Energy Systems in 2050

1. 2050 Energy Goals

The nature of the energy system in 2050 cannot be predicted with any certainty. Energy supply and demand infrastructures will largely be replaced within half a century. The technologies available will develop in both type and cost. Market structures and institutions will, in all probability, change beyond recognition. Predicting our current patterns of energy supply and use in 1950 would have been impossible; similarly, it makes no sense to attempt now to make predictions for 2050 with any certainty.

Even the objectives of energy policy are uncertain on these timescales. Society and its requirements from the energy system will be very different. However, there are some fixed points. We can probably assume that society in 2050 will want an energy system that:

- delivers energy services at reasonably low cost,
- is secure, i.e. provides a range of energy services with high reliability,
- has low environmental impact,
- is consistent with social justice in allowing access to energy services, and
- is compatible with industrial policy goals.

The balance between these different objectives is likely to change over time. In recent years energy policy has effectively prioritised economic objectives. But the Energy Review is a recognition of the importance of energy security and environmental goals. Our assumption is that costs will remain important, but that, as wealth increases, other objectives may grow in importance. In particular, the very large reductions in the emissions of carbon dioxide that are required to stabilise the global climate will require fundamental changes to the energy system. And the projected decline in UK oil and gas production raises new concerns for energy security. In assessing policy goals for energy out to 2050 we therefore give most attention to costs, environmental sustainability and energy security.

2. Approach

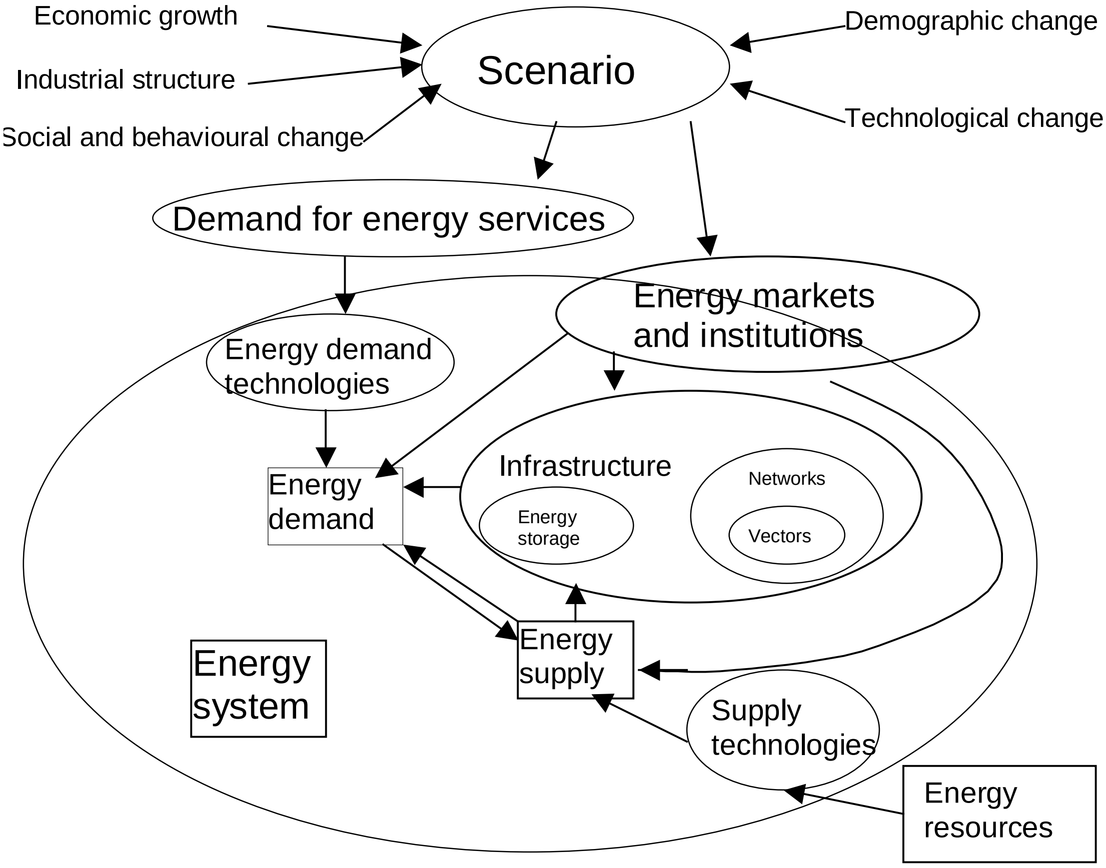
Assessing long term energy systems requires consideration of a variety of issues. Our approach to the relationships is shown diagrammatically in Figure 1.

- **Scenarios** outline possible future socio-economic development, including economic growth, economic structure, rates of technological, social and demographic change. These factors are treated as given in our analysis, i.e. outside the energy system. Different scenarios can be envisaged (see section 3).
- Each scenario is associated with a level and structure of **energy services demand**. This acts as the basic driver of the energy system, as it determines the output required from the energy system (including imports). Although, in practice, aspects of the energy systems (notably costs) will affect demand, for simplicity we treat the demand for energy services as determined by the scenario.
- **Energy systems** in 2050. These are at the core of our analytical work. They are defined to include the both technological and market/institutional aspects, i.e.
    - **Energy demand technologies,** the efficiencies of which determine energy demand for any given level of energy services,

- **Energy supply technologies** to meet that demand,
- **Technical infrastructure** consisting of the **energy vectors** used for transporting energy, the **networks** within which they operate and **energy storage** used for matching supply and demand in time, and
- **Energy markets and institutions**, e.g. the fiscal and regulatory framework.

The last of these – the market and institutional framework - is shown in Figure 1 as only partly within the energy system. This reflects the fact that some aspects of energy markets and institutions are primarily 'energy issues', but others are more influenced by broader economic and social factors. For example, the relative use of public and private transport has an important impact on the demand for petroleum, but it is not a issue that can be addressed solely with reference to energy.

Figure 1
Relationship of Socio-Economic Scenarios and Energy Systems



The **energy policies** that form part of any energy system operate on all elements of the system, i.e. everything not assumed to be determined by the scenario. For example, policy can affect:

- the rate of technological development and the priority given within this to different energy options,
- the regulation and development of energy networks, and
- the taxes, regulations and incentives faced by energy market actors and mediated through the institutions of the energy system.

3. Scenarios

Deterministic models of energy systems are not robust against the uncertainties inherent in the long term. Scenario analysis is therefore required to reflect the diverse range of possible futures against which energy policy decisions need to be made.

There is an extensive literature on scenarios relevant to long-term energy system development. It includes work at an international level, including the detailed scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). However, UK focused scenarios provide a more detailed background. As a basis for our analysis, we have therefore used the scenarios developed by the DTI Foresight Programme. These are described briefly in Box 1.

The scenarios have been used to:

- make informed assessments of projections of the demand for energy services in each major sector to 2050, and
- provide broad social and economic trends as an input to developing scenario dependent changes in energy systems (technology, markets and institutions).

Further details are provided below on the possible implications of the scenarios for energy systems in 2050.

Box 1

Scenario: World Markets (WM)*: a world defined by an emphasis on private consumption with a highly developed and integrated world trading system.*

- GDP growth averages 3%
- Sustainable development is marginalized
- Light regulation with a declining role for government in economic management
- Policies increasingly developed at the EU level or in global institutions
- Strong growth in international trade
- Energy markets dominated by fossil fuels
- Energy prices remain low in the short term with low priority for energy efficiency

Scenario: Provincial Enterprise (PE)*: a world of private consumption values coupled with policy making reflecting local, regional and national concerns and priorities.*

- GDP growth averages 1.5%
- Sustainability disappears as a political objective
- UK independence in economic and foreign policy prioritised
- Use of existing sources of energy including indigenous coal and nuclear power
- Renewables not developed
- Energy prices for consumers higher than in the world markets scenario
- Energy efficiency limited by available capital and the low priority of environmental investment.

Scenario: Global Sustainability (GS): *social and ecological values are more pronounced and there is greater effectiveness of global institutions, including stronger collective action in dealing with environmental problems.*

- GDP growth averages 2%
- Adoption of more sustainable technologies and behaviour
- Greater co-operation and management within the international system
- Strong technological innovation
- Education underpins sustainable development and consumers eco-aware.
- New dwellings built to high environmental standards
- Energy prices high due to environmental policy
- Large global markets for renewable energy developed.
- Energy suppliers move towards the provision of integrated services

Scenario: Local Stewardship (LS): *stronger local and regional governance allow social and ecological values to be demonstrated to a greater degree*
- GDP growth averages 1%
- Social values encourage co-operative self-reliance and resource conservation.
- Decision-making power, including regulation, are devolved
- Widespread take up of energy efficiency measures
- Trend towards smaller households reversed
- High eco-awareness
- High energy prices for all sectors particularly transport
- Willingness to invest in local renewable energy technologies

4. Demand for Energy Services

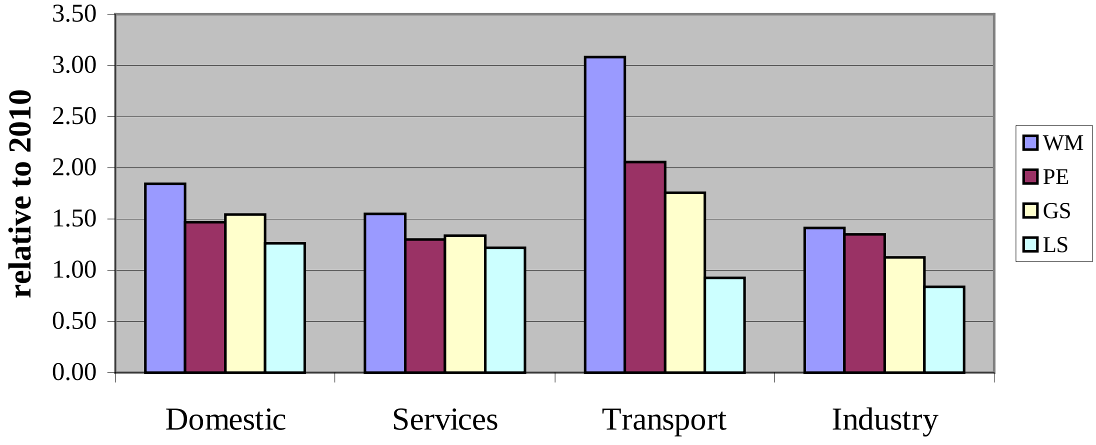
It is important to distinguish between the growth in demand for energy services (i.e. what society wants from its energy system) and growth in consumption of energy. The latter is a derived demand and depends on the technical efficiency with which the demands for energy services are met. The rate of change in energy demand is therefore determined by two factors:
- changes in economic activity producing changes (usually increases) in demand for energy services, and
- changes in the technological efficiency (generally improvements) with which energy is used.

