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Electricity System Diversity in the UK and Japan – a Multicriteria Diversity Analysis

Go Yoshizawa, Andy Stirling, Tatsujiro Suzuki
(Sussex Energy Group, SPRU, University of Sussex)

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University of Sussex
SPRU – Science & Technology Policy Research

**The Freeman Centre, University of Sussex,
Falmer, Brighton BN1 9QE, UK
Tel: +44 (0) 1273 877118
E-mail: a.c.stirling @sussex.ac.uk
http://www.sussex.ac.uk/spru/**

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Abstract

This paper describes the first empirical application of a novel approach to the analysis of diversity in portfolios of alternative options in technology policy. Pioneering the multicriteria diversity analysis method, this pilot study focused on the highly topical subject of diversity in the national electricity supply mixes of the United Kingdom and Japan. This is a property recognised by governments and industry internationally, as a strategically important means to help foster enhanced energy security – as well as to promote wider resilience, hedge against other sources of uncertainty and ignorance, foster innovation, mitigate lock-in and accommodate contending social values and interests portfolios. Involving a series of in-depth interviews with leading figures in energy diversity debates in the UK and Japan, the diversity analysis method elicits detailed information characterising divergent expert perspectives on the performance and distinguishing attributes of a wide range of electricity generating options. The method allows full and symmetrical attention to alternative ways of framing and appraising option performance and mutual disparities, as well as different possible viewpoints on system-interactions between options, diversity itself and the trade-offs between portfolio diversity and overall performance. The result is a heuristic 'map' of alternative concepts of 'optimal' diversity in electricity supply systems in each country. A number of interesting features emerge in this picture, suggesting systematic distinctions in both the systems and expert perspectives extant in the UK and Japan. This offers a potentially fruitful basis for further research, both in further examining energy diversity in the UK and Japan, and in developing this method for possible application in other areas of technology policy.

Keywords

Diversity, portfolio analysis, energy security, technology appraisal

JEL codes

D81; G11; O13; Q57; Q40; Q42; Q48; L12

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This pilot study would not have been possible without the exceptional patience and attention offered by nine expert interviewees. It is unfortunate that understandable requirements for anonymity mean that this acknowledgement may not be extended on a personal basis. But we are very grateful to these leading figures in energy policy and appraisal debates in both the UK and Japan, for the time and effort that they expended in support of this exercise. We are deeply appreciative of the generosity with which these nine individuals shared with us the fruits of their expertise and experience.

We also would like to thank Gordon MacKerron, Jim Watson for their useful comments on the draft version of this working paper.

1. Introduction

There exists a growing number of studies, exploring ways to identify 'optimal' future portfolios of possible energy options. Such is the complexity, dynamism, uncertainty and context-sensitivity in this field, that it has always been a difficult task to justify any single apparently precise set of analytical results. Many of the most important strategic issues implicated in such analysis are highly judgemental, often ambiguous and frequently controversial. Although techniques proliferate, aims at ostensibly definitive quantitative analysis are especially challenging. As attention extends from historic fuel prices, it becomes ever more difficult to justify apparently precise prescriptive conclusions. Now, as never before, a diverse array of important strategic appraisal criteria have come into view, under which it is difficult indeed to claim that probabilities of contending possible future trends are fully addressed in past experience. Examples of such issues include long-run economic competitiveness, supply stability, technology change, resource depletion, climate change, social acceptance, and the many disparate aspects of environmental sustainability. Although heroic attempts are still made to assert precise prescriptive findings, these are often achieved at the cost of multiple (contestable but often invisible) 'framing assumptions' (Saltelli, 2001). Quite apart from the substantive issues above, for instance, there typically remain many questions, even over the nature of energy diversity itself: what are its characteristics, why is it desirable and what are the trade-offs with other aspects of performance? Taken together, it does seem that these daunting complications conspire to undermine any great confidence in the results that may be obtained for 'optimal' future energy mixes.

These difficulties are, however, not grounds for despair. Although these kinds of challenges may preclude confidence in claims at transcendent 'definitive objective' conclusions, they need not detract from the value of rigorous, systematic – even quantitative – analysis. This involves explicit treatment of the divergent 'framing assumptions' that emerge under alternative (equally valid) technical and expert perspectives. Without assuming that any single (or aggregate) view presents a final picture, careful analysis of contending judgements, uncertainties, issues and assumptions can ‘map’ the alternative possible conclusions. In the process, many initially apparently viable outcomes may be revealed as unsupported under any reasonable assumptions. Attention can thereby reduce to a relatively narrow field of possible energy mixes, which – though they may themselves be quite diverse – do not rely on such volatile or idiosyncratic assumptions. Such ‘plural and conditional’ analysis is all the more robust, for being transparent about its own dependencies and sensitivities (Stirling, 2008a). Using an innovative framework for heuristic energy appraisal, this is the kind of analysis that is undertaken in the present pilot study (Stirling, 2008b).

Nowhere are these challenges more acute than in the evolving energy policies of the UK and Japan. Here, as in other countries, it has long been widely accepted that diversification of energy sources is a crucial means to address a broad range of issues and hedge a variety of risks and uncertainties. In Japan, the Energy Policy Basic Plan of 2002 presents a guideline both for resource diplomacy and energy research and development. This stipulates that policies have to be made based on a diversification of supply sources to secure stable availability of energy. In the UK, a succession of government energy strategy documents and a recent White Paper also highlight the central role of energy diversity (PIU, 2001; DTI, 2003). In both countries, this background requires that energy policy appraisal make serious efforts systematically to address the complexities that are implicated in contemplating current and future energy options.

For its part, the Japanese government admits that high level policy assessment of these kinds of issues has displayed relatively low performance. They ascribe this difficulty to methodological immaturity and observe that appropriate techniques for analysis and assessment towards credible implementation are not developed and effectively deployed for the purposes of policy administration (CSTP, 2005). In the UK, attempts have been made in the past to address some of the complexities of energy diversity (DTI, 1995). Indeed, this analysis is based directly on antecedents of the present analytical framework (Grubb et al., 2007). But, for the most part, recent UK policy appraisal has also stopped short of any explicit or systematic effort at analysing the implications of contending views of energy diversity. An illustration of this situation lies in the UK Government's treatment of diversity in the official energy sector indicators 2008 (BERR, 2008: 20-22). Although it is positive that diversity is addressed systematically at all, the particular indicator that is used (the Shannon-Wiener index – Stirling, 1994) addresses only a subset of the relevant aspects of diversity (see below) and is highly sensitive to subjective categories (Stirling, 1998). These issues are discussed in more detail elsewhere (Stirling, 2008b) and in Section 2 below.

It is against this background that the conclusion might be drawn that – both in the UK and Japan – there exists considerable scope for experimental studies to test new frameworks for the appraisal of energy diversity. Recognising the serious indeterminacies addressed above, there is a particular premium on interactive studies, based on in-depth engagement with a diverse array of specialist perspectives in each energy policy arena. Rather than relying on a single analytical perspective, this will allow resolution of a 'map' of contending possible expert judgements. It is only in this way that we may hope to develop novel methodologies to become more mature and robust, and inform more rigorous, legitimate and accountable policy discourses in this area. It is with this general aim in mind, that the present pilot study therefore aims to apply and test a novel heuristic approach to energy diversity analysis (Stirling, 2008b). In the process, the study will develop and refine this framework in a number of significant ways. The result will be the first empirical analysis in either Japan or the UK of a concept of energy diversity that addresses the full array of strategic issues identified above. The parallel examination of perspectives from the two quite radically divergent policy contexts in these two countries will provide an additional comparative dimension to the exercise.

In setting out to achieve this, the present working paper is a final product of the international collaboration project between SEPP (Sustainable Energy/Environment & Public Policy, University of Tokyo) and SPRU (Science and Technology Policy Research, University of Sussex) in 2007/08. The specific objectives of the project were:

(1) to develop a computer program for a practical interview methodology integrating two quantitative strategic appraisal techniques (multicriteria mapping and diversity analysis – both developed in at SPRU at the University of Sussex (Stirling, 1997; 1998));

(2) to apply and test this integrated package for multicriteria diversity analysis in a pilot study of the UK and Japanese energy policy contexts, involving a wide range of relevant actors such as government policymakers, industrial engineers, university scientists and NGO leaders; and

(3) to analyse the resulting energy portfolios comparatively across perspectives and national contexts and identify social and policy implications of the similarities and differences of their portfolios of a kind that may warrant further research or policy analysis.

The basic outline of this report is as follows. Chapter 2 offers a brief overview of multicriteria diversity analysis by looking back the concept of diversity based on the existing literature. Chapter 3 introduces the methods underlying multicriteria diversity analysis. It first explains the basic parameters of this pilot study and details of the interview process. Since the multicriteria mapping method is already extensively published (Stirling, 1997; Stirling & Mayer, 2001; Davies et al., 2003; Stirling et al., 2006), the subsequent discussion concentrates on the diversity analysis method – explaining in some detail the procedures employed in using a specialised Excel spreadsheet interface for a dedicated Matlab program. Chapter 4 begins by outlining key features and outputs of each interview on a participant-by-participant basis. With appropriate caution given the small sample sizes involved, it then analyses how individual perspectives are distributed across affiliations and countries and discusses possible reasons for this emerging distribution. Finally, the discussion explains how the many uncertainties that are inherent in such appraisal yield sensitivities in the final energy portfolios that emerge. Chapter 5 summarises the findings of this project and concludes this working report.

2. Concepts

At root, diversity is a property of any system whose elements may be apportioned into categories (Leonard & Jones, 1989). Energy diversity is no exception, where the 'systems' in question may variously be construed as electricity supply infrastructures, or energy systems taken as a whole; where the 'elements' are individual generating facilities or primary fuel sources and the 'categories' are variously-aggregated types of technology or resource. Any method that is adapted to examine diversity as a property of a system whose elements are apportioned into categories is thus well-placed as a framework for examining a variety of perspectives on energy diversity.

In the area of focus of the present study – the electricity supply sector – discussions of diversity span an array of disparate supply and demand side technologies and primary resources. The scope of diversity analysis is further extended by a variety of other relevant factors, including: the regional sourcing of fuel and associated supply routes; concentration among trading, supplier or service companies; reliance on generic equipment or component vendors; dependencies on monopoly utilities, shareowners or labour unions; and the configurations and spatial distribution of infrastructures (PIU, 2001; Farrell et al., 2004; CEC, 2007). These are all prominent features of debates over diversity in energy security. Likewise, each is potentially relevant to diversity as a means to hedge ignorance, foster innovation, mitigate lock-in or accommodate plural values and interests, in the broader senses discussed above in relation to transitions to energy sustainability (Stirling, 2008b). It is therefore desirable that any framework for the analysis of energy diversity be equally applicable in principle across all these aspects.

A general examination of interdisciplinary approaches to the analysis of diversity reveals that this system quality is repeatedly defined in terms of three basic properties (Stirling, 1994).

- Variety: the number of diverse categories of 'option' into which system elements may be apportioned.

- Balance: the apportionment of the energy system across the identified options.

- Disparity: the manner and degree in which energy options may be distinguished.

Each is a necessary but individually insufficient property of diversity (Stirling, 1998). A series of methodological questions follow from this. How can these quite distinct aspects of diversity be aggregated into a single coherent framework? How might such an analytical framework be applied such as to accommodate the range of relevant perspectives typically engaged in real debates over energy strategy? And how can the results of any diversity analysis on these lines be articulated with wider policy considerations – such as the performance of individual generating options under criteria of economic efficiency, environmental quality, social impact and security of supply raised earlier in relation to broad sustainability goals? General investigation of the property of diversity yields a series of evaluative criteria, with which any candidate analytical framework must comply (Stirling, 2007).

Although there presently exists no uniquely specified axiomatic way to resolve these contending analytical criteria, it is remarkable that there does exist a relatively simple quantitative framework which satisfies the demands of all criteria taken together. Although this is quantitative in nature, it takes the form of flexible general heuristic, rather than an ostensibly definitive index. Instead of aiming to measure diversity in some unconditional objective fashion, a heuristic offers an explicit, systematic basis for exploring sensitivities (Stirling, 2007). In this way, a heuristic framework for the analysis of energy diversity aims to combine the rigour, transparency and specificity of quantification with the scope, applicability, flexibility and symmetry of qualitative approaches. The way in which this can work in practice, is the subject of this pilot demonstration exercise.

The details of this approach and its associated rationale are discussed elsewhere (Stirling, 2007; 2008b). For now, the basic underlying mathematical formulation is readily expressed. This specifies the aggregate policy value of an energy portfolio (V{S}) as a function of the value due to the performance of the individual energy options (V{E}) plus the incremental net value due to the degree of diversity displayed by the system as a whole (V{P}) (see also Section 3-2).

$$V\{S\} = V\{E\} + V\{P\} = \sum_i \sum_c (w_c \cdot S_{ic}) \cdot p_i + \delta \cdot \sum_{ij(i \neq j)} (d_{ij})^{\alpha} (p_i \cdot p_j)^{\beta} \cdot \iota_{ij}$$

Here, the performance of the individual energy options (V{E}) is characterised as the simple linear product of technical scores (s_{ic}) assigned to each of i options under a series of c appropriately-weighted (w_c) evaluative criteria: $\sum_i \sum_c (w_c \cdot S_{ic})$). This is a model that is well-established in decision analysis – including that favoured for application in UK Government policy appraisal (DTLR, 2001). It is important to note here that there exist different formal ways in which various specialist disciplines have become habituated in characterising option performance (Vincke, 1992; Bana e Costa, 1990). Preferences or allegiances in this regard may sometimes be raised as an issue (for instance, in the present study, in discussion with JP4 addressed in the results chapter below). In short, the 'linear additive weighting' method embodied in the above algorithm, is that which is widely held to comply best with basic tenets in rational choice theory (DTLR, 2001; Salo, 1995). It is closest in character to the body of this theory underlying conventional economic assessment (Bonner, 1986). Although arguably deficient in these ways, other choice models (eg: 'pairwise comparisons' or 'outranking methods') might equally be adopted for the present purpose, without altering the basic framework of this present analysis of the trade-off between diversity and performance.

The second part of the term expresses the value due to the degree of diversity displayed by the system as a whole (V{P}) in terms of the 'Stirling diversity heuristic' under which diversity is simply the sum of the degree of disparity displayed between each pair of energy options (d_{ij}), weighted by the proportional contribution of each option (p_i, p_j): $\delta \cdot \sum_{ij(i \neq j)} (d_{ij})^{\alpha} (p_i \cdot p_j)^{\beta} \cdot \iota_{ij}$. The additional parameters α and β are exponents which govern the relative priority assigned to the diversity properties variety, balance and disparity. (i_{ij}) is an expression of positive and negative portfolio interactions between options and δ is a coefficient expressing a subjective judgement of the relative priority to place on system diversity compared with option performance.

The practical logic underlying this mathematical framework will be explained in discussing the elicitation process below (Section 3-2).

3. Methodology

3-1. Introduction

Multicriteria diversity analysis is conducted through an in-depth face-to-face interview with an individual participant. There are two basic steps to the process. First, participants appraise the performance of individual energy options. Second, they analyse a series of diverse portfolios. Each step is facilitated by use of a unique dedicated computer software package.

(1) Performance appraisal: Participants are asked to identify a set of relevant energy options and appraise their relative performance under a range of evaluative criteria. These criteria can address any issue felt to be relevant by the participant (e.g. cost, environmental sustainability, security). Based on whatever technical data is felt to be salient, options are then scored by the participant under each criterion, with uncertainties expressed by defining a range of scores in each case. The criteria are then weighted to reflect the participant's judgement of their relative importance, in order to yield a set of overall performance ranks for each option. This is a multicriteria mapping (MCM) process, using the 'MC-Mapper' software. Further details of this methodology are widely published and explained in Appendix 1 to this report.

(2) Diversity analysis: By entering this MCM data into an Excel spreadsheet interface for a dedicated diversity analysis program (written in Matlab), the interviewer can derive in real time a picture of various diverse portfolios reflecting different possible valuations of diversity in relation to performance. This range of diverse portfolios is based on the degree to which options are disparate from each other in terms of the structures of their performance as obtained in the participant's MCM. This is displayed as a continuum ranging from the option mix that yields maximum portfolio performance, to that which yields maximum portfolio diversity. The diversity analysis package also produces a dendrogram to indicate the basic structure of the underlying option disparities implicit in the MCM data.

On this basis, participants can then address a series of more detailed factors relevant to the analysis of diverse portfolios. First (using the Excel spreadsheet interface), they can identify any constraints held to act on the contributions of individual options, groups of options, or sub-tranches of particular options. Second, if they are unsatisfied with the structure of the disparities embodied in their performance appraisal, they can define further 'disparity attributes' such as to modify this structure to arrive at a picture of disparity with which they are happy. Third, they may also enter their estimations of the effects of portfolio-level interactions between energy options.

The final stage of the interview (time permitting) is to conduct sensitivity analysis on all the key input parameters. If at any stage a participant wishes to define variant options or subdivide options into distinct tranches (for instance to reflect constrained subordinate contributions available at different cost), then this may also be conducted using the MC-Mapper software. If necessary and possible, participants may iterate to return to the performance appraisal and define entirely new options, criteria or re-assess performance using MCM.

During this iterative two-stage process, participants typically comment on why they evaluate performance scores and diversity characteristics in such a way and how the final energy portfolio relates to their prior intuition. In a more elaborate multicriteria diversity analysis exercise, this information – suitably prompted by questioning from the interviewer – can be transcribed and provide a rich source of contextual qualitative information. As conducted for the present study, the whole process takes 1 to 3 hours, depending on participants' availability and enthusiasm – and the detail of their appraisals. As it transpired in the present project, all Japanese participants completed the exercise far more quickly than the British. They instantly valued each performance data and disregarded many criteria for the assessment. Although this was evidently partly because they could not afford to spend much time for this, it is interesting to observe here a cross-cultural contrast in subjects' engagements with this analysis. It appears that Japanese respondents were more uncomfortable than their British counterparts with the unfamiliar and subjective character of this exercise. Our experience in interviews suggests that the policy culture on these issues in Japan is somewhat more sympathetic to a 'technocratic' style of analysis, under which – rather than being elicited on the basis of expert judgement – aspects like option disparities are derived automatically from some technical parameter and treated as 'objective'.

Either way, this issue is somewhat tangential to the focus of the present study. The affiliations of participants are shown in Table 1. Participants are anonymised in order to protect privacy as this is a pilot case study and there are sensitivities concerning how the results might be represented or interpreted by other energy specialists or policy actors.

Table 1: List of Participants

ID	Affiliation	State	Interview date
UK1	Senior academic energy economist	UK	16 Nov. 2007
UK2	Research director, public energy research institute	UK	16 Nov. 2007
UK3	Former industry energy executive, government advisor	UK	19 Nov. 2007
UK4	Senior executive, major national utility	UK	20 Dec. 2007
JP1	Senior academic energy policy researcher	Japan	30 Nov. 2007
JP2	Senior executive, public energy research institute	Japan	10 Dec. 2007
JP3	Executive director, private energy research institute	Japan	11 Dec. 2007
JP4	Academic energy system engineer	Japan	20 Dec. 2007
JP5	Councillor in government ministry	Japan	26 Dec. 2007

The participants were selected in order to ensure an appropriate degree of pluralism in each country, both of affiliation and expertise. The selection also reflected the necessity for the purpose of the present pilot exercise that each could be assumed to hold the requisite knowledge meaningfully to appraise the various energy technologies and policies.

