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Diversity and Security in UK Electricity Generation:

The Influence of Low Carbon Objectives

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Abstract

We explore the relationship between low carbon objectives and the strategic security of electricity in the context of the UK Electricity System. We consider diversity of fuel source mix to represent one dimension of security – robustness against interruptions of any one source – and apply two different diversity indices to the range of electricity system scenarios produced by the UK government and independent researchers. Using data on wind generation we also consider whether a second dimension of security - the reliability of generation availability - is compromised by intermittency of renewable generation. Our results show that low carbon objectives are uniformly associated with greater long-term diversity in UK electricity. We discuss reasons for this result, explore sensitivities, and briefly discuss possible policy instruments associated with diversity and their limitations.

JEL Classification: *Q40 (Energy - General), Q42 (Alternative Energy Sources)*

Keywords: *Diversity, Security, Low Carbon, Wind Generation, Electricity*

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Introduction

As part of the resurgent debate about energy policy in the UK, issues of strategic energy security have again acquired a high profile. This has been driven in part by increasing concern over oil dependence; however in the UK context there has been equal or greater debate over issues of gas dependence. The latter has been driven by a rapid move towards natural gas in power generation, a trend that is projected to accelerate in the near term as part of government efforts to address environmental concerns. Combined with the decline of UK coal production and projections of declining production in the North Sea, this has resulted in projections of rapidly rising dependence upon imported fossil fuels.

Nevertheless, many professional energy analysts remain deeply sceptical about security-related arguments. They point to co-dependence of importers and exporters and the nature of international markets as reasons not to fear overt dependency-related threats, and highlight that the threats to energy security are more subtle and varied than portrayed in the crude expression of concerns about import dependence. The major interruptions of the UK energy system in the past three decades have arisen from miners' strikes, domestic fuel blockades, and occasional power cuts – not from foreign supply dependence. Throughout this debate there has been little analysis of security issues drawing on any quantified methods. Fears about import dependence are ranged against an established view that sees little rationale even to engage in much debate on issues of energy security, let alone consider methodologies by which to do so.

At the same time, in the recent White Paper (DTI, 2003a), the UK government established highly ambitious long-term goals relating to climate change, with the objective of moving towards a 'low carbon economy' and a target to cut CO2 emissions by 60% by mid Century. The White Paper states that this should be achieved without detriment to UK competitiveness or security.

To our knowledge, neither the Department of Trade and Industry (DTI) nor independent researchers have previously used any formal method to study the consistency (or not) between the White Paper's low carbon goals and the systems security. In this paper, we develop a quantified analysis to assess the diversity of UK electricity generation over the coming decades, and explore its relationship to low-carbon objectives. Particular attention is paid to the role that wind power may play in improving system diversity, including a review of the UK wind resource and its potential integration in to the UK electricity network.

1. **Analysing Security and Diversity**

There are many different kinds of security. In relation to energy systems, Mitchell (1996) identifies three different kinds of threat to security – the threat of sudden interruption, the economic threat posed by a cartel, and the threat of long-term disruption of supplies associated with resource distribution and depletion. In terms of threat management, these raise different specific responses. Our analysis is primarily in relation to issues of long-term strategic dependence, though a more diverse system is likely to be less vulnerable to all three kinds of challenge.

Diversity within electricity production has been broadly defined as "avoiding excessive reliance on any single technology, fuel or other factor."[4] A more diverse system is perceived as having a number of benefits that make it preferable to one that is less diverse. In particular, diversity is considered to contribute to achieving energy security since disruption of any one source will have a smaller impact on overall energy supply. Similarly, the effects of price volatility are likely to be mitigated where an increasing range of sources is employed in electricity production.

Quantified diversity evaluation was introduced to the analysis of energy systems by Stirling (1994) who applied the Shannon-Wiener index described below to examine the diversity of UK electricity supplies. His core argument was that the sources of security threats are inherently hard to predict, so that policy instead should 'concentrate on the solution', namely acknowledge that diversity is an inherent and value-free property of systems that can be quantified. More recently, a technical paper developed as part of the Energy White Paper process applied a diversity index approach to demonstrating that over recent decades, the UK electricity system has become more diverse (DTI, 2003b).

The following analysis extends this work, exploring the relationship between low carbon objectives (and in particular the related deployment of renewable technologies) and the diversity and security of the UK electricity system. In brief, the approach adopted involves calculating a diversity index for a range of future scenarios each of which describes the fuel mix in a future electricity system. This enables us to identify the implications that these scenarios have for the diversity and thus security of the system. Conducted as part of the SuperGen programme, which examines the challenges involved in developing a sustainable electricity system in the UK, the focus is the electricity sector. It is this sector, more than any other, that underpins the modern economy and in which security is of increasing concern, particularly in relation to natural gas.

2. Diversity methodology

This paper relies on two methods for the quantification of diversity in the UK electricity system. The first draws upon work by Stirling (1994), assessing diversity using the Shannon-Wiener index, which is derived from the study of the vulnerability and other characteristics of biological systems. This index has the merit of incorporating both the

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[4] The Review of Energy Sources for Power Generation (DTI, 1998)

concepts of variety and balance, recognising that a system which relies on a given number of fuel types may be more or less diverse, depending on the proportion of generation accounted for by each of these fuel sources. The index is calculated according to:

$$\sum_{i=1}^{I} - p_i \ln(p_i) \qquad (1)$$

where p_i is the proportion of generation represented by the ith type of generation.

The minimum value taken by the index is zero, where there is only one source of generation. Since the index seeks to quantify an inherently nebulous concept, it is not easy to explain precisely the significance of different values, but a good indication may be obtained from Figure 1, which shows how the diversity index for systems of *n* equal independent contributions changes as *n* grows. A system with 2 equal components has diversity 0.69, with 3 equal components this rises to 1.1, and with 10 equal components to 2.3. The diversity index rises above 2 for a system with more than 7 equal components.

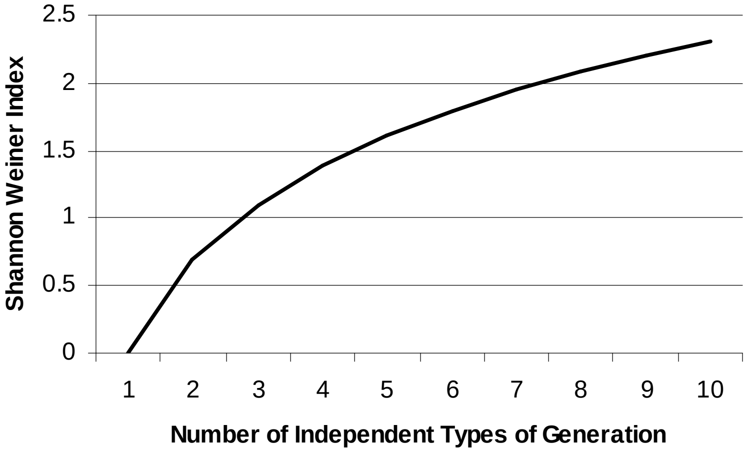

Figure 1: *Shannon-Wiener Index*

From Figure 1 it is apparent that a value below 1 indicates a system that is highly concentrated and dependent upon one or at most two sources, to a degree that would clearly threaten supply security in the event of any sustained interruption. A value above 2 indicates a system with numerous sources, none of which play a dominant role; such a system can reasonable considered to be quite secure in the face of interruption of any individual supply component.

As with any single measure, it should be recognised that the Shannon-Wiener Index is a simplified measure of diversity. In particular, the results are dependent on assumptions made about the independence of sources.[5] The value of the index increases with the number of sources so that the finer the degree of disaggregation, the more diverse the system appears. Since no one source is either entirely independent of or dependent on any other, the measure is a simplification.[6] Here, we pay particular attention to the interdependence between different forms of gas and wind (see Section 4). Since we are ultimately concerned with security, decisions on the appropriate level of aggregation are made with reference to whether the security of one source is independent of the security of the second or third. In Section 6 a basic analysis is conducted to determine the sensitivity of the results to the assumptions made concerning source differentiation.

The second method of diversity assessment presented in this paper is the Herfindahl-Hirschman index, which measures the degree of market concentration. Assuming that p_i is the market share assumed by the ith firm, or the proportion of generation met by one particular fuel source, then the index is calculated according to:

$$H = \sum_{i=1}^{I} p_i^2 \tag{2}$$

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[5] Defined by Stirling (1998:40) as disparity: "the nature and degree to which the categories themselves are different from each other".

[6] Following Stirling (1994:198), we note that the concept of diversity is not restricted to type of fuel, but also to technologies employed, the geographical source of fuel and to institutional frameworks.

where p_i is expressed as a percentage. The Herfindahl-Hirschman Index takes into account both the relative size and distribution of each source, increasing as the number of firms falls and the disparity in the size of those firms increases. The maximum value of the index is 10000 in the case of a monopoly, falling towards zero as the market moves towards a situation of perfect competition. Figure 2 shows the value taken by the index as the number of sources of generation increase.

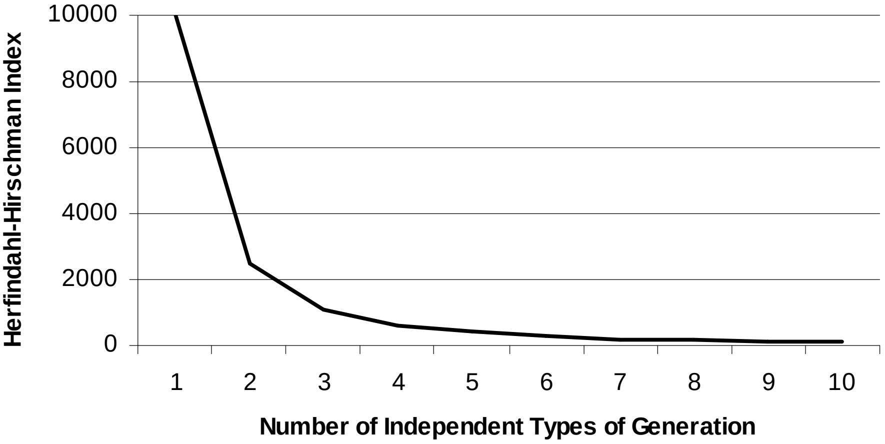

Figure 2: *The Herfindahl Hirschman Index*

The US Department of Justice use the Herfindahl-Hirschman index to assess market concentration, and suggest that a result less than 1000 indicates a competitive market place, and that a result greater than 1800 indicates a highly concentrated market place. However, these benchmarks are not necessarily appropriate in the case of electricity generation. Furthermore, the Herfindahl-Hirschman index is again a simplified measure, with assumptions having to be made as to the independence of energy sources. The results obtained using the Herfindahl-Hirschman index are presented throughout Section 5, and are consistent with those obtained using the Shannon-Wiener index.[7]

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[7] Stirling (1998) outlines reasons for using the Shannon-Wiener index in preference to the Herfindahl-Hirschman index. Amongst these (i) the S-W index is more readily derived from first principles (ii) under the S-W index, the rank orderings of systems are not sensitive to changes in logarithm base, whereas changes in the exponent used in the H-H index lead to changes in the rank orderings of systems.

3. Scenario Selection

Amongst the scenarios that have been developed for the electricity generation sector are those by Future Energy Solutions for the DTI (HMSO, 2003a), the Institute of Public Policy Research (IPPR, 2004), and the Tyndall Centre (2003), based on work by the Royal Commission on Environmental Pollution (RCEP, 2000).

In particular, we consider the scenario work conducted by FES for the DTI White Paper analysis. The modelling process is of greater technical sophistication than that adopted by the IPPR and RCEP, and is thus of greater relevance and interest. Moreover, the data allows the examination of changes in the fuel mix (and therefore diversity) over time, rather than being limited to a point in time. Finally, these scenarios were used by the government as the basis for analysis in the Energy Paper White Paper. The scenarios developed by the IPPR and the Tyndall Centre will be considered as part of the broader discussion of results and exploration of sensitivities.