The two factors tend to operate in opposite directions, so that energy demand may fall or rise with economic development. Both effects have been observed in the UK and other developed economies at different times in recent years.

The PIU team has worked closely with colleagues in the Inter-Departmental Advisory Group on Low Carbon Options (IAG) to develop estimates of changes in demand for energy services over the period 2000-2050 for each sector and scenario. A summary in shown in Figure 2. More detailed results are given in Annex 1. It is important to emphasise theses are not predictions. However, the range of scenarios considered gives us some confidence that future demands are very likely to fall within the range spanned by the different scenarios.

Figure 2

Demand for Energy Services in 2050



There is an important element common to all scenarios. The demand for energy services grows, but at a rate significantly lower than the growth rate in the economy. This results from 'saturation effects' in some of the key demands for energy services:

- in the household sector demand for space heating saturates as homes of lower income families reach a comfortable level,
- in the commercial services sector, the main demands for energy are heating and lighting, which are more closely linked to building floor area and number of employees than to economic output.
- in the industrial sector, economic growth continues to be predominantly in high added value products, rather than the basic, energy intensive materials such as crude steel, cement, bricks and basic chemicals.
- in road transport, demand saturates with car ownership.

However, increased wealth will be spent on additional goods and services. Some new important uses for energy will appear and grow. Current trends indicate that two of the most important may be an expansion in the use of air travel and much increased use of the Internet and other information and communications technology (ICT). It seems likely that ICT technology already is, and will continue to contribute to improved energy productivity. It is also expected that there will be increased use of air-conditioning in domestic and commercial properties.

Air travel, on the other hand poses serious issues for environmental and climate change policy. In some scenarios, notably *World* Markets, this growth might lead to greater energy use in air travel than in road travel by 2050.

The demand for energy services will depend on choices society makes about the way it develops. The differences between scenarios in Figure 2 represent not only the level of economic activity, but also the types of social and economic activity that are prioritised. These include:

- the formation of new households due to population change and other social trends,
- the extent of globalisation with its effects on personal and freight transport,
- spatial and transport planning impacts on the 'need to travel',
- social trends in 'conspicuous consumption',
- education about and attitudes towards 'environment friendly' behaviour such as cycling, use of public transport, energy conservation and waste recycling.

In our analysis we have treated these as given by the scenario, on the grounds that energy policy is unlikely to be the major driver of any of these changes. However, outside energy policy, Government has a key role to play in affecting the direction and pace of these changes. The demand for energy services rises fastest in the scenarios with least emphasis on sustainable development. The effect is most marked in transport, where social change can lead to very different outcomes. Future transport policy may need to pay greater attention to its impacts on energy policy objectives.

5. Energy Efficiency and Energy Demand

The number of demand side technologies is very large and there is great uncertainty about long term developments. Nevertheless, there are some important pointers to the scope for significant improvements.

Energy efficiency improvement has contributed more than supply side changes to carbon emissions reduction over the last half century. With the exception of buildings, the capital stock (cars, appliances, industrial plant etc.) is replaced more quickly than the energy supply infrastructure. Apart from a few specialised industrial processes, thermodynamic efficiencies remain very far short of the optimum, and therefore major improvements remain possible. Most advances rely on technological improvements in materials technology, design and control, often undertaken for other reasons. These are the types of advance where the pace of change is expected to accelerate in the 'knowledge economy'.

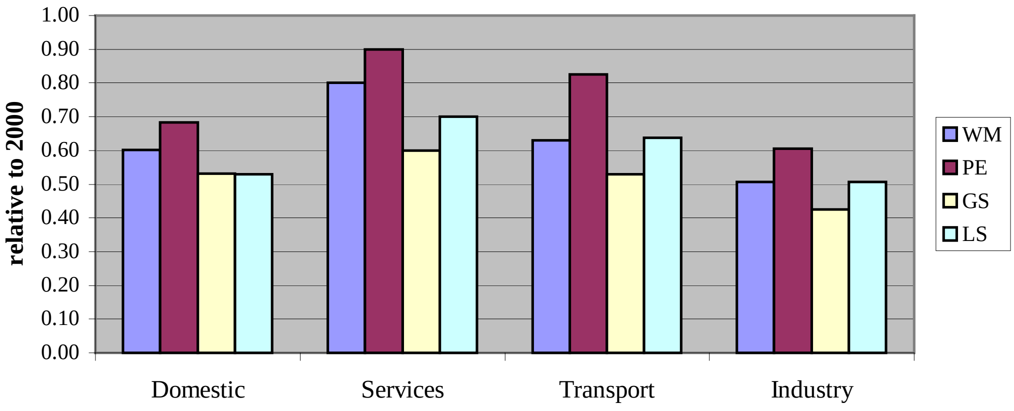
The PIU team has worked closely with colleagues in the Inter-Departmental Advisory Group on Low Carbon Options (IAG) to develop estimates of changes in energy intensity (the inverse of energy efficiency) over the period 2000-2050 for each sector and scenario. A summary of PIU estimates is presented below in Figure 3 with more details in Annex 1.

In the buildings sectors the slow turnover of the stock prevents very rapid improvements. Even if the scope for currently cost effective technology is exploited over the next decade, new technologies will continue to add to the technical and economic potential. These include new construction techniques, micro-CHP, heat pumps, super-insulating windows and high efficiency appliances. In non-domestic buildings, design improvements to use solar energy for heating, cooling and lighting could also be significant.

In the industrial sector, significant improvements have already been made in energy efficiency, especially since the first oil crisis of 1973. But a very large potential remains, especially through more fundamental changes to products and processes. Technologies that are already known but currently not widely used include membrane and crystallisation separation, process intensification, advanced refrigerants, absorption heat pumps, high temperature CHP and advanced motor controls. And technologies that might be in common usage by the middle of the century may yet to be discovered.

Figure 3

Energy Intensities in 2050



In the transport sector, a very large potential lies in fundamental redesign of the car. Electric traction based on hybrid technology is entering commercial production. Fuel cell technology is the focus of major R&D programmes. Both offers large ‘well to wheel’ efficiency improvements. With advanced control technology and some battery storage they also potentially facilitate a number of other improvements including braking energy recovery, individual wheel control and engine capacity reduction. Combined with lightweight materials and aerodynamic design improvements, these can yield major efficiency improvements. Vehicles with fuel consumption of 3.4 litres/100 km (83 mpg) are already on the road. Design ‘concept cars’ could deliver even higher efficiencies. The scope for improvements in freight transport and bus technology is lower but still very significant.

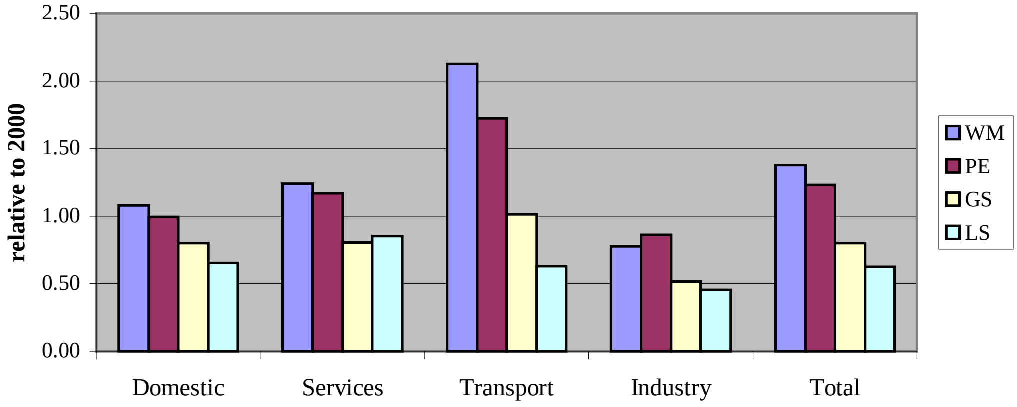
The long term rate of energy efficiency improvement will depend to a large extent on the rate of innovation in sustainable energy technology. These are likely to be highly scenario dependent – highest in *Global Sustainability* and lowest in *Provincial Enterprise*. Policy to support innovation is therefore critical in energy efficiency, just as much as in energy supply.

Energy demand is determined by the product of energy service demand (Figure 2) and energy intensity (Figure 3). Estimates of energy demand by sector and scenario in 2050 relative to 2000 are given in Figure 4 with more details in Annex 1.

