a general agreement within the first focus group that geological sequestration may have a greater chance of being accepted if it was seen to be part of an integrated climate change policy, perhaps containing more publicly 'visible' elements:

Mike Could you not 'butter-up' the public by planting some trees as well, as they are cheap and visible. As part of a CO_2 reduction policy we are going to plant loads of trees…and put some under the sea. Put it in small print at the bottom.

(group 1)

One of the key differences between carbon sequestration and the other analogues is that climate change policies operate on a global stage whereas individual countries can decide upon their own policy vis-à-vis GM foods. This introduces the question of which institutions or organisations will influence whether or not carbon sequestration is accepted and implemented on a global level. It was agreed that as the world's largest economy and producer of CO_2 emissions, the United States would have a major role to play in whether carbon sequestration became accepted. Similarly in Europe, lobbying by the protagonists on both sides of the argument was considered to be important:

Pete In this it will be the same thing, who lobbies first and best, oil companies or the environmental groups…as I think happened in Europe with GM foods, who gets to the people first.

(group 1)

And as far as determining whether the policy has support on a global level:

Paul Certain countries will take the lead. Look at Kyoto. America's refusing to ratify, Japan, Australia… There are certain groups in the world who are the leaders. The G7, G8, whatever it is now. They will formulate the opinion of the smaller countries.

(group 1)

Storage Options

The members of the focus groups were introduced to several different storage options: namely depleted oil and gas reserves, storage in deep saline aquifers and direct ocean disposal and were asked to comment on the relative attractiveness of each option. The most contentious storage issue in both groups was ocean disposal of CO_2. There was some disagreement regarding the impact that the ocean storage of CO_2 may have on the marine environment:

Mike	Will that not lead to an increase in sea acidity?…that could kill fish and cause more problems than you could solve.
Tim	Were there not certain benefits with pumping CO_2 into the sea, including an increase in certain types of fish stocks?

(exchange in group 1)

The overall conclusion within both focus groups was that the large scale introduction of CO_2 into the ocean may have unforeseen and unpredictable effects upon the entire marine food chain:

Pete	There are deep-sea environments, once you disturb a portion of it…an ecological system is not isolated.
Mike	It creates a ripple effect
Pete	You don't know how certain micro-organisms on the sea floor affect larger organisms higher up.
Larry	Plus there are a lot of unknown and unstudied sea creatures at that depth.

(exchange in group 1)

Both groups were concerned about the uncertainties surrounding the behaviour of CO_2 underwater and had reservations regarding the integrity of the bubble, particularly after a substantial period of time:

Pete	What happens after a couple of hundred years? Does it just stay as a bubble?
Alan	What about seismic influences? If you get a tsunami in the sea, you would get a huge explosion of CO_2 all over the seabed…you don't know what is going to happen.

(exchange in group 1)

The option of storing CO_2 geologically, either in depleted oil and gas fields or under the seabed in saline aquifers, was received more positively by both of the focus groups. The perception was that the CO_2 would pose less of a threat if it were contained within a physical structure, in this case a theoretically impermeable rock formation. The first group also stated that they would feel more confident in the solution if there were a barrier in place that would physically prevent the CO_2 from escaping and returning to the atmosphere. The second group thought that there would be an element of 'out of sight out of mind', particularly as there was a physical barrier in place to prevent the captured carbon from escaping. The favouring of geological storage over ocean disposal by both groups appeared to be based not primarily on the presence of a visible barrier to prevent CO_2 escaping rather than on concerns for the marine ecology. Even given scientific research demonstrating the integrity of CO_2 storage within the ocean, participants felt more secure with a solution that provided a 'visible' physical barrier. Concerns about the use of geological reservoirs related predominantly to the integrity of the seal and the possibility that the CO_2 could escape:

Mike If you spend a lot of money putting it there and it just comes back you've wasted your money.

Tim What would be the result if all of it suddenly came out at once?

(exchange in group 1)

A further issue was the integrity of the reservoir, particularly the effects that oil and gas exploration may have had upon the cap rock. There were also uncertainties about the behaviour of carbon dioxide in the reservoir. (There is no precedent for this as the CO_2 stored at the Sleipner test site has only been monitored over a very short timescale). There were also concerns regarding the effect that seismic activity, particularly earthquakes, may have upon the integrity of the cap seals. The possibility of a large-scale sudden release, and the potential catastrophic consequences of such an occurrence, were identified as areas of concern. A slow release was regarded as less dangerous, while still conferring certain benefits:

Sue A slow release would surely put out less than if it had all been released at the start.