For the purposes of facilitating the interviews, the research team compiled from government policy documentation and peer-reviewed sources an illustrative set of performance data for a representative range of consistently-defined electricity supply options and a series of energy policy appraisal criteria. The data compiled included issues of economic cost, various atmospheric emissions, land use, employment intensity and so forth. This database was made available as a reference point to all participants when conducting their own individual MCM appraisal, in order to enable them more readily to understand the kind of issue that they might wish to consider. However, the participants (as energy experts in their own right) were at liberty where they felt they could justify this, to modify this data to accord better with their own specialist judgement.

Given that the purpose of the multicriteria mapping methodology is quite specifically to 'map' divergent views, this is conducted not to enforce an artificial coherence across participants, but to provide back-up resources only where these are felt to be necessary. In practice, as expected, all participants were sufficiently specialist in the fields in question, that these criteria and data were employed simply as a prompt, with attention focusing overwhelmingly on each individual's own technical knowledge and expert judgement. That this is so, can be seen in the manifest divergence between the pictures of energy option performance, as derived by different individual interviewees (Chapter 4). However, the basic template of 'core options' which formed the basis for this initial dataset, did serve the successful function of somewhat standardising the definition and partitioning of energy options, such as to enable effective comparison across individuals and national contexts. This will be discussed further in the chapter on comparative analysis below.

3-2. Diversity Analysis

As summarised above, the present diversity analysis method is based initially on data generated in performance appraisal. The basic idea is that the degree of disparity displayed between any pair of energy options is, to a first approximation, expressed by the differences observable in their performance profiles. Other aspects – such as the intrinsic physical nature or origins of the resources or technologies involved – may be taken into account as a second order consideration. But it is found in practice that these kinds of additional attributes beyond those routinely considered in performance appraisals, actually typically exert relatively little impact on the structure of disparities as embedded in the performance data. In this way, for instance, an option displaying relatively high air quality scores, low catastrophic risk scores, high security scores and low economic scores will be highly disparate from one displaying the opposite characteristics in each respect. Other options with more mid-range values in each case will be correspondingly intermediate in their mutual disparities. A dedicated Excel macro program has been devised for this pilot study with the aim of quickly converting output data from the MC-Mapper software to input data for the Matlab diversity analysis program. See Appendix 2 for more detail on the macro program and Excel spreadsheets.

4. Analysis

4-1. Interview Results and Output Figures

The following pages illustrate, for each participant, (1) charts displaying the overall performance rankings obtained in the MCM appraisal for each energy option defined by the participant; and (2) a range of diversity-optimal portfolios obtained in the diversity analysis process (Figure 4 from the Matlab program; see Appendix 3). Each picture represents the outcome of detailed deliberation on the part of the participant in question. Key features that emerge from these pictures are discussed in each case. This includes some discussion of the underlying performance criteria and associated scoring (which also forms the basis for the disparity attributes), as well as further qualitative information arising from the interview and more reflexive observations concerning the overall process of interaction and analysis.

Taken together, these empirical findings confirm other comparable 'mapping' studies, in demonstrating the relatively high degree of variability between the perspectives of different specialists – even within a particular national context. Suitably qualified by reference to the small numbers of respondents engaged with in this pilot study, the following sections will undertake various forms of comparative analysis to identify cross-cutting issues, questions and potential generalisations, that span the two national contexts.

The individual disparity structures that underlie these pictures will be discussed separately in later analysis – and also be taken as a basis for more general comparison.

1. UK1

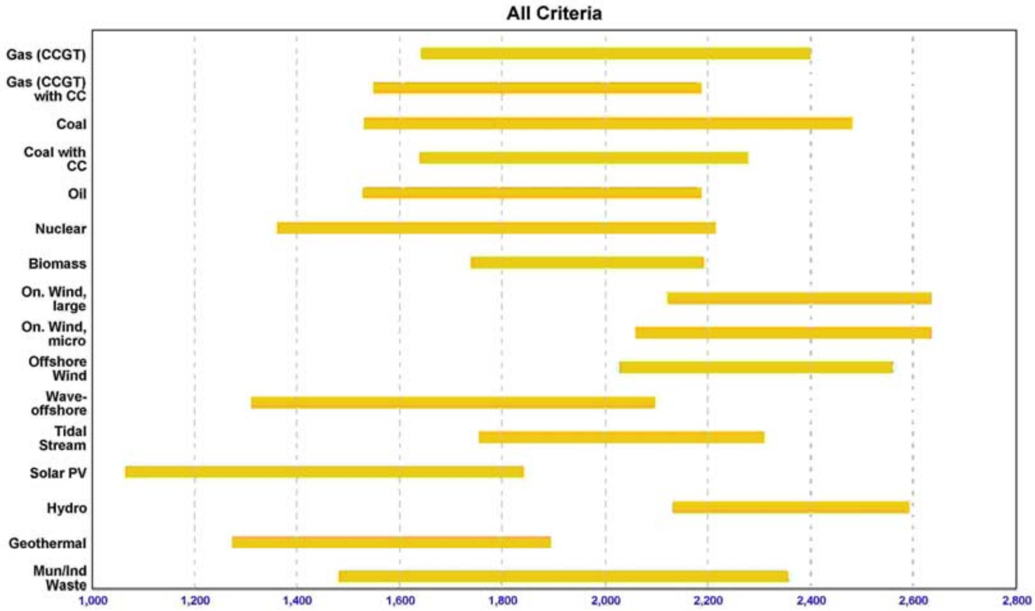

Figure 1: Overall Performance Rankings (UK1)

UK1 is a senior academic energy economist. The performance appraisal criteria in this case comprise engineering cost, climate change impact, land use, employment, regional economic development, public acceptability, community empowerment, proliferation, catastrophe, and long-run security. UK1 noted that land use includes infrastructure and amenity issues, catastrophe includes all catastrophic and mortality risks and commented that public acceptability and community empowerment are somewhat related each other.

The criterion weighting for engineering cost is the highest (1200), followed by climate change impact (600), long-run security (600) and public acceptability (300).

Wind and hydro energy options are the best performing options overall, and quite distinct in this respect from other options. Driven by (highly weighted) poor economic scores, solar PV displays the worst performance. The uncertainty intervals displayed by these rankings are relatively wide, which means that UK1 takes into account a considerable degree of uncertainty.

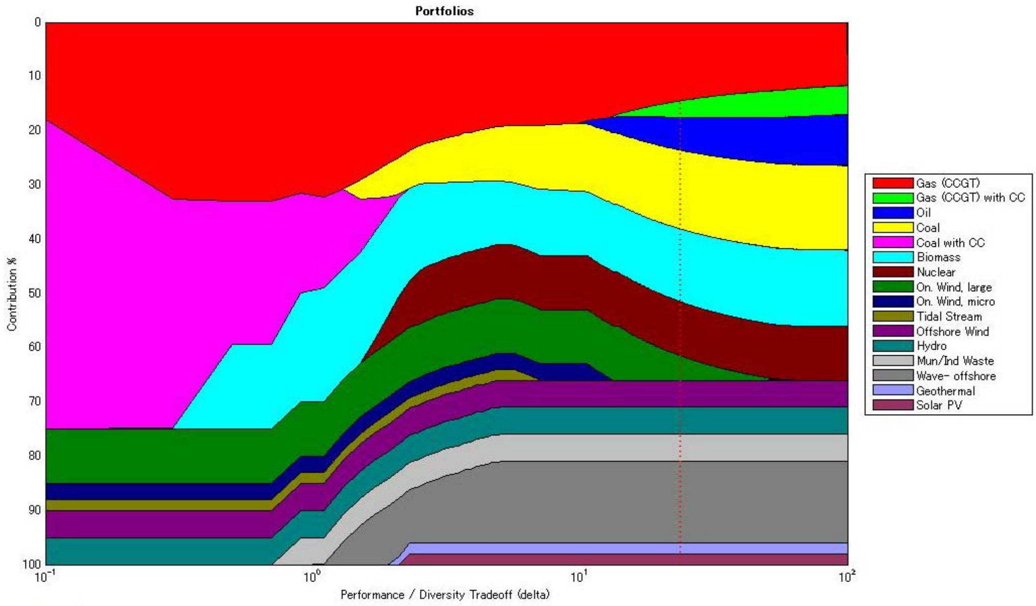

Figure 2: Diversity-Optimal Portfolios (UK1)

UK1's range of diversity-optimal portfolios illustrates that gas CCGT (combined cycle gas turbine) and coal with CC (carbon capture) are dominant where the performance is prioritised over diversity (left-hand side of the above figure). In other words, the parameter represented on the horizontal axis (delta) represents the relative weighting placed on aggregate option performance as compared with aggregate portfolio diversity (see equation in Section 2). This is due to the constraints held to limit contributions from better-performing options. As the value of diversity increases against that of performance, biomass, coal, nuclear and offshore wave options each enter the portfolio in succession and acquire significant shares. As the performance-diversity trade-off continues to rise, wind and tidal stream options diminish their shares and – at high weightings on diversity – actually leave the portfolio.

This latter feature is due to the fact that these better-performing renewable options are positioned in an intermediate region of the multidimensional disparity space defined for all options taken together. As the weighting on performance diminishes, so the diversity-optimal portfolios select for those options occupying the envelope of this disparity space. In UK1's case for example, wind and tidal stream show better performance than other renewables such as waste, wave, geothermal and solar power and lie in the 'interior' of UK1's disparity space – with these other renewables defining the envelope of the disparity space. In other words, waste, wave, geothermal and solar power display similar kinds of disparity to wind and tidal stream (with respect to other prominent options in the portfolio – like gas, oil, coal, biomass and nuclear), but to a more pronounced extent. With relatively low weightings placed on diversity, then, wind and tidal stream enter the portfolio before these other renewables. As the diversity weighting increases, however, and wave, geothermal and solar power all begin to enter the portfolio, then the diversity benefits accrued through the wind and tidal stream contributions are increasingly dominated by the diversity benefits accrued through these lower-performing options. This is because these latter options display similar disparity characteristics with respect to other prominent options, but – being at the 'edge of the disparity envelope' – these are more pronounced. As the diversity weighting continues to rise and the performance advantage displayed with respect to these options by wind and tidal stream continues to diminish, so wind and tidal stream are eventually displaced from the portfolio by the options that dominate them in terms of disparity.

This phenomenon reflects a general feature of diversity analysis that is also relevant in other cases in this pilot study. Where the exit of options with rising diversity weightings is held to be counterintuitive, this is simply because the underlying disparity attributes have been incompletely specified, such that they are readily dominated. In other words, it is an indication that the exiting options need to be characterised more distinctively. This can be addressed by defining a higher resolution disparity space in which more fine-grain differences are resolved between the options on the envelope of the space and those in the interior. This can readily be achieved by defining further disparity attributes during the diversity analysis, but was not conducted in the present pilot exercise.

2. UK2

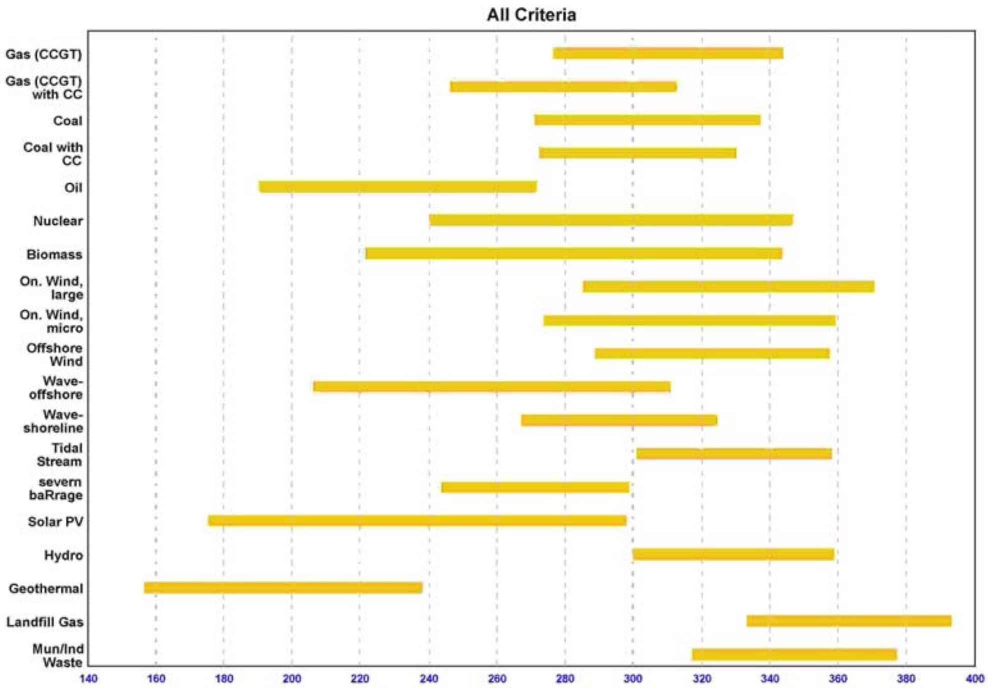

Figure 3; Overall Performance Rankings (UK2)

UK2 is the Research Director of a public energy research institute. The evaluation criteria comprise engineering cost, climate change impact, SO_2 emissions, land use, noise, indirect energy input, regional economic development, public acceptability, community empowerment, proliferation, catastrophe, and long-run security. In this view, land use also means land sterilised for other uses. Public acceptability is regarded as an outcome of political process. Options are assessed under a time frame of 2025-30, which in allows for full consideration of new options. The Severn Barrage, a potential site for tidal power generation in the UK, is added to the initial set of energy options and distinguished from the tidal stream option.

Engineering cost is the highest-weighted performance criterion (230), followed by climate change impact (60) and long-run security (40).

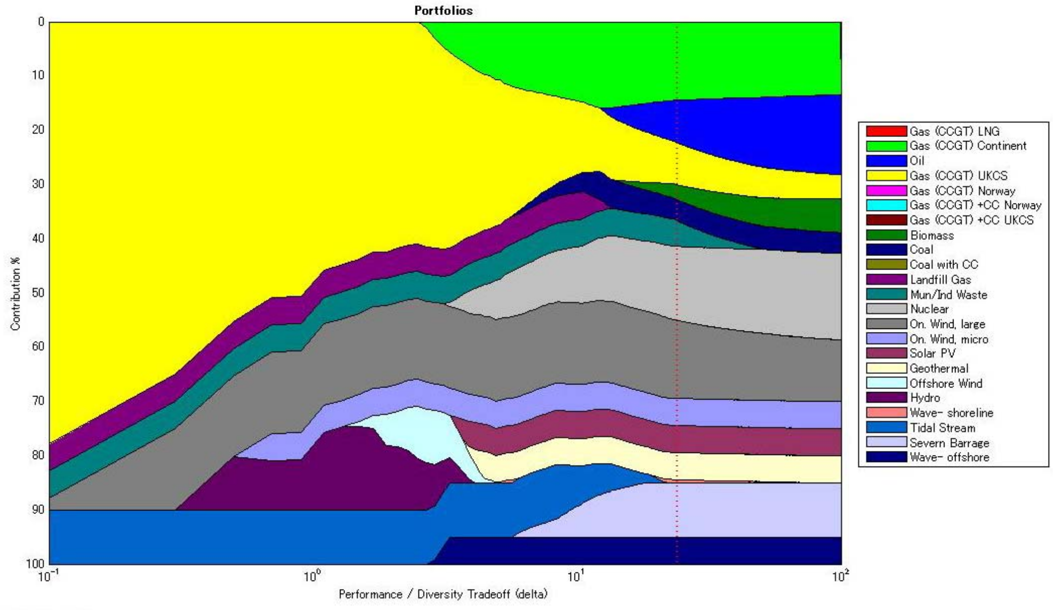

Figure 4: Diversity-Optimal Portfolios (UK2)

In the diversity analysis, UK2 subdivided the gas CCGT option into six, according to the origin of the resource. Among others, gas CCGT-UK continental shelf is dominant at the performance-oriented side of the range of portfolios, since UK2 did not constrain the maximum proportional contribution from this energy option.

As with UK1, it is evident that several options move in and out of the diversity-optimal portfolios as the weighting on diversity increases, giving the portfolio range a particularly dynamic and complex appearance. Again this reflects the configuration of the disparity space noted for UK1, amplified by the greater variability in the performance ranks.

3. UK3

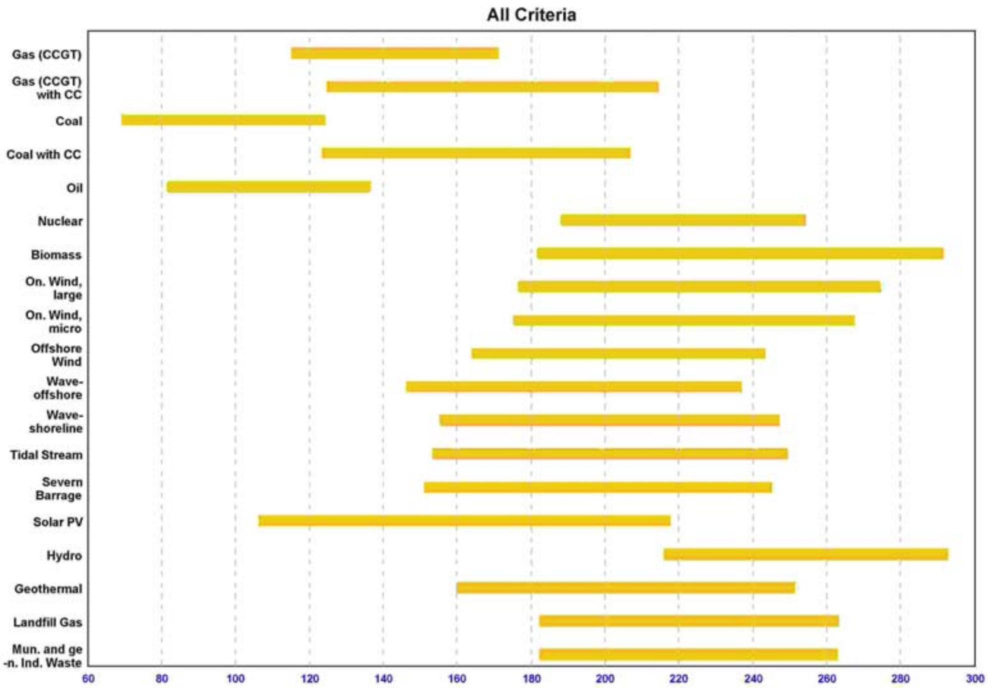

Figure 5: Overall Performance Rankings (UK3)

UK3 is a former senior energy industry executive and member of a UK government energy policy advisory committee. The evaluation criteria comprise engineering cost, climate change impact, speed of implementation, infrastructure compatibility, intermittency, investment risk, and geopolitical exposure. Speed of implementation includes wider issues like research, the state of technology, barriers and their removal, such as regulatory and other non-market obstacles. The meaning of 'infrastructure' in the infrastructure compatibility criterion is broader than just electricity infrastructure including, for instance, carbon capture and storage – which are regarded as highly uncertain technologies. UK3 also notes that investment risk is a particular issue for nuclear power.

Unlike others, UK3 put a relatively low weighting on engineering cost (20) as compared to the two main criteria – climate change impact (100) and speed of implementation (100). Other criteria are weighted at the same level as engineering cost.

The performance ranking chart clearly distinguishes hydro option as holding highest performance. Gas and coal (each with carbon capture) and oil have significantly lower performance scores than other options.