Energy demand rises in the *World Markets* and *Provincial Enterprise* scenarios where technological improvement fails to offset growth in demand for energy services. Growth is particularly noticeable in the transport sector. In contrast, in the *Global Sustainability* and scenarios, energy demand falls. In *Global Sustainability*, this is predominantly because of rapid technological change. In *Local Stewardship*, the limited growth in demand for energy services also plays a major part.

Figure 4

Energy Demand in 2050



Energy efficiency therefore improves most where there is high environmental concern, but also where there is technological innovation and capital stock turnover. In scenarios where innovation is high and applied to energy efficiency technology, it more than offsets the growth in demand for energy services driven by economic growth.

We have compared these conclusions with those of the RCEP. It is important to bear in mind that all the RCEP scenarios were 'goal driven' to achieve a 60% emissions reduction in 2050. None is therefore comparable with the *World Markets* or *Provincial Enterprise* worlds where environmental drivers are weak. In the RCEP's four scenarios – primary energy demand reduction ranges from 0% to 47%, compared to our estimates of 29% in *Global Sustainability* and 48% in *Local Stewardship*. Given the uncertainties this constitutes broad agreement on the plausible scale of demand in these sorts of scenarios.

We therefore conclude that plausible differences in future demand side changes are critical for the energy system. The rate of improvement of energy efficiency will have a key impact on the scale of the energy system, primary energy use and emissions.

6. Energy Supply Technologies

6.1 Introduction

In 2050 a wide range of options will be available to meet the demand for energy. The contribution of each will depend upon:

- the relative costs of different options,

- their technical characteristics –which include plant size and operating characteristics[1],
- fuel availability and price, and
- environmental impacts.

The technology mix that is favoured in different scenarios will depend heavily upon the institutional and market arrangements consistent with each scenario, and these will in turn depend upon policy priorities of each scenario.

Given such a long time horizon considerable technical progress is certain. This is likely to change the relative economics of current options, and their environmental and other characteristics. It is also possible that technological developments will bring to market technologies currently at the laboratory stage, and even throw up new and unforeseen technologies. Whilst this analysis does not speculate about the development of unforeseen 'surprise' technologies, the likely development of options that are currently a long way from commercial reality is considered.

6.2 Approach

Assessment of the likely development of each technology is a key task for this analysis. Technical progress is complex and 'spillover' of technologies from outside the energy sector is likely to have important impacts. However, innovation does not take place in a vacuum - a number of scenario dependent factors will impact on the rate and direction of technical progress. These include:

- the rate of growth of economic activity. Higher growth scenarios therefore deliver more technical progress.
- international trade, which brings ideas sharing and technology transfer. The more 'internationalised' scenarios are thus also more innovative.
- market and policy drivers that induce technical change. These will tend to favour technologies with characteristics best suited to them. For example, scenarios with stronger environmental policy drivers will favour technologies that bring environmental benefits, those that emphasise national or local supplies will favour those that use indigenous fuels.

In order to create a picture of the development of the supply-side of the energy system for each scenario the following process is being undertaken.

First, trends for each technology are assessed in order to provide a quantitative view of the likely development to 2020. This gives us a view of how technical development may change relative costs, other factors and, in some cases, the quantity of energy a given technology is able to provide. 2020 is taken as the time limit for quantitative projections because of:

- what is technically sensible to predict based upon current trends, and
- what socio-economic change might be envisaged without the use of scenarios.

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[1] such as flexibility of operation, and capacity for rapid 'dispatchability' in response to changing demands, power quality and reliability), proximity to consumers (is the energy source close to demand or will it require transmission or transportation?

Secondly, the implications of each scenario are worked through to assess the *drivers* of technical progress, and what this might mean for the relative development of each technology out to 2050.

Finally, the relative development of each technology in each scenario is combined with the likely policy and market environment for each scenario to paint a picture of the energy mix in each scenario.

The PIU is not using a formal modelling approach to 2050. However, we are co-operating closely with work that is ongoing for DTI by AEA Technology and Imperial College, using the MARKAL energy system model to provide a quantitative view of the energy mix in 2050.

6.3 The technologies

There are many energy supply technologies covering every stage of the energy chain from fuel extraction, transportation and refining through electricity generation and transmission. For simplicity we intend to treat fossil fuel extraction, transportation and refining separately – in work on fossil fuel prices and reserves. New energy vectors, particularly hydrogen, and energy storage technologies are considered in the next sections. This leaves a focus here upon electricity generation. The key technologies that we consider are:

- Natural gas fired power generation
- Coal fired power generation
- Carbon capture and sequestration[2]
- Nuclear power generation
- Renewable sources of energy, both for electricity generation and fuel production
- Fuel cells
- Combined heat and power based upon fuel cells or combustion technologies

6.4 Trends to 2020

The central focus of this work is an assessment of what is likely to happen to relative costs. Energy markets will tend to favour a least-cost mix of technologies. And over time there is potential for relative costs to change, through technological development and through changes to fuel prices.

The task of estimating future costs is difficult and uncertain. However, it is important for business as well as policymakers and has been explored in depth in the literature. Our analysis uses two broad approaches:

- engineering assessments based on expert judgement of likely reductions in costs to place technologies on a spectrum from ‘infant’ or ‘emerging’ to ‘mature’; and
- extrapolation of historic relationships between cost reductions and cumulative production – ‘learning curves’.

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[2] The separation of CO2 either pre- or post-combustion and the engineered sequestration of this deep underground. This technology is considered separately from the individual fossil fuelled power options because of its potential importance in reducing carbon emissions, because of its relative novelty, and because it is essentially and ‘add-on’ that can remove carbon from a range of power generation options and fuels for other purposes, such as transport.

The latter approach is well established analytically and widely used in business, but has not been used extensively[3], for the assessment of UK energy policy. Experience over a wide range of industrial products indicates that costs fall by 10%-30% for each doubling of cumulative production, and there is some evidence that learning rates are higher in the early stages of development[4]. The former approach enables us to consider the potential for newer products that have yet to gain sufficient market experience to allow assessment of learning curves and also provides a means to check extrapolations and avoid an excessively ‘deterministic’ approach.

Both approaches suggest a number of conclusions that are important for assessing the potential impact of policy:

- Technologies that have newly emerged and currently have a very small market share have much larger potential for securing cost reduction than more established products.
- However established technologies can effectively ‘lock out’ less developed alternatives that are initially more expensive, even if such technologies have the potential to become much cheaper in the longer term. In energy supply, where investments are long-lived, this can delay development for a long time.
- Uncertainties about the potential for cost reduction decrease as market experience increases.

This suggests a potential role for policy in facilitating the development of new technologies that may bring benefits not fully accounted for in private sector investment decisions. This will always include improved environmental performance. And where policy timeframes are longer than those of private sector investment decisions, intervention may also be justified to achieve cost reduction. However, such policies should be framed to minimise the risk associated with all new technologies.

6.4.1 Renewables

There are many renewable energy technologies that can make some contribution to meeting UK energy demand. In the PIU’s work to date, analysis has focussed on those options that have the potential to provide the largest amounts of energy in the long term – those with the largest ‘technical potential’[5]. Details of the UK’s renewable resources are provided in annex 2. The technologies considered are:

- solar photovoltaics,
- wind (onshore and offshore)
- wave and tidal stream
- energy crops

With the exception of the last, these only generate electricity. Energy crops may be used for power, heat or liquid fuels. This list excludes some important technologies that are already cost competitive, considered technologically mature, or have more limited potential for expansion in the UK[6].

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[3] A notable exception is the ‘simulation Model for UK energy Demand’: Departments of Environment and Transport, Research Report 33. 1981

[4] McDonald et al, 2000, IEA 2000

[5] Based upon estimates of technical potential derived from DTI 1998

[6] In particular solar hot water, hydropower (large and small), biomass wastes, geothermal. This is not to suggest that technologies not listed do not have a valuable current or potential role, either in the UK

New renewable energy technologies currently contribute less than 1% of global energy demand, and less than 3% of electricity, but collectively have the potential to deliver orders of magnitude more. The scope for cost reduction is therefore very large, although quite uncertain.

Detailed conclusions of the PIU's work on renewables[7] are as follows:

- There is good evidence that onshore wind is likely to become amongst the cheapest of *all* generating technologies within 20 years[8], **– less than 2 p/kWh on average in good wind speed locations.**

- There is equally robust evidence that PV is likely to continue to experience sustained and substantial cost reductions over the next 20 years[9]. However, though PV will become cost competitive in many applications in sunnier climes, it will still **be some way from being generally cost competitive in the UK – 10 to 16 p/kWh –** even taking into account the value of being a decentralised source of power. However PV is widely expected to continue to secure cost reductions after 2020 and extrapolation beyond 2020 suggests PV could become cost competitive with *retail* electricity in the UK by around 2025.

- Though we can be less certain about developments in offshore wind, where world experience is limited, engineering assessment of offshore technology issues suggests that offshore wind is likely to become **broadly competitive with conventional 'baseload' stations by 2020 – at 2 to 3 p/kWh**.

- Advanced combustion technologies for energy crops also have considerable potential for cost reduction, with capital costs projected to fall by around 50% once demonstration plants such as 'ABRE' in Yorkshire move into commercial deployment. Reductions in crop production and processing will also be required if energy crops are to become cost competitive. This makes **cost reductions in biomass more difficult to assess. Best estimates lie in the range 2.5 – 4 p/kWh.**

- More uncertainty surrounds wave and tidal technologies, with many competing devices currently at an early stage of development. As yet it is not clear which technologies will 'win', and all face technical hurdles. Parametric estimates of potential costs suggest that costs will be of the order of **4 to 8 p/kWh** for early devices, but it is not yet clear when this might be achieved.

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or elsewhere. We focus on a limited number of technologies in order to develop a broad picture of the potential of renewables to provide cost-competitive power on a large scale over a long time horizon.

