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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. Our results show that low-carbon objectives are uniformly associated with greater long-term diversity in UK electricity generation. With reference to data on wind generation we also consider the impact of source variability on a second dimension of security—the reliability of generation availability. We conclude that this does not undermine our fundamental conclusion that low-carbon scenarios are associated with greater strategic security of supply 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; Q42

Keywords: Energy diversity; Low carbon; Supply security

1. 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 by increasing concern over both oil and gas dependence. The latter has occurred due to a rapid move towards natural gas in power generation, a trend that is projected to continue as part of government efforts to address environmental concerns. Combined with the decline of UK coal production and projections of declining gas production in the North Sea, this has resulted in projections of rapidly rising dependence upon imported fossil fuels.

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 rather than 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, therefore, ranged against an established view that remains skeptical about this as an indication of insecurity, but there is little analytic, quantified input to any more fundamental debate about security.

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 CO_2 emissions by 60% by mid-century. The

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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 system 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.

2. Defining security and diversity

2.1. Defining security of supply

While there are many definitions of security of supply, for the purposes of this paper it can be defined as a system's ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy. Symptoms of a non-secure system can include sharp energy price rises, reduction in quality (e.g. brown-outs), sudden supply interruptions and long-term disruptions of supply. 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 most kinds of challenges to the system.

In relation to electricity, there are a number of sources of threat to the security of supply (Mitchell et al., 1996; NERA, 2002). These include:

- failure in primary fuel sources, due to possible import reliance or domestic issues;
- transmission network problems, possibly due to poor maintenance or under-investment;
- generation capacity limitations due to under-investment;
- operational failures arising from inadequate protection against sudden loss of generation or transmission with inadequate spinning reserve.

Since the cost of a completely secure system is prohibitively expensive, the *risk* and cost of these occurrences is a fundamental concept for security of supply (Lieb-Doczy et al., 2003; NERA, 2002). In common with security of supply, the concept of risk has been defined in many ways. Awerbuch and Berger (2003) apply a probabilistic risk approach to assess economic security of supply considerations (e.g. the threat of higher prices due to cartels). The advantage of this approach is that it enables the use of statistical techniques and the employment of mean-variance portfolio theory from the theory of finance, to model the risk-return impacts of each technology on the total generation portfolio mix.

However Stirling (1994, 1998) argues that such quantified probabilistic-based analysis reflects only one of three types of 'incertitude'—namely *risk*. Here there is both knowledge of the possible outcomes and a probability density function may meaningfully be defined for the range of possible outcomes. The second is *uncertainty* where there is knowledge of the possible outcomes but there exists no basis for the assignment of probabilities. The third is *ignorance* where there exists no knowledge on the possible outcomes, let alone probabilities to assign to them.

Stirling argues that the latter two types of incertitude—uncertainty and ignorance—are the most relevant to questions of strategic security in the electricity sector. Attempting to quantify the probability of either strategic shocks that might interrupt gas supplies or block coal transit, or of some extreme event that render nuclear operation unacceptable, for example, raises as many problems as it solves and may give a misleading impression of knowledge where the reality is ignorance.

A number of researchers have developed security of supply indicators (Markandya et al., 2005; von Hirschhausen and Neumann, 2003). The measures can be basically be subdivided along two dimensions: (i) dependence or vulnerability, and (ii) physical or economic. Dependence refers to an economy's relative level of reliance on a particular fuel source or technology, whilst vulnerability refers to economy's exposure to energy supply or price shocks. Physical measures describe the relative level of imports or prospects for shortages or disruptions, whilst economic measures describe the cost of fuels or prospects for price shocks.

This paper focuses upon strategic security of the electricity sector—in this context we concur with Stirling that uncertainty and ignorance are the key concepts to analysing security in this context.[2] In the face of uncertainty and ignorance, an important insight to have emerged from a number of sciences is that *diversity* provides resilience to systems exposed to such incertitude.[3] This measure may be classed as a vulnerability indicator and is applicable on both physical and economic dimensions.[4]

2.2. Defining diversity

The basic intuition that lies behind diversity is captured by the popular proverb "don't put all your eggs in one basket". However, it is not always clear what the diverse set of "baskets" should be. Diversity might refer to fuel type, fuel sources (by geographic region or company), technology types or even to technological knowledge source (by country, sector, or company). This paper

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[2] For a recent attempt to merge the approaches of Awerbuch and Stirling see Awerbuch et al. (2005).

[3] See Baumgyarner (2004) for a discussion of conceptual differences between the ecological and economic approaches to measuring diversity in systems.

[4] It should be noted that diversity is not the only possible response or remedy to strategic security of supply problems. For example, the ability of a system to respond to shocks is also an important issue. An electricity system developed around smaller, modular generation, for example, may be able to respond more quickly to an unexpected rise in demand than a system centred around large centralised energy sources, which have long lead times in construction.

concentrates on diversity in technologies as grouped by fuel sources, thus covering aspects of the first three categories. In sensitivity studies we consider some variations in the groupings.