The three reference scenarios hypothesised by the DTI correspond to Business As Usual ("Baseline"), high environmental concern ("Global Sustainability"), and low environmental concern ("World Markets").[8] For each of these three scenarios, reductions in the level of carbon dioxide emissions are imposed, ranging from a 0% reduction to a 70% reduction on 2000 levels. The fuel mix for the electricity demand in each of these three scenarios is generated under a range of cost assumptions, as outlined in DTI (2003c). The focus is on the 0% and 60% reduction case since the latter corresponds to the target recommended by the RCEP and adopted by the Government (DTI, 2003a). Brief consideration is also

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[8] Further information on the assumptions underlying these scenarios is given in DTI (2003c). In the Baseline scenario, the values of society and environmental policies remain similar to today. The Global Sustainability Scenario is based on strong social and ecological values, with collective environmental activity. In the World Markets Scenario, consumerist values predominate and environmental concerns are sidelined. In both the Baseline and the Global Sustainability Scenarios GDP growth is projected at 2.25%, whilst in the World Markets Scenario growth is 3.0%.

given to the 45% reduction case in order to show the sensitivity of results to changes in emissions targets.

The diversity indices are applied to each of these three scenarios. This requires that energy sources are aggregated appropriately so as to reflect the level of independence. One production technique may use different fuels, for example, and thus represent two different sources of energy in terms of security. With conventional forms of electricity generation, it is possible to assess the independence of electricity supply through an analysis of its source, transport, storage and combustion pathways. Where there is little correlation between these factors for different sources of electricity generation, the sources are seen as independent and therefore adding to system diversity.

4. Renewable Generation and System Security

Adding renewable technologies to the generation mix will increase the number of independent sources of generation. However, the security of a system is not only dependent on diversity in fuel sources, but also on the availability of these fuel sources. Since much renewable generation is intermittent in nature, it is frequently suggested that a system that relies on such sources is inherently less secure than a system reliant on conventional generation techniques. In the UK, this debate has centred on the impact that an increased proportion of wind generation will have on the reliability of electricity supply. This section examines how the intermittency of wind might affect its contribution to system security and whether this calls into question the incorporation of wind in diversity analysis. Also, we consider and whether wind generation is best represented as one source of generation, or whether it should be somehow disaggregated according to the location of the turbine.

4.1 Wind Power and Capacity Credit in Electricity Networks

The introduction of intermittent generation, such as wind energy, into the analysis adds a further level of complexity. Electricity supply from wind power is not affected by other conventional energy sources, thus wind generators represent an independent electricity supply that adds to the diversity of the generating system.[9] However, the availability and variability of wind forms an intrinsic part of the resource that cannot be controlled, raising the obvious issue of how reliable wind power is in meeting electricity demand.

Wind power will be integrated into existing electricity generation and supply systems. When seen as a whole, these systems reliably deliver electricity from a range of generating technologies. None of the individual components of the system are wholly reliable: strictly speaking, all show some degree of intermittency in their electricity output. As such, the electricity generating system can be seen as a collection of generators with statistically varying output, which together form a reliable electricity supply system. When seen in this light, wind power represents the addition of an electricity generator that has different statistical properties of supply availability than conventional generators.

The *capacity credit* of a source represents its ability to replace conventional generating capacity whilst maintaining the same level of overall system reliability, and wind energy has some capacity credit because it makes a statistical contribution to system reliability. A typical wind farm operates with a *capacity factor* of around 30% (site dependent), meaning that over the long term the farm will produce around 30% of the ‘rated capacity’ (i.e. the maximum output at optimum wind speeds). A large body of published research (Grubb, 1991; Grubb & Meyer, 1993; Milborrow, 2001 & 2003; Dale et al, 2003) has demonstrated that capacity credit of wind energy is approximately equal to its capacity

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[9] It could be argued that the diversity value of wind is greater than that of other additional (conventional) fuels, as its availability is independent of any commodity, transport, trading, pricing or political system.

factor when the installed capacity of wind is small in comparison to the remainder of the network. The capacity credit of wind (relative to the total installed capacity) decreases as the installed capacity of wind rises.

To understand wind’s contribution to system peak reliability (and its capacity credit), it is crucial to recognise that because no plant is 100% reliable, power systems always carry a ‘reserve margin’ of spare capacity. The reserve margin is typically at least 20% of capacity (to allow not only for plant failures, but also the unpredictability of electricity demand on the timescales that would be required to build more plant). Because wind energy *may* be available at times of high demand, or when other sources are unavailable, the level of reserve margin on conventional plant can be reduced for the same overall level of reliability. Various studies of wind energy in the UK show its *capacity credit* declines as the capacity rises above a few gigawatts (compared to total installed capacity of about 60GW), but it remains non-negligible for contributions up to around 20% of UK electricity supply. The extent of contribution is an empirical question which we now briefly consider.

4.2 Wind Variability and Geographic Diversity

The variability of wind is not a fixed property, because different geographic locations will experience different wind conditions at any given time. Just as the profile of total electricity demand is far smoother than the demand profile of any one household or office, combining the output from different wind generators (via the network) acts to smooth the aggregate profile of wind electricity production.

The key to this smoothing effect is that wind speed correlation decreases with increasing distance between wind generating sites. No two wind sites will experience identical patterns of wind speed over the long term, and this difference in wind characteristics can be exploited to reduce the overall level of intermittency from a diversified portfolio of wind generating sites. Figure 3 presents the correlation between pairs of onshore wind sites in the UK as a function of the distance between the sites, and demonstrates that sites far apart exhibit very low cross-correlation.

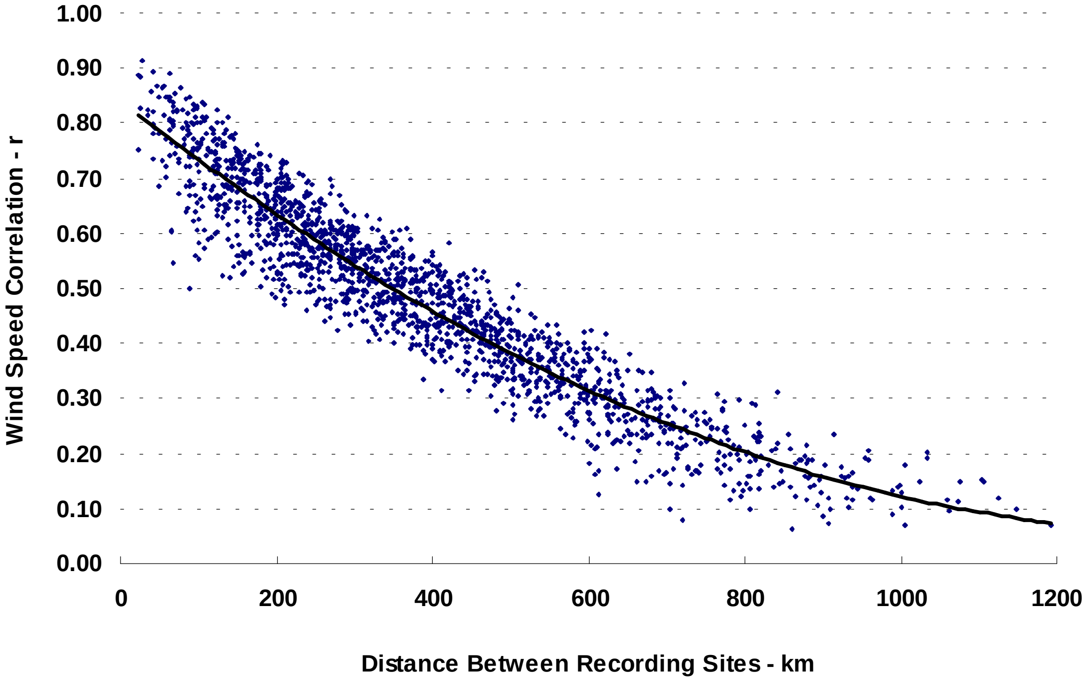

Figure 3: *UK Wind Speed Correlation by Distance between Recording Sites*[10]

By developing new wind farms with wind patterns that show a low correlation with existing sites, the overall variability of electricity supplied from the wind power portfolio would be reduced, and hence the reliability of supply improved. Clearly this smoothing effect is limited by the area over which the electricity network extends – once wind capacity has been installed at the most distant locations available on the network, additional capacity will exhibit higher correlation to the existing capacity as there is necessarily less distance between them.

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[10] Data refers to 1770 pairs of wind speed recording sites, uncorrected surface wind speed. Data recorded over a period of 15-20 years.

Despite the effects of geographical diversity, concerns have been raised that occasional, large scale weather systems will cause output to drop across the system. Were this to occur during a time of high electricity demand - between 5-7pm in winter in the UK - the value of wind to peak security would be seriously undermined. The likelihood of such a drop in output is explored in Figure 4(a) which shows the percentage of UK sites that have simultaneously experienced calm conditions for one hour, over the period for which adequate data is available (1982-2000). It is apparent that with a diversified wind power system, the chance of all wind generating capacity experiencing calm conditions is extremely remote. Indeed, there has not been a single hour in the last 15-20 years when conditions of total calm were experienced right across the UK. Figure 4(b) represents the same data for calm conditions persisting for 1 day (24 hours midnight to midnight). The result is even more stark: such periods are extremely rare and typically affect less than 2% of the UK with the remaining 98% of the UK experiencing wind at these times.

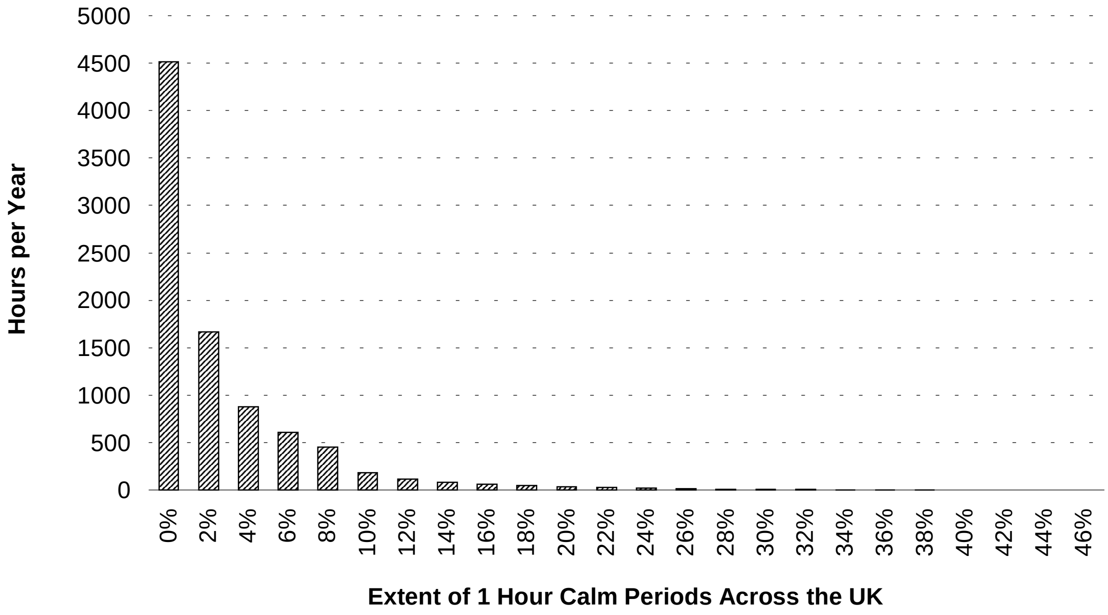

Figure 4(a): Frequency & Extent of Calm Conditions in UK, Persisting for One Hour[11]

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[11] Calm Period = 1 Hour, 50 or more records per hour.