[7] This paper, produced for the PIU's earlier work on renewable energy is available on the PIU website

[8] The PIU's analysis in based upon a learning rate of 20%, falling to 10% as the technology matures, and market growth of 25%, falling to 10% as markets mature. Other analyses using both engineering assessment and learning curve approaches suggest similar results, see UNDP/WEC 2000

[9] The PIU's analysis is based upon a learning rate of 18% and market growth of 25% per year. Other analyses using both engineering assessment and learning curve approaches suggest similar results, see UNDP/WEC 2000

> The UK is currently at the forefront of wave and tidal power, continued development could be secured at modest short-term cost.

It is important to note that the potential for renewable energy to make such significant contributions is not inevitable. Markets will need to be expanded under conditions where fossil fuels provide cheaper alternatives and therefore can potentially ‘lock-out’ sustainable alternatives for decades. In other words, a transition to a renewable energy based system requires active intervention in energy markets. This is likely to require support for the technologies whilst they are pre-competitive, but also measures to ensure energy markets and regulation do not continue to discriminate against small sources.

6.4.2 Combined cycle gas turbines (CCGT)

Despite recent increases in global gas prices CCGT technology is currently the cheapest generating option in all locations with well-developed natural gas supply infrastructure and is the least-cost option in the UK. CCGT plant combines low capital cost and relatively short build times (1 – 3 years) with high thermal efficiency relative to coal-fired plant.

CCGT offers a number of additional advantages: It is economic at a range of scales from around 300MW to 1500MW and in the UK at least, the widespread availability of gas means that CCGT plant may be located where it is needed on the national grid, relatively close to demands. In addition, gas-fired power stations face relatively few planning constraints. By contrast coal, nuclear and wind energy face considerable constraints upon where they may be located. Gas-fired turbines are also becoming economic at ever-smaller scales, particularly when operated in cogeneration (CHP) mode. The potential for CHP is considered separately below.

Current capital costs of a modern CCGT plant are around £270 /kW and delivered energy costs around 2.2 p/kWh. Capital costs are widely projected to continue to decline, but not by much **– falling to around £260/kW by 2020**. Engineering assessments suggest that future development will be focused on continued efficiency improvements. Today’s so called ‘F frame’ turbine technologies enable CCGTs to deliver electricity at around 55% thermal efficiency. The next generation, so called ‘H frame’ are widely predicted to raise efficiency to around 60%[10]. **Efficiency is likely to rise to around 60% by 2020.** These capital cost reductions and efficiency gains would reduce costs to around **1.9 p/kWh by 2020, given today’s gas price. A decrease of around 15%.** Projected increases in gas prices would increase CCGT power prices to around **2.05 p/kWh.**

Important though these efficiency gains undoubtedly are there is little doubt that the days of rapid cost reductions in gas turbine technology are over. Learning rates of around 20% were typical in the period to 1980, but figures of 3% to 10% are commonly cited for the period 1980 – 1995[11]. In engineering assessment terms, gas turbines are widely considered to be ‘mature’. Despite this, continued innovations are predicted, such as the so called ‘Tophat’ cycle that could eliminate the relatively expensive steam cycle, whilst maintaining overall efficiencies. In the longer term

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[10] UNDP/WEC 2000

[11] IEA 2000, UNDP/WEC 2000

many analysts suggest that gas-turbine technologies will give way to fuel cells for many applications.

6.4.3 Fuel cells

Fuel cells electrochemically convert hydrogen (or a hydrogen-rich fuel stream) and oxygen into electricity. They combine high efficiency with very low pollutant emissions; if run on hydrogen the only emission at point of use is water. If run on hydrocarbons (or hydrogen derived from hydrocarbons), emissions of NOx, SOx and particulates are near zero, with CO2 emissions dependent upon the hydrogen source. If hydrogen is derived from non-fossil sources such as renewables or nuclear, or if the waste CO2 from hydrogen production from fossil fuels is sequestered, then fuel cells offer the prospect of ‘zero emission’ power for transport and stationary applications. Fuel cells are also modular, and potentially suitable for application at a wide range of scales from micro-generation (tens of kW) to large scale power generation.

Interest in fuel cells is focussed upon two main areas of application:

- road transport, where potential for zero emissions of local air pollutants combined with high efficiencies and high power density (high power from small units) is driving considerable R&D activity; and
- stationary power generation – primarily for small scale decentralised (less than 1 MW) applications, where fuel cells offer considerable efficiency gains over combustion technologies. Quiet operation and availability of waste heat for CHP[12] make them particularly suitable for small scale CHP installations in buildings.

The potential for low cost, mass produced generation units is driving interest in both areas.

Fuel cells offer only limited efficiency advantages over CCGT for large-scale power generation and the potential for cost advantages in this area also appear more limited. CCGT already offers relatively low emissions of local air pollutants. However ‘combined cycle’ fuel cell plants, where the waste heat or gases from fuel cells are used to run a secondary steam or gas turbine, offer efficiency gains over CCGT and some analysts argue that combined cycle fuel cell plants could eventually displace CCGT for large scale power[13].

For transport applications, emissions reductions depend greatly upon fuel source. Although fuel cells are more efficient than internal combustion engines this advantage is lost if petroleum based fuels are used, as on-vehicle reformation of petroleum (to produce hydrogen) absorbs considerable energy. The role of the fuel cell in securing significant carbon emissions advantages is therefore intimately bound up with the development of low carbon supplies of hydrogen and the infrastructure, including storage that might be needed to facilitate this.

There are several basic designs of fuel cell, and whilst some are commercially available, others remain at the laboratory stage. Different types of fuel cells have different characteristics (see footnote 12). Taken together these two factors mean that

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[12] Fuel cells are often divided into ‘high temperature’ (500C+) and ‘low temperature’ (>100C) designs, generally speaking high temperature designs are further from commercial application and better suited to larger scale stationary applications, they are also able to operate on a wider range of fuels. Interest in low temperature designs has focussed more upon transport applications

[13] UNDP/WEC 2000

some fuel cells are closer to commercial competitiveness with combustion technologies in some applications than others[14]. However, at present, fuel cells are not cost competitive with combustion technologies in most applications. Estimates of current costs range from $500/kW (£300) to $10,000/kW (£7500). The speed with which fuel cells will achieve cost reductions is not yet clear. It has not proved possible to provide estimates of costs in 2020. There is widespread agreement that in the long term fuel cells will become competitive in many applications[15], with decentralised stationary CHP the first market, followed by transport applications. The central uncertainty is how quickly this will happen.

6.4.4 Combined Heat and Power

Medium and large scale combined heat and power (CHP) (with typically $30kW_e$ to $30MW_e$ output) is a well established technology. As the economic size of the technology has decrease, smaller scale CHP, often known as mini-CHP, has become available for smaller commercial buildings. However, the smallest scale products, micro-CHP (MCHP), suitable for individual homes is an emerging technology with the first units on commercial trial now.

In principal, any fuel can be used for CHP. However, gas is currently the preferred choice for new applications, except where cheap waste products are available. The electrical efficiency of CHP tends to reduce with the size of plant, the best achieving 45% and the current micro-CHP units 10% to 15%. However, in all cases, because of the association with a heat load, the effective power generation efficiency (the efficiency with which additional gas use is converted to power) is typically 80%-90%.

The economics of CHP are complex. Compared to the current alternative of CCGT from centralised power plants, there are additional costs associated with the distribution of heat, but savings from increased efficiency. However, there are also different costs associated with the locations and scale at which gas is used and electricity is produced. CHP costs therefore span a wider range than centralised supply using gas. However, smaller turbine costs are expected to continue to fall. Using the same range of gas prices as above, we estimate power costs will be in the range **1.6 – 2.4 p/kWh by 2020**. The economics are crucially dependent on the gas to electricity price difference, which is both a function of real costs and market structures. The New Electricity Trading Arrangements have reduced prices for smaller generators, and thereby severely affected CHP.

The large and medium scale CHP plants are used on industrial sites, in service sector complexes (e.g. large hotels, hospitals) and in community heating schemes with tens or hundreds of properties connected to a heat distribution system. In a level playing field market, industrial CHP would be expected to be competitive, where there are large and continuous heat loads. Effective generation costs will be site specific. Further work on the economics of industrial CHP is underway as part of the Government’s CHP Strategy. There is considerable scope for expansion in these sectors. Current output is approximately 23 TWh/year, the Government has a target that amounts to more than 40 TWh by 2010 and estimates that the cost effective potential is in the range 50 to 80 TWh/year.

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[14] For a full exploration of fuel cell types and characteristics see Hart and Brandon 1999

[15] UNDP/WEC 2000, ICCEPT 2001, Brandon and Hart 1999

In the longer term, industrial heat loads are expected to continue to decline. The scope for further large CHP increase in industry will therefore be limited. Longer term growth is therefore likely to be more for heating in buildings. For example, in most large commercial buildings and residential homes the lead boiler could be replaced by a medium sized CHP unit. This will depend on the rate of technology development. However, it is expected that improvements in micro-turbines and other small engine technology will outpace that in larger turbines, and therefore that smaller scale CHP will become increasingly economic.

The greatest potential for growth by 2050 is in micro-CHP which provides a direct replacement for a conventional gas boiler at an additional cost of a few hundred pounds[16]. Several manufacturers have units based on Stirling engines. At these capital costs, the effective generating cost is around 3.5 p/kWh, perhaps falling to 2.5 p/kWh as the market grows. This seems likely to be the lowest cost power sources for households. Within a decade it is expected that units based on fuel cells will become available and that these will have a significantly higher electrical efficiency. The technology is particularly effective in dwellings with large heat loads – for example older solid-wall dwellings. In some household application, for example very high density areas such as flats, larger scale CHP may well remain the preferred option. For the domestic sector as a whole, assuming that the issues associated with embedded generation can be quickly resolved, we estimate that CHP could contribute an additional 5TWh by 2010, 20TWh by 2020 and between 25 and 110TWh by 2050, depending on the scenario [17].