Diversity itself comprises at least three subordinate properties (Stirling 1998; Jansen et al., 2004). *Variety* refers to the number of categories into which the quantity in question is partitioned (e.g. gas, coal, wind, etc). *Balance* refers to the pattern in the apportionment (spread) of that quantity across the relevant categories. Given the number of categories, the more even the spread, the greater is the diversity. Finally, d*isparity* refers to the nature and degree to which the categories themselves are different from each other. For example, coal and gas generation are more closely related (via linked fuel prices) than wind and nuclear.

Stirling (1994) reviewed the ecological literature and found no measure of diversity that addressed the property of disparity. The Shannon–Weiner index, defined below, was considered to be the most satisfactory since although it does not take account of disparity, it does incorporate the concepts of variety and balance. Stirling then applies this index to the UK electricity system in order to quantify its diversity. More recently the Energy White Paper used a similar approach to demonstrate 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. We also apply a second index—the Herfindahl–Hirschmann measure of industrial concentration—to the scenarios to explore the extent to which the results depend upon the specific choice of diversity index (see Section 3).

In brief, the approach adopted here involves calculating diversity indices 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 projections of high dependence upon natural gas.

3. Diversity methodology

We divide generation sources according to fuel type, as discussed below, and derive the Shannon–Weiner index, which is calculated according to

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

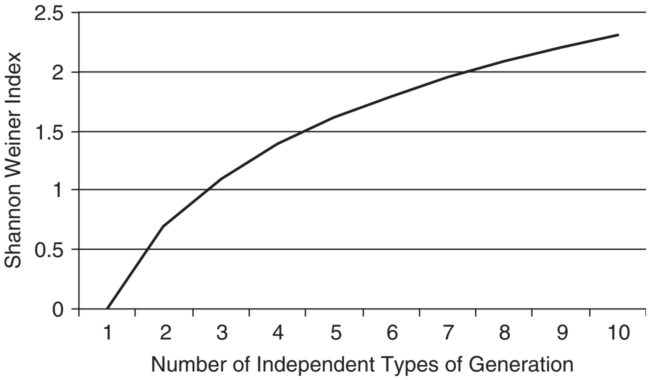

Fig. 1. Shannon–Wiener index.

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 difficult to explain the precise implication of different values, but a good indication may be obtained from Fig. 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 raises 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.

From Fig. 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 reasonably be 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] In particular we discuss the interdependence within different forms of gas and wind energy (see Section 5). 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

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

[6] Following Stirling (1994, p. 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.

the second or third. Section 8 presents a basic analysis of the sensitivity of the results to the assumptions made concerning source differentiation.

As indicated, we also assess diversity using the Herfindahl–Hirschman index. This index is generally applied in competition analysis to measure the degree of market concentration, taking into account both the relative size and the distribution of each individual firm. Assuming that p_i is the market share assumed by the ith firm, or the proportion of generation met by one particular fuel source, the index is calculated according to

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

where p_i is expressed as a percentage. We apply the same approach to generation diversity, where p_i is the percentage contribution to generation as in the Shannon–Weiner index. In the context of market concentration, the US Department of Justice 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.

Stirling (1998) suggests a number of reasons for preferring the Shannon–Weiner index to the Herfindahl–Hirschman index, primarily emphasising the mathematical properties. In particular, the Shannon Wiener index is more readily derived from first principles and the rank orderings of systems are not sensitive to changes in logarithm base. We consider that presenting results from both indices generates increased confidence about the qualitative conclusions drawn from the analysis, and show that in general the Herfindahl–Hirschman index generates results consistent with those obtained with the Shannon–Wiener index.

4. Scenario selection

Amongst the scenarios that have been developed for UK electricity generation are those by Future Energy Solutions (FES) for the DTI (DTI, 2003a), the Institute of Public Policy Research (Institute for Public Policy Research, 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”).[7] 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 demanded in each of these three scenarios is generated under a range of cost assumptions, as outlined in United Kingdom Department of Trade and Industry (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 (United Kingdom Department of Trade and Industry, 2003a). Brief consideration is also given to the 45% reduction case in order to show the sensitivity of results to changes in emissions targets.

5. Energy source categorisation and aggregation

Applying diversity indices to each of these scenarios requires that energy sources are differentiated appropriately. 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 at a micro level 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 as adding to system diversity.