Alex Half of it down there is better than none of it down there.

(exchange in group 2)

Neither group made much distinction between the geological storage of CO_2 in onshore or offshore locations. This was slightly surprising given the potential dangers associated with a sudden release of CO_2 to life in the immediate vicinity at an onshore site (Holloway, 1997). When the moderator reiterated the potentially catastrophic consequences of a sudden increase in local atmospheric CO_2 concentration, opinions were reconsidered. A majority of participants in each group moved to favour geological storage at offshore locations away from potentially inhabited areas. However, a minority in each group still considered the possibility of such a sudden release to be small, posing less of a threat to population centres than technologies such as nuclear power. It is worth noting that local public opposition has recently emerged in Cheshire (UK) surrounding the construction of an undergound salt cavern for the storage of methane, seemingly on the grounds of health, safety and environmental hazards. This dispute has all the hallmarks of NIMBYism (Not in My Back Yard), yet other natural gas storage facilities in the UK and Germany have gone ahead with little if any local opposition. Underground natural gas storage is another useful analogue to CO_2 storage in terms of public opinion and would merit further research.

Future Concerns

The final section of the discussion related to the acceptability of imposing CO_2 storage on future generations. The groups were also asked whether they considered that institutions would be in place to regulate and monitor storage sites and the ownership and responsibility for potential sites? This last point will be particularly salient if geological carbon sequestration technologies are ever included in a global greenhouse gas protocol, with the potential for financial benefits in an international emissions trading scheme to countries possessing suitable storage sites.

With reference to the burden of regulation and monitoring of stored CO_2 to future generations, it was felt that in principle this is acceptable. The view was held within both groups that sequestered CO_2 posed less of a long-term environmental risk than toxic waste. There was general agreement that the potential benefits to the atmosphere from lower net carbon concentrations outweighed the potential risks from the storage process. There were a number of concerns raised regarding the cost and scale of the monitoring process that would be required to ensure that the storage sites are secure:

Alex (group 2) — How much maintenance would they require…or should they be pretty self-sufficient once they are in place?

Alan (group 1) — You may have to pay out so much money to monitor them, that you should have invested it elsewhere in the first place.

On the provision of institutions that could be guaranteed to monitor stored CO_2 over a period of several centuries, both focus groups noted how institutions have changed over the preceding centuries. In the last century alone there have been two world wars, resulting in major political changes and highlighting the difficulties of establishing sufficiently robust and long-lived institutions. There was also a perception that long-term consequences would not be adequately considered since governments are elected for approximately five-year terms while corporations are primarily motivated by short and medium term profit. In these circumstances the provision of institutions that would be equipped to monitor the sites in the long-term would not, it was felt, be a high priority.

The groups felt that there was a lack of clarity over whose responsibility it should be to monitor the storage facilities: was it the corporations, individual governments or some international body? One solution to this problem was proposed by the first group, referring to the example of Yucca Mountain in the United States, a proposed facility for the storage of nuclear waste. The design criteria depend on the facility continuing to operate effectively in the event of a breakdown in the fabric of society. It was suggested that similarly stringent criteria be proposed for potential CO_2 storage sites, in order to minimise the reliance on the existence of monitoring institutions in the future.

The discussion groups also considered ownership of storage sites. This is particularly relevant in Europe, where there is a large saline aquifer situated under the North Sea. This aquifer alone could potentially sequester the total CO_2 produced by power stations across Europe for many decades (Holloway, 1996) and hence could be an important and lucrative part of a global emissions trading market. Should the aquifer be the property of Norway and the United Kingdom, in whose territorial waters the aquifer is located, or should it be a European resource?

The feelings of the discussion groups were that potential storage sites should be treated in the same way as any other natural resource, which allow the country or countries in which the resource is situated to benefit from revenue derived from that resource. An analogy with precious metals and ores was drawn - these are the property of the country in which they are located and the groups agreed that there is little distinction between the two cases. However the point was made by the second group that global acceptance of geological storage of anthropogenic CO_2 could be affected if it was felt that some countries stood to benefit financially from its implementation.

The concept of imposing stored CO_2 on future generations was not considered to be unacceptable. It was perceived to pose less of a danger to future generations than failure to act to prevent further global warming. There were however some concerns that long-term monitoring costs could offset short-term benefits, in which case an alternative solutions should be sought.