6.4.5 Coal technologies

Current coal-fired generation, based upon steam-cycle pulverised coal technologies, with flue gas desulphurisation (PC-FGD) are not cost-competitive with CCGT in the UK or most countries with well developed natural gas infrastructures. The reasons for this are that coal plant is more capital intensive, has longer build times and offers lower efficiencies than gas. In addition, current coal technologies produce much higher emissions than CCGT of all air pollutants, and flue gas desulphurisation results in large quantities of solid or liquid waste.

However there is considerable interest in advanced coal technologies worldwide, which raise efficiencies and reduce pollutant emissions compared to current designs. Interest in coal is driven primarily by the widespread availability of coal compared to gas, with particular interest in countries with limited access to gas resources, and cheap coal, such as India and China.

Leading options for 2020 include super-critical pulverised coal steam cycle plants and integrated gasification combined cycle plants (IGCC). Examples of both technology types are operating in many countries, and though IGCC is not yet considered fully commercial it is considered by any analysts to offer the best prospects for the long-term[18], and we therefore take IGCC technologies as the ‘benchmark’ for 2020.

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[16] Early units are expected to have a premium of £600 which is expected to fall to £400 once mass production starts. This can be expected to reduce further, to £200-300 once the market matures.

[17] Based on “Domestic CHP”, report by EA Technology to Energy Saving Trust and on PIU working paper projecting domestic energy use and uptake of micro-CHP to 2050.

[18] UNDP/WEC 2000

IGCC technologies gasify coal (or indeed other solid or liquid fossil fuels) to produce 'syngas' – essentially hydrogen and carbon monoxide, which is then combusted in a combined cycle gas turbine. IGCC plants could also be operated in 'polygeneration' mode to produce electricity, hydrogen and heat. The main advantages of IGCC are improved efficiency, 43 – 45% for current designs, with 50% estimated for new designs based upon more efficient 'frame 7H' gas turbines. By comparison 35% is typical for PC-FGD. IGCC plants also offer much lower emissions of SOx, as sulphur is removed in an elemental state pre-combustion, lower NOx as a result of improved combustion, and lower CO2 emissions. IGCC is also well suited to CO2 separation and sequestration, as a relatively pure CO2 stream can be removed from the syngas pre-combustion, which is much less costly than extracting highly diffuse CO2 from the post-combustion gases.

IGCC technologies are currently more expensive than conventional PC-FGD designs, with capital costs of the order of £900 - £1200 and £700 - £900 respectively[19]. This suggests that energy costs for current IGCC designs is of the order of 3.5 – 4.5 p/kWh. However, as yet, though a significant number of commercial scale IGCC plants are in operation around the world, the technology has yet to be deployed on a fully commercial basis. Commercial IGCC designs with efficiencies of around 50% and lower capital costs are predicted to be available post-2010, such designs would have capital costs of around £750 - £900 and would deliver energy at a range of approximately **3.0 - 3.6 p/kWh. This appears to be a reasonable estimate of costs for 2020.** In the longer term, efficiencies as high as 65% are claimed, based upon so-called 'Tophat' technologies. In addition continued cost reduction in the gasification cycle is also believed to be achievable.

6.4.6 Capture and engineered sequestration of CO2 ('C&S')

There is growing interest in the fossil-fuel industries in the possibility of removing CO2 from fossil-fuelled generation plants before it is released into the atmosphere and sequestering the carbon in repositories deep underground (or beneath the ocean bed[20]) such that it is effectively 'locked up' for centuries and does not enter the atmosphere.

Removing CO2 from fossil fuel plants requires two discrete steps: firstly the CO2 must be captured, and this may be done either pre- (carbon is removed from the fuel source, effectively creating a hydrogen rich fuel) or post- combustion (CO2 is removed from the waste gas stream); secondly the CO2 must be transported to a geologically appropriate repository. As yet there are no operating examples of CO2 capture and sequestration. However carbon is already stripped out from fossil fuel sources in a wide range of refining processes, and CO2 gas is removed from natural gas sources. Technologies for separation of CO2 are well understood and widely used, and long distance CO2 pipelines exist in the USA. There is also experience of sequestering CO2. The Norwegian oil and gas company, Statoil, are sequestering 1 million tonnes of CO2 per year in a deep saline aquifer beneath the Sleipner oil field. And CO2 is injected into oil fields for enhanced oil recovery – if the geological

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[19] UNDP/WEC 2000, AEAT 2001

[20] It is also possible to inject CO2 into the deep ocean, where it will effectively 'form a lake' or to dissolve it in more shallow waters. Both techniques are already attracting considerable opposition on environmental grounds see Johnston et al, 1999, Herzog et al, 2000

conditions are right, and if original reservoir pressure is not exceeded, the majority of this CO2 will remain sequestered.

C & S is feasible for both coal fired and gas fired plants. It is also feasible to produce hydrogen for vehicle fuels from fossil fuels and then to sequester the waste CO2. Interest is growing in ‘polygeneration’ plants that produce both hydrogen and electricity. But this possibility is not explored further here.

Despite the relative maturity of all the technologies involved, the two halves of the process are yet to be brought together and demonstrated. CO2 capture and sequestration is thus at the beginning of a demonstration phase. Engineering cost estimates are available in a number of studies, these suggest that natural gas and coal-fired **power generation with CO2 sequestration would cost between 3.0 and 4.5 p/kWh**[21]. A potentially important point is that advantages that stem from coal gasification technologies for the ‘ease’ with which CO2 may be removed compared to both pre- and post- combustion removal from natural gas streams **appears to effectively ‘close the cost gap’ between coal and gas if sequestration is included**.

These costs represent ‘first commercial’ application and as such could be secured before 2020 if development proceeds rapidly, however it is not clear how rapidly development of C&S technology will proceed and we therefore suggest that such figures represent a reasonable ‘ballpark’ cost for 2020. As the technologies involved in C&S are considered mature, dramatic cost reductions by 2020 appear unlikely. In the longer term it appears probable that costs could continue to fall as experience is gained and technology improves. However uncertainties about the scale and speed of development make this difficult to quantify.

A great deal of uncertainty still surrounds CO2 C&S, in particular as to the safety, environmental risks and public acceptability of sequestration. The size of the potential ‘CO2 reservoirs’ available is also uncertain. Estimates of the potential of deep saline aquifers range from 40 GtC (10 years global emissions at current rates) to 13,000 GtC (carbon content of estimated recoverable fossil fuel reserves is around 5,600 GtC) [22]. Estimates of the potential of depleted oil and gas reservoirs also vary – from 90 to 500 GtC. These aspects, as much as the technologies themselves, will have a profound impact on the development of this technology.

6.4.7 Nuclear Power

Despite the hopes of early pioneers, nuclear power has not yet been able to deliver low-cost electricity in comparison to fossil-fuelled power plants. In part this reflects the continued abundance of fossil fuels and in particular the emergence of CCGT, with all of the cost advantages outlined above. Current technology for nuclear power plants remains highly capital intensive – capital costs for current designs in UK conditions would be at least £1500/kW - and build times are long (around 5 – 7 years). Fuel costs are low – around 0.3 p/kWh, but fixed operating costs (largely resulting from the relatively large numbers of skilled personnel required to run the

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[21] , UNDP/WEC 2000

[22] The main source of this wide variation is uncertainty about the integrity of geological formations – if only ‘capped’ aquifers are suitable then the resource is much more limited (UNDP/WEC 2000, ICCEPT 2001).

plants according to current safety regulations) are high – around £80/kW, four times that of CCGT[23].

In addition, public opposition to new nuclear stations tends to result in protracted periods for planning consent – 7 years in the case of Sizewell B and, in the UK at least, projects have been characterised by cost and build-time over-runs[24].

Costs of power from new-build of current designs is largely hypothetical as no new-build nuclear has taken place in liberalised markets. The most recent UK government report on the subject suggested that new-build current designs could achieve costs of **3.9 p/kWh**[25]. Industry sources suggest that the most recently completed power station in the UK, Sizewell B, which began operation in 1995, had capital costs of £2200/kW (1990 prices), which translates (depending upon financing assumptions) to **5.0 p/kWh**,[26] though at today's prices, this figure would be substantially higher. However much depends on the assumptions made about discount rates, amortisation period and build times, as well as capital costs. Some analysts argue that if liberalised markets were to bear the full set of risks associated with nuclear power[27] current designs could cost up to **6.5 p/kWh**. Varying social and regulatory environments can also result in significant cost differentials between countries, even where basic reactor designs are the same.

Historic cost trends accurate enough to allow the meaningful construction of a learning curve for nuclear power are not available. In part this reflects the fact that the technology was historically confined to public sector investments where costs were not made transparent, partly due to national security concerns. In addition it is argued that because individual countries pursued parallel and competing state-run programmes, with significant differences in reactor design and limited ideas sharing, 'normal' market learning could not occur and construction of learning curves would not be appropriate. This is also cited as one reason for the failure of nuclear power to deliver the kind of cost reductions that would in most industries be associated with decades of market development. As a result assessment of future costs is based upon engineering assessment of new designs.

Despite the relative lack of enthusiasm in electricity markets for nuclear power in recent years there remains a plethora of new designs for nuclear reactors. The US DoE is sponsoring development of so-called 'Generation IV' reactors. Advanced designs, some of them radical departures from current reactors, aim to reduce costs, improve safety and reduce waste arisings. However, the long lead-times required to develop new concepts and secure licensing from national regulatory bodies mean that it is unlikely that any of these will be commercially available by 2020.