5.1. Conventional and nuclear generation sources

The degree of aggregation and disaggregation depends upon the application. For example, in the scenarios developed by the DTI combined gas turbines and combined gas turbines with carbon capture are classified 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 thus we aggregate the two categories. Potentially more significant is that gas from different sources could be considered to represent independent forms of supply. In particular, pipeline gas could be regarded as separate from liquefied natural gas (LNG), since the supply routes are

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[7] 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%.

generally entirely different up to the point of entry into the UK gas network. However, from that point on, they are common and interruption in the supply of one could obviously have major knock-on effects on markets and prices. Further, one could speculate that gas producers might ultimately form a grouping equivalent to OPEC.[8] In our main analysis we treat gas as one source, and then conduct sensitivity analysis with respect to differentiating both sequestration, and categories of piped gas vis-à-vis LNG.

We treat nuclear power as one independent category. On the strategic timescales of our study, the UK's Magnox stations will have been long closed down, and it is unlikely that many of the existing AGRs will still be operating. The major questions will thus surround whether and how a new nuclear build programme would contribute to security, and it seems unlikely that any new programme would have such internal technological diversity as to rank as providing two separate sources types. This is particularly so, when the emphasis in the industry is on the need for scale economies through standardisation and the risk sources include threats (such as terrorism) that might span all nuclear technologies. Similarly we consider coal as one category, since new domestic coal production is unlikely to be developed in the UK. However, coal does not play a large role in the scenarios.

5.2. *Aggregation of wind energy*

Adding renewable technologies to the generation mix will increase the number of independent sources of generation. However, the geographical clustering of many renewable sources raises questions regarding the appropriate level of aggregation. Further, the variable nature of many of these sources is often assumed to compromise another aspect of system security—the short-run availability of electricity supply.

Consideration of geographical dispersion raises the question of whether regional resources should represent independent sources of energy. Dividing the resource on the basis of location would increase the level of system diversity, as assessed by the Shannon–Weiner and the Herfindahl–Hirschman indices. This issue is most relevant with respect to wind energy, which is the dominant renewable contribution in most of the low-carbon scenarios. Although wind energy in central Scotland would have a considerable degree of independence from sites in Southern England, for example, the reality is that wind energy is being developed across a reasonably wide geographical basis making it hard to model any one region as statistically independent from another. Further, there is no evidence indicating that the pattern of offshore wind variability is likely to be radically different from onshore (Sinden, 2005). On this basis, the initial analysis presented in Section 6, treats UK wind energy as a single source of electricity generation, whilst Section 8 looks more closely at the implications of dividing the wind resource according to location.

In addition to geographical dispersion, renewable resources are characterised by variability. It is frequently assumed that this characteristic compromises the availability of energy and therefore the security of the system. 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. An in-depth analysis of plant availability and dynamic considerations is given in Nedic et al. (2005). In Section 7 of this paper, we focus on how the variability of wind might affect its contribution to system security and whether this calls into question the incorporation of wind in diversity analysis.

5.3. *Classification of other sources*

Within the context of the UK, Solar PV may be regarded as a single source, whilst 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.[9] 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.

6. 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 4 for details of these scenarios). Fig. 2 shows the Shannon–Wiener index applied to the corresponding data.

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

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

[9] In the scenarios developed by the Tyndall Centre, generation from waste is separated into generation from agricultural sources and generation from municipal/industrial sources.

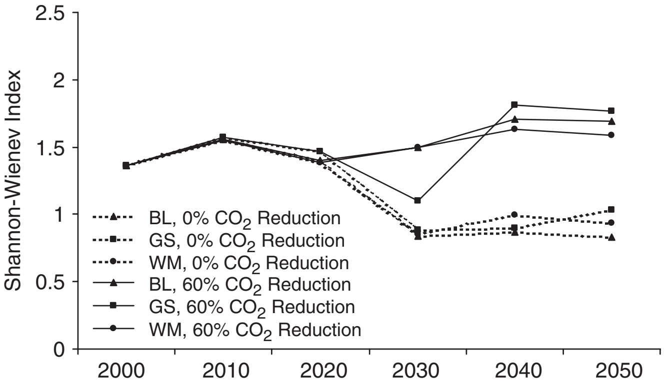

Fig. 2. Shannon–Wiener index under DTI scenarios.

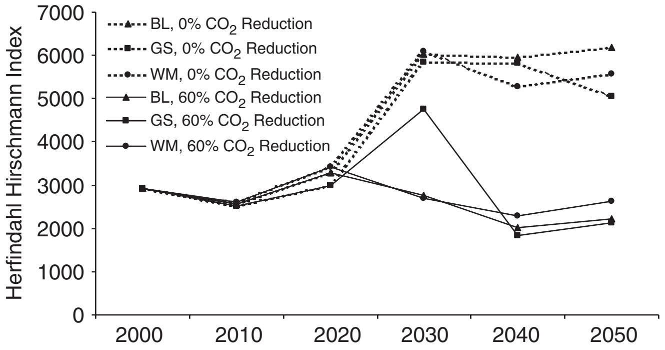

Fig. 3. Herfindahl–Hirschman indexunder DTI scenarios.