Conclusions

The findings in this paper are highly preliminary given that they represent the views of only two focus groups, one of which was composed of postgraduate students with a scientific background. There was no existing knowledge of physical carbon sequestration within the groups and therefore no prior opinions or pre-conceptions. We found that there was little opposition in the groups to the principle of capturing and storing CO_2 from power stations. A major component of this acceptance appears to the level of concern expressed over the problem of anthropogenic climate change. The seriousness of this problem was felt to demand action from the leading industrial countries. Some level of risk arising from a mitigation effort was deemed to be acceptable it is associated with a significant contribution to reducing the potentially more serious effects of climate change. Thus the groups viewed carbon sequestration differently to, for example, the introduction of Genetically Modified Organisms (GMOs) perceived to be introducing a new risk without an associated reduction in risk elsewhere.

Concerns were raised, however, over the safety of carbon storage, in particular the integrity of the storage reservoirs and the security of the stored CO_2. There were also objections on the grounds of cost given that such a policy may be rendered unnecessary by expected advances in power generation technologies. There was a consensus however, that carbon sequestration would be an acceptable ‘bridging policy’ until such technological improvements could be implemented. The concern was voiced that once CO_2 storage policies had become widely adopted and accepted, the resources required to develop alternative strategies would not be made available.

Whilst there were no prior opinions of geological sequestration, the same cannot be said of some of the agencies involved in carbon sequestration. Oil companies are suspected by some in the groups as being primarily concerned with ensuring the continued use of fossil fuels to protect their current business interests. The media are identified as being highly important in framing the debate on sequestration for the general public. The disposal of the Brent Spa oil platform was discussed as a potential ‘analogue’ for the perception of physical carbon sequestration, yet was regarded as a much ‘smaller’ or ‘isolated’ issue, relating to a single oil platform, whereas carbon sequestration is seen as a much bigger and longer-term proposal. Nuclear waste was seen as a good analogue with respect to the need for long-lived institutions to conduct thorough monitoring and security, but a poor analogue in terms of overall levels of implied risk.

There were differing levels of support for alternative storage options. Ocean disposal was deemed to be undesirable for a variety of reasons, including the potential impacts on the poorly understood deep oceans and the possible ramifications throughout marine ecosystem. However the main objection to this potential storage solution lay in scepticism over whether the CO_2 would remain in the deep ocean for a sufficient period of time. For this reason, geological storage received greater support due to the presence of a reassuring physical barrier to prevent the CO_2 escaping. Because of the potential risk of CO_2 release long term monitoring was considered to be highly important.

The findings presented here provide some useful indications of the potential public perception of physical carbon sequestration, though clearly more extensive research is required (both more diverse and extended focus groups and survey work). The assumption that off-shore and contained hydrocarbon reservoirs and aquifers will be more readily accepted than other storage options is given credence here. More specific information about the monitoring of physical carbon sequestration and its costs needs to be provided to inform the public debate. There is a good basis for believing that the public will distinguish between risks in relation to disposal of the Brent Spa oil platform, nuclear waste, GMOs and carbon sequestration. Although an element of risk associated with carbon sequestration may be considered acceptable relative to the avoided risks from climate change, there is a general scepticism of the motives of oil companies. Widespreasd acceptance of geological carbon sequestration may be require evidence that renewable alternatives to fossil fuels are being actively pursued. It was also clear to our groups that the media would have a crucial role in shaping public opinion and that the skill of proponents and opponents in conveying the appropriate messages through the media would, therefore, be crucial.

We finish by offering two theoretical observations on the methodology and findings:

1) From a theoretical point of view, our results raise a question about the very notion of 'the public'. Whilst the MSc students were a sample of 'the public' for the research team, they referred to 'the public' as being quite distinct from themselves. This lack of identification (not experienced in the second group) highlights the diversity of social groups and the need for more comprehensive sampling in future work. The student sample seems to us to be, however, a rather useful 'sounding board' for those professionals in business, government and research who tend not to identify themselves as the 'public' - some of the most influential and well-resourced social groups.

2) The implicit cognitive models entertained by respondents are worthy of more detailed analysis in further research. Two that emerged here are: a) belief in an interconnected ecosystem web in which interference in any part will concatenate throughout with deleterious consequences. Kempton *et al.* (1995) identified this belief in their interview work and argued that it arose from the popularisation of the 'web of life' view of ecology in education and popular media in the 1970s following the discovery of PCBs in food chains (rather than reflecting the state-of-the-art thinking in ecological science); b) belief in 'natural' progression of technology; the notion of technology having some autonomous power of its own is observed in technology studies (e.g. Wynne, 1998). Such cognitive models can be important in understanding where perceptions come from and how open they are to new interpretations and information.

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