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[23] All figures from UNDP/WEC 2000

[24] G.MacKerron 1992

[25] 1995 White Paper 'The Prospects for Nuclear Power in the UK'

[26] S. Goddard 'Future Nuclear Programmes' in 'Where are we now on Nuclear Power' Institute of Energy Seminar, London March 1991, table on p. 69.

[27] These include political risks inherent in gaining consent, risks associated with back-end costs and decommissioning, political risks associated with waste management, and nuclear power's track record of cost and build-time over-runs.

Nearer to commercial application are so called ‘evolutionary’ designs – developments of existing designs that again aim to reduce costs and improve safety. None of these have yet been built, however the Westinghouse AP series ‘AP600’ has secured generic approval from the US Nuclear Regulation Commission. In series production, and on the basis of large scale installations based upon multiple units (four 600MW Reactors), the manufacturers claim that this reactor would cost around £1300/kW in UK conditions. However large-scale installations such as this have not been proposed for the UK market. Reactors of a similar design are likely to be commercially available in 2020, and if series production is indeed achieved by this time a cost range of between £1200 and £1700/kW seem reasonable for 2020, which would suggest costs of delivered energy of **3.0 – 4.5 p/kWh in 2020.**

With a view to the longer term – out to 2050 – nuclear development could offer ongoing cost improvements as new design concepts emerge, though nuclear fusion is not predicted to appear on the commercial scene within this timeframe[28]. A great deal will depend on levels of global support for nuclear over this period, given stiff competition from advanced fossil fuel technologies, engineered sequestration of CO2 and the renewables.

6.4.8 Summary of Power Generation Costs

Table 1 provides our preliminary estimates of power generation costs in 2020 and their likely trends over the following 30 years.

Table 1
Future Power Generation Cost Estimates

Technology	2020 cost	Basis for assessment	Level of certainty	Cost trends to 2050
PV	10 – 16 p/kWh	Learning rate and market growth rate	High	Sustained decrease
Onshore wind	1.5 – 2.5 p/kWh	Learning rate and market growth rate	High	Limited Decrease
Offshore wind	2.0 – 4.0 p/kWh	Engineering assessment & onshore learning rate	Moderate	Decrease
Energy crops	3.0 – 4.0 p/kWh	Engineering assessment & biomass combustion learning rate	Moderate	Decrease
Wave	3 – 6 p/kWh	Engineering assessment	Low	Uncertain
CCGT	1.8 – 2.1 p/kWh	Engineering assessment and learning rates	High	Limited decrease
Fuel Cells	Unclear	Engineering assessment	NA	Sustained decrease
CHP	1.6 – 2.4 p/kWh	Engineering assessment	High	Limited Decrease
Micro CHP	2 – 3 p/kWh	Engineering assessment	Moderate	Sustained decrease

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[28] PCAST (Presidential Advisory Committee on Science and Technology) Fusion Review Panel 1995

Coal (IGCC)	3.0 – 3.6 p/kWh	Engineering assessment	Moderate	Decrease
Fossil generation with CO_2 C&S	3.0 – 4.5 p/kWh	Engineering assessment	Moderate	Uncertain
Nuclear	3.0 – 4.5 p/kWh	Engineering assessment	Moderate	Decrease

6.5 Fossil Fuel reserves and prices

Analysis of the potential for development of fossil fuel reserves, extraction technologies and transmission and transportation technologies is underway. This will provide an input to our work on fossil fuel prices and trends in energy supply, in order to facilitate evaluation of energy systems development by scenario to 2050.

7. Evolution of energy systems to 2050

Analysis of potential development trends for each of the main technology options allows us to consider continued development of the supply side options by scenario. This work is currently being undertaken in detail for DTI by AEA Technology and Imperial College using the MARKAL energy system model. In close co-operation, we are undertaking an analysis of the likely development of the main technologies in order to suggest likely cost trends to 2050. It is not possible to provide detailed estimates on the basis of this work.

8. Energy Networks and Vectors

The infrastructure of the energy system consists of the physical assets required to connect the sources of supply to the points of demand. The energy carriers used are known collectively as ‘energy vectors’. Currently, the infrastructure is dominated by petroleum based liquid fuels (largely carried by rail and road), the natural gas pipeline system, and the electricity transmission and distribution network. By 2050 this infrastructure will be largely replaced, much of it incrementally. If the structure of supply and demand changes significantly or new energy vectors become more attractive, the nature of the infrastructure will need to change accordingly.

Electricity is likely to remain a key energy vector to 2050. It has a rising share of energy demand under all scenarios and is clean and convenient at the point of use. The growth in use of renewable energy sources will have important implications for the network. In all energy scenarios, the increased use of renewable energy and CHP implies major increases in the connection of ‘embedded generators’ (power stations connected to the lower voltage regional distribution networks rather than the high voltage transmission grid). This has major implications for the construction, operation and regulation of the electricity distribution networks. Beginning the process of change is urgent if sustainable generators are to be accommodated on the network in growing amounts. The Embedded Generation Working Group provides an agenda for action. In the longer term the regional networks may form the natural frameworks for electricity markets with an increased role for local generation and demand side management. There may also be a role for new local direct current networks.

Infrastructure investment in the transmission system will also be required if significant use is made of off-shore power sources (wind, wave, tidal) or if a stronger connection with European systems is required (either for increased security or to add an element of diversity).

New liquid fuel vectors may develop for transport applications. These may be only modest adjustments still based on fossil fuels, e.g. liquid petroleum gas (LPG) and compressed natural gas (CNG). More radical, low carbon options are liquid fuels derived from biological materials – biofuels. Biodiesel is already a significant fuel in some European countries. Ethanol, however, may prove a better long term prospect. Further work is required on this issue.

Hydrogen is the vector with the most potential for radical change to the energy system (see Box 2). The implications for both the environment and energy security depend on the source of the hydrogen – the benefits are most significant if it is manufactured from sustainable sources, probably renewable electricity. Its deployment by 2050 is likely to depend upon both technical developments (fuel cells and finding low cost methods of storing hydrogen) and the development of a national infrastructure. In the past, large-scale distribution infrastructures have been constructed by monopolies or public bodies; it is not clear how a hydrogen infrastructure would be constructed in any of the scenarios examined.

Box 2

Towards a Hydrogen Economy?

Energy futurologists have long predicted the rise of hydrogen economy.

Hydrogen is **not** an energy source – it does not exist in major quantities naturally and therefore cannot be mined. It has to be made, either chemically from fossil fuels or biomass, or by electrolysis of water. It is an alternative energy vector.

Hydrogen (or other hydrogen containing fuel) is required for fuel cells. Fuel cells are essentially batteries that use a fuel input. Most of the world's major vehicle manufacturers are investing heavily in fuel cell vehicle R&D programmes.

The key advantages of hydrogen for use in fuel cells are that it:
- is clean at the point of use;
- is potentially cost effective;
- would be used in modular and small scale devices;
- could be derived from many sources – central and decentralised;
- could be used introduced as a mixture with natural gas – 'hythane';
- would have both transport and stationary uses;
- would provide zero carbon fuel storage;

However, these are some key problems to be resolved before the hydrogen economy can be introduced. These include:

- perceived safety problems,
- low cost fuel cells,
- low cost hydrogen storage, and
- low carbon hydrogen production from clean sources.

The last is probably dependent on developments in renewable energy. Storage is a key issue to be addressed within hydrogen research

We conclude that, if low production costs can be achieved, hydrogen fuel cells are likely to prove very attractive in transport and some stationary power markets because of pollution and efficiency benefits. However, they only allow transformation to a very low carbon energy system in context of zero carbon electricity supply, for example a high renewables energy system. In this case, the storage potential of hydrogen may be a key factor in addressing renewables intermittency

9. Energy Storage

Energy storage is a key component in all energy systems. It provides a means of balancing supply and demand and also provides a buffer against ‘shocks’ that would otherwise interrupt supplies to consumers. In the current energy system, fossil fuels effectively act as a very cheap and convenient store.

Electricity storage is expensive, both in capacity (£300/kW) and energy (£50-100/kWh)[29] terms. Electricity systems have sufficient generating capacity to meet peak demand and using “spinning reserve” to balance short-term fluctuations in demand. In the UK pumped storage is used to reduce peak loads. In an electricity system that has a large renewable electricity component, storage issues may well be exacerbated for two reasons:

- there is less potential for using fossil fuels for storage, and
- some renewable sources (notably wind and solar) are intermittent.

There is general agreement that a contribution of up to 20% of supply is possible from intermittent sources without incurring extra costs or operational problems for managing the electricity system[30]

If the contribution of renewables to the electricity system is to exceed 20% then issues of intermittency need to be addressed. Both short term fluctuations within a day (diurnal) and summer-winter differences (inter-seasonal) need to be considered. There are four broad approaches to the problem:

- reliance on peaking plant based on storable fuels, i.e. fossil fuels or biomass,.
- load management, for example on-line scheduling of ‘interruptible’ loads such as some industrial processes, freezers and water heaters. The development of metering, signalling and control technology will facilitate this.
- interconnection with the European grid to take advantage of the reduced correlation of wind and insolation over long distances, and
- the development of improved storage technology

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[29] This is cost for a single storage cycle. The cost as an alternative to peaking plant needs to be divided by the number of cycles over the lifetime of the storage system.