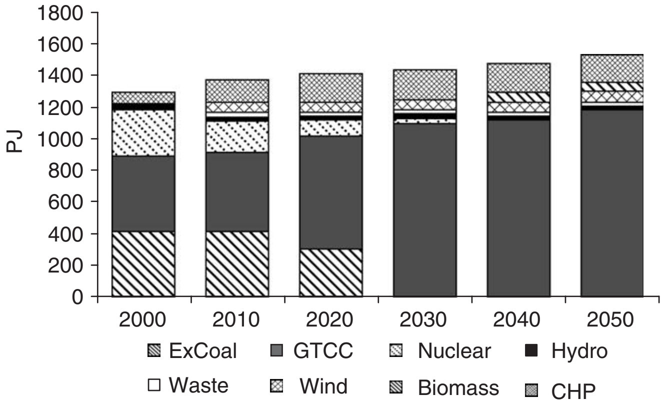

Fig. 4. Baseline, 0% reduction in CO_2 emissions.

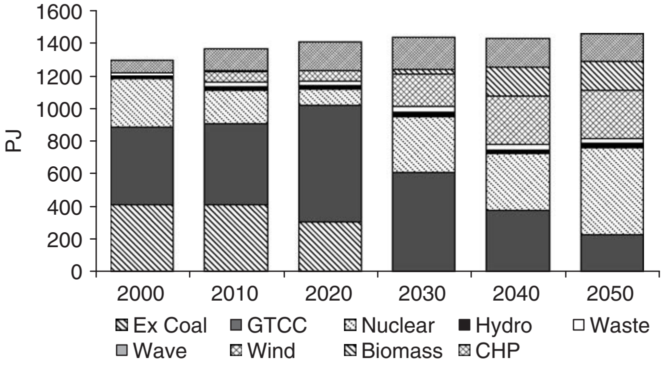

Fig. 5. Baseline scenario, 60% reduction in CO_2 emissions.

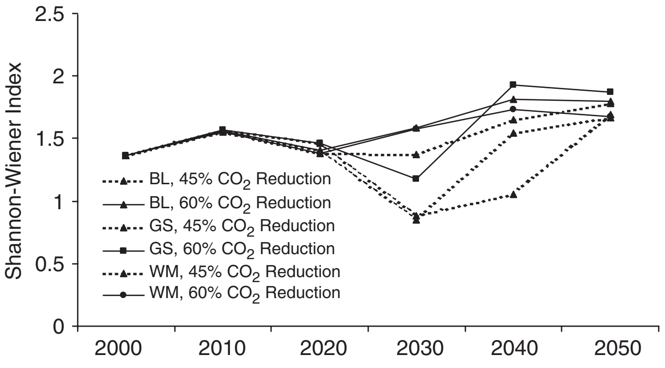

Fig. 6. Shannon–Wiener index,60 and 45% reduction in CO_2 emissions.

natural gas goes into decline. Fig. 3 shows that these findings are replicated when we consider the Herfindahl–Hirschmann index rather than the Shannon–Wiener index.

These basic results prompt two observations. First, across all three baseline scenarios, low carbon emissions 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 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.

The evolution of diversity can be broken down to examine the fuel mix in each generation scenario. Fig. 4 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. Fig. 5 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.

A similar pattern exists in the global sustainability and world markets scenarios (see Appendix1A). 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. Fig. 6 shows that diversity attained in 2050 is

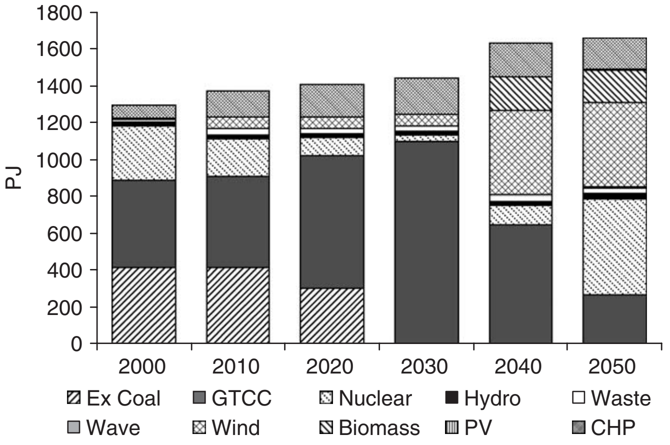

Fig. 7. Fuel sources in baseline scenario with 45% reduction in CO_2 emissions.

not substantially different 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. In terms of security, it thus makes little difference if the target for carbon dioxide emission reduction is 45% or 60%.

Although the end-point under a 45% reduction and a 60% reduction is similar, the trend in the diversity index is different, and scenario dependent. Under the "baseline" and the "global sustainability" scenarios, there is a significant fall in diversity between 2020 and 2030 for the 45% reduction. This fall is also evident in the 60% case, but is moderated by the sharper rise in renewable sources. Fig. 7 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 10-year time horizon and diversity does not increase until 2050.