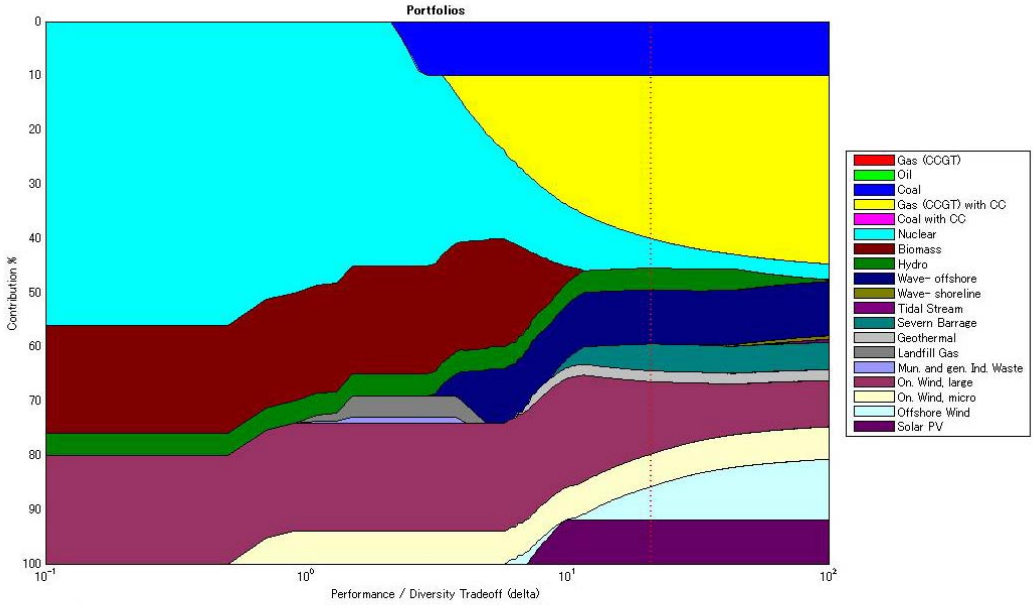

Figure 6: Diversity-Optimal Portfolios (UK3)

UK3 obtains a high contribution for nuclear at the performance-weighted side of the range of portfolios. This reflects the tight constraints that are held to bear on the similarly-performing renewables. Gas CCGT with carbon capture is a growing option as diversity increases. In this case, as that of other participants, the specific rationales for these kinds of framing assumption were not fully explored in the present pilot exercise – the focus being on testing the elicitation of diverse portfolios. However qualitative elicitation of framings is a strong feature of other full multi-criteria mapping exercises aimed at exploring performance alone (as distinct from performance *and* diversity). More comprehensive and in-depth follow-on research may thus extend the analysis to include full consideration for the divergent rationales underlying the contrasting evaluative positions of different participants.

4. UK4

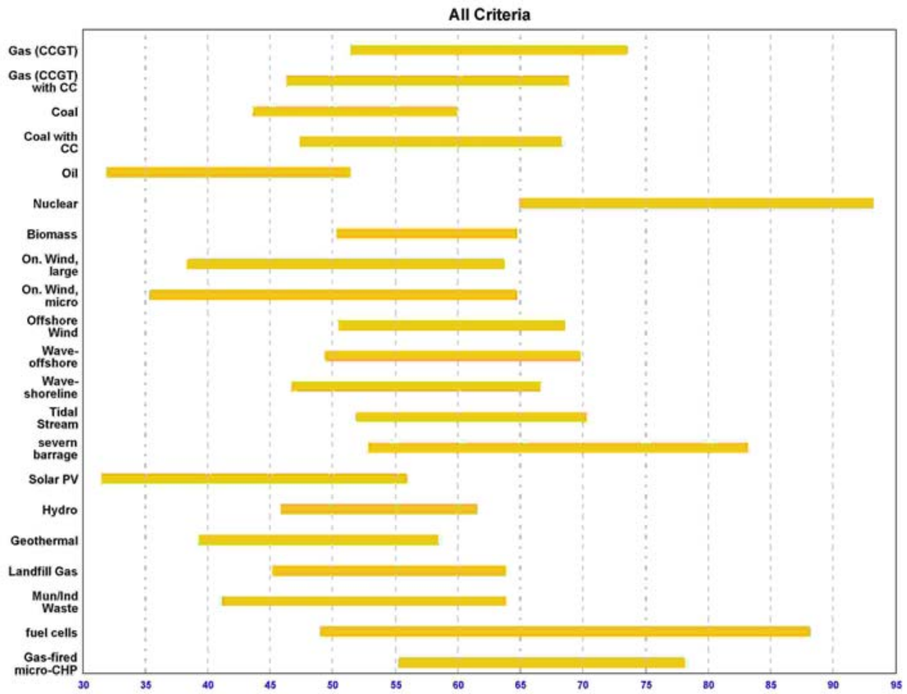

Figure 7: Overall Performance Rankings (UK4)

UK4 is a senior executive with a major national utility. The evaluation criteria comprise engineering cost, development cost, climate change impact, SO_2 emissions, land use, noise, indirect energy input, regional economic development, public acceptability, community empowerment, terrorism/proliferation, catastrophe, long-run security, and load factor. UK4 expressed a need for further information in performance appraisal, requiring government data on disaggregating capital and operational costs within the category of engineering cost. Load factor refers to the proportion of time and rated capacity that a given type of plant is actually generating power. UK4 added fuel cells as an additional energy option. There are in this view two types: micro-CHP (combined heat and power) and larger cells for electricity storage/generation.

The highest-weighted criteria are engineering cost (19), climate change impact (19), load factor (17) and public acceptability (13). The rest are weighted at values that are less than half of this. With regard to overall performance, nuclear clearly outranks all others, with little to distinguish the rest, aside from the relatively high ranks for large tidal and fuel cells and low-ranking positions for oil and solar.

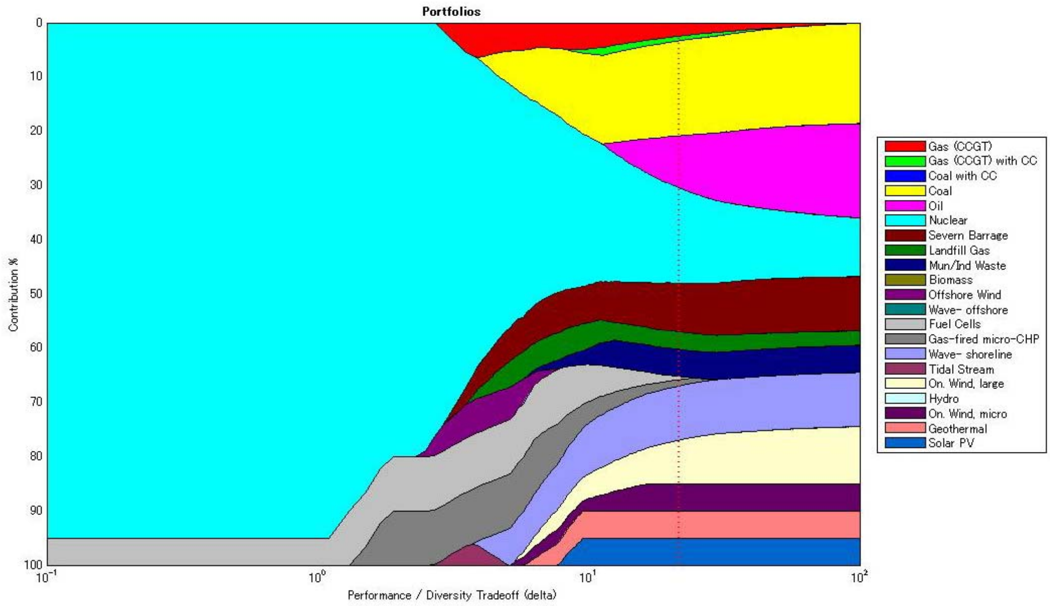

Figure 8: Diversity-Optimal Portfolios (UK4)

The range of diversity-optimal portfolios shows a clear pattern of increasing diversity. Nuclear dominates at the performance-oriented side of the portfolio, constrained only by system-operational factors to admit a 5% contribution from fuel cells. This reflects UK4's overall performance rankings as illustrated in Figure 7, in which nuclear shows the best performance followed by fuel cells. Of course, it is not realistic that the UK could accept nuclear at 95% of total electricity supply. Again, a more detailed exercise than the present pilot study would prompt participants to return to introduce further second order constraints, according to their own judgement of the technical position. As the weighting on diversity increases, so many energy options enter into the portfolio and the contribution of the nuclear option decreases significantly. The large tidal option enters in a gradual fashion, because a large step size was not specified for the purpose of this pilot study.

5. JP1

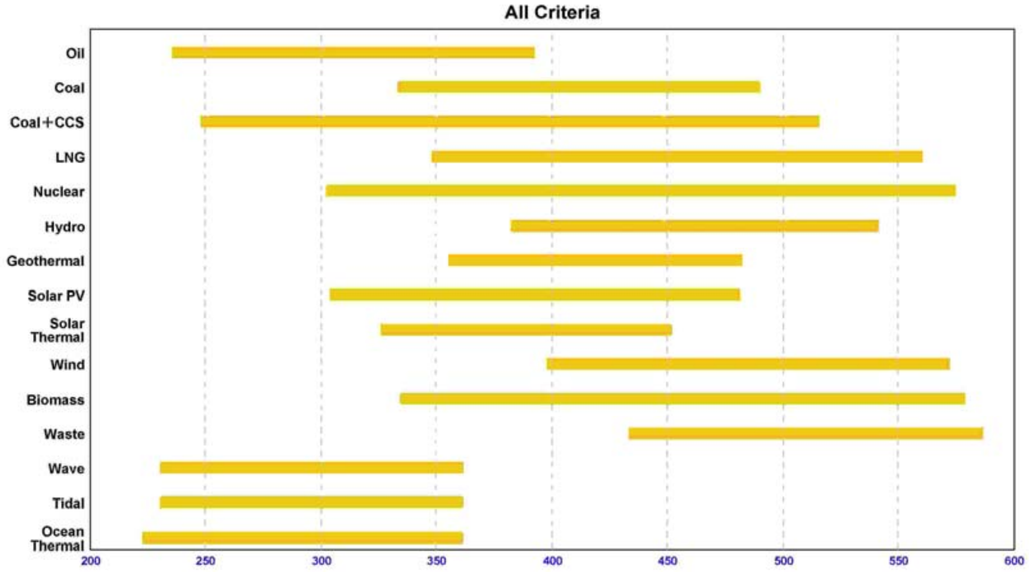

Figure 9: Overall Performance Rankings (JP1)

JP1 is a senior academic energy policy researcher. The evaluation criteria comprise engineering cost, climate change impact, regional economic development, public acceptance, proliferation, catastrophe, intermittency, air pollution, waste, and ecosystem risk. JP1 notes that regional economic development includes employment.

The highest-weighted criterion is engineering cost (300), followed by climate change impact (60), public acceptance (50), catastrophe (50) and intermittency (50). The rest have the same weightings (30).

Regarding overall performance, the waste option ranks highest, slightly above wind, hydro and biomass. LNG (liquefied natural gas) and nuclear are also high performing, but have wider uncertainties. Oil, wave, tidal and ocean thermal are relatively low performing, with other options intermediate.

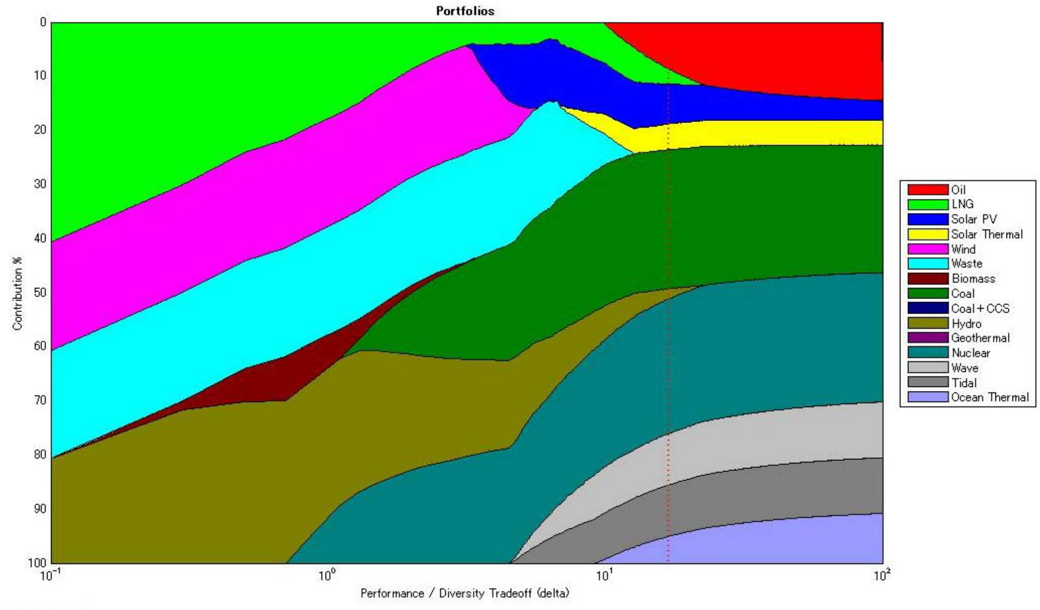

Figure 10: Diversity-Optimal Portfolios (JP1)

As with UK1, JP1's range of diversity-optimal portfolios displays the feature of certain options leaving the portfolio as the weighting on diversity increases. JP1 queried this, for instance in relation to LNG. Again (as discussed above for UK1), the reason lies in the positioning of the excluded options in dominated regions of the disparity space. In this way, it is contrary to JP1's intuition – but not to JP1's definition of disparities as embodied in the performance appraisal – that LNG is not so distinctive from oil. As discussed in relation to UK1, further refinement of the disparity space by addition of further disparity attributes such as to more finely resolve the options in question would reverse this effect. In particular, this would allow JP1 to define further disparity attributes under which LNG is credited more fully with its own distinguishing attributes.

JP1 also asked what about adding energy conservation to the initial set of energy options for appraisal in MCM. This raises a question about the focus in this study on electric power supply technologies. Energy conservation can indeed be taken into account as an energy option by adopting an 'integrated resource planning' framework. It was not possible for the purpose of this pilot exercise to adapt the framework accordingly, or acquire the necessary data, so this remains a potentially significant issue for a future larger-scale study.

6. JP2

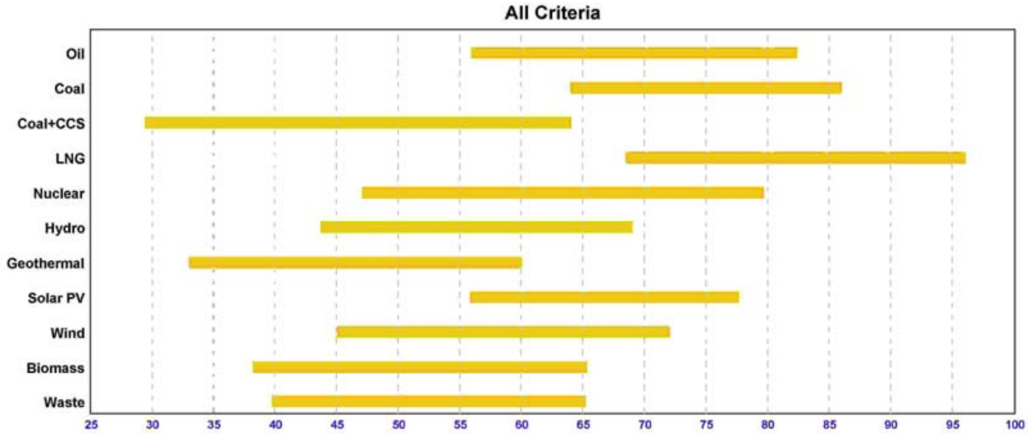

Figure 11: Overall Performance Rankings (JP2)

JP2 is a senior executive for a public energy research institute. The evaluation criteria comprise cost, political risk, technological risk, public acceptance, environmental impact, and available supplies. JP2 notes that environmental impact is mainly based on global warming.

The available supplies criterion has the highest weighting (23) and political risk has the lowest (7). Other criteria are equally weighted in between (19).

In performance terms, LNG emerges as the best option overall, with coal, oil and solar PV following in succession. Nuclear performs highly at one end of the range, but displays high uncertainty. Coal with carbon capture and storage is the lowest performing option, although also displaying high uncertainty.

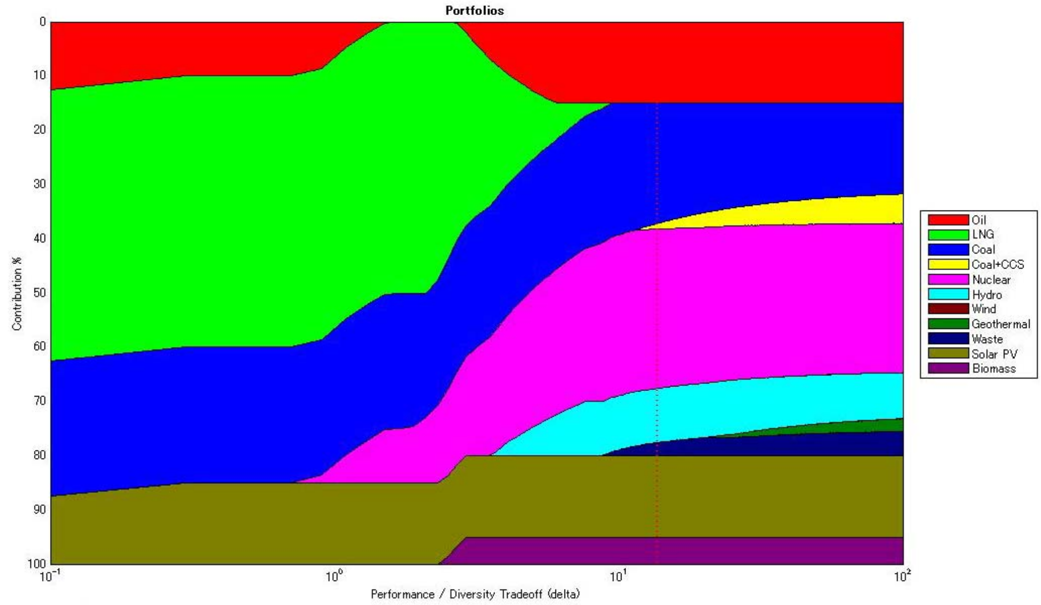

Figure 12: Diversity-Optimal Portfolios (JP2)

As with JP1, JP2 queried why LNG is eliminated from the diversity-optimal portfolios at higher weightings on diversity. The reason is due to the same cause as discussed for UK1 and JP1, reflecting a logical but intuitively difficult feature that is resolvable through more refined definitions of disparity of a kind that were not carried out for this pilot study. Both JP1 and JP2, as energy security experts, appraised LNG to perform better than oil under almost all criteria, recognised a difference of kind between oil and LNG in geopolitical and economic terms. The counter-intuitive aspects of the portfolios they have each obtained, thus offer a concrete basis for applying more fine-grain disparity attributes which reflect the full depth and extent of their understanding of the issues bearing on distinctions between these energy options.