[30] see for example, National Grid Company, 1999, Evidence to House of Lords select Committee on “Electricity from Renewables”. The Stationery Office, HL 78-II

Commercial energy storage options use a variety of forms of energy that are easily inter-convertible with electricity, either directly or through turbines. To date only pumped storage has been cost competitive for electricity storage at the grid scale and batteries off-grid. Other options include flywheels, compressed air and electrolytes. The Regensys system[31] developed by Innogy promises to provide a low-cost option for the future. At current construction costs the storage system has to be used to provide network services[32] other than simple storage to be cost-effective.

Providing that the technical issues associated with hydrogen storage can be overcome then its use with fuel cells provides another viable option for the future. If a future transport system had a significant hydrogen component this would significantly improve the usefulness and cost-effectiveness of renewable electricity. Longer term, inter-seasonal storage might be required to accommodate large amounts of solar power. Hydrogen storage in geological structures such as disused gas fields seems to offer the only prospect for viable inter-seasonal storage.

A number of other related conversion technologies may be important in enabling the use of different vectors. These include gas reformation, manufacture of liquid biofuels, and power conditioning, including conversion from alternating to direct current.

10. Energy Markets and Institutions

The types of changes to energy use and supply set out in the previous sections will depend upon and stimulate corresponding changes in energy market and institutional structures. Further work is planned on this issue.

11. Implications for Energy Policy Objectives

11.1 Energy System Costs

Further work planned in co-operation with DTI contractors AEA Technology and Imperial College.

11.2 Implications for Energy Security

Further work planned.

11.3 Implications for Carbon Emissions

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[31] The system is based on a regenerative fuel cell which uses a reversible electrochemical reaction between two salt solution electrolytes. Particular advantages of the system include a modular cell construction, the ability to design electrodes for power performance (the electrodes do not enter into the reaction) and the bulk storage of electrolyte thereby providing potentially very large energy capacity. See for example "A novel approach to utility scale energy storage" by Price, A et al, Power Engineering Journal, June 1999

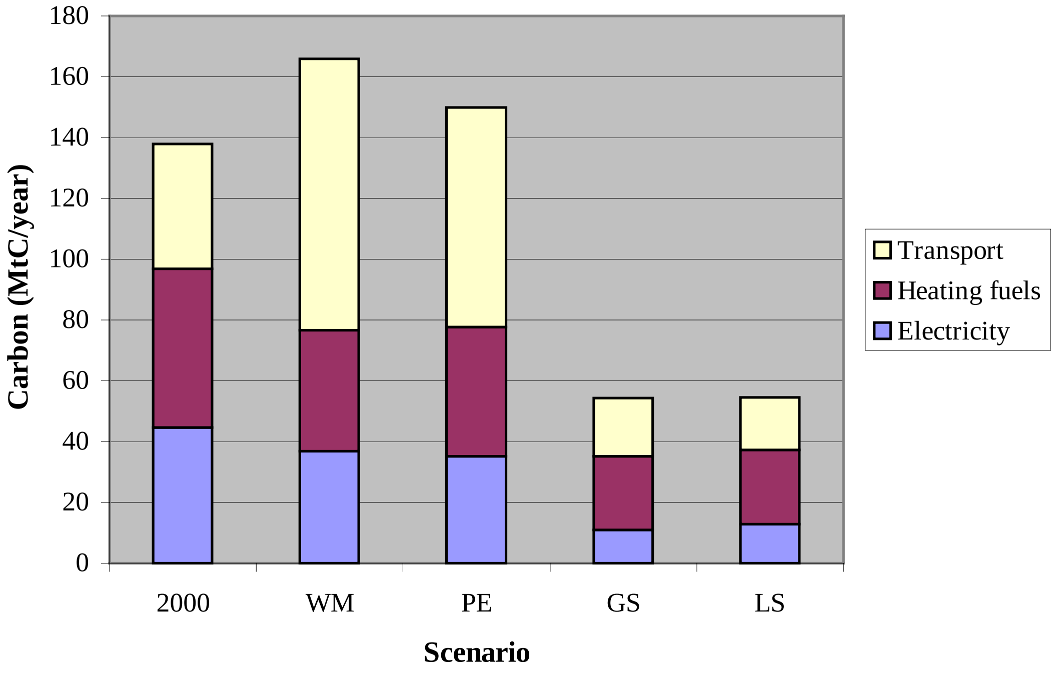
[32] For example providing reactive power, black-start and voltage and frequency stabilisation

Figure 5 shows the approximate carbon emissions from the energy system in each scenario. The data are preliminary, as further work on the energy supply mix is ongoing.

The Global Sustainability and Local Stewardship scenarios achieve an approximate reduction of 60%, although by very different means. Global Sustainability requires extensive use of hydrogen and some carbon sequestration, in addition to major increases in renewable energy use and improved energy efficiency. Local Stewardship has lower rates of innovation and only achieves a 60% reduction because of low economic growth and social change.

In the World Markets and Provincial Enterprise scenarios, carbon emissions rise to some extent. Achieving 60% carbon emissions reductions seems very unlikely in either of these scenarios. It is important to note that even a 100% non-fossil power generation system would not achieve this goal. Substantial changes in the heating fuels and transport fuels markets are required as well.

Figure 5
Carbon Dioxide Emissions (preliminary estimates)



12. Emerging Conclusions

Further work is required before a full set of conclusions can be drawn from this work. However, at present, the following seem likely.

High levels of energy efficiency and major increases in the use of low carbon supply are likely to be key constituents in sustainable energy system. There are a number of low carbon options, renewables, nuclear power and the use of fossil fuels with carbon sequestration. Our initial analysis indicates that, with continued support and development, renewables may provide the most cost effective options. In addition, they have less environmental risks in other ways.

The development of a low cost, sustainable energy system will depend mainly on two factors:

- the general rate of technological development, and
- the commitment of society and policy-makers to sustainable development.

In the *Provincial Enterprise* scenario, both these factors are low. In *World Markets*, the former is higher, but insufficient to compensate for low attention to the latter and high economic growth rate. In both cases, demand for conventional fuels is very likely to grow at a rate that will ultimately prove unsustainable. Even a wholesale conversion of the electricity system to zero carbon fuels does not alter this conclusion – the transport and heat market demands need to be addressed as well. Our analysis indicates that a sustainable energy system is unlikely to develop under market and policy conditions compatible with these scenarios. Our preliminary conclusion from this is that patterns of socio-economic development along the lines of the *World Markets* and *Provincial Enterprise* scenarios are very likely to prove incompatible with the Government's core objective of sustainable growth.

In contrast, it seems likely that the sorts of energy systems compatible with the *Global Sustainability* and *Local Stewardship* scenarios will prove able to deliver a 60% reduction in carbon emissions. Further work is required to assess in more detail the supply mixes that might be required in these scenarios, to test them against other energy policy objectives (notably energy security) and to assess costs and benefits.

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Annex 1
Scenarios for Energy Demand to 2050

This annex provides more detail on final energy in the UK, both now and in the 2050 scenarios.

Table 1 provides the current data. It distinguishes between heating fuels, transport fuels and power (energy demands for which electricity is required.) The demands are provided for each of the major energy using sectors – domestic, services (commercial and public sectors), industry and transport. Some sub-division between important end use is also provided.

Table 1
Current Energy Use in the UK

	Energy Use in 2000 in TWh			
Demand category	Heating fuels	Power	Transport fuels	Total
Domestic Sector				
Space heating	319			319
Water heating	123			123
Lights		18		18
Appliances		73		73
Total	442	91		533
Service Sector	167	98		265
Transport Sector				
Cars			320	320
Light goods vehicles			36	36
Heavy goods vehicles			115	115
Buses			14	14
Total Road Transport			485	485
Air Transport			128	128
Other Transport			26	26
Total			638	638
Industry Sector				
Industry heat	349			349
Industry power		116		116
Industry Total	349	116		465
Total	958	305	638	1902

Energy use is expected to change over time, as a result of both the changes in demand for energy services (comfort, illumination, mobility etc.) and the efficiency with which energy is used. Estimates of the change in energy services demand in 2050, relative to 2000, are provided in Table 2. These are based on the broad scenario descriptions.

The estimates have been made by the PIU in consultation with other Government departments, with reference to both historical trends and the changes in these that might occur as a result of social change. The precise numbers are, inevitably, speculative, but we have more confidence in the relativities between different activities and different scenarios. For example, we are confident that industrial power demand will grow faster than industrial heat demand, and we are confident that most demands will grow faster in *World Markets* than in *Local Stewardship*, because of underlying economic and social factors.

Table 2
Energy Services Demand in 2050 (relative to 2000)

Demand category	**Scenario** **WM**	 **PE**	 **GS**	 **LS**
Domestic Sector				
Space heating	2.06	1.60	1.72	1.40
Water heating	1.40	1.30	1.21	1.04
Lights	2.04	1.58	1.59	1.28
Appliances	1.60	1.16	1.30	1.00
Service Sector	**1.55**	**1.30**	**1.34**	**1.22**
Transport Sector				
Cars	1.85	1.70	1.11	0.65
Light goods vehicles	3.19	2.92	2.39	1.00
Heavy goods vehicles	2.48	2.28	1.86	1.00
Buses	1.63	1.63	3.58	2.39
Air Transport	7.11	2.69	2.69	1.00
Other Transport	1.66	1.29	2.75	2.75
Industry Sector				
Industry heat	1.15	1.10	0.90	0.70
Industry power	2.21	2.11	1.80	1.25

Demand for warmth in the domestic sector will grow under all scenarios, but will depend on the number of new houses built and the internal temperatures people expect. The demands for hot water, lighting and appliances will depend more on wealth and the extent of consumerism in each scenario.

Demand for energy services in commerce and the public sector will grow under all scenarios. The level of growth is expected to depend primarily on the floor area of service sector buildings.