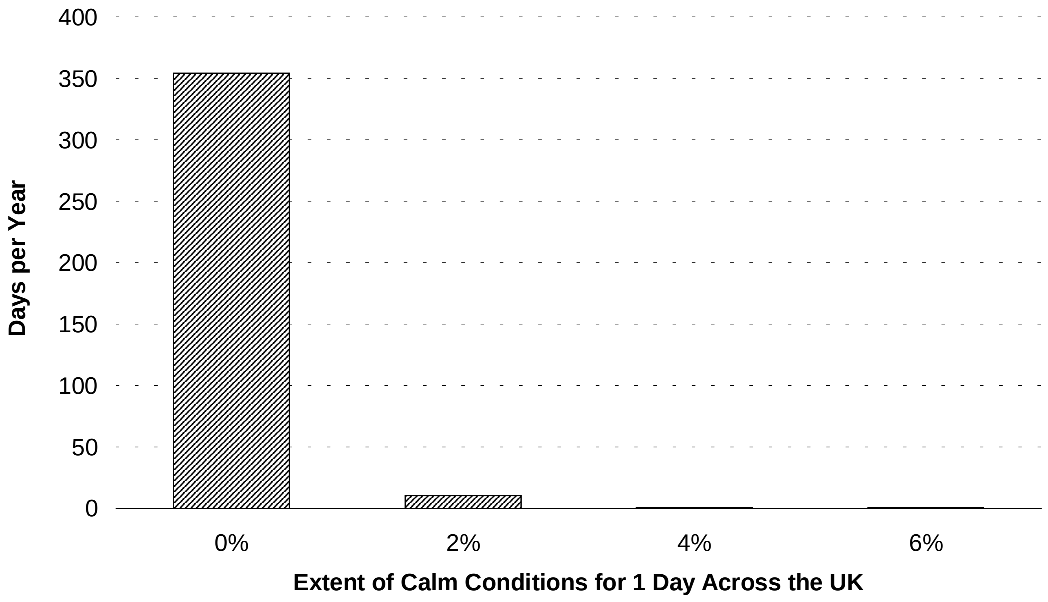

Figure 4(b): Frequency & Extent of Calm Conditions in UK, Persisting for One Day[12]

Thus by developing new wind farms at a range of locations in the UK, the overall variability of electricity supplied from the wind power portfolio would be reduced, and hence the reliability of supply improved. Clearly this smoothing effect is limited by the area over which the electricity network extends – once wind capacity has been installed at the most distant locations available on the network, additional capacity will exhibit higher correlation to the existing capacity as there is necessarily less distance between them.

4.3 The contribution of wind energy to system diversity and security

The impact of geographical diversity raises the question of whether regional wind resources should represent independent sources of energy, thereby increasing the assessed level of system diversity. From the correlation/distance relationship shown in Figure 3, the average correlation between different sites exceeds 0.5 for sites 300km apart, and remains around 0.3 even for sites 600km apart. Whilst this does imply that

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[12] Calm Period = 24 consecutive hours to midnight, 50 or more records per hour

wind energy in central Scotland would have a considerable degree of independence from sites some 600km south in the Thames Estuary, for example, the reality is that wind energy is being developed across a reasonably wide geographical basis from an early stage and it would be very hard to model any one region as statistically independent from another. Nor is there evidence to indicate that the pattern of offshore wind variability is likely to be radically different from onshore (Sinden, 2004). On the basis of these two findings, it was decided that the UK wind resource should be treated as a single source of electricity generation in the following diversity assessment.

Even with wind considered as a single generating source (with characteristics corresponding to geographically diverse siting), the collective wind output will still show variability. For wind power to gain a significant portion of the electricity generating market (up to 20%), there will need to be confidence that it can both contribute to diversity and be reliable in contributing to electricity supply. The preceding discussion confirms that this is possible. By taking a planned approach to the development of wind power, the impact of distance on correlated output can be fully exploited within the UK, improving the reliability of wind power and minimising the additional backup capacity required due to the presence of wind power on the network. The additional backup required to support 20% electricity generation from wind is estimated at around 4GW.[13] This level of additional backup would result in system-wide reliability of supply equal to that currently enjoyed, while exploiting the distance/correlation relationship of wind may result in a reduced backup requirement.

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[13] Around 26GW of wind generating capacity would be required to meet 20% of UK electricity demand, which would in turn displace around 5GW of conventional capacity. This calculation assumes a reduced capacity credit for wind of around 20%. Applying the reduced capacity credit to the installed wind capacity: 20% x 26GW = 5.2GW of displaced conventional capacity (Dale et al, 2003). However, the 26GW of wind is actually providing the equivalent electricity production of around 8GW of conventional capacity (this calculation assumes a capacity factor for wind of 35%. Applying this capacity factor to the installed wind capacity: 35% x 26GW = 9.1GW of conventional capacity equivalent). To meet the shortfall between the 9GW equivalent capacity displaced and the 5GW actually displaced by wind, around 4GW of conventional capacity would need to be retained (in the case of wind displacing existing conventional capacity) or built (in the case of wind providing a net increase in overall generating capacity). It is this 4GW that represents the additional backup capacity required due to the variability of wind power output.

Note that the ability of wind energy to contribute to system security, in the context of possible supply interruptions and diversity arguments, is not necessarily constrained by its capacity credit. Whereas capacity credit concerns only issues of capacity adequacy, supply interruptions may be just as likely to affect *energy* inputs. So, for example, as the capacity of wind energy rises, the capacity 'backup' is most likely to emerge as either CCGTs, or the maintenance of old coal plant held in reserve. There is modest capacity to store gas in the UK, and the storage capacity would probably be enhanced if the gas capacity rises; the ability of coal plants to produce in the event of coal supply interruptions may also depend on coal stocks. In the event of fuel interruptions, the contribution of wind energy to security would then be in terms of its ability to displace gas (or coal) usage that would draw down on the storage capacity. This contribution clearly exceeds the pure capacity contribution at peak; it is defined by the probability of wind (or other sources) contributing at any point within the period covered by the storage capacity of the interrupted fuel.

In none of the DTI scenarios here, even with 60% CO2 emission reductions, does wind energy significantly exceed 20% of electricity supply. Given the data presented above, this indicates that for the purposes of diversity analysis, wind energy can quite reasonably be treated as an independent contribution to the diversity and security of UK electricity on a par with conventional sources.

4.4 Aggregation of Other Generating Systems

Application of the Shannon Wiener index to future scenarios involves a similar consideration of other sources of generation. The DTI, for example treats combined gas turbines and combined gas turbines with carbon capture as separate sources of generation. Although justified when looking specifically at emissions of carbon dioxide, this separation is less appropriate when addressing system security. Given that gas is still required for generation, carbon capture does little to change system security and the two categories are thus aggregated. In Section 6 we examine whether changes in this assumption have a significant effect on measures of diversity.

However, gas from different sources may be considered to represent independent forms of generation. In particular, pipeline gas may be regarded as a separate from Liquefied Natural Gas (LNG), since interruption in the supply of one may not significantly affect the other (though it could obviously have knock-on effects on markets and prices).[14] In line with this observation and with predicted trends in energy supply, sensitivity analysis is conducted to examine the implications for diversity when it is assumed that until 2020 the gas supply is through pipeline only. From this date onwards, it is assumed that half of demand is met by piped gas and half by LNG, and that these sources can be considered independent.

Consideration of other generation sources also suggest that further disaggregation may be necessary to make an accurate assessment of the security of the system. Whereas Nuclear and PV may each be regarded as a single source, other generation techniques may represent a number of independent sources. Hydropower, wave and tidal generation may each represent more than one source, depending on the resources available in specific locations. Tidal generation, for example, may be disaggregated according to different tidal patterns in different parts of the UK. Both CHP and Biomass encompass a range of independent fuel sources, such that further disaggregation would allow a more accurate assessment of the diversity and security of future scenarios. Similarly, generation from agricultural waste is likely to be independent of generation from industrial or municipal waste.[15] However, such a precise disaggregation is unlikely to be reliable, and is not provided in the scenarios. Due to these limitations, each renewable technology is treated as one source of generation.

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[14] Similarly, gas from Russia may be regarded as separate from the Middle East. Note that the IPPR does specifically include an ‘import’ category.

Once the data has been aggregated or disaggregated as described above, the Shannon-Wiener index is calculated for the fuel mix given in each scenario. In the case of the DTI estimates, the index is calculated at ten-year intervals over the period 2000 – 2050. The results are presented in the first part of Section 5. For all other scenarios, the index is calculated for the date described in the scenario, with results discussed in Section 6.

5. Results of Analysis

The data presented by the DTI allows examination of the evolution of system diversity between 2000 and 2050 under each of the proposed scenarios (see Section 3 for details of these scenarios). We apply the Shannon-Wiener index to this data and present the results in Figure 5(a).

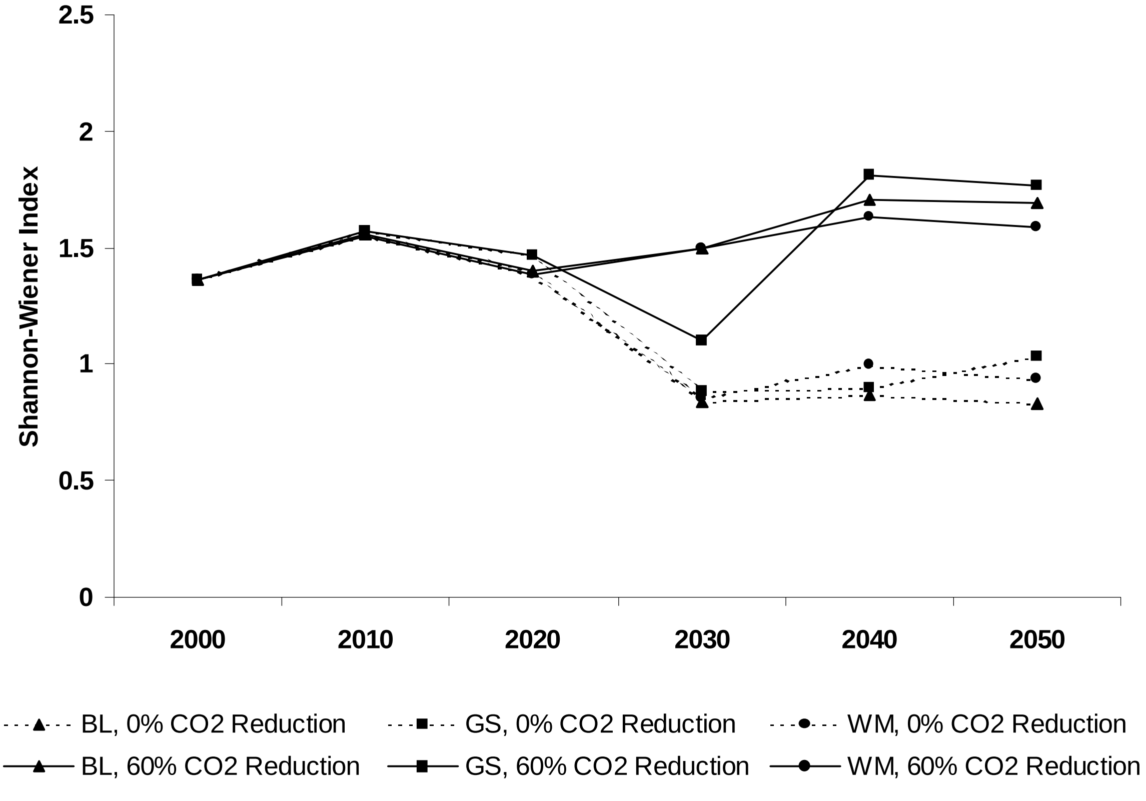

Figure 5(a): *Shannon Wiener Index under DTI Scenarios*

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[15] In the scenarios developed by the Tyndall Centre, generation from waste is separated into generation from agricultural

Where no emissions target is imposed, there is a decline in diversity in all three scenarios. This decline is driven by an increase in the proportion of generation accounted for by natural gas. The implication of this fall in diversity is an increase in insecurity, as the electricity system becomes more exposed to one fuel source. By contrast, under an emission target of 60% there is a substantial increase in diversity under all three scenarios as the dominance of natural gas goes into decline. Figure 5(b) shows that these findings are replicated when we consider the Herfindahl-Hirschmann index rather than the Shannon-Wiener Index.