7. JP3

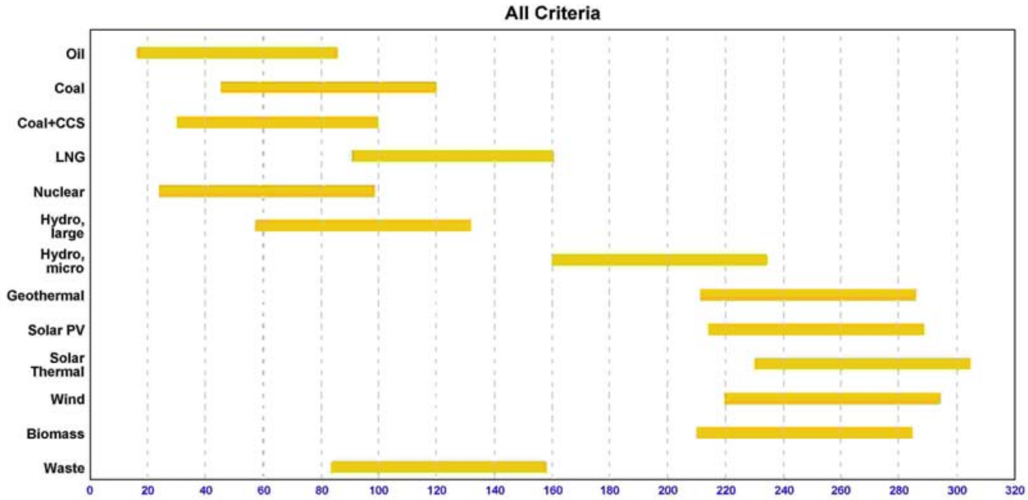

Figure 13: Overall Performance Rankings (JP3)

JP3 is the Executive Director of a private energy research institute. The evaluation criteria comprise cost, public engagement, environmental impact, resources constraint, regional economic development, industrial economic impact, geopolitical risk, local/national politics, technological uncertainty, and innovation effect (facilitating spill-over and industrial infrastructure development). The cost criterion includes social cost and the biomass option excludes traditional grain and ethanol as first generation biofuels.

JP3 assigned three levels of weightings. The heaviest weighting (50) is assigned to cost, environmental impact, and resource constraint. The lightest (10) is assigned to technological uncertainty and innovation effect. Middle-level weightings (30) are assigned to the other criteria.

The performance ranking chart clearly illustrates two groupings of energy options. One consists of renewable energies including solar thermal, solar PV, wind, geothermal and biomass, which display higher performance. The other group includes the conventional energy options. This group displays greater variability in rankings than does the higher-ranking group, but the uncertainty ranges for the individual options is similar across all groups.

JP3 notes this distinction between two groups of energy options reflects a general perspective that is characteristic of the particular energy-environmental interests of the associated independent research institute, which broadly favours renewable over conventional energy options. In particular, the waste option is regarded as broadly similar to the conventional energy options, with a performance that also reflects this.

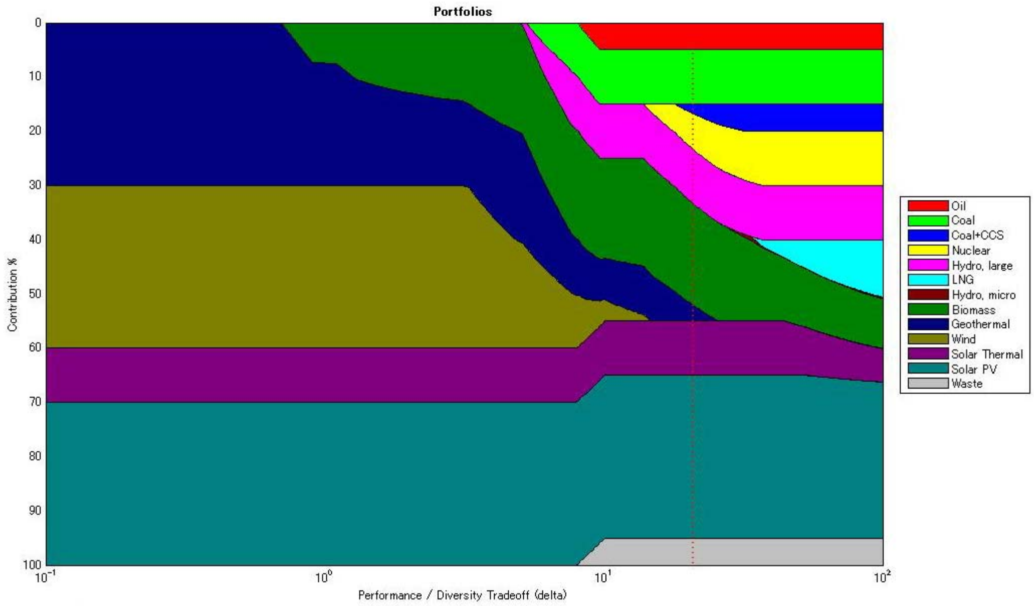

Figure 14: Diversity-Optimal Portfolios (JP3)

The range of diversity-optimal portfolios further reflects this picture of performance, with renewable options dominant at the performance-oriented side. Solar PV remains dominant throughout the range of portfolios. As with UK1, JP1 and JP2, it is notable that one of the highest-performing options (in this case, wind) is removed from the portfolio at high weightings on diversity. As discussed in these other cases, this reflects the relatively course-grained characterisation of disparity in the present pilot study.

8. JP4

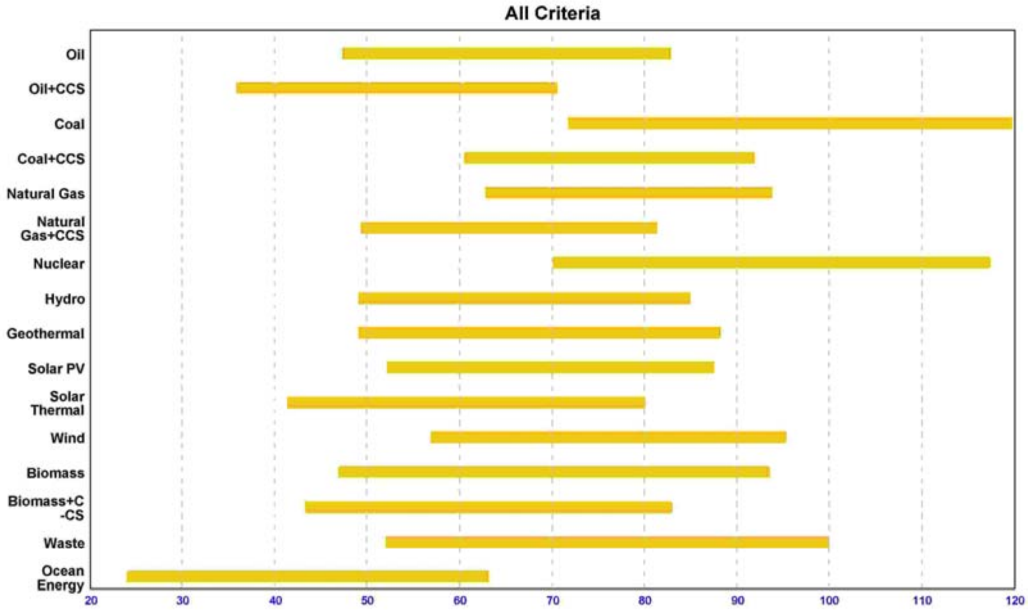

Figure 15: Overall Performance Rankings (JP4)

JP4 is an academic energy system engineer. The evaluation criteria comprise cost, political risk, public acceptability, environmental impact and supply capability. Political risk, in these terms, includes resistance of electric power companies. Ocean energy as an option that includes wave, tidal and ocean thermal.

Cost is the highest-weighted criterion (50) taking up one third of the total allocated weighting. Environmental impact (30) and supply capability (30) weight second, with political risk (20) is third.

Coal and nuclear perform significantly better than other options in the overall rankings. Ocean energy displays a particularly low ranking.

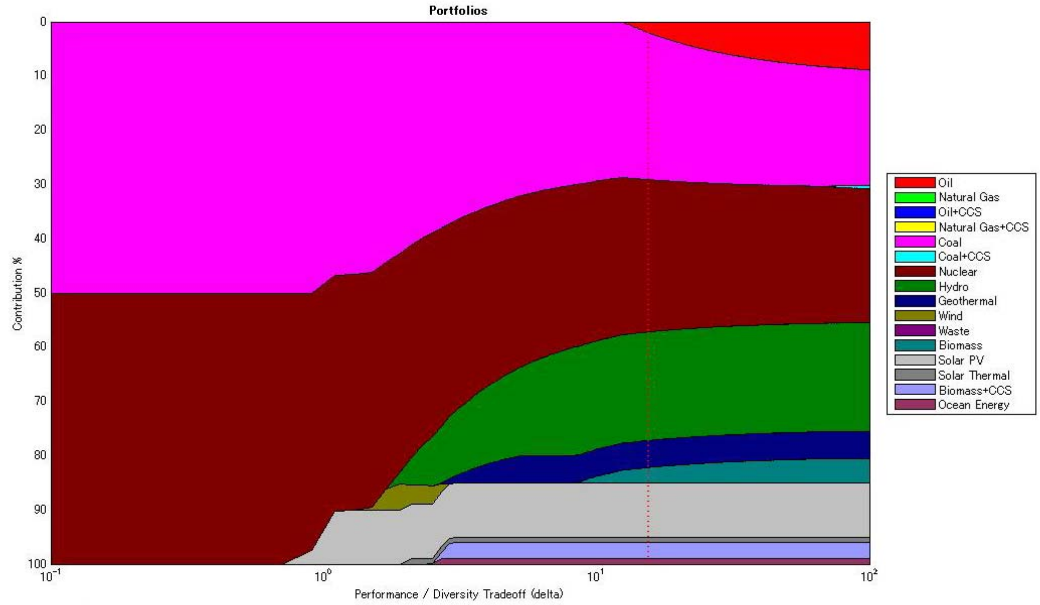

Figure 16: Diversity-Optimal Portfolios (JP4)

JP4 expressed some surprise that natural gas does not become included in the portfolio, even as the weighting on diversity increases to high values. Intuitively, JP4 considers natural gas to be quite distinctive in its characteristics, and should thus be expected to appear where higher values are placed on diversity. Again, this is likely to arise from this high degree of distinctiveness being under-reflected in the actual disparity attributes that underlie the analysis, as based on the MCM performance criteria. By taking further time to define additional disparity attributes, this would be resolved.

JP4 pointed out that it is difficult to address 'rapid dispatch' as a collective constraint because it is dependent on temporal considerations. The present static analysis does not allow full account to be taken of these kinds of dynamic characteristics.

JP4 also mentioned that he had trouble in weighting some performance criteria in the MCM process. This was based on the view that two criteria can be compared, but more than two are difficult to compare in a direct way. JP4 explained this in terms of the 'intransitivity' of criteria. This refers to a detailed technical debate in multicriteria analysis, mentioned in the 'Concepts' chapter earlier of a kind that does not affect the nature of the outcome of this exercise.

9. JP5

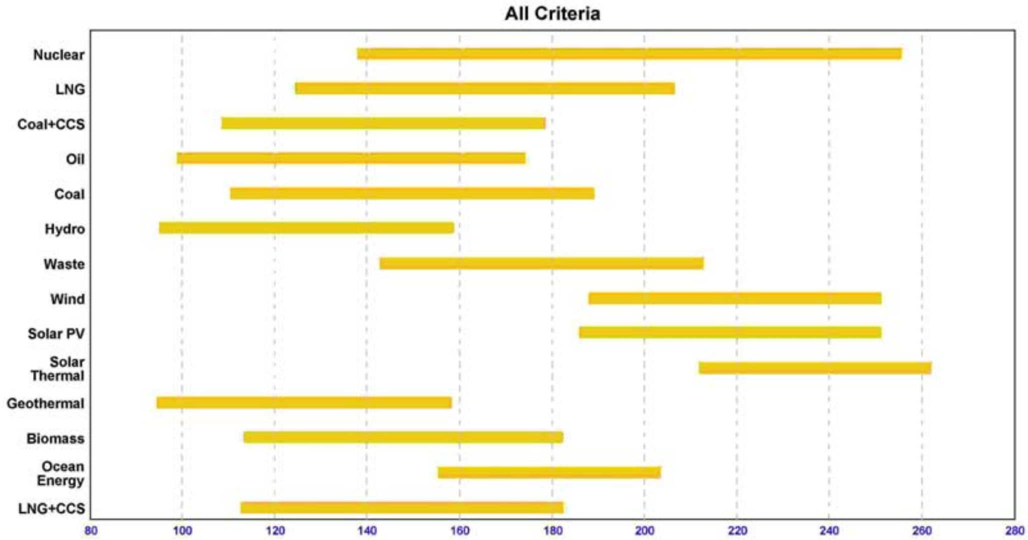

Figure 17: Overall Performance Rankings (JP5)

JP5 is a councillor in a government ministry. The evaluation criteria comprise environmental impact (90), cost (70), technological risk (40), public acceptability (50) and political risk (60). Note that environmental impact mainly reflects impacts on global climate change. The waste option includes agricultural, forestry and municipal waste.

Solar thermal, solar PV and wind are the best-performing options, followed by the nuclear option, although this displays high uncertainty.

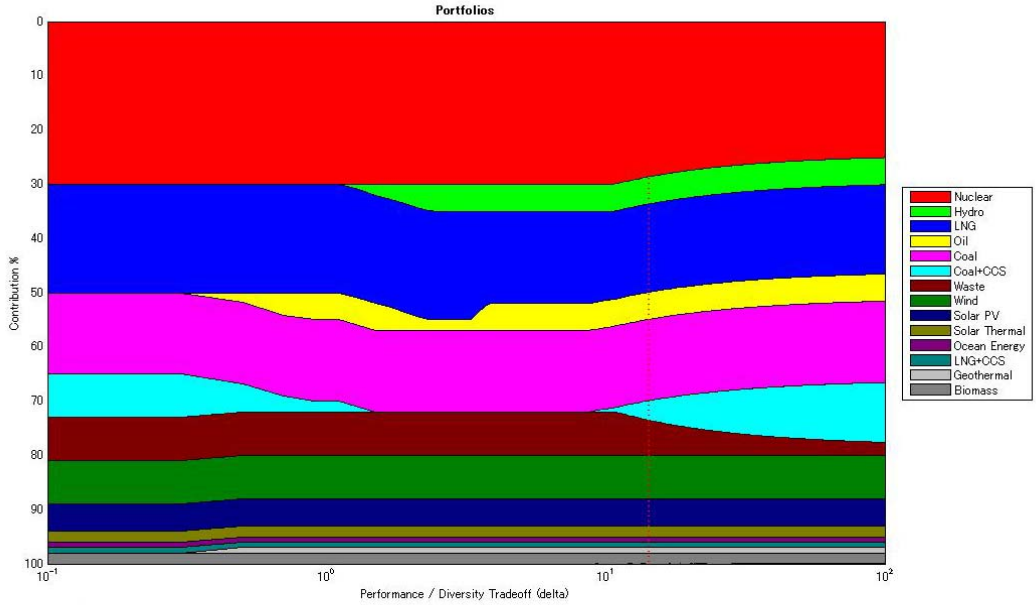

Figure 18: Diversity-Optimal Portfolios (JP5)

The highly static nature of the range of diversity-optimal portfolios in this case, reflects the highly restrictive set of constraints that JP5 set for the contributions from individual energy options. Indeed, JP5 carefully calculated the sum of individual constraints to be nearly 1. Taking pride in being an environmentally cautious decision-maker (which is also suggested as the heavy weighting for the 'Environmental Impact' criterion in MCM), JP5 claims that the policy challenge is not so much a matter of pursuing energy diversity as an end in itself, but of harnessing the intrinsic diversity in the energy options (including as many renewable options as possible) required to comply with international environmental treaties and agreements. Accordingly, JP5 expressed little surprise at the form taken by the performance picture yielded in the MCM appraisal or the structure of the diversity-optimal portfolios.

4-2. Two-Dimensional Scaling

The present exercise is a pilot study primarily for the purpose of demonstrating and exploring the diversity analysis methodology. Accordingly, the numbers of participants involved in this study are relatively low – much too low to aggregate analysis seeking high levels of statistical significance across groupings like that contrasting the UK with Japan. On the other hand, difficulties of this kind are likely to be experienced even in a more detailed analysis. This is due to the highly specialised nature of the information required in diversity analysis coupled with the relatively small pool of appropriately-engaged people and the high degree of variability typically displayed between individual specialists in this kind of complex technical area. Subject to this general qualification, then, there is some value in demonstrating the kind of comparative analysis that might be conducted (with correspondingly greater confidence) in a more elaborate application of the method piloted in this study.

The most obvious comparative question that might be asked, concerns the possible existence of patterns in the highly varied ranges of diversity-optimal portfolios obtained by these nine expert participants from disparate institutional backgrounds in two different countries. This is a question that can be approached – even for relatively low numbers of participants – using two-dimensional scaling. The first step required in undertaking such a comparative analysis, is to render consistent the different sets of energy options. This is necessary, because many participants defined additional options to those suggested in the core set developed by the analysts. The present comparative analysis is thus based on a 'core set' of options, that were defined consistently and appraised by all nine participants from both countries involved. The distributions of portfolio contributions for these core options can then be analysed and two principal components extracted for a series of different points in the spectrum of portfolios (Table 2). This operation is expected reveal the internal structure of the data in a way which best explains the variance in the data. It transforms the data to a new orthogonal coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (called the first principal component), the second greatest variance on the second coordinate. In simpler terms, the first principal component identifies the main contrast in viewpoints across all participants taken together over the performance of different energy options, whilst the second component explains the second most significance contrast in views.

Table 2: Factor Loadings for Two Principal Components

	1	2
Gas (CCGT)	-0.637	-0.156
Gas (CCGT) + CC(S)	-0.436	-0.211
LNG	0.322	0.341
LNG + CCS	0.247	0.441
Coal	0.911	-0.335
Coal + CC(S)	0.262	0.796
Oil	7.20E-02	1.74E-02
Nuclear	0.787	-0.204
Hydro	0.627	0.297
Wind (On. large/micro, Off.)	-0.837	-0.277
Solar PV	1.11E-02	0.757
Solar Thermal	0.289	0.161
Geothermal	-0.34	-0.126
Biomass	-0.11	0.726
Waste (incl. Landfill Gas)	-0.276	0.427
Tidal (incl. Severn Barrage)	-0.492	-0.718
Wave	-0.443	-0.757
Others	0.7	-0.449

The horizontal axis and the vertical axis in these figures represent the normalized factor scores for the first component and the second component in Table 2, respectively. The factor scores are computed by the regression method, which works by multiplying the factor loadings by the inverse of the original correlation matrix. Conceptually, the factor score represents the degree to which each individual performance score rates high on energy options that have high loadings on a factor. Factor extraction, rotation and factor score computation is processed by SPSS computer software and two-dimensional scaling is displayed with the help of Excel software.

In the present study scaling analysis was performed for four different points in the ranges of diversity-optimal portfolios. These were bounded at one end by the 'maximum performance' portfolio (with no weighting on diversity) as shown in Figure 19 and at the other end by 'mid point' of the range (where the total portfolio value is constituted equally by the performance of the individual options and the value placed on portfolio diversity) as shown in Figure 23. Intermediate between these two cases, scaling analysis was also conducted for portfolios displaying 75%, 60% and 55% of total value being due to option performance (Figure 20, Figure 21 and Figure 22).

Despite the variability displayed within the two national groups of experts, the overall picture arising from this two-dimensional scaling procedure across all four sampling points is a pretty clear separation between UK and Japanese participants. This implies that UK participants tend to favour gas CCGT and wind as high-performing energy supply sources whereas Japanese participants tend rather to favour coal, nuclear and hydro. This may to a large extent reflect the different contexts and resource endowments in each country, but may also to some extent be a reflection of distinct cultural and institutional aspects of a kind that might bear further exploration.

Reviewing the picture represented in Table 2 in more detail, the first component (shown on the horizontal axis in the charts that follow) is defined at the extremes by coal, nuclear and hydro in positive terms and gas CCGT and wind in negative terms. This is the axis that discriminates best between the UK and Japanese cases. Japanese portfolios favour coal, nuclear and hydro, whilst wind and gas CCGT are relatively favoured in the UK. The second component consists of coal with carbon capture (and storage), solar PV and biomass at one extreme and wave and tidal at the other. This component is displayed on the vertical axis. For its part, the second component seems to reflect the common distinction made across participants as a whole between renewable energy options (as a group) and conventional options (as a group – including carbon capture and storage).