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 2, in the strategic security of the UK electricity system.

7. Wind variability and generating availability

The above analysis has quantified the contribution of each source on the basis of their percentage contribution to total electricity supply (i.e. in proportion to annual electricity output). This may be an imperfect measure given the difficulties of storing electricity. These difficulties make the contribution of any source to strategic security dependent upon the availability of its generation capacity at times when the system may be vulnerable to interruption. This is most obviously a consideration in relation to wind energy and other variable sources that fluctuate with the elements.

Three broad approaches to this issue are possible. One, extending the arguments about uncertainty and ignorance to their limit, is to assert that one cannot predict any long-term temporal pattern to system vulnerability or project the extent to which storage may be available. Thus, to argue that the whole system may be so different that any discrimination on the basis of source characteristics is misguided. For example, a general assumption that the UK system is most vulnerable during winter may be wrong if rapid growth of air conditioning loads start to offset the winter peak or if intense heat and drought in summer lead to the shutdown of thermal capacity or the reduction of transmission carrying capacity. If the major source of risk is assumed to be gas supply, the UK's gas storage might well be enhanced so that any other contribution during periods of extended interruption would be equally valuable in conserving gas supplies. As a final example, fuel cells may become potential feed-in generating sources in their own right, again providing implicit storage for the system in the form of hydrogen. Under this perspective source variability is largely irrelevant—it is subsumed in general uncertainty and ignorance.

A second approach is to equate the problem of strategic security directly with short-term generating availability, arguing that peak availability of generating capacity is a key risk indicator and that both source variability and lack of storage are intrinsic properties that are likely to persist. Assuming that current electricity demand patterns can be extended, this argues for trying to evaluate the statistical contribution that different sources might make at times of peak system demand and leads into more complex debates on capacity credits attributable to variable sources. Numerous studies have addressed this question from a theoretical perspective. The key is to recognise that no individual component in the system is wholly reliable—all show some degree of intermittency in their electricity output. As such, the system can be seen as a collection of generators with statistical varying output, which together form a reliable supply system. Variable sources represent the addition of another generator with different statistical properties of supply availability to conventional generators. A large body of published research (Grubb, 1991; Grubb and Meyer, 1993; Milborrow, 2001, 2003; Dale et al., 2003) has demonstrated that when the installed capacity of wind is small in comparison to the remainder of the network, its statistical contribution to system capacity is roughly equal to its average output.

The capacity contribution decreases as the installed capacity of wind rises in ways that depend upon the combined characteristics of the system and the geographical spread of the resource. Just as the profile of total electricity demand is much smoother than the demand profile of any one household or office, combing the output from different wind generators acts to smooth the aggregate profile of wind electricity production. For a large system such as England and Wales, studies suggest that the contribution of wind energy to peak generation availability starts to decline significantly for contributions in the range of 10–20% of the total system supply. In none of the DTI scenarios analysed above, even with 60% CO_2 reductions, does wind energy significantly exceed 20% of the electricity supply.

These are mainly theoretical conclusions based on assumptions that wind energy varies independently of electricity demand. Note that the ability of wind energy to contribute to system security is not necessarily constrained by its capacity credit. Whereas capacity credit concerns only issues of capital 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 either as CCGTs or as 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 as 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 on the storage capacity. This contribution clearly exceeds the pure capacity contribution at peak—it is dependent on the probability of wind or other sources contributing at any point within the period of potential generation shortfall across the entire period of fuel interruption.

This leads to a third approach, which would be to roughly equate times of system vulnerability with the broad temporal patterns of electricity demand, allowing for some fuel storage capacity able to smooth across periods of a few days, and assuming therefore that peak demand *seasons* define the times of greatest potential risk to the system. This suggests that variable sources should be weighted according to their availability characteristics during the peak period—for example using wind energy to conserve a diminished gas supply and reduce storage draw down. Assuming that the UK remains a winter peaking system this would make wind and wave energy *more* valuable contributors to strategic security than indicated in the analysis above, given their greater output in winter. Sinden (2005) concludes on the basis of 30 years data across 60 UK sites that periods of potential "winter calm" are far too rare, and brief, to undermine this conclusion.

Given the data presented above and the fact that our analysis has modelled wind energy as a single source across the UK, this suggests that the intermittency of wind does not undermine the broad conclusions of the previous section. For the purposes of analysing the contribution of different sources to strategic security using diversity indices, wind energy can reasonably be treated as making an independent contribution to the diversity and security of UK electricity on a par with conventional sources. Indeed, under such an assumption, its real contribution may be even greater than indicated.

8. 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. In particular, we consider the effect of changing the assumptions made about the aggregation of energy sources. Further sensitivity studies can be found in AppendixA where we discuss the low carbon scenarios developed by the Tyndall Centre and the IPPR.

8.1. 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.