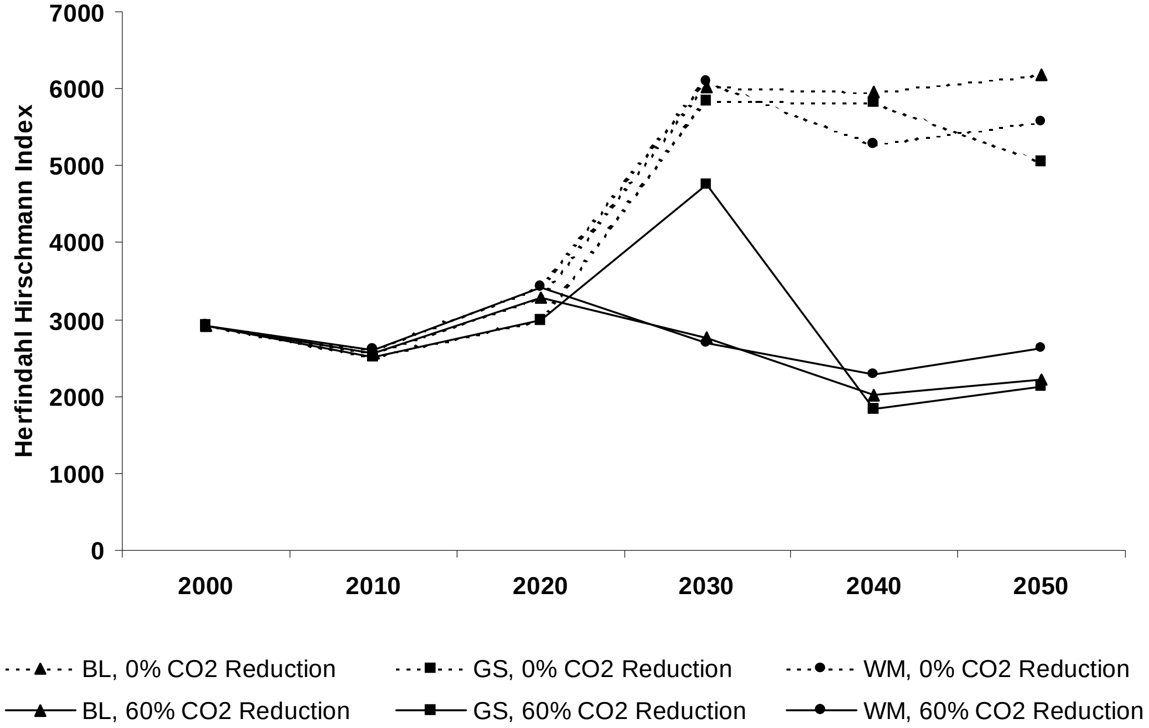

Figure 5(b): *Herfindahl-Hirschman Index under DTI Scenarios*

These basic results prompt two observations. First, low carbon scenarios appear to be associated with higher diversity. Second, these results are largely driven by changes in the share of generation accounted for by gas. An increase in the proportion of generation accounted for by gas explains, for example, the fall in diversity between 2010 and 2030 that occurs in the "Global Sustainability" scenario under a 60% reduction target. Over this

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sources and generation from municipal/industrial sources.

period coal is phased out entirely and there is a substantial decline in nuclear generation, with the majority of the difference made up by an increase in gas generation, already the dominant fuel.

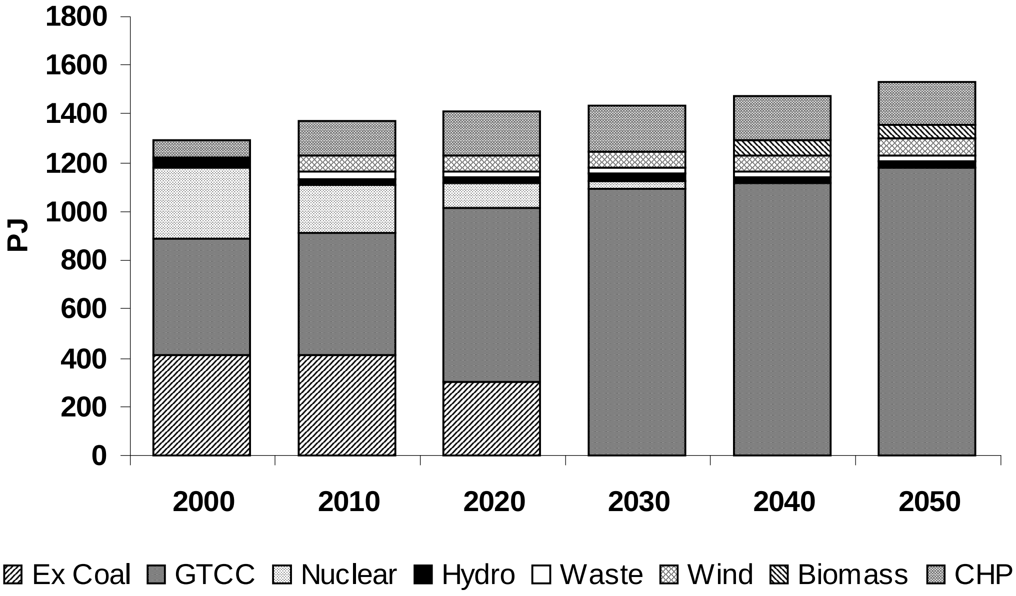

Figure 6: *Baseline, 0% Reduction in CO2 Emissions*

The evolution of diversity can be broken down to examine the fuel mix in each generation scenario. Figure 6 shows the fuel mix in the baseline case with no reduction in carbon dioxide emissions. Between 2000 and 2050, generation is increasingly dominated by gas at the expense of other sources of generation. Figure 7 shows the fuel mix under the baseline case with a 60% reduction in carbon dioxide emissions. Here, coal and gas account for a decreasing share of generation from 2020, and are replaced by nuclear and a range of renewable energy sources.

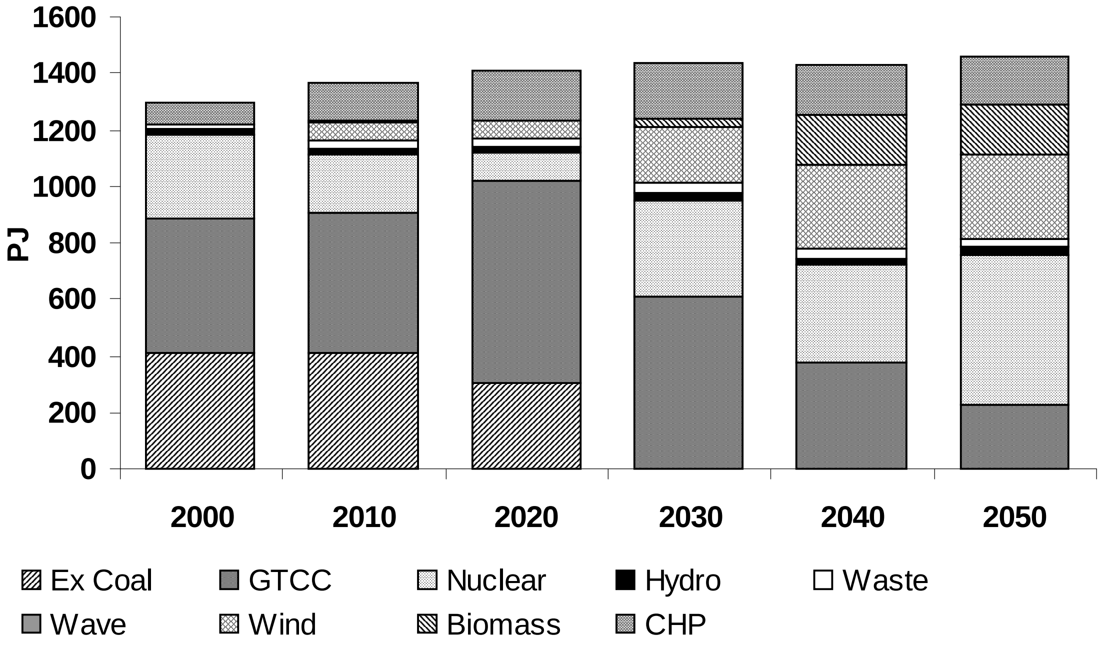

Figure 7: *Baseline Scenario, 60% Reduction in CO2 Emissions*

A similar pattern exists in the Global Sustainability and World Markets Scenarios (see Appendix, Figures 1a and 1b). Where there is no reduction in carbon dioxide emissions, there is an increase in the share of the fuel mix accounted for by gas, so that this accounts for the majority of generation. The remainder of generation is taken up by renewable sources, with no nuclear energy after 2030. With a 60% reduction in carbon dioxide emissions specified, there is a decline in generation from gas and an increase in generation from nuclear and renewable sources. The exact proportion accounted for by each fuel varies, but the pattern is consistent across all three scenarios.

The DTI also develops fuel mixes for each of the three scenarios assuming a 45% reduction in carbon dioxide emissions. Figure 8 shows that diversity attained in 2050 is not substantially greater under the 60% reduction case than under the 45% reduction case. Under the more stringent target, gas generation is replaced by gas with carbon capture. Although this reduces carbon dioxide emissions, it does not increase the diversity of the system (see section 4.4). In terms of security, it thus makes little difference if the target for carbon dioxide emission reduction is 45% or 60%.

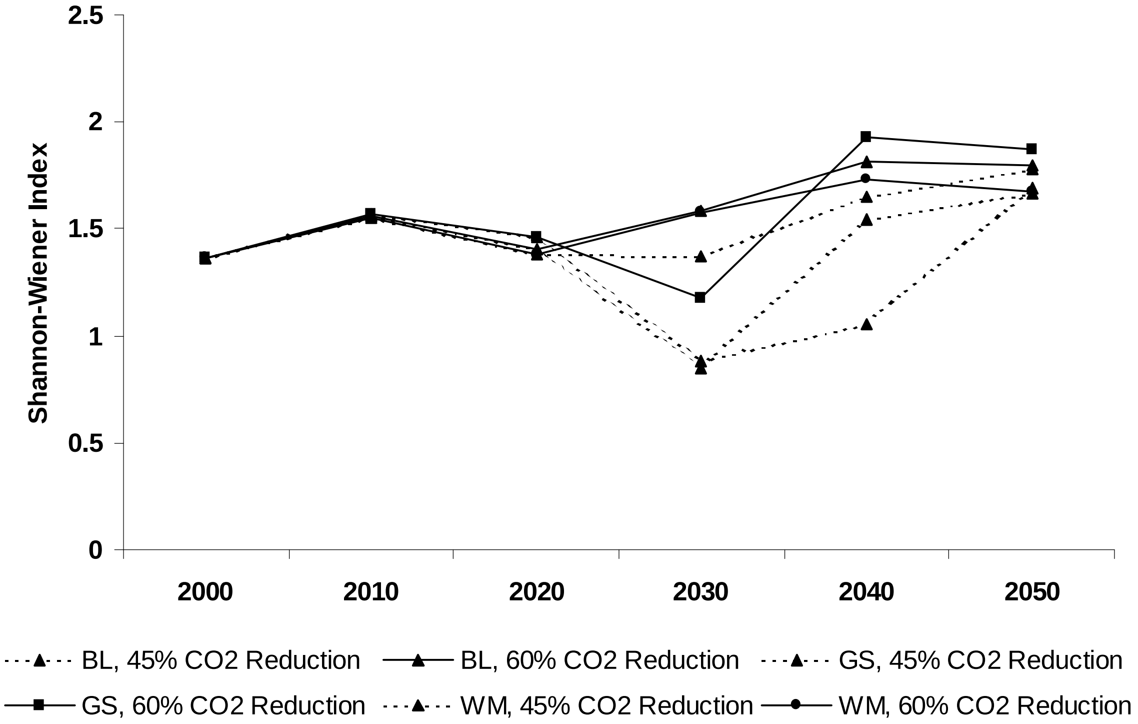

Figure 8: *Shannon-Wiener Index, 60 and 45% Reduction in CO2 Emissions*

Although the end-point is similar under a 45% reduction and a 60% reduction is similar, the trend in the diversity index is different. Under the "Baseline" and the "Global Sustainability" scenarios, there is a significant fall in diversity between 2020 and 2030. Figure 9 illustrates the changing fuel mix that lies behind these trends in diversity. In the Baseline Scenario, the trend is a result of phase-out of coal and a significant decline in nuclear, which are replaced with gas. New renewable sources do not come on line until 2040 when generation from gas decreases by half, leading to an increase in diversity. The growth rate is lower in “Global Sustainability”, so this switch takes place over a twenty-year rather than a ten-year time horizon and diversity does not increase until 2050.