Here, significant differences emerge in the two-dimensional representations obtained in the case of 100% weighting on performance and 50% weight on performance. Among other things, this reflects the fact that, the share of renewable options becomes more similar between participants as diversity increases.

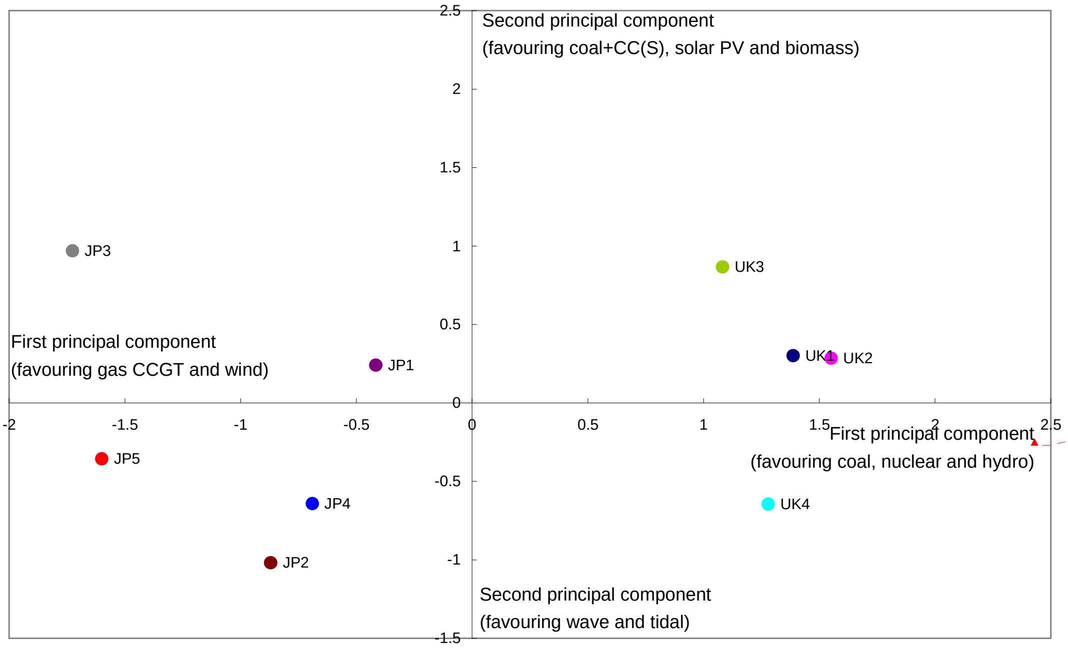

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Figure 19: Distribution of Participants at Performance 100%

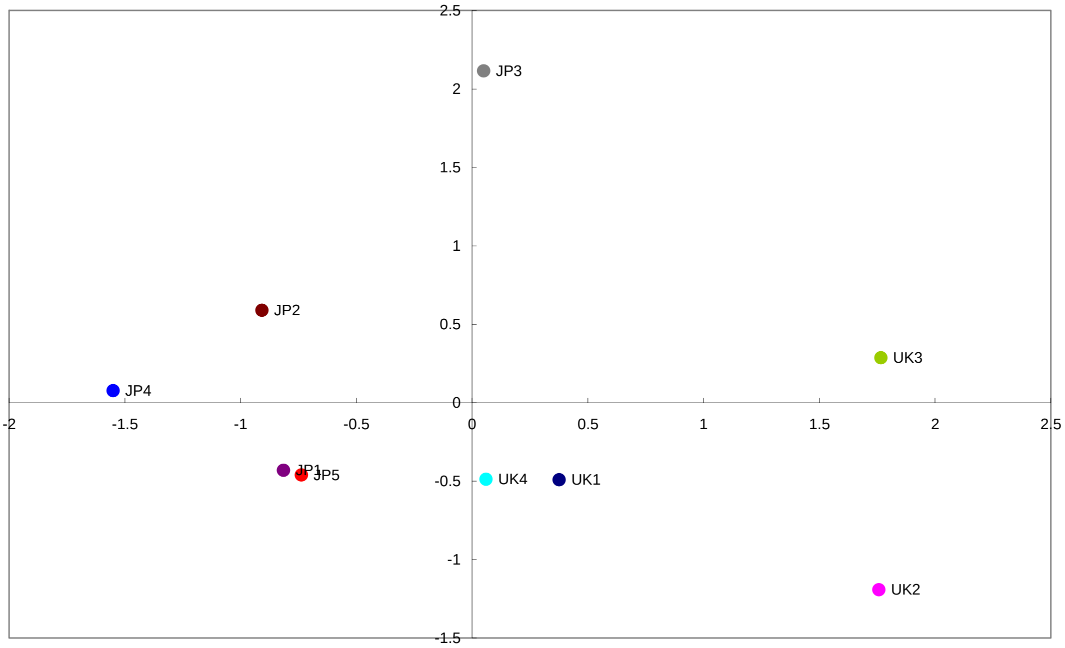


Figure 20: Distribution of Participants at Performance 75%

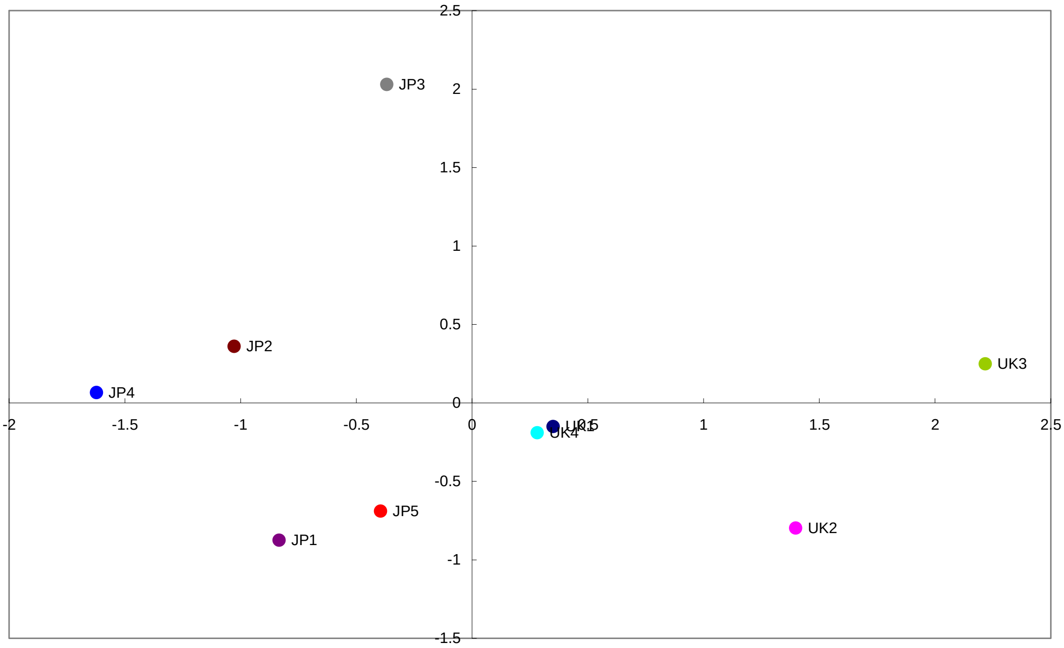


Figure 21: Distribution of Participants at Performance 60%

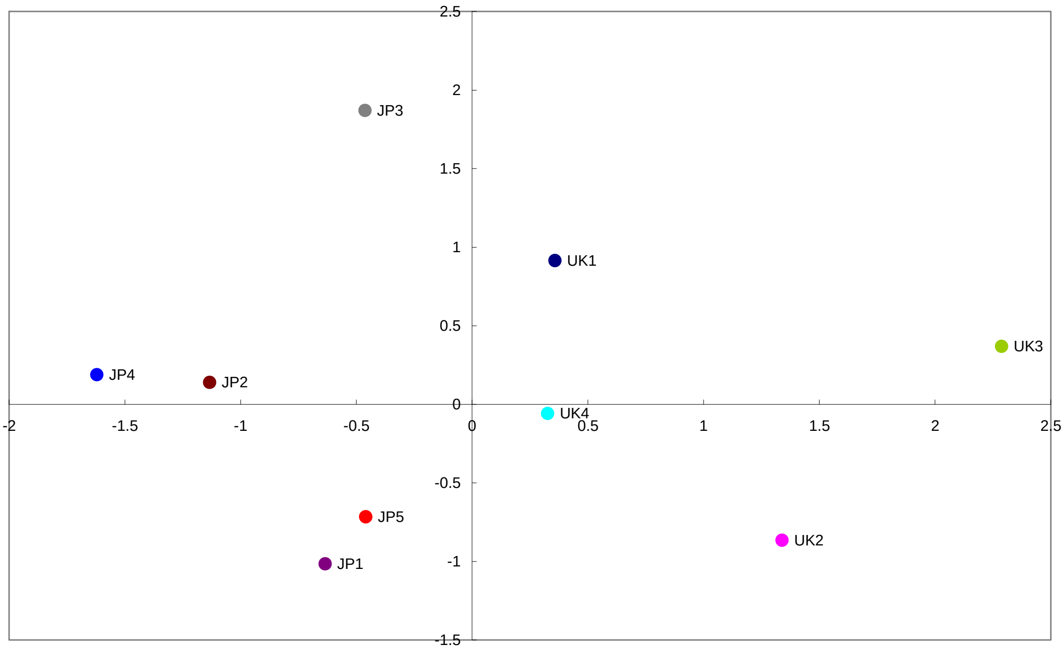


Figure 22: Distribution of Participants at Performance 55%

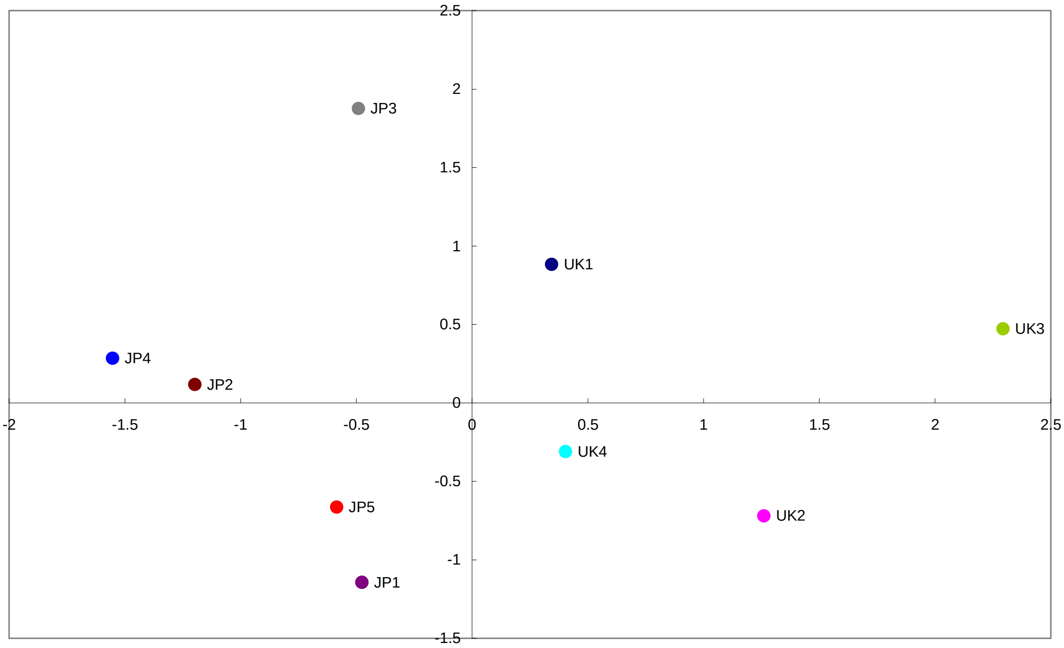


Figure 23: Distribution of Participants at Mid Point

As noted above, it is difficult to be confident about results obtained in a pilot study involving such small samples sizes. Despite this there are some conspicuous features, which warrant further attention.

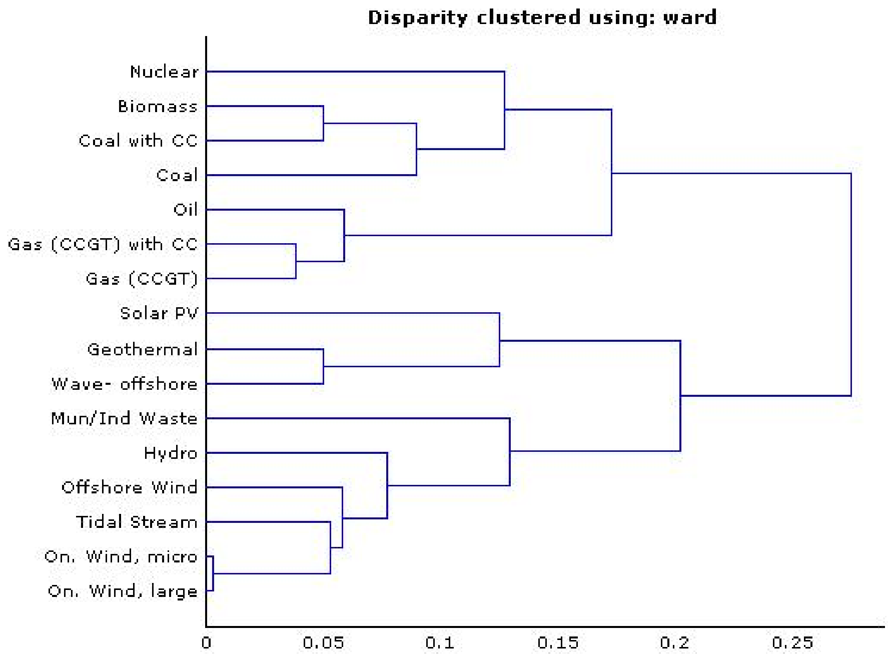
First, there is the strikingly consistent distinction between the perspectives of UK and Japanese participants (as displayed on the primary scaling axis for all points in the range of diversity-optimal portfolios).

Second, these is a marked convergence in the distribution of participants on the secondary scaling axis, as the weighting on diversity increases. This illustrates the tendency for increasing valuations of diversity in the energy mix, not only to address matters of uncertainty and energy security (as is much discussed), but also to enable a higher degree of reconciliation between the highly contrasting evaluative perspectives of different stakeholder groups. In a hotly contested arena such as energy policy, this presents a degree of empirical support (both in the UK and Japanese cases) for the hypothesised importance of diversity as a means to accommodate greater pluralism in the politics of energy technology choice.

4-3. Analysis of Disparity Structures

This section provides a comparative analysis of the disparity structures obtained in the MCM performance appraisals conducted by the nine participants. For this purpose, it makes use of qualitative deliberation over the form of the dendrograms (obtained using the Ward method) obtained in each individual participant's diversity analysis (as described above). The purpose is to examine the degree and type of difference that may be observed between the basic structures in the disparities displayed under these specialist perspectives. In particular, it will be interesting to compare the nature of these differences, with the quite radical variabilities that have been documented in Chapter 4 concerning the relative performance (and consequently portfolio compositions) of the different options.

UK1


Disparity clustered using: ward
Nuclear
Biomass
Coal with CC
Coal
Oil
Gas (CCGT) with CC
Gas (CCGT)
Solar PV
Geothermal
Wave- offshore
Mun/Ind Waste
Hydro
Offshore Wind
Tidal Stream
On. Wind, micro
On. Wind, large
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0.15
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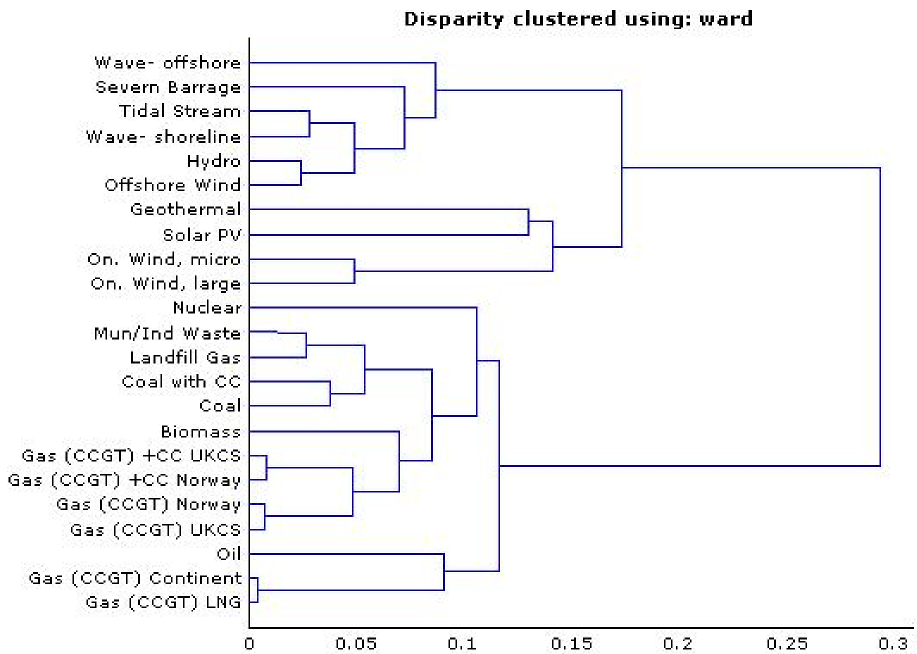
0.25