8.1.1. Generation from gas

First, we follow the approach adopted by the DTI and treat GTCC with and without 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.

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 Figs. 8 and 9: 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

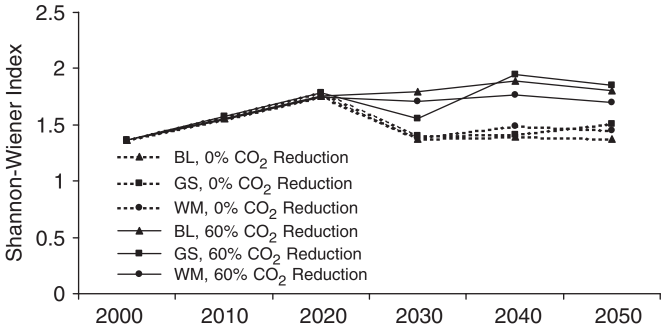

Fig. 8. Shannon–Wiener index, aggregated wind and disaggregated gas.

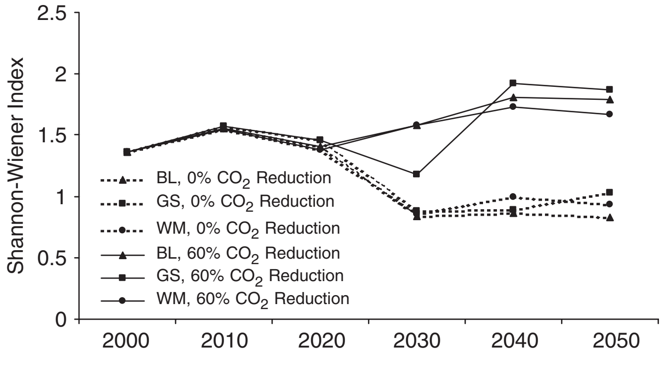

Fig. 10. Shannon–Wiener index, disaggregated wind and aggregated gas

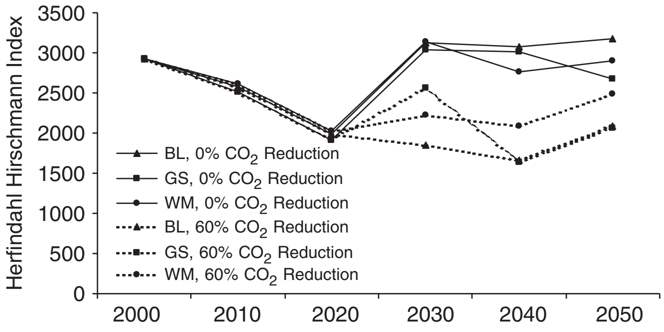

Fig. 9. Herfindahl–Hirschmann index, disaggregated wind and gas.

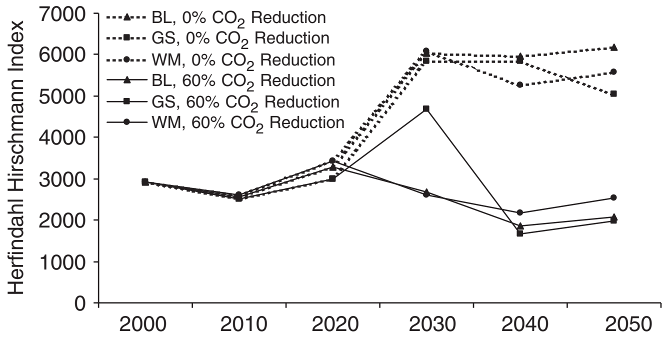

Fig. 11. Herfindahl–Hirschmann index, disaggregated wind and aggregated gas.

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.

8.1.2. Generation from wind

Figs. 10 and 11 illustrate the changes in diversity when gas is treated as one category, and wind is disaggregated into offshore and onshore generation.[10] 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.[11] Since no emissions constraint exists, the development of wind generation is limited to onshore facilities, with development of 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.

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

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[10] We reiterate that this is a sensitivity analysis to changing the categorisation for the Shannon–Wiener index. Unfortunately there is no direct test for what counts as a category. In the case of onshore and offshore wind, the long–term energy output can be fairly well estimated in advance and is strongly correlated between offshore and onshore. However, on the cost side there may well be between diverging costs in planning, sitting, construction and connection to the grid.

[11] 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.

generation fuel mix that is accounted for by this particular source.

9. 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. This means that a given contribution of renewables will be served more cheaply by a variety of sources (which have not reached their capacity limit or substantially decreased marginal returns) rather than by a single source. 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.

Referring back to our opening distinction between different types of incertitude, expecting markets to deliver adequate investment might be a plausible expectation in the context of *risk*, where investors might in theory assess the potential benefits arising from being able to supply energy when other supplies are unavailable. Even this is problematic.