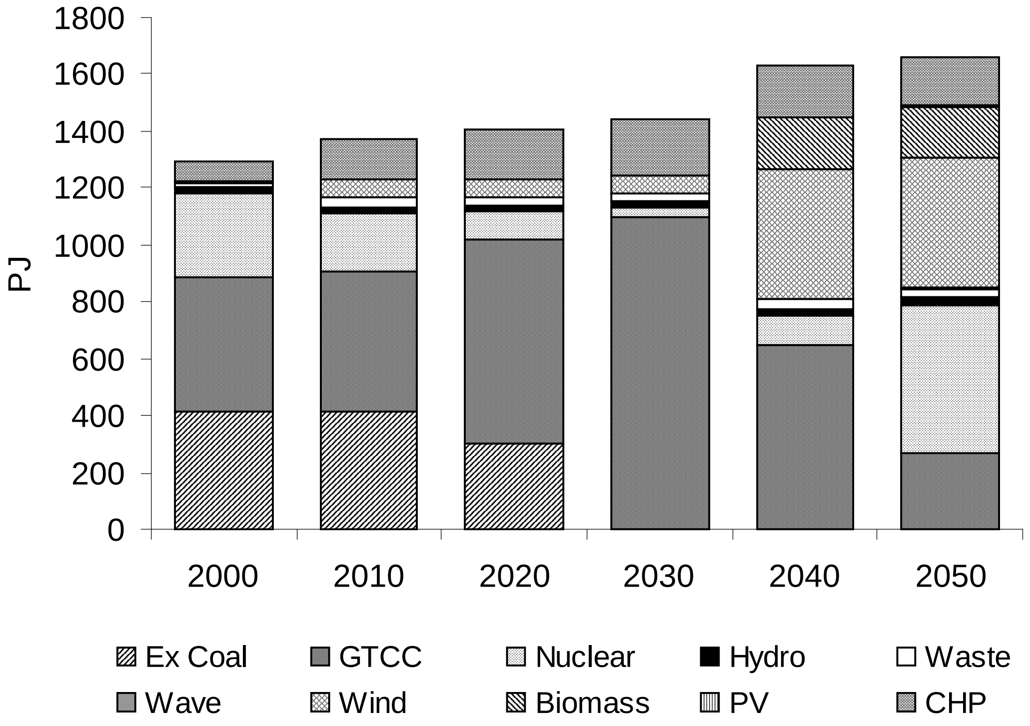

Figure 9: *Fuel Sources in Baseline Scenario with 45% Reduction in CO2 Emissions*

The foregoing has explored the changes in the diversity of electricity generation implied by the scenarios developed in the Energy White Paper. The shifts in the fuel mix driving these changes in diversity were also examined. Without the imposition of a carbon dioxide emissions reduction target, there is a decrease in diversity across the scenarios, driven by an increase in the proportion of generation from natural gas. However, the imposition of a 45% or 60% emissions reduction target forces a decline in dependence on natural gas, and increasing reliance on renewable sources. This shift in the relative importance of generation sources drives an increase in diversity and, under the hypothesis outlined in Section 1, in the security of the UK electricity system. Analysis of the scenarios generated by the DTI therefore suggests that a reduction in carbon dioxide emissions is associated with a higher level of system diversity.

6. Sensitivity Analysis

The previous sections outlined the methodology and the assumptions underlying the application of the Shannon Wiener Index. Here we consider the sensitivity of the results obtained to this methodology and these assumptions. Part (a) considers the effect of changing the assumptions made about the aggregation of energy sources. Part (b) considers the low carbon scenarios developed by the Tyndall Centre and the IPPR.

(a) Aggregation of Energy Sources

Here we consider the effect that a different aggregation or disaggregation of energy sources has on diversity. In particular, we consider the effect that breaking down gas and wind has on diversity. Disaggregating gas into GTCC and GTCC with carbon capture has little effect on diversity, whereas disaggregating gas into Liquefied Natural Gas (LNG) and Pipeline Gas has a more significant effect. Considering wind, the impact of disaggregation on diversity depends to a large extent on the proportion of generation accounted for by offshore wind. Where this proportion is high, separation of wind into onshore and offshore has a significant effect on the measure of diversity.

i. Generation from Gas

First, we follow the approach adopted by the DTI and treat GTCC and GTCC with carbon capture as two separate sources. Diversity does not change significantly as a result of this separation, since in only one case is there simultaneous generation from GTCC and GTCC with carbon capture (World Markets, 60% Reduction, 2040). Accordingly, it is only in this one case that disaggregation leads to an increase in diversity.

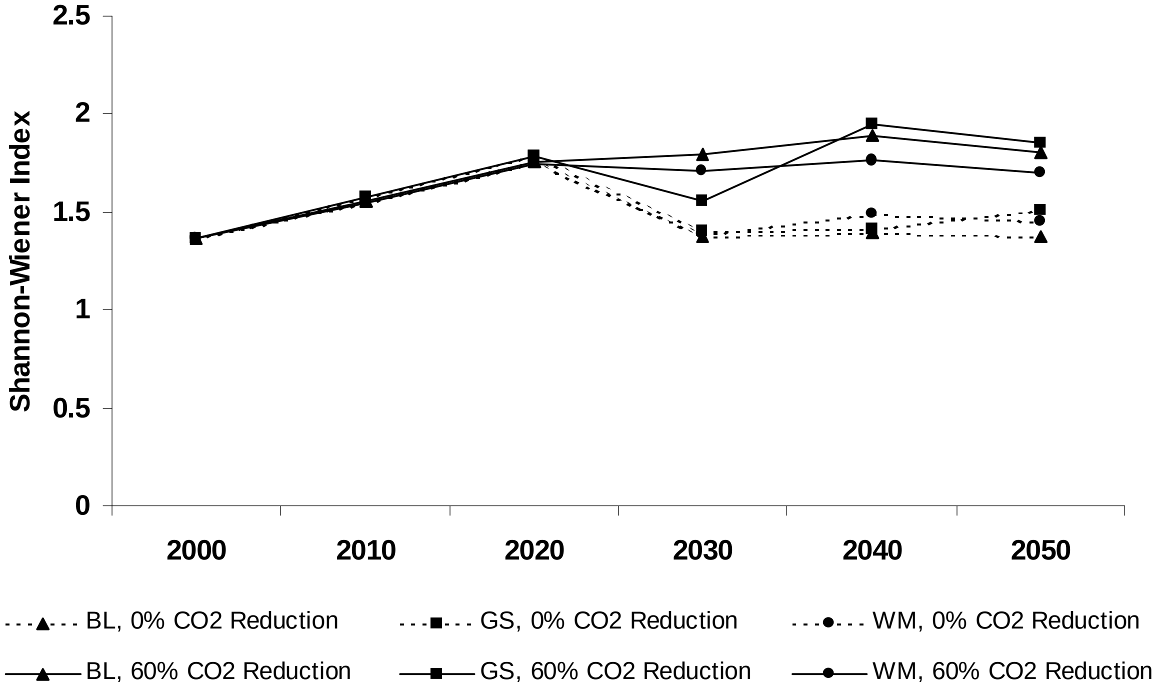

Figure 10(a): *Shannon Wiener Index, Aggregated Wind and Disaggregated Gas*

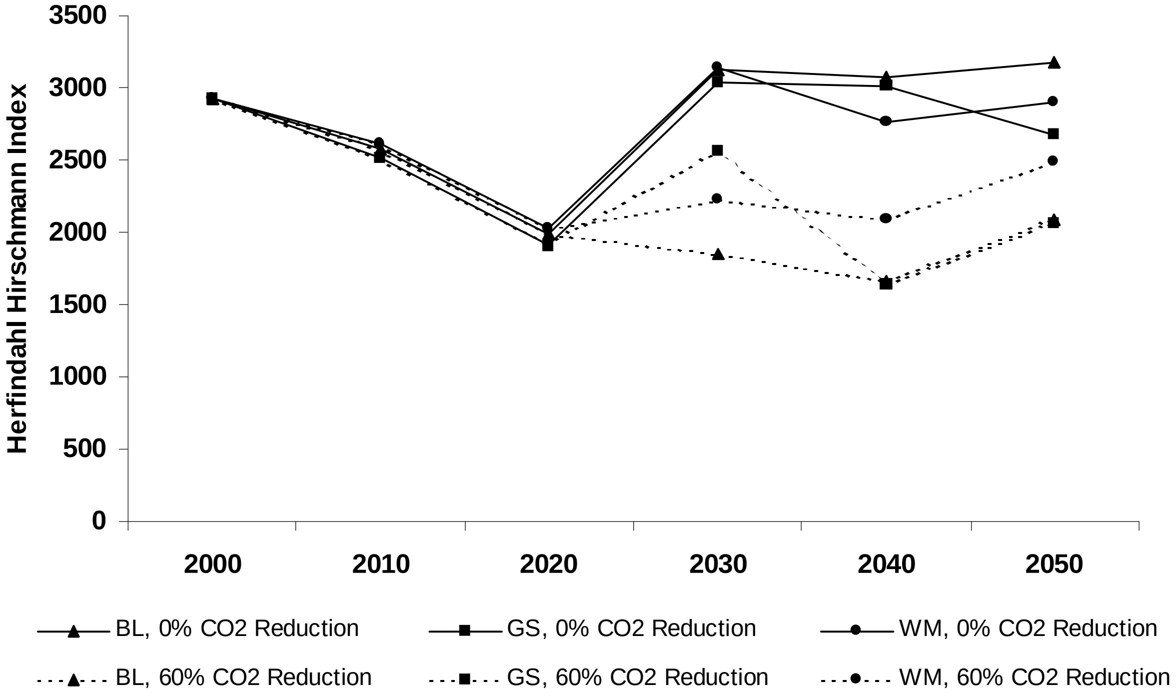

Figure 10(b): *Herfindahl-Hirschmann Index, Disaggregated Wind and Gas*

An alternative approach is to separate gas into LNG and Pipeline, since consideration of the security of supply suggests that these may be regarded as independent. We assume that LNG accounts for a negligible proportion of supply in 2010 and half of supply from 2020 onwards. The evolution of diversity is shown in Figures 10(a) and 10(b): there is little difference in the results obtained with the Shannon-Wiener and the Herfindahl-Hirschmann index. In both cases, although diversity follows a similar pattern over time, disaggregation increases the level of diversity compared to the case in which gas is treated as one source. The increases in diversity are particularly marked under the 0% reduction case where gas accounts for the majority of generation so that any split of this generation has a significant effect on diversity. Although separation also leads to an increase in diversity under the 60% reduction case, this increase is much smaller since gas accounts for a smaller proportion of generation. The forgoing suggests that where we treat Pipeline and LNG as separate fuel sources, carbon constraints appear to have a significantly more modest effect on security than where gas is treated as an undifferentiated source.

ii. Generation from Wind

Onshore and Offshore Wind Generation

Section 4 considered the aggregation of energy sources, particularly wind and gas. Figures 11(a) and (b) illustrate the changes in diversity when gas is treated as one category, and wind is disaggregated into offshore and onshore generation. There is no significant change in diversity in the 0% emission reduction scenarios, since in the scenarios developed by the DTI, there are only a few instances in which onshore and offshore wind are deployed simultaneously.[16] Since no emissions constraint exists, the development of wind generation is limited to onshore facilities, with development of

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[16] Where onshore and offshore wind *is* deployed simultaneously, the latter accounts for only a small proportion of total generation. The effect on the results is therefore insignificant.

offshore wind only occurring in the World Markets Scenario. Under the 60% emissions constraint, deployment of offshore facilities is much more widespread and the separation of wind into onshore and offshore sources leads to an increase in diversity in all three scenarios. This suggests that under carbon constraints, greater independence of output between onshore and offshore wind may enhance system security, holding the total proportion of energy generated by wind constant.