UK2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Wave- offshore
Severn Barrage
Tidal Stream
Wave- shoreline
Hydro
Offshore Wind
Geothermal
Solar PV
On. Wind, micro
On. Wind, large
Nuclear
Mun/Ind Waste
Landfill Gas
Coal with CC
Coal
Biomass
Gas (CCGT) +CC UKCS
Gas (CCGT) +CC Norway
Gas (CCGT) Norway
Gas (CCGT) UKCS
Oil
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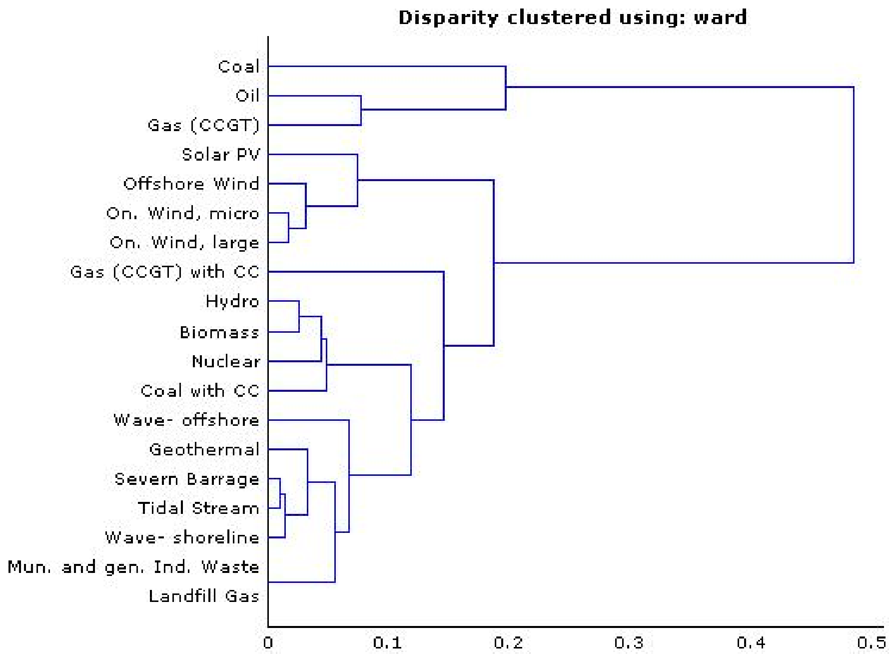
UK3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Oil
Gas (CCGT)
Solar PV
Offshore Wind
On. Wind, micro
On. Wind, large
Gas (CCGT) with CC
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Nuclear
Coal with CC
Wave- offshore
Geothermal
Severn Barrage
Tidal Stream
Wave- shoreline
Mun. and gen. Ind. Waste
Landfill Gas
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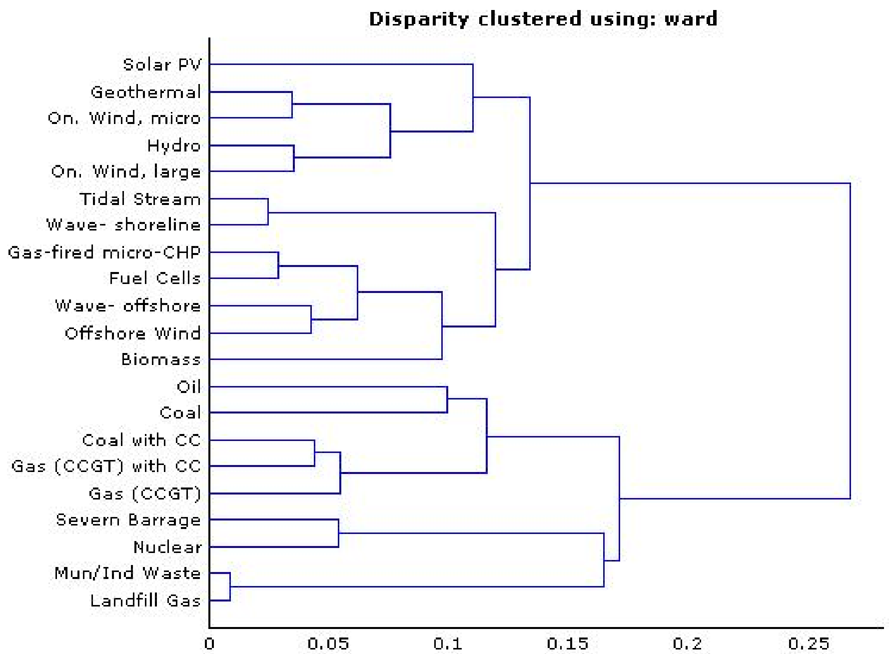
0.5

UK4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Geothermal
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Hydro
On. Wind, large
Tidal Stream
Wave- shoreline
Gas-fired micro-CHP
Fuel Cells
Wave- offshore
Offshore Wind
Biomass
Oil
Coal
Coal with CC
Gas (CCGT) with CC
Gas (CCGT)
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Nuclear
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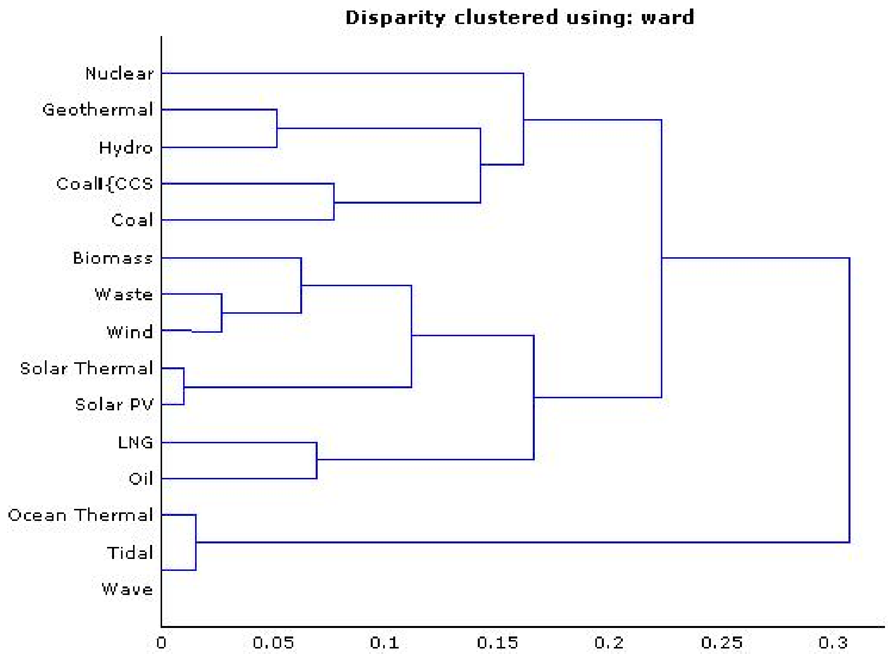
JP1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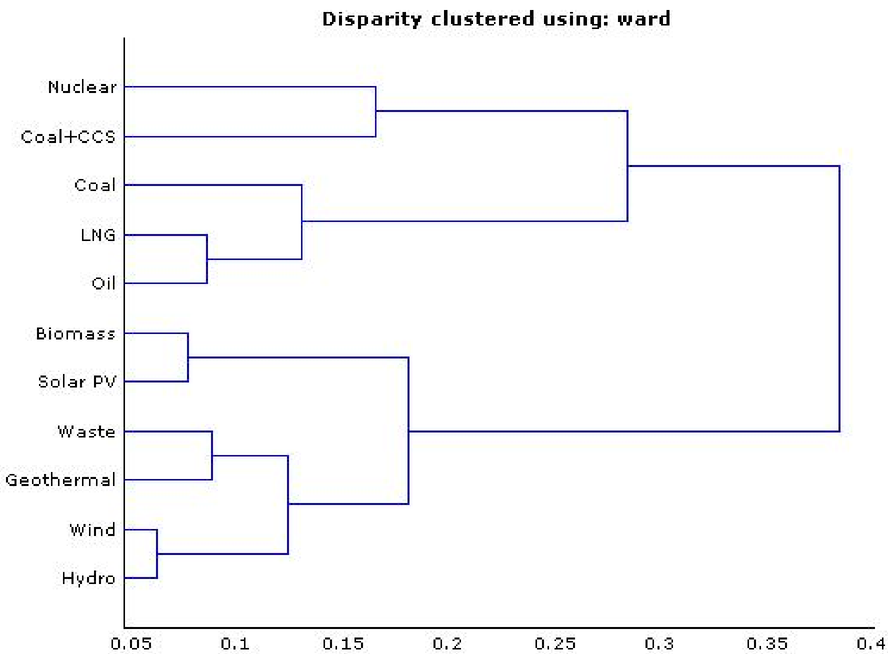
JP2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Coal+CCS
Coal
LNG
Oil
Biomass
Solar PV
Waste
Geothermal
Wind
Hydro
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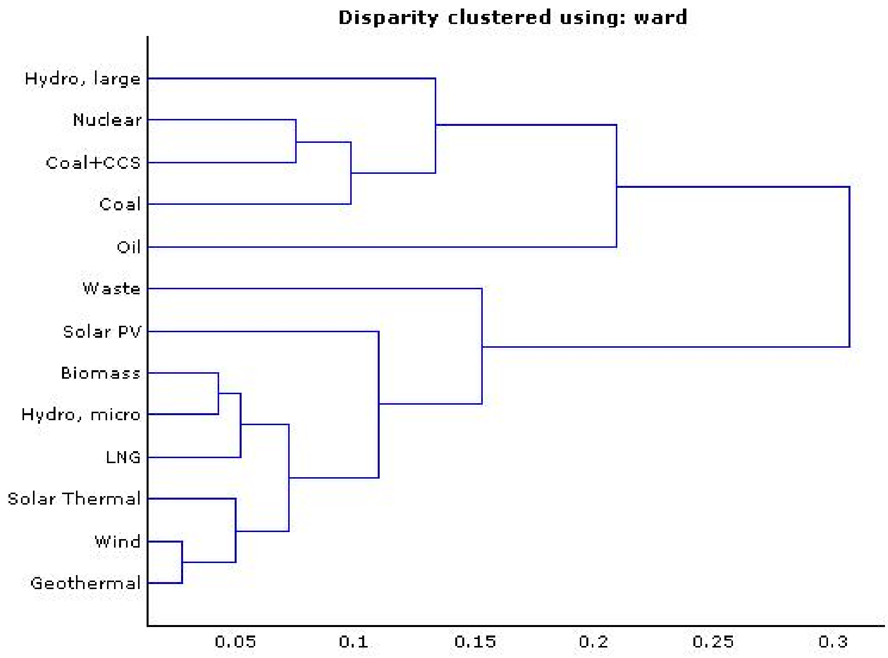
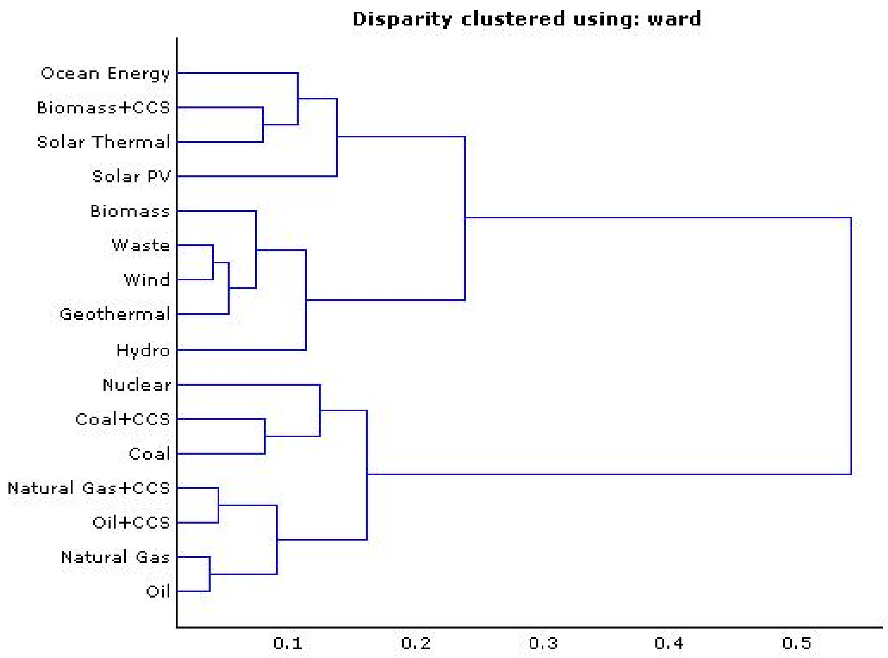
0.35
0.4

JP3



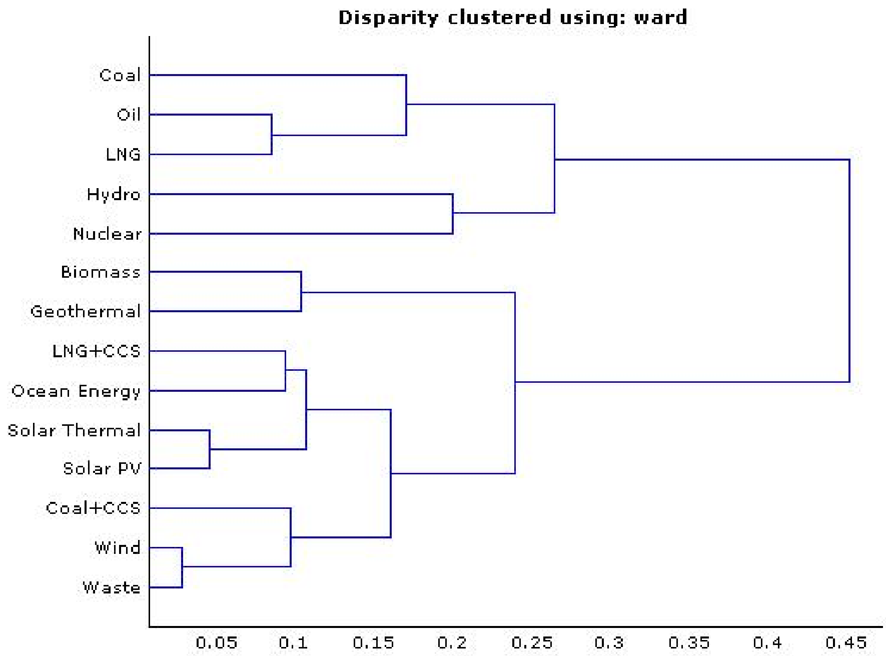
Disparity clustered using: ward
Hydro, large
Nuclear
Coal+CCS
Coal
Oil
Waste
Solar PV
Biomass
Hydro, micro
LNG
Solar Thermal
Wind
Geothermal
0.05
0.1
0.15
0.2
0.25
0.3

JP4



Disparity clustered using: ward
Ocean Energy
Biomass+CCS
Solar Thermal
Solar PV
Biomass
Waste
Wind
Geothermal
Hydro
Nuclear
Coal+CCS
Coal
Natural Gas+CCS
Oil+CCS
Natural Gas
Oil
0.1
0.2
0.3
0.4
0.5

JP5



Although there are many differences between these alternative independent assessments of disparity, there are some notable – and potentially significant – common features.

(1) Conventional energy vs. renewable energy

First, the great majority of participants discriminate at a fundamental level between conventional energy options (as a group including coal, oil and nuclear) and the renewables as group. This is shown by the repeated appearance of a two-cluster solution at the right-hand (high disparity) side of the figure. This is not remarkable in itself, but it does present an unusually detailed empirical grounding for what is often little more than a casual assertion. In particular, this makes a novel direct link to performance appraisal results, of a kind that are widely available – thus suggesting a ready means to test the reproducibility of this finding. The distinction is also interesting in that it highlights a number of potentially significant exceptions.

- **Partitioning of 'conventional' options**

A relatively minor variant on the general conventional/renewable distinction described above is UK3, who groups coal, oil and gas CCGT as one cluster, with nuclear, gas+CC and coal+CC. grouped separately at a high level of disparity. Likewise, JP1 clearly differentiates coal and nuclear from LNG and oil.

- **Hydro as conventional or not**

There is a tendency for the UK participants to regard hydro energy as a renewable option whereas several of the Japanese participants (JP1, JP3 and JP5) regard it as conventional.

- **Biomass and waste as conventional or not**

There is particular ambiguity in the UK over the 'renewable' status of biomass, with some UK participants grouping it alongside conventional options and others including it with the renewables. All the Japanese participants group biomass with the renewables. This distinction of patterns is even more pronounced in the case of waste. This probably reflects the particular (and sometimes ambiguous) environmental status of combustion technology, but provides an interesting indication of divergent cultural views on this.

Taken together, the detailed features of this conventional/renewable divide provide interestingly explicit confirmation of some often-implicit features of energy policy debates. In this respect, the analysis of disparity structures that are inherent in performance appraisal, may offer a useful basis for more rigorous and transparent attention to this important aspect. Of course, this overall picture of a quite fundamental difference between broad categories of 'conventional' and 'renewables' may be significant in its independent substantiation, but it is hardly surprising. There is however a more important and less intuitive consequence of this, discussed below.

(2) The internal diversity of the renewable energy options

It is a feature of every disparity structure, without exception, that the broad category of 'renewable energy' is disaggregated by the clustering algorithms on the basis of its internal disparity at a level that is at least equal to the conventional partitioning of coal, oil and gas. This constitutes a very important finding, to the effect that conventional analysis of diversity, based on accepted linguistic and official statistical categories like "coal, oil, gas, nuclear and renewables", seriously understates the diversity benefits of the renewables. In other words, for no better reason than casual use of historically-contingent terminology, conventional analysis tends to group renewables together as if they were less disparate than renewables are as a group from coal, oil, gas and nuclear. What this analysis shows is that, under every one of the diverse expert perspectives involved, renewables are actually subdivided on the basis of disparity at levels at least equivalent to the distinctions between fossil fuels. Although the details vary, what this means is, that rather than being analysed according to categories 'coal', 'oil', 'gas', 'nuclear', 'renewables', energy systems should rather be analysed in terms of 'coal', 'oil', 'gas', 'nuclear', 'renewables 1', 'renewables 2', 'renewables 3', 'renewables 4' and so on.

More specifically, although the details vary between different specialist perspectives, it is a common feature that this large group of energy options (including, for instance, "wind, wave, tidal, hydro, biomass, waste, geothermal and solar") may be seen generally to be equally disparate from each other, as are the fossil fuels, and indeed even as the fossil fuels are from nuclear. Whatever the differences in other respects, this robust general result has potentially enormous implications for the considerations over how to realise diversity benefits in electricity supply portfolios. In short, the common practice of aggregating a number (even all) of the 'renewables' together as a category for the purposes of diversity analysis will have the effect of seriously understating the diversity benefits of renewable energy options.

(3) Scale of Disparities

The horizontal axis may be thought of as providing an indication of the levels of disparity at which different clusters of energy options differ from one another. Although the scale is arbitrary, the normalisation of the input data means that it is comparable across participants. As shown by the contrasting horizontal distributions of the dendrograms against this axis, then, the overall degree of disparity obtained by each participant as a consequence of the multicriteria mapping exercise, varies quite significantly.

Let us compare UK3 and UK4. UK3 displays a disparity distance of 0.5 to obtain a one-cluster solution, whereas UK4 needs a corresponding disparity distance of only about 0.25. UK3's dendrogram has a more complex and deeply-nested structure as compared to UK4's. Comparison of dendrogram structures also tells us that, for instance, UK2 and JP4 have a relatively clear mind-set over the extent to which conventional and renewable energy options are distinct.

It is thus clear from these dendrograms, that – despite the significant underlying patterns noted above – different specialists do hold quite distinct views not only over the performance of individual energy options, but also over the scale and nature of their mutual disparities. This is also an important finding for analysis that tends to impose finely-specified concepts of energy diversity.

4-4. Sensitivity Analysis

In any complex policy appraisal exercise of this kind, it is always important to be transparent about the scale and nature of the key uncertainties. This is especially true where the object of assessment is as ambiguously-defined and the analytical framework as novel as is the case with conventional energy debates over diversity. The present section will therefore outline the form of the sensitivity analysis that has been conducted and convey the main findings. For the purposes of the present pilot study, this should also assist in conveying some of the features, limits and qualifications associated with this methodology. In order to illustrate a much more general set of issues, we will here take as an illustrative example, the range of diversity-optimal portfolios generated by UK1. As such, the picture in the diagrams below should be compared with the default picture shown in Figure 2.

Since both the disparity structures and the performance profiles are represented as ranges, the sensitivity analysis focuses on the effect of taking different specific values with these ranges. It begins by displaying the median values for these ranges, as used as defaults in the diversity analysis. As discussed in the following, there are three kinds of sensitivity analysis. The first analysis observes the change from the lowest value (pessimistic) to the highest value (optimistic) accommodated in the performance appraisal for each energy option. The second analysis performs the same sensitivity analysis with respect to performance criteria (rather than options). The third analysis explores a difference between lowest and highest weighting amounting to a total factor of one order of magnitude. Note that the choice of a total sensitivity interval of one order of magnitude is purely illustrative (although it should accommodate most scope for reasonable differences of expert judgement).

(1) Scoring sensitivity by performance option

This can be illustrated by considering the case of coal with carbon capture. If the default performance values are substituted with the lowest ranking in the interval obtained for the coal with carbon capture option (and everything else is left *ceteris paribus*), then it has the significant effect of entirely excluding this option from the entire range of diversity-optimal portfolios (Figure 24). The contribution is substituted instead by the biomass option, which also further substitutes gas CCGT at the 'high performance' end of the spectrum.