Growth in demand for transport services is expected to be the largest and shows the most variation across scenarios. In the ‘individualistic’ scenarios (WM and PE), demand for car use grows rapidly, being constrained primarily by the time available for travel and congestion. In the ‘socially oriented’ scenarios, car uses rises less quickly or even falls as alternatives become available and acceptable. The growth in demand for goods transport shows a similar pattern, but is generally higher as it is more closely connected with economic growth. Bus and rail use show the opposite effect – growing more where there is investment in public transport. Air transport generally has the largest growth, especially in the WM scenario, where the trends of high economic growth, globalisation and low environmental concern are compounded.

In the industry sector, the current pattern of very different trends for heating fuel and power are expected to continue. Fuel demand is broadly driven by the weight of materials processed in the energy intensive sectors of the economy (metals, minerals, chemicals and paper). The expected trend is low growth, as at present, or a decline in scenarios that are more resource productive. Power demand is more dependent on the number and complexity of operations, and therefore is more closely related to value added.

Table 3 shows the change in energy intensity (the inverse of energy efficiency) that is projected for each category of activity in each scenario. This depends primarily on the rate of technical innovation in the economy and the extent to which it is devoted to improving the efficiency with which energy is used. It is therefore generally higher where growth is higher and/or environmental concern is more evident.

Table 3
Energy Intensity in 2050 (relative to 2000)

	Scenario			
	WM	PE	GS	LS
Domestic Sector				
Space heating	0.51	0.64	0.46	0.48
Water heating	0.65	0.68	0.63	0.58
Lights	0.65	0.57	0.49	0.41
Appliances	0.91	0.91	0.69	0.69
Service Sector	**0.80**	**0.90**	**0.60**	**0.70**
Transport Sector				
Cars	0.51	0.74	0.39	0.46
Light goods vehicles	0.61	0.77	0.58	0.65
Heavy goods vehicles	0.74	0.85	0.71	0.80
Buses	0.62	0.77	0.58	0.71
Air Transport	0.80	1.00	0.70	0.90
Other Transport	0.80	1.00	0.50	0.75
Industry Sector				
Industry heat	0.44	0.55	0.36	0.44
Industry power	0.72	0.78	0.61	0.72

In conjunction with colleagues in DEFRA, we have examined historical rates of improvement in industry and the potential in buildings and transport technology based on reasonable expectation of technical change.

Energy efficiency improves in all end use in all scenarios. In all cases it improves fastest in GS, due a combination of rapid technical innovation, policy and the support of citizens and business. Improvements are lowest in PE, where these factors are largely lacking. WM and LS have intermediate (though very different) characteristics. Average annual efficiency improvement rates vary from 0% for freight transport in PE to 2% annually for industrial heating technologies in GS. These are consistent with rates experienced in the recent past.

The biggest improvements are seen in:

- space heating – where the scope for long term improvements in building fabric and heating system efficiency are large;
- lighting – where the uptake of current efficient technology is very low;
- cars – due to the large scope for improvements, with the high rates of efficiency that exist in this sector, in both engine efficiency and design; and
- industrial fuel technology – representing a continuation in historic trends as new, more efficient products and processes enter the market.

Lower rates of improvement seem likely in technologies such as water heating, freight transport and air transport, largely because they are currently less inefficient than some other uses of energy.

Table 4 shows the resulting effect on energy use in 2050.

Table 4
Energy use in the UK by Scenario in 2050

	Final Energy Use in 2000 in TWh			
Demand category	WM	PE	GS	LS
Domestic Sector				
Space heating	334	327	253	215
Water heating	112	109	94	74
Lights	23	16	14	9
Appliances	106	77	65	50
Total	576	529	426	349
Service Sector	329	310	213	226
Transport Sector				
Cars	302	402	138	96
Light goods vehicles	70	81	50	23
Heavy goods vehicles	211	223	152	92
Buses	14	18	29	24
Total Road Transport	597	724	369	235
Air Transport	727	344	241	115
Other Transport	34	33	35	53
Total	1359	1101	646	403
Industry Sector				
Industry heat	175	210	114	106
Industry power	186	191	127	105
Industry Total	360	401	241	211
Total	2624	2341	1526	1189

Final energy use grows by 40% in WM and 23% in PE. In GS it falls by 20% and in PE by 37%.

In the domestic and service sectors, the potential for change is somewhat constrained by the long lifetime of buildings. New buildings will have much higher efficiency than the current stock in all scenarios. In the domestic sector, some efficiencies gains will be taken as comfort. In both sectors we expect modest increases in demand in WM and PE, but falls in GS and LS

The biggest differences between scenarios are in the transport sector. Road transport energy use grows considerably in WM and PE, but falls in the very different transport systems that develop in GS and, especially, LS. Air transport use grows hugely in WM, but also quite significantly in GS and PE.

In industry we expect demand for energy as a whole to fall in all scenarios, and very significantly in GS and LS. This reflects a continuation of historic trends. However, there is a major difference between fossil fuels and power use. The latter is expected to rise in all scenarios except LS, where the decline is small. In all cases, power demand is broadly comparable with fuel demand by 2050, in contrast to today when it only forms 25% of demand.

Annex 2
Renewable energy resources

A large number of studies have estimated the future potential of renewable energy technologies, both in terms of the technically feasible energy output that could be secured from each technology type, and the economic potential, taking into consideration cost and other limiting factors.

Precise terms and definitions differ, but it is important to distinguish a number of key concepts, most of which are common to all studies:

Available resource refers to the total amount of different forms of renewable energy available for extraction – for example the energy in ocean waves, or solar insolation levels. For several technologies (essentially solar, wind and wave and biomass), UK available resource is very large indeed.

Technical potential (also referred to as accessible resource) refers to the amount of energy that might be extracted from the available resource, using known technologies (note that for future technologies judgements are required about conversion efficiencies – will they improve, how much?). Again, for a number of technologies, technical potentials are very large – taken together they exceed UK primary energy consumption several times over.

Practicable potential (also referred to as practicable resource) refers to the amount of the technical potential that might reasonably be accessed, taking into account various technical and physical limiting factors such as competing land (and ocean) use and often includes further limitations, such as electricity grid and system constraints. A closely related concept (definitions of terms do differ) is *accessible potential*. Practicable resource is more difficult to assess in the long term, since many constraints may change over time, or reflecting different political/societal priorities. For the latter reason, it also tends to show significant variation between studies in different parts of the world.

Economic potential refers to the amount of accessible potential that is economically viable, given current technology, or with future, better (and cheaper) technologies. Economic potential depends upon the cost of alternative/competing energy sources, which for the UK generally means conventional means of generating grid electricity (though some renewables can also provide heat, and there are some niche markets such as remote telecommunication/navigation where the electrical alternative is not grid power). It is important to note that policy may influence both the development of renewables and the cost of conventional competitors – for example though a carbon tax.

2.a.1. Existing Analysis

Analysis of the full range of renewable resource available in the UK was undertaken for the DTI by ETSU, *Renewable Energy* (DTI 1994 ref) synthesised several studies of individual technologies commissioned for the DTI New and Renewable Energy Programme. This work was updated for the review of renewables policy in the UK initiated in 1998 and published as *New and Renewable Energy: Prospects in the UK for the 21st Century, Supporting Analysis (DTI 1998).* Often considered the 'benchmark' UK renewable energy assessment, this work forms the starting off point for our discussion here. The main findings in terms of estimates of technology potentials for 2025 are summarised in table 1.

Table 1. Resource and cost in 2025 (derived from DTI 1998)

Technology	Cost* p/kWh	Economic potential at this cost* TWh/yr	Technical potential TWh/yr	Practicable potential TWh/yr
Building integrated photovoltaics (BIPV)	7.0	0.5 **	266	37**
Offshore wind	2.5 - 3.0	100	~3500	100
Onshore wind	<3.5	58****	317	8****
Biomass (energy crops)##	4.0	33	'large'	'large'
Wave	4.0	33	600 +	50
Tidal stream#	7.0	1.8	36	1.8
Small Hydro	7.0	1.8	40	3
Waste technologies: MSW (municipal solid waste) Landfill gas	7.0	6.5	13.5	6.5
	2.5	7	7	7

This table is an interpretation and simplification of the DTI analysis, therefore some caution is needed in interpreting these figures:

'Technical potential' here is termed 'accessible resource' in the DTI study and practicable potential is termed practicable resource. These terms are used in order to convey that all figures are for potentials – potential energy output, not available resource input – and because these terms are closer to those used in the international studies considered below.

* ETSU derive 'resource cost' curves for all technologies, essentially supply curves, that increase with cost, in most cases up to a maximum level at which external (practicable potential) constraints cut in. The costs quoted are those at which this maximum level of deployment would be achieved. Smaller resources would be available at lower costs. In other cases, cost rather than technical constraints is the limiting factor, and larger resources would be available at higher costs

** BIPV- practicable potential limited by assumptions about penetration rate into new buildings, economic potential to even lower penetration of those new buildings with potential for offset building costs

**** Assumes minimal constraints due to planning, network and build rate

***** Assumes constrained build rate and no network reinforcement – hence the rather perverse result that economic potential higher than practicable potential!

Tidal stream devices exclude large barrages, ruled out by the DTI on capital cost and environmental grounds. Practicable potential/resource is not provided in the study for this technology type

Assessment restricted to energy crops for the purposes of this analysis for reasons discussed below, additional contributions are assessed in the DTI work – from forest and agricultural wastes and residues, and from other biodegradable wastes.

The DTI assessment also includes passive solar design and active solar, although important these are dealt with in work on energy productivity because of the close overlap with building efficiency in total building design.

All figures quoted are based upon 8% discount rate.