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.) Furthermore the economic incentives may not align as expected: in a Monte Carlo simulation of the commercial incentives faced by a utility, Roques et al. (2005) have found that the current market framework does not give investors adequate diversification incentives. This result is primarily driven by the correlation between electricity prices and gas prices and the fact that investors are concerned with both cost and revenues streams. Cost streams which are correlated with revenue streams result in profits that are less volatile and hence commercially less risky. With the current market design, the marginal generator (which is typically a gas turbine) sets the electricity price and thus gas turbine costs are typically correlated with their electricity revenue. By contrast, the diversification benefits of renewable energy sources may provide less volatile costs stream but may also result in more volatile profit streams, as their costs are not correlated with electricity prices. Thus there may be greater commercial risks from diversifying into renewable technologies even though from a security of supply perspective the system effect from additional diversity in supply is beneficial.

The obstacles to current market designs delivering adequate diversity as a hedge against unquantifiable incertitudes seem even more intractable. This relates to more general questions about how well markets can incentivise investment in relation to strategic, large-scale risks, especially where these risks carry national and political consequences. Investments for security would also be subject to political risk—the Californian experience show some of the limits to which governments will tolerate the price spikes that would reward diversified investment. Ultimately, increasing security is a public good—individual consumers can "free ride" on the benefits of a more secure system—and it is implausible that electricity markets will deliver it adequately in the absence of more direct incentives.

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:

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

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 technology 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 ones. 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).

10. 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 of 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 2. 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 may 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.

Variability 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 variability will be mitigated by the distribution of capacity across the UK.

More detailed studies of the UK resource indicate that under 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 variability 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 cases 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 technology entrants. A concentration charge might help to encourage diversity amongst established technology options, but on its own it could not plausibly displace other policies related to encouraging new technologies.

Appendix A. : Sensitivity of results to different scenarios

This annex 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. We also present the evolution of fuel mix in the DTI scenario variants.

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. Fig. A.1 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. Fig. A.2 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.

A comparison of the Shannon–Wiener index derived by the Tyndall centre and DTI shows that the scenarios

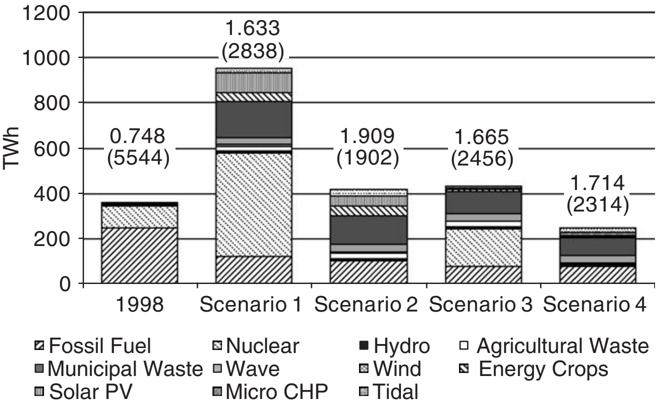

Fig. A.1. Fuel mix in Tyndall scenarios for 2050, aggregated wind.

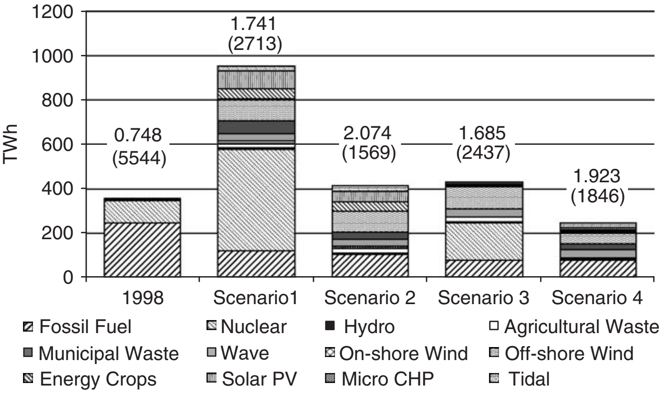

Fig. A.2. Fuel mix in Tyndall scenarios for 2050, disaggregated wind.

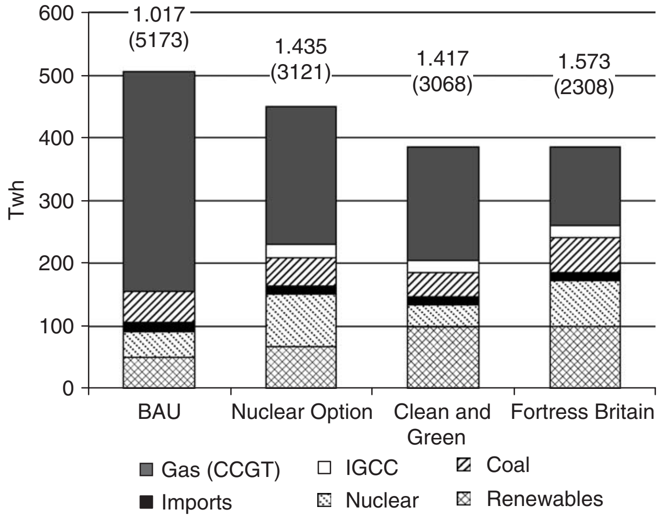

Fig. A.3. Fuel mix in IPPR scenarios for 2020.