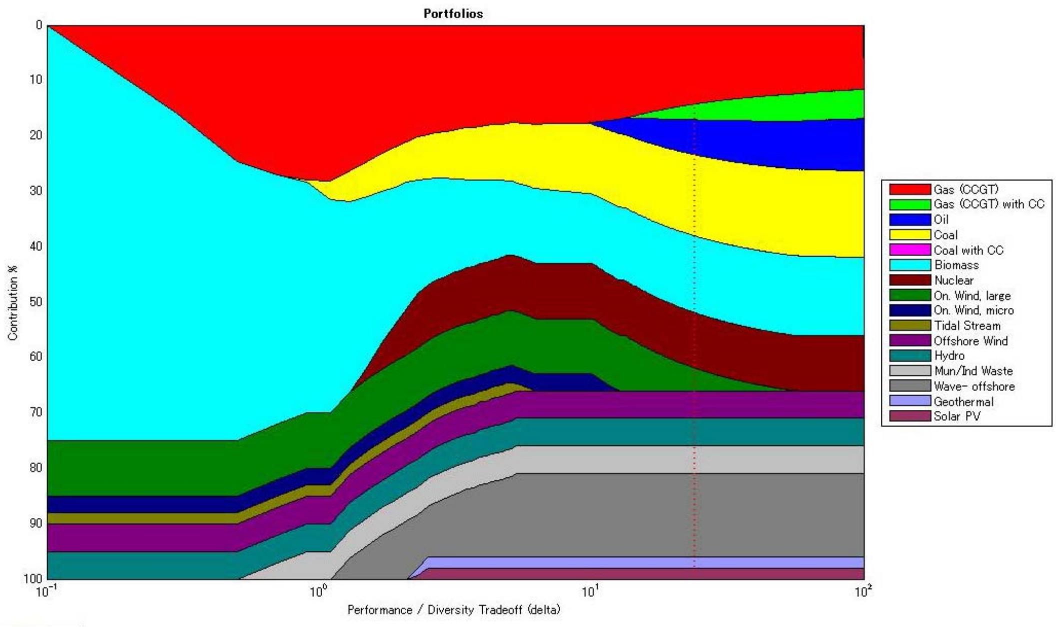


Figure 24: Lowest Ranking for Coal with CC (UK1)

On the other hand, if we take the highest ranking value in the performance interval for coal with carbon capture (again *ceteris paribus*), then this option (unsurprisingly) significantly increases its contribution at the high-performance side of the spectrum (largely at the expense of gas CCGT), and continues to make contributions to high-diversity portfolios at a stage when this option is eliminated under default assumptions (Figure 25).

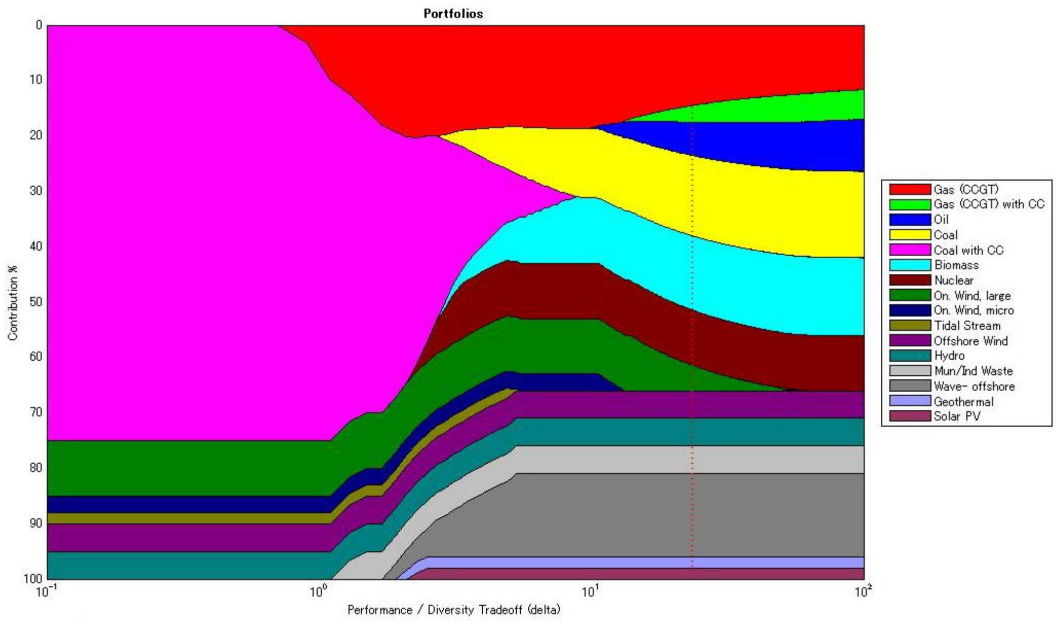


Figure 25: Highest Ranking for Coal with CC (UK1)

(2) Scoring sensitivity by performance criteria

Turing to indicative sensitivity analysis on criteria (again using UK1 as an example), if we take the lowest values for performance scores (for all options) under the engineering cost criterion, then we see only some relatively minor changes of contribution in the high-performance end of the range of diversity-optimal portfolios (Figure 26). The contribution of gas CCGT is somewhat diminished and that of biomass increased.

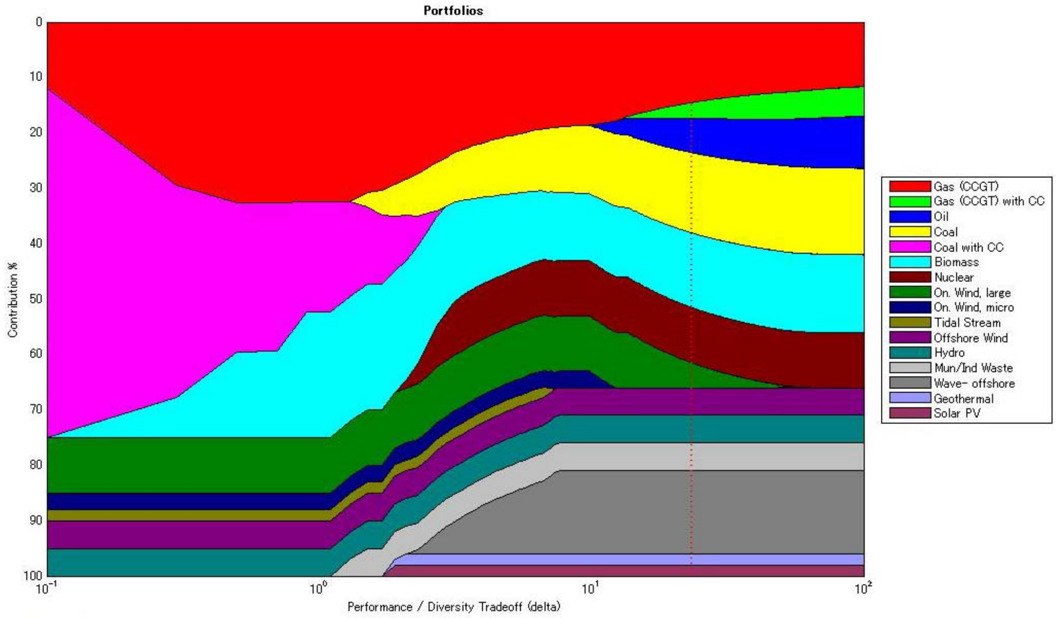


Figure 26: Lowest Scores under the Engineering Cost Option (UK1)

(3) Weighting sensitivity by performance criteria

If we take the corresponding highest scores in the range obtained in appraisal under this cost criterion, the effect on the form of the range of portfolios is again relatively gentle (Figure 27). Indeed the relatively low sensitivity of the portfolio structures to the taking of optimistic and pessimistic scores under this criterion is a fairly general finding where (as is often the case) the uncertainties in scores are rather similar across all options, thus leaving the relative orderings also similar at either end of the range.

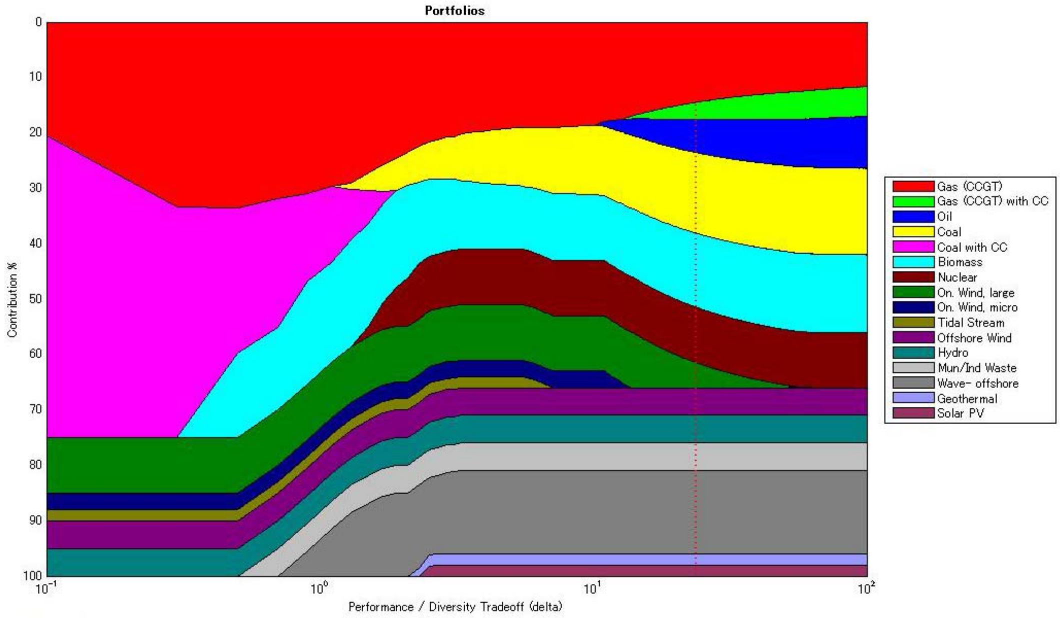


Figure 27: Highest Scores under the Engineering Cost Criterion (UK1)

By contrast with this, there is typically much higher sensitivity to shifts in weighting across criteria. For instance, if this same engineering cost criterion is divided by root ten (leaving other criteria weightings in the same proportion to one another but correspondingly higher than cost), then coal with carbon capture comes to dominate the high-performance end of the range at the expense of other 'conventional' options, leaving the renewable contributions relatively unaffected (Figure 28). Again, the choice of root ten as a baseline is determined by the judgement that an overall sensitivity interval of factor ten accommodates a reasonable range of expert debate.

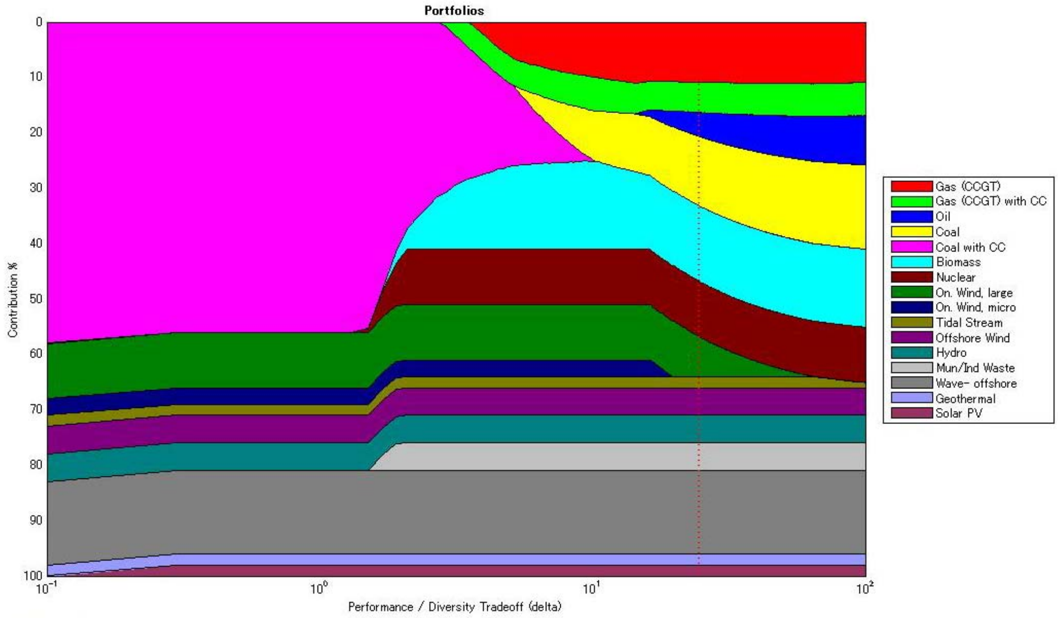


Figure 28: Lowest Weighting on the Engineering Cost Criterion (UK1)

If this same cost criterion weighting is instead multiplied by root ten (again, *ceteris paribus*), there is an even more significant change. With its economic benefits (under this view) thus amplified, gas CCGT becomes the highest performing option and so dominates the performance-oriented end of the range of diversity-optimal portfolios (Figure 29). At higher weightings on diversity however, the effect of substituting coal with carbon capture with the lower-cost option of conventional coal (which displays similar disparity characteristics and therefore dominates coal with carbon capture as increasing weight is placed on diversity).

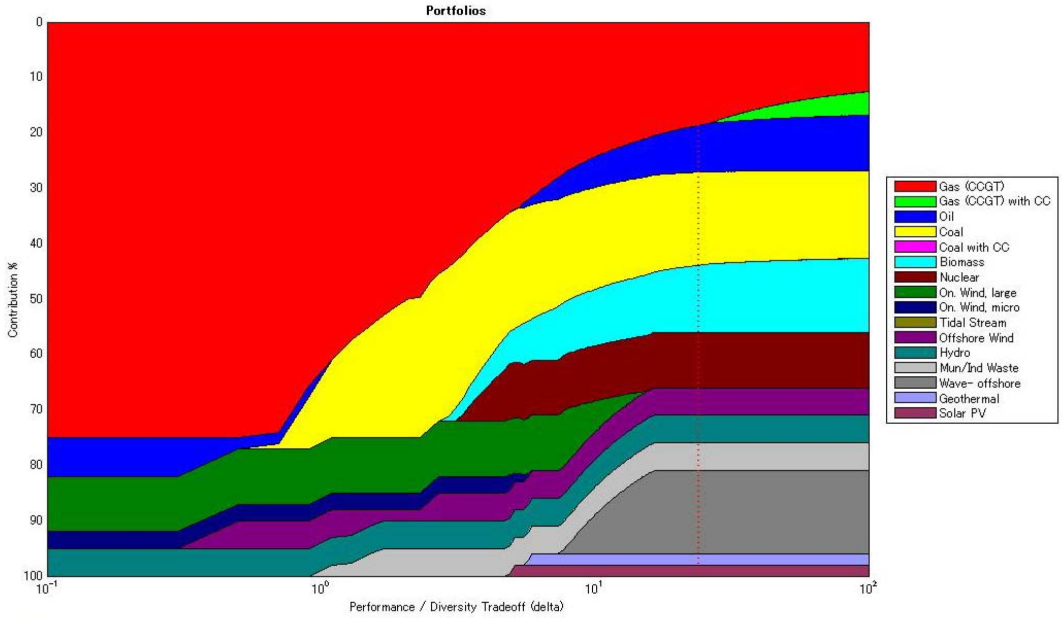


Figure 29: Highest Weighting on the Engineering Cost Criterion (UK1)

These indicative findings are simply illustrative of the kinds of sensitivities that may be expected in this kind of analysis – or indeed any attempt at assessing such a complex and uncertain area of technology policy. The details will of course be different in the case of the multiple options, criteria and parameters included in this analysis. For present purposes, this discussion at least serves to underscore the need for caution over specific details of any given appraisal, with attention best concentrated instead on the overall structural form of the picture. However, when repeated over a number of different sets of portfolios, it does appear that the general structures are quite robust to fairly radical shifts in the underlying performance data.

5. Conclusion

With particular emphasis on the methodological implications, the present working paper has discussed a pilot case study of a novel general framework for the analysis of energy diversity. It has shown that the multicriteria energy diversity analysis technique is applicable to an unconstrained array of different specialist, institutional or stakeholder perspectives. Participants in the two rather contrasting policy contexts of the UK and Japan have shown themselves able to undertake the procedure and derive intuitively interpretable results. Taken together, they show that it is possible to obtain meaningful representations of energy option performance and diversity of a kind that is substantively novel in this field. What is particularly of interest, is that these detailed and intuitively interpretable representations of energy diversity are directly constructed on the basis of performance appraisals, of a kind that are widely available in the energy policy debate. This suggests that the method is potentially quite widely applicable.

With respect to the particular empirical findings obtained in this pilot study, caution has been repeatedly emphasised over the small sample size. However, the two-dimensional scaling illustrates a strikingly consistent distinction between the perspectives of UK and Japanese participants. This is despite an equally striking general convergence in the position taken by participants over the distinctions between renewable options and conventional options. The comparative analysis of the disparity structures revealed in the dendrograms shows that the great majority of participants discriminate at a fundamental level between conventional energy options and the renewables as group. It further argues that the broad category of 'renewable energy' is disaggregated at a level that is at least equal to the conventional partitioning of coal, oil and gas. This is also a finding of some potential general importance for the wider analysis of energy diversity.

In examining the range of different portfolios, it is clear that – despite the consistencies and convergences noted above – different expert perspectives in both national contexts yield radically different pictures of the best means to procure diversity in electricity supply systems. Even when taking an overall interval as high as an order of magnitude, sensitivity analysis shows that the differences displayed between individuals are typically greater than the volatility of individual portfolio ranges under radical changes of input parameters under a single perspective. This is again, a finding of some significance with regard to studies which assume a single 'optimal' configuration for diverse future energy systems. More detailed conclusions concerning the most favourable structures for diverse future energy portfolios in each national context, would require more elaborate and wide-ranging interviews than it has been possible to undertake in this short pilot study. However, the results do suggest that a meaningful and potentially quite significant input to policy making might be obtained by this means. In short, it does appear that this analytical framework shows some promise, as a way to be more systematic and transparent in articulating a range of different salient perspectives. In the end, the value of such a framework lies not in prescribing decisions, but simply in informing more robust, rigorous and accountable policy deliberation.

In methodological terms, the dedicated software package for multicriteria diversity analysis developed through this pilot project has performed successfully. Although very demanding on interviewees, it is capable of yielding policy-relevant findings on the basis of a broadly feasible interaction with busy high-level experts. The method allows articulation of a wide range of highly complex factors in a way that is broadly intuitive for specialists. Of course, a range of more detailed issues have arisen concerning the appropriate implementation of the interview procedure, the use of the software and the conduct of the analysis – as well as the design of a diversity analysis study as a whole. These may usefully inform future larger-scale initiatives. In short, the method appears to offer an operational and potentially robust approach to unpack the otherwise often highly obfuscated concept of energy diversity.

It is also worth observing that – aside from the methodological and empirical outcomes themselves – the process of undertaking this kind of analysis can yield benefits for participants and analysts alike in terms of reflexive learning about the issues in hand. In particular, an appreciation for the nature and sources of differences between perspectives offers a potentially important way to focus, in an otherwise sometimes prohibitively complex field, on those issues that are of greatest policy (and political) salience.

Finally, this pilot study has revealed a number of important areas for further research. As discussed in Section 4-4, since diversity is in large part a strategy for responding to uncertainty, there is the potential to make greater use of the interval data obtained for uncertainties in option performance. Techniques developed in applied mathematics, operational research and risk studies bring theoretical insights and computational techniques that may prove highly relevant to methodological development in this area.