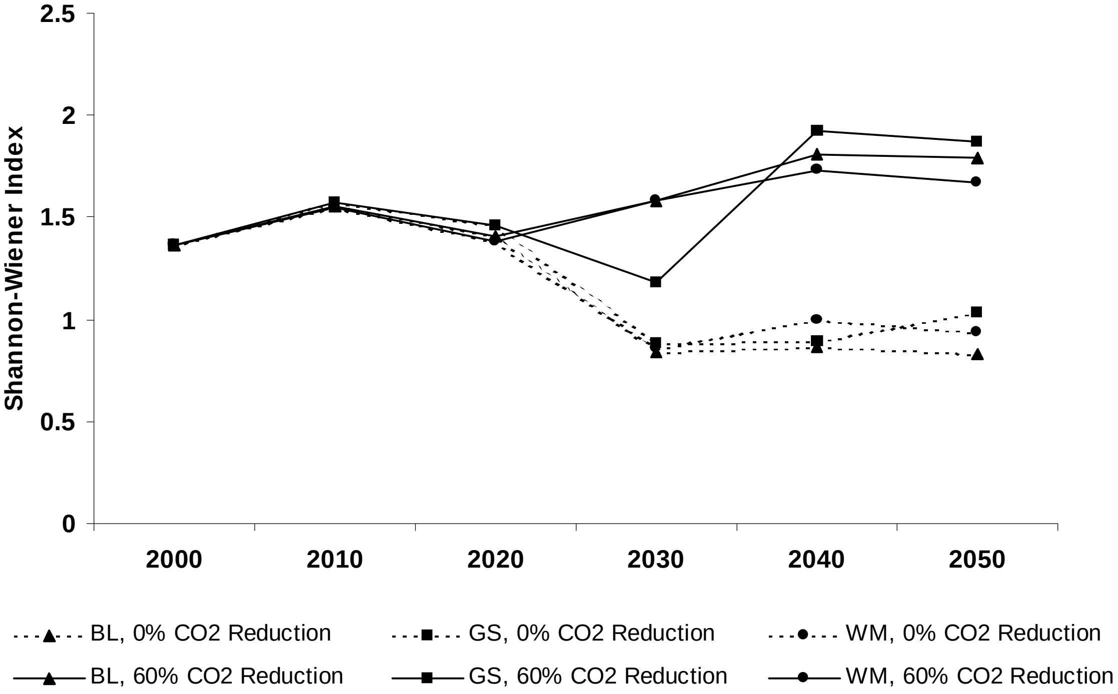

Figure 11(a): *Shannon Wiener Index, Disaggregated Wind and Aggregated Gas*

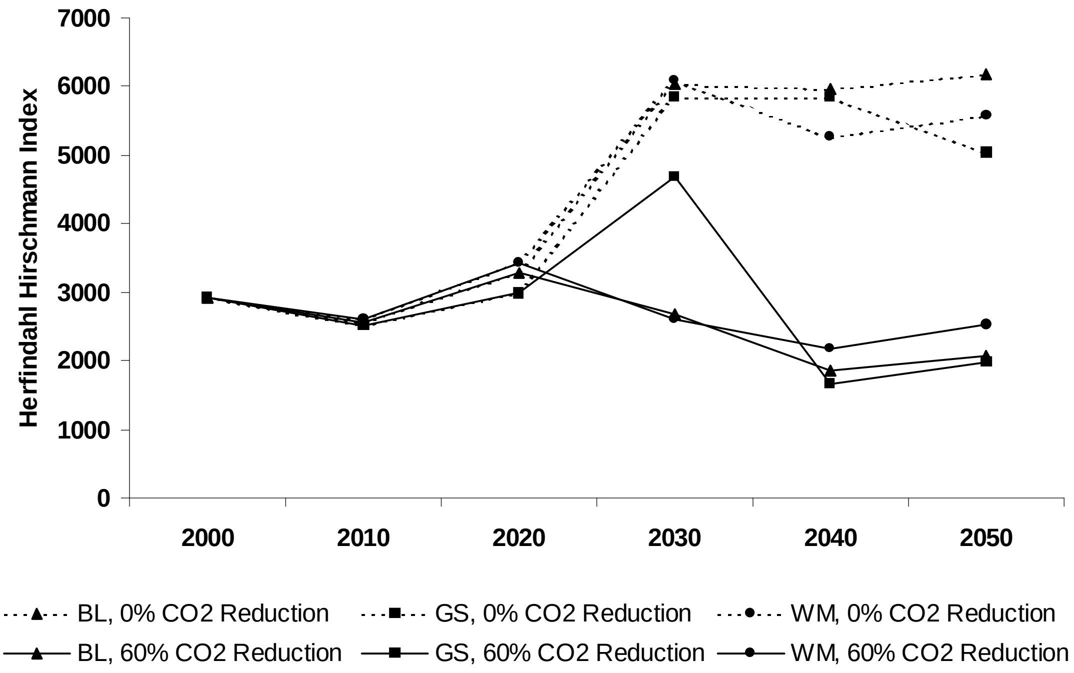

Figure 11(b): *Herfindahl-Hirschmann Index, Disaggregated Wind and Aggregated Gas*

Assuming no emissions constraint, the disaggregation of wind does not have a large impact on measured diversity since offshore wind does not account for a significant proportion of generation. However, where an emissions constraint is imposed, disaggregation leads to an increase in diversity since offshore wind accounts for a much greater proportion of generation. By contrast, the disaggregation of gas into LNG and pipeline has a significant impact on diversity where there are no constraints on emissions and a much smaller impact where constraints are imposed. Again, this is a consequence of the proportion of the generation fuel mix that is accounted for by this particular source.

(b) Sensitivity of Results to Different Scenarios

The following compares the results on diversity obtained using the DTI model data with those obtained under different scenarios. In particular, we consider diversity of fuel mix in the scenarios presented by the Tyndall Centre and the IPPR. Since this work only considers fuel mix at any one point in time rather than the evolution of this mix over time, this comparison is limited in scope.

i. Fuel Mix in the Tyndall Centre Scenarios

The Scenarios described by the Tyndall Centre were derived by applying the RCEP estimates for energy generation in 2050 to the electricity sector. Following RCEP, each of the scenarios incorporates an emission reduction of 60%, but differs in the assumptions made on GDP growth and on proportion of generation met by renewable energy. Under scenarios 2 and 4, electricity supply is met entirely by renewable sources, but demand reductions are greater in the latter. Figure 12(a) gives the fuel mix and the Shannon-Wiener Index for each of these Scenarios, with values of the Herfindahl-Hirschmann Index given in parenthesis. By each measure, diversity is higher under those scenarios where renewable sources account for a greater proportion of generation. Figure 12(b) shows that the disaggregation of wind into onshore and offshore sources increases diversity as measured by both the Shannon Wiener and the Herfindahl-Hirschmann index.

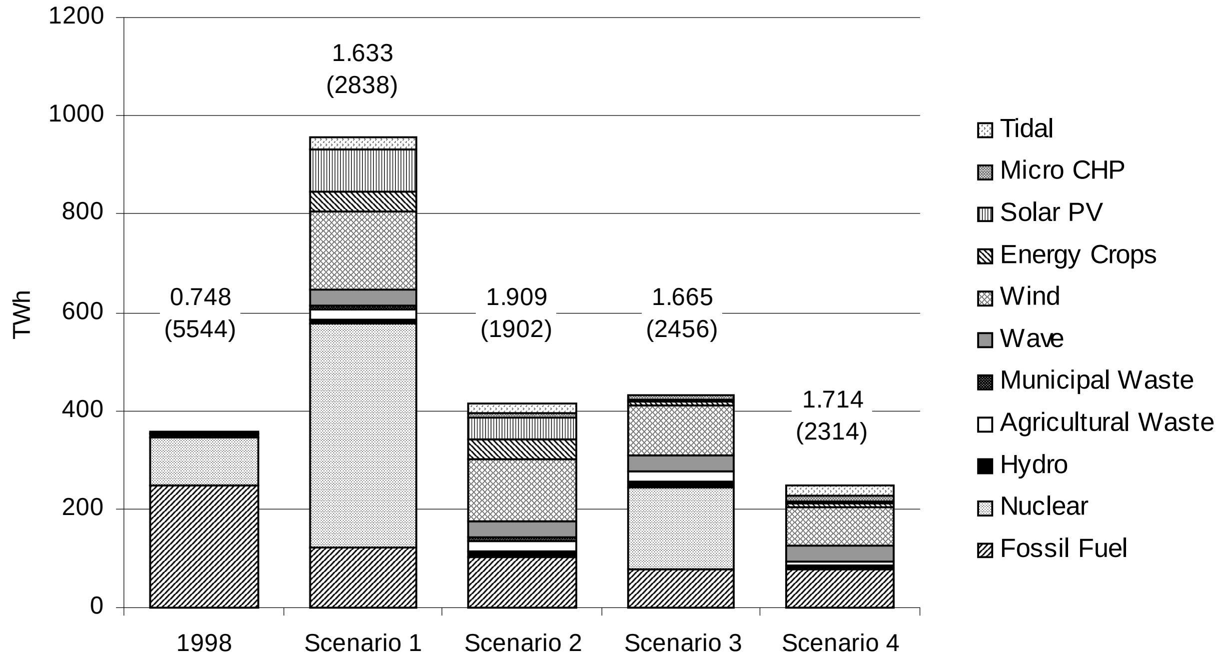

Figure 12(a): *Fuel Mix in Tyndall Scenarios for 2050, Aggregated Wind*

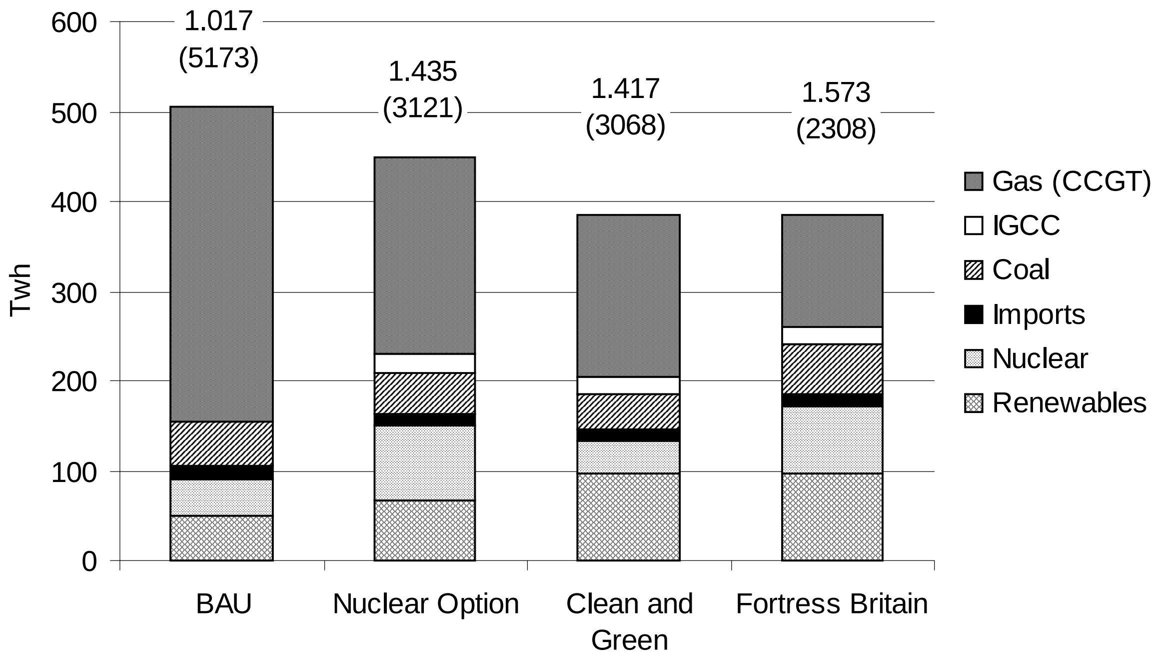

Figure 12(b): *Fuel Mix in Tyndall Scenarios for 2050, Disaggregated Wind*

A comparison of the Shannon-Wiener index derived by the Tyndall Centre and DTI shows that the scenarios outlined in the former are generally associated with higher diversity. When wind is disaggregated into onshore and offshore sources, diversity continues to be higher under the Tyndall Centre Scenarios than under the DTI scenarios. This partly reflects a wider range of fuel sources and a more even distribution of generation across the fuel sources in the Tyndall Scenarios than in the DTI Scenarios. In particular, generation from waste is separated into generation from agricultural and generation from industrial/municipal sources (see Appendix, 2(a) and Appendix 2(b) for data with generation from waste aggregated into one category).

ii. Fuel mix in the IPPR Scenarios

Figure 13 gives the fuel mix and the Shannon-Wiener Index for each of the Scenarios developed by the IPPR, with values for the Hirschmann Herfindahl Index given in parenthesis. Direct comparison of the IPPR and DTI Scenarios is difficult since the categorisation is significantly different. Under the IPPR Scenarios, renewable energy sources are regarded as one category, rather than being disaggregated. Furthermore, the level of renewable generation is specified rather than arising as a result of the assumptions made in the model (10% in the BAU case, 15% in the Nuclear Option, and 25% in the other scenarios).