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 Figs. A.5 and A.6 for data with generation from waste aggregated into one category).

IPPR scenarios

Fig. A.3 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).

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.

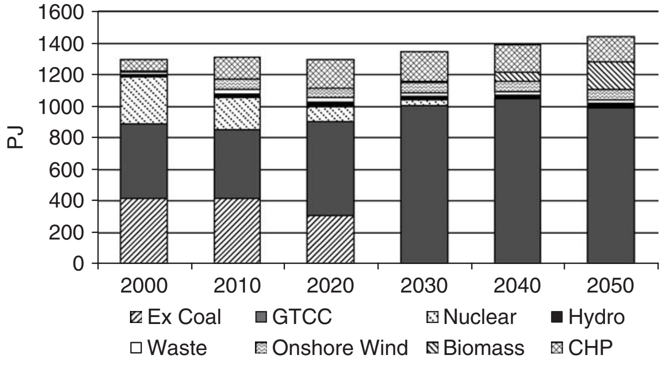

Fig. A.4. Fuel mix in DTI global sustainability scenario, 0% emissions reduction.

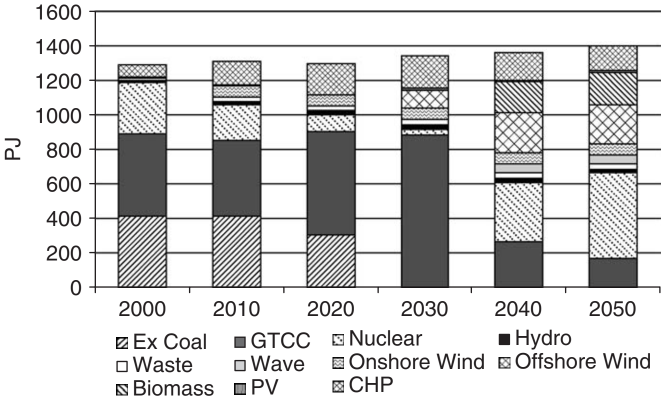

Fig. A.5. Fuel mix in DTI global sustainability scenario, 60% emissions reduction.

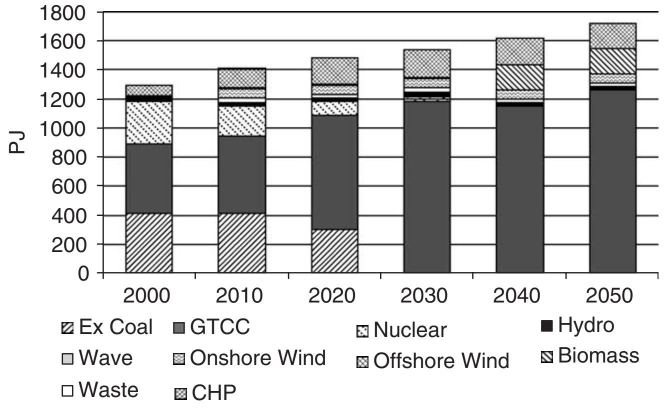

Fig. A.6. Fuel mix in DTI world markets scenario, 0% emissions reduction.

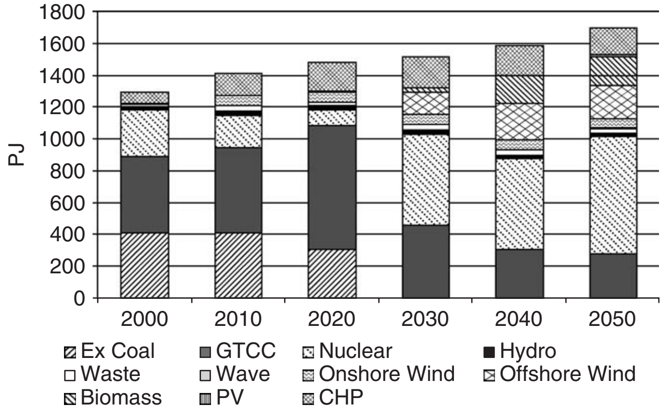

Fig. A.7. Fuel mix in DTI world markets scenario, 60% emissions reduction.

Fuel mix in DTI scenario variants

Finally, Figs. A.4–A.7 show the fuel mix in the DTI scenario variants, to complement the results and presentation of the 'baseline scenario' in Section 6. The most striking feature is the similarity of the supply mix (though not demand) in the reference cases (i.e. without CO_2 constraints), with total dominance of gas by 2030 as it fills the vacuum of the nuclear phase out, but the very different responses to the CO_2 constraints in 2030 and beyond.

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