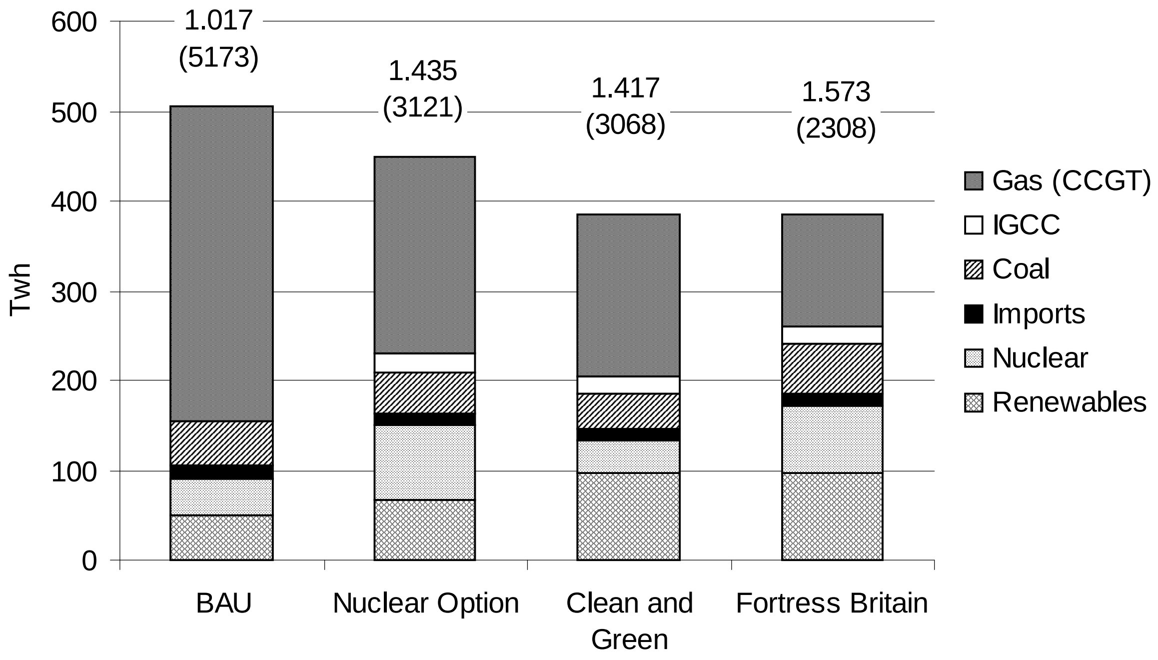

Figure 13: *Fuel Mix in IPPR Scenarios for 2020*

One strong conclusion that emerges from the results of the IPPR analysis, is that diversity increases with the proportion of generation accounted for by renewable sources. The value taken by the Shannon-Wiener index is significantly lower under the BAU scenario, in which renewable sources account for only 10% of generation, than in any of the other three scenarios, in which renewable sources account for either 15 or 25% of generation. This result holds when the Herfindahl-Hirschmann index is used. The higher levels of diversity result less from the increase in the proportion of renewable generation than from the decline in the share of generation accounted for by gas. As is expected, the aggregation of coal and "clean coal" drives a decline in diversity in each of the three scenarios. This finding holds when the Herfindahl-Hirschmann index rather than the Shannon-Wiener index is considered.

7. **Diversity Objectives and Policy Implications**

We have shown that low-carbon scenarios in the UK electricity system tend to be more diverse than reference cases, in which generation becomes heavily dominated by natural gas. The same would tend to be true in coal-based systems, where moves towards natural gas generation would both reduce emissions and increase diversity. We also suggest there are more fundamental reasons why low-carbon scenarios – or at least, renewable-intensive scenarios - tend to be more diverse. Renewables face greater natural resource limitations on contributions from individual sources, with a rising resource cost as capacity grows; moreover intermittency does reduce the marginal value of a given intermittent renewable as capacity increases to high levels. There is thus an inherent tendency for renewable-intensive systems to be more diverse.

Nevertheless, imposition of a carbon constraint by itself would still tend to focus effort on the development of a few generation techniques that can meet requirements at the lowest unit cost with no explicit attention to diversity; moreover there are also circumstances in which carbon constraints might reduce rather than increase diversity.

Treating diversity as a fortunate by-product of low-carbon policy is not the only option. Diversity could itself be considered as a policy objective with inherent value. The key question then is whether competitive electricity markets could be expected to reflect this value in ways that drive investment. From a theoretical standpoint, the problems are to do with the uncertain and asymmetric nature of the risks (the costs to consumers of supply interruption may be very high, but very difficult to predict or price adequately; and increasing security is a public good – individual consumers can ‘free ride’ on the benefits of a more secure system).

Investments for security would also be subject to political risk. It would be a brave investor that committed significant capital primarily to protect against unlikely - and sometimes intrinsically unforeseeable - scenarios of supply interruption. It would also be a brave government that enforced penalty clauses against generators that were already, for example, struggling in the event of a gas supply interruption. As a result, financing such investment could be difficult and costly. If companies went bankrupt, then the pure price incentive would again have failed to deliver adequate investment.

This relates to more general questions about the how well markets can incentivise investment in relation to strategic, large-scale risks, especially where these risks carry national and political consequences. Critics argue that the UK electricity market is not delivering, and will not deliver, adequate capacity investment simply to ensure that the ‘lights stay on’ even if there are no major disruptive surprises (cf. Helm, 2004). Reasons given include the interaction of uncertainty with the contrast between capital market time-scales and investment time-scales (by the time a risk of shortfall is apparent, it may be too late to construct sufficient new plant); difficulty in raising capital for projects that may only payoff through rare (and hard-to-predict) circumstances; beliefs that governments will not in fact allow prices to spike dramatically in the event of shortfall; and the view that most companies try foremost to protect themselves against downside risk relative to competitors, more than trying to benefit from taking contrary risks, and thus tend to follow a ‘herd’ approach to investments rather than taking the high-risk approach of ‘being different’ (and thereby exposed). The ongoing debate about the adequacy of investment incentives in competitive electricity markets thus provides a set of concerns about the inadequacy of market signals for strategic, security-related investments, that seem even stronger in the context of strategic security of supply systems in the way discussed in this article.

If this view is accepted, then a direct and economically-grounded way of rewarding greater diversity could be to impose a ‘concentration charge'. There would appear to be two qualitative different approaches to this. One could focus on the overall diversity of sourcing of different supply companies, levying a surcharge on them in proportion to the diversity index of their overall portfolio. This has the drawback of discouraging specialisation in supply companies, when the security issue is more likely to be a national or regional concern.

Alternatively, a charge could be levied source-by-source to reflect the concentration of each source in the system - a ‘concentration charge’ reflecting the percentage contribution of each source in the total This could be take many forms, the most simply and obvious being a direct analogy of the Herfindahl-Hirschmann index:

$$\text{Concentration Charge (/kWh) on source } i = c \bullet p_i^2 \tag{3}$$

Assuming that the instrument is deliberately set as technology-neutral (constant c across all sources), this would mean for example that a source that supplies 50% of the electricity in the country pays a charge four times as high as one that supplies 25%. It would also be possible to vary *c* between sources if some were perceived as particularly problematic.

Concentration charging would tend to favour new entrants, but the incentive may be modest; it is more of a deterrent to over-dependence on one or two sources than an incentive to new entrants. It may encourage wider deployment of technologies that already comprise a few percent of total supply, but it is unlikely to be sufficient to support the development of less mature technologies. The development of a diverse generation system may still require a range of policies to help technologies traverse the full innovation chain from research to diffusion (Neuhoff, 2004).

8. Conclusion

On the time-scales implicit in long-run energy projections, it is impossible to predict with confidence the specific sources of insecurity in energy systems. A more realistic approach is to seek systems that are diverse, and that are consequently more robust against a range of possible interruption. We have applied two types measures of diversity to explore the characteristics of projected electricity systems in the UK and explored the influence of low carbon objectives.

In all cases, we find that low carbon scenarios are more diverse than reference projections, and are therefore likely to be more secure against the threats identified in Section One. This is largely because the fuel mix in these reference projections tends to be dominated by natural gas whereas the low carbon scenarios rely on a broader fuel mix. There are also more fundamental reasons why low carbon scenarios tend to be more diverse. These relate to the natural resource limitations on contributions from individual sources, and the tendency of such sources to have a rising resource cost and declining benefits as capacity increases to high levels.

Intermittency does not undermine these fundamental conclusions. In none of the DTI scenarios examined here does wind energy contribute more than about 20% to the UK’s electricity generation mix. Intermittency studies demonstrate that contributions of this order can be accommodated without technical difficulties. Further, the effects of intermittency will be mitigated by the distribution of capacity across the UK.

More detailed studies of the UK resource indicate that in these conditions, the probability of having negligible wind contribution at times of high system demand is extremely low. Even with the current limited capacity for electricity storage, the intermittency of wind does not negate the contribution it makes to system security in the DTI scenarios. Some other scenarios involve wind energy contributions exceeding 30% of supply – in these case the relationship between security, intermittency and operational and network costs needs further exploration.

Finally, we have touched upon the question of policy incentives related to such diversity. A simple ‘concentration charge’ could deter over-dependence upon individual sources. This might encourage contributions from sources that are contributing a few per cent of supply, at costs close to competitiveness. By itself, however, such a policy is unlikely to provide sufficient incentives for new entrants. A concentration charge might help to encourage diversity amongst established options, but it could not plausibly displace policies related to encouraging new entrants.

Appendix

Fuel Mix in FES Scenarios

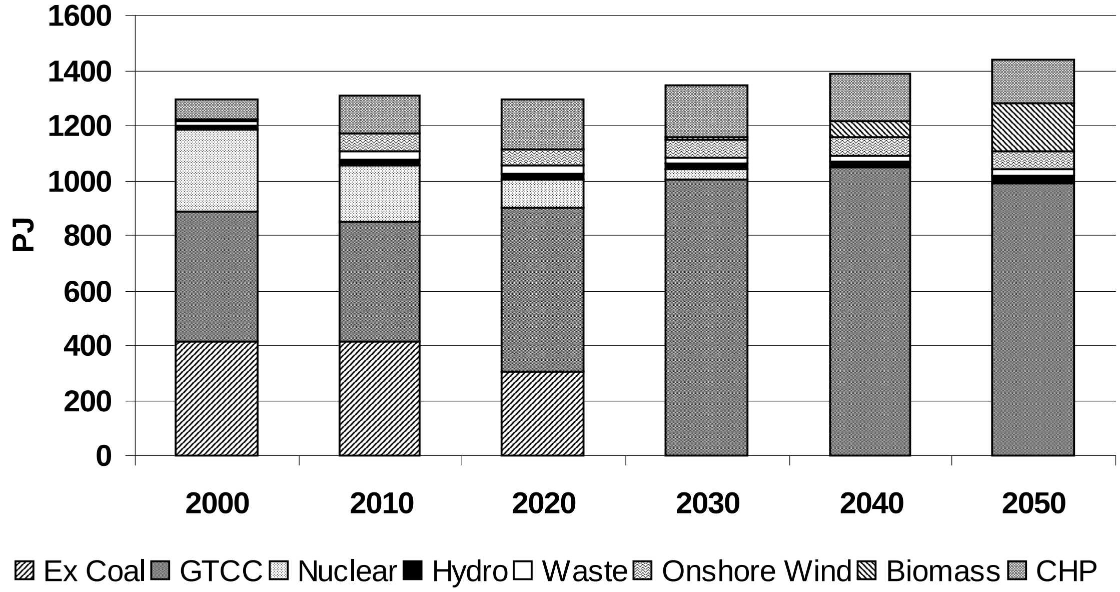

Figure 1(a): *Global Sustainability, 0% Emissions Reduction*

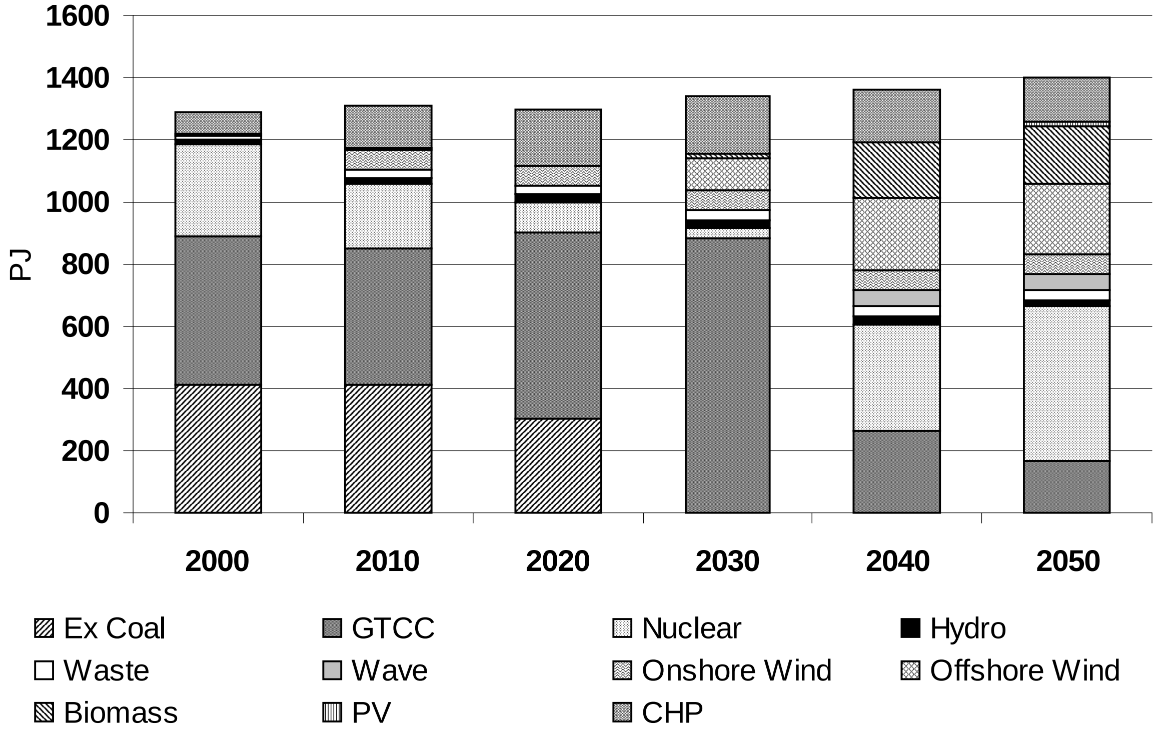

Figure 1(b): *Global Sustainability, 60% Emissions Reduction*

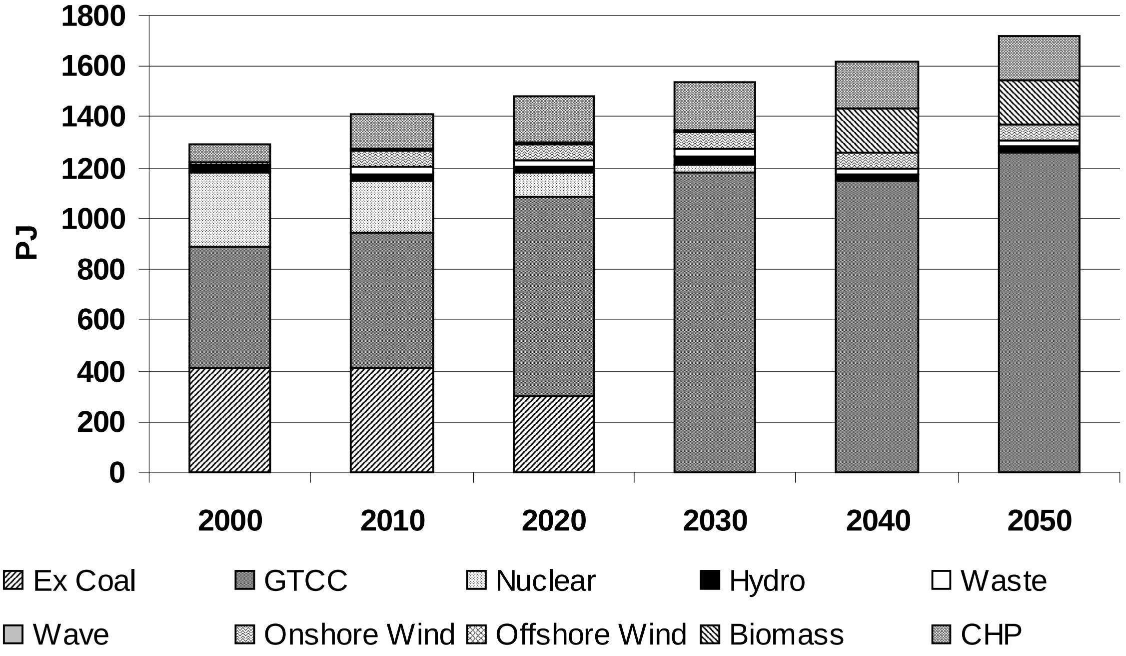

Figure 1(c): *World Markets, 0% Emissions Reduction*

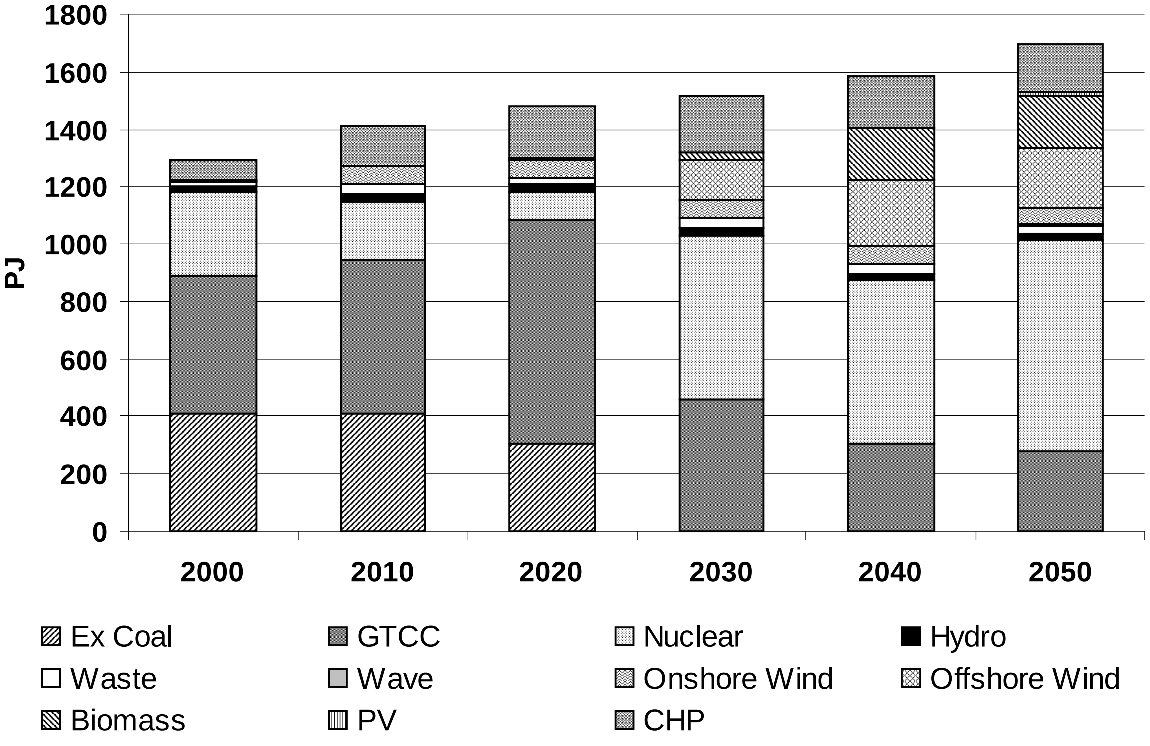

Figure 1(d)*: World Markets, 60% Emissions Reduction*

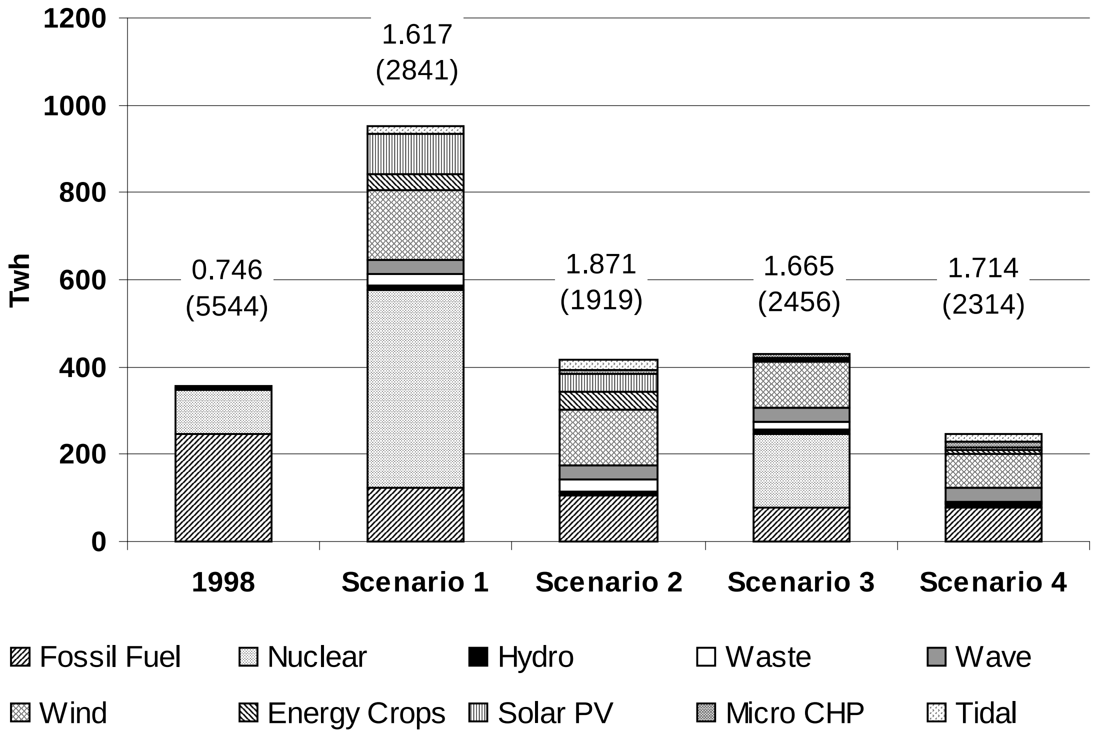

Figure 2(a): *Waste Aggregated, Wind Aggregated*

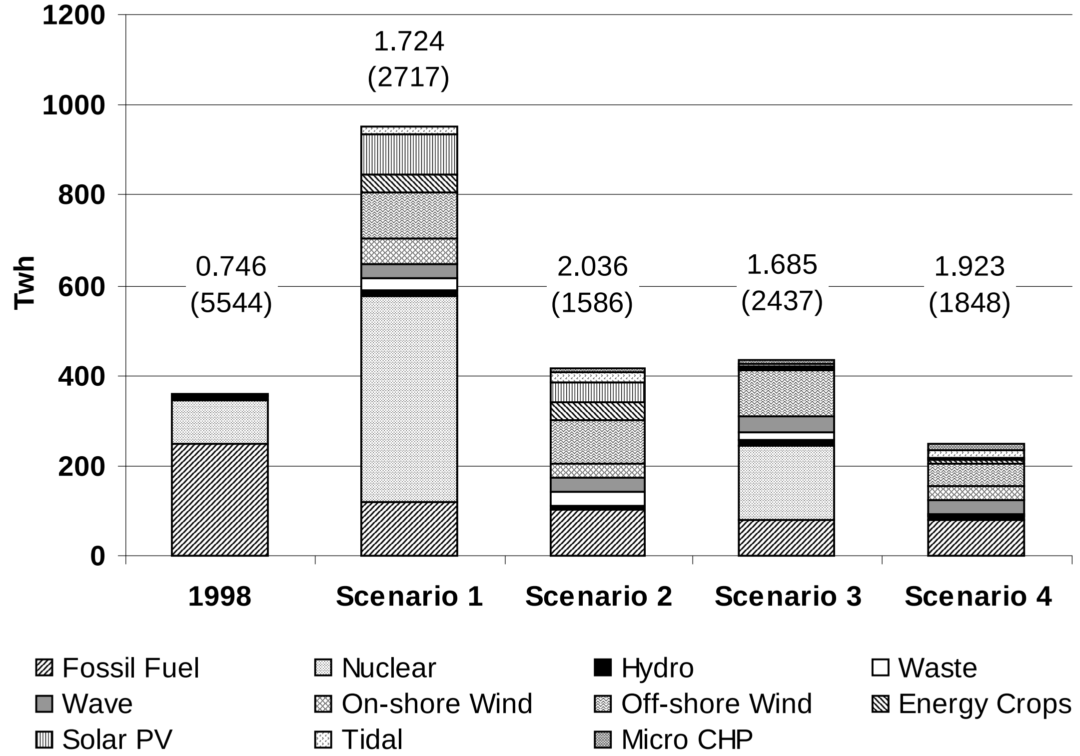

Figure 2(b): *Waste Aggregated, Wind Disaggregated*

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