It only remains to conclude this pilot study. As is discussed in introducing this report – and further shown by the results of the multiple appraisals and sensitivity analyses reported here – decision making over the future composition of diverse energy mixes is fraught with uncertainty. A prerequisite for robust responses to such uncertainty is the promotion of more systematic and sophisticated deliberation over the nature and implications of energy diversity – and the contending means to achieve it. Efforts towards this end, should have the capacity symmetrically to accommodate the disparate array of expert perspectives and associated uncertainties, without circumscribing the options that may be considered or privileging some particular scenario or viewpoint. They should combine the rigour and precision of quantitative analysis with the open-ended flexibility and unconstrained fidelity of qualitative approaches. They should convey the full plurality of implications of different equally-valid technical perspectives, yet also highlight the underlying convergences and common ground. It is in this way, that methods for the analysis of energy diversity might best yield clear practical messages for policy-making, expressed in terms of the available resources and technologies and respecting their many complexities and limits. It is in all these various regards that we would argue that the diversity analysis methodology piloted in this study, represents a potentially significant first step forward.

Appendix 1. The Multicriteria Mapping (MCM) Process

The MCM process has four stages, although it is possible to go back and review, add or remove things at any stage. The information will be recorded on a laptop computer and we can leave with a participant a copy of the MCM software and their own assessment after the interview if they are interested.

This note will explain the main stages in the MCM process and then provide a concrete example from energy generation options, where the UK Government wishes to take advice over its policy priorities concerning which electricity generating options to encourage, and which to discourage.

Stage 1. Defining the Options

The options represent a range of possible things that could be done in a certain situation. For the present exercise on energy generation options we have several 'core options' that we would like participants to evaluate. We are specifying these in order to enable us to make comparisons across the perspectives of different participants.

In this example, the 3 core options were:
1. Nuclear power
2. Coal burning
3. Wind energy

However, there may be other options they believe should be considered and they will be asked if there are others they would like to add.

Finally, participants are entirely free to add further options of their own choosing, defined as they wish, at their own discretion. These may involve slight permutations on some of the options specified above, or may be entirely different.

Example

One specialist undertook an MCM exercise as part of this exercise. The specialist added 'gas generation' to the list of the above core options because of the importance of gas to current energy production in the UK (Figure 30).

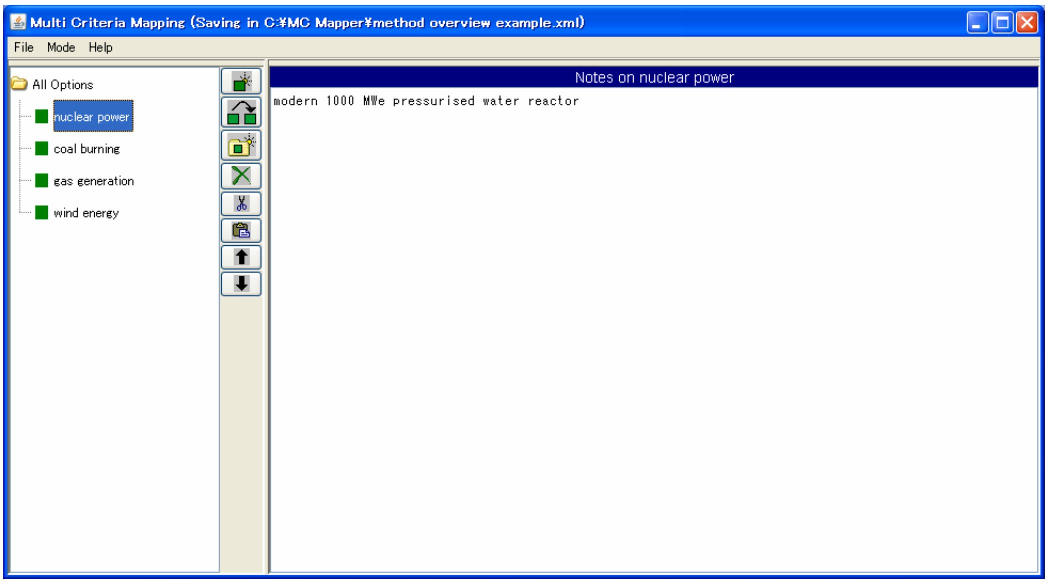


Figure 30: Choosing the Options

Stage 2. Defining the Criteria

The criteria are the different elements that participants consider when they choose between, or compare, different courses of action. These may address any issue that they feel has relevance to their assessment of the performance of the different options. For instance, in the present case, they may involve economic, environmental, social or geopolitical aspects.

Participants are entirely free to identify and define their own criteria as they think fit. However, it is important to be as specific as possible in their definitions, to be clear about the differences between criteria and to minimise any overlaps or dependencies. Any residual minor overlaps or dependencies between criteria can be dealt with as uncertainties in assigning scores (see below).

It is recommendable that participants restrict themselves to identifying twelve criteria or less. The interviewer will ask them to explain what they mean by each criterion and why it has been chosen. Criteria definitions will typically become more clear and detailed as scoring proceeds, so they are free at any time to amend or refine their criteria.

Example

The specialist decided upon the following criteria:

- **worker safety**: incidence of fatal or serious injuries or disease across whole 'fuel cycle' (from mining to waste disposal)
- **public health**: incidence of adverse public health effects due to emissions, wastes or accidents (excluding global warming effects)
- **contribution to climate change**: equivalent carbon production taking into account whole fuel cycle and material and energy use during construction
- **electricity cost**: taking account of capital costs, fuel cycle costs and waste management costs under prevailing market conditions

An additional criterion introduces an issue of principle as follows:

- **maximum accident**: a limit on the maximum extent of acceptable damage arising from a single possible accident. Set at costs in excess of £ 15 billion or total committed public mortality in excess of 10,000

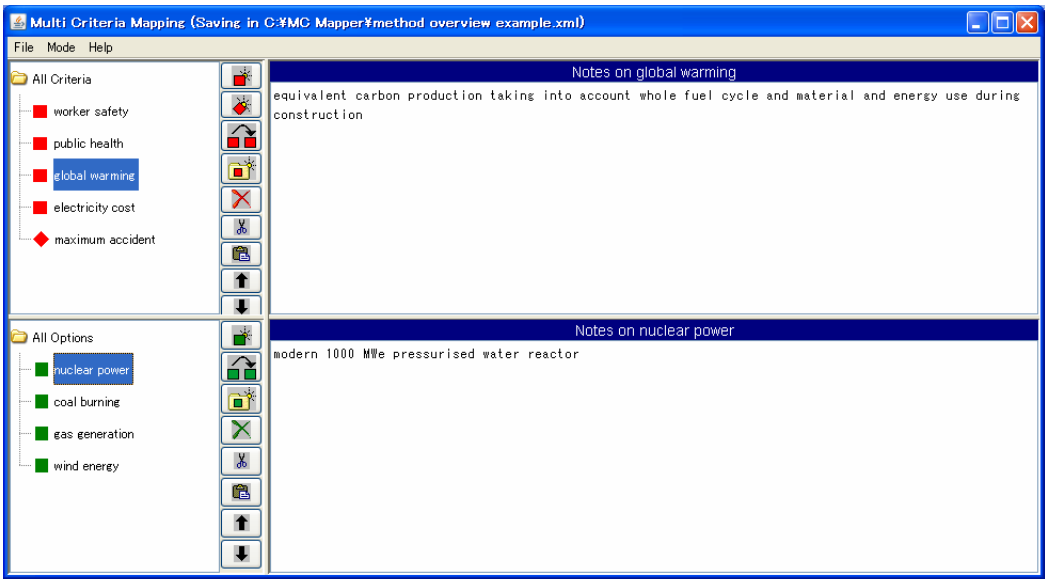


Figure 31: Defining the Criteria

Stage 3. Scoring

Criteria are issues under which participants can evaluate the relative performance of the difference options. Typically, they can express this by using numbers to rate the performance 'scores' of different options on a scale. On the other hand, a criterion may sometimes reflect an issue of principle, which does not admit relative ratings, but simply allows them to say whether an option is acceptable or not.

Where participants feel able to come up with a relative ordering of different options, they can use any scale they like in assigning scores. For instance, this may range from one to ten, or one to a thousand. We recommend a scale of one to one hundred. Either way, the higher the number, the better the performance. Fractions may also be entered.

Usually, participants express their technical performance evaluations using a subjective personal scale under each criterion. Sometimes, they may wish directly to consult suitable quantified information, such as cost data. But it is important to remember that their judgements of performance (and so their scores) need not translate directly from this data. However they approach this, the scoring follows a simple rule. An option that is assigned a score of eight is judged to perform twice as well under that criterion as an option that is assigned a score of four.

We will ask participants to score each option under each criterion by assigning a number in this way. Of course, it is often difficult to be sure about this. They may feel uncertain about the performance. Or the performance may depend in some way on the circumstances or some other particular assumptions. In order to enable them to express this kind of uncertainty or variability, the MCM process lets them assign two scores for each option under each criterion. One to reflect the most optimistic end of their judgement over likely performance, the other to reflect the most pessimistic end.

As they proceed with their scoring, the interviewer will ask them to clarify the reasons for their decisions on the relative performance of the different options. Here, we are interested in their 'technical' justifications for their judgements. With two scores to be assigned for each option under each criterion, the scoring process is the most time consuming part of the MCM process.

If they find that a criterion does not lend itself to quantification or 'trading off' against other criteria, but instead reflects an issue of principle under which different options are either acceptable or not, this can also be accommodated by the MCM process. Here, they simply identify that criterion as a 'principle'. You are then invited to register those options that are in some way inadmissible under that criterion.

This can also be used as a way to reflect absolute performance thresholds. Above the threshold, performance can be expressed by a scoring process as described above. But options whose performance falls below this level are ruled out in the same way as under an issue of principle.

As participants proceed through the scoring process, the interviewer will note the reasons for their judgements and may prompt them to clarify or elaborate certain points.

Example

The specialist scored each option under each criterion. A scale of 1-10 was chosen, with 10 being good and 1 being bad. Where she was uncertain, or where her judgement of likely performance depended on particular assumptions about the context, she assigned a pessimistic (low) and an optimistic (high) score. Based on her understanding of the available data, the specialist explained some of her scoring processes this way:

"Worker safety in nuclear power is generally very good but there can be accidents although these are very rare. I'd score worker safety for nuclear as 6-8.
Worker safety for coal is not so good. Mines can collapse and many miners can be killed. I'd score worker safety as 4-7 for coal…….

"Nuclear and wind power don't contribute to climate change unless the energy used in their construction is produced by burning carbon, so they both score between 9 and 10. Coal is the worst and so scores 1-3. Gas is somewhere in between, scoring 3-5…….

"Nuclear power is the only option that presents risks of a type of disaster that, although very unlikely, is beyond the threshold of what is acceptable to society, so it is ruled out on principle in relation to maximum accidents"

The final set of performance scores arrived at by this specialist were as follows:

Scores	Worker safety	Public health	Climate change	Electricity cost	Maximum accident
Nuclear	5-6	3-8	9-10	5-6	Ruled out
Coal	4-5	4-5	1-3	6-7	
Gas	5-6	7-8	3-5	7-8	
Wind	5-6	8-9	9-10	5-7	

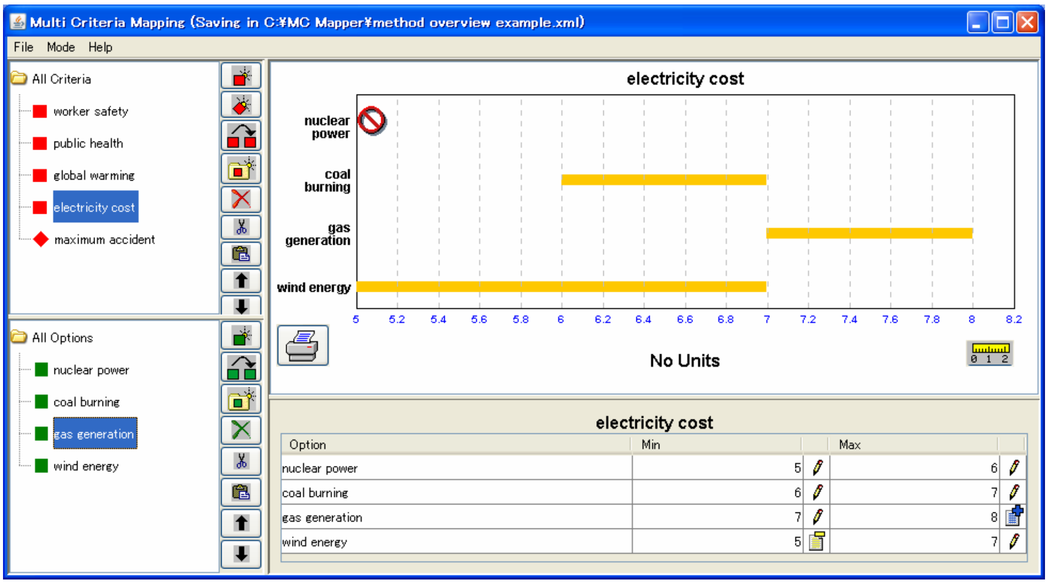


Figure 32: Scoring

Stage 4. Weighting

This is when we ask participants to tell us the relative importance of the performance judgements they have made under different criteria. For example cost may be more important to you than safety or vice versa. The way we express this is by assigning a numerical 'weighting' to each criterion. If something is half as important as something else, it will be assigned half the number of points.

This business of weighting is very different to scoring. Scores reflect relatively technical judgements about the relative performance of options under individual criteria. Weights reflect essentially subjective judgements about the relative importance of the different criteria themselves. For instance, how much something costs (a score) is a very different matter to the relative importance of cost and, say, safety (a weight).

When making these kinds of judgements, it is important to bear in mind exactly what is being compared with what. For instance, a judgement over whether cost is more important than safety will depend on “how much cost?” and “how much safety?”. Even if safety is felt to be a key issue, a tiny improvement in safety may nonetheless be considered less important than a massive improvement in cost – so participants might end up assigning a bigger weight to the large cost difference than to the small safety difference.

For this reason, judgements about weightings are based on the difference in the scores for the best and worst option under each criterion. It is the relative importance of these performance differences that are being compared and weighted. To help participants, the MCM software reminds them of the worst and best performing options under each criterion and the particular assumptions that they made in assigning these scores.

There are a number of ways to go about assigning these weightings. One way is simply to share out some round number – say 100 – ‘importance points’. Another way is to start with a particular criterion and then weight all the others in relation to this. We recommend that they start by assigning a weight of ten to the least important criterion and then move on to the next most important and so on. At any time, the MCM software allows them to scale the weightings that they have assigned as proportions of a total of 100 ‘importance points’. But their weightings can total to any number they like.

Where they have identified a criterion as being an issue of principle, then they cannot ‘trade off’ performance with other criteria. Here, an option is either acceptable or not. For this reason, such issues of principle are not part of the weighting exercise.

Example

Bearing in mind the magnitude of the differences between best and worst option under each criterion, the specialist first identified the criterion that was least important to her. Worker safety and climate change first seemed fairly equal in this respect. But when she noticed that the difference between best and worst options under health (between 3 and 9) was significantly larger than under worker safety (between 4 and 6), she decided the latter difference was less important. She therefore assigned worker safety ten 'importance points' and climate change twelve 'importance points'.

She then thought about which were the next most important criteria. She settled on the difference in public health performance being twice as important as the difference in workers safety performance and so assigned it twenty points. To her, the difference in financial costs was the most important single criterion, and she assigned this forty points.

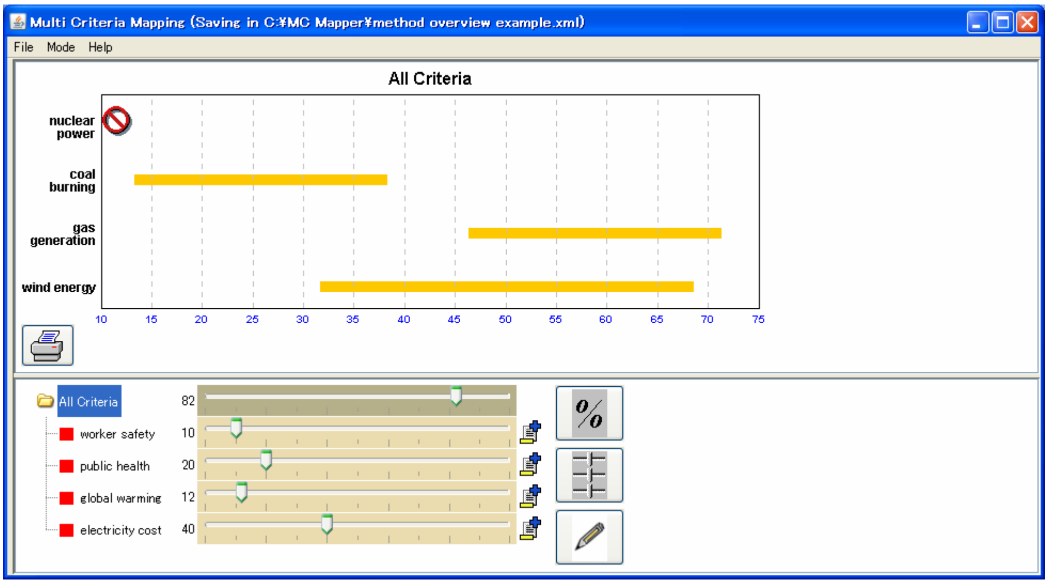


Figure 33: Assessing the Weighting

The outcome

At the end of the process the computer will generate a simple picture of how the options perform overall under all their criteria scores and weightings. Effectively, this involves multiplying the scores by the weightings, taking into account the different scales that have been used.

A simple chart shows the relative performance of all the different options, as well as the range of uncertainties associated with each. Where an option has been judged inadmissible under an issue of principle, then this is also clearly displayed on the chart.

Participants will be able to use this chart to help them decide how their picture of relative performance concurs with their general expectations. They will have the opportunity to express any surprises they may feel and then explore the model to see what the reasons are. For instance, they will be able to test the effect of changing the weightings. This may help them settle on a pattern of weightings which better reflects their viewpoint. During this process, the interviewer will ask them to explain the reasons for any judgements they make.

In the end, the outcome is a detailed picture of the relative performance of all the options that they have defined, reflecting their choice of criteria, their technical judgements over the performance of their options under their criteria, their uncertainties and their subjective priorities concerning the relative importance of the different criteria.

Later, their MCM results will be compared with those of other participants. We will look for similarities and differences and consider what these together say about the various options and perspectives. The results will form a basis for helping to inform, clarify and structure continuing discussions over the best way forward.

Example

As a result of all these inputs, the final chart shows a pretty clear distinction between relatively high ranks for wind and gas and a relatively low rank for coal (Figure 33). The ranking ranges for wind and gas show considerable overlap.

Focusing on the detail, the chart shows that gas – at the most favourable end of its range – offers the best option overall. The top end of the range for wind power comes next. However, the pessimistic end of the range for wind power ranks significantly worse than that for gas. Despite the overlap, this suggests that – for this participant – wind is a second best option to gas.

The range for coal burning overlaps a little with the low end of the range for wind, but is clearly lower than the range for gas. This places coal third in the rankings.

Nuclear power is ruled out under the 'maximum accident' criterion and so ranks last among these four options.

In order to explore some of the hidden implications of her judgements, the participant decides to see what would happen if she slightly changed the maximum accident principle so that nuclear would no longer be excluded. In this case, it becomes clear that the ranking range for nuclear would overlap considerably with coal. Indeed, tho' the low end of the range for coal is slightly higher than the low end of the range for nuclear, the high end of the range for nuclear is significantly higher than that for coal. Under these new conditions, then nuclear is placed third overall, with coal becoming the lowest ranking option.

As a final exercise to test the robustness of this final ranking picture, the participant decides to explore the effect of varying her criteria weightings. First saving a file recording the weights settled on already, she uses the sliding scale to move the weightings to and fro. She notices that, if climate change were to become a much more important issue, then nuclear could readily move into second place position overall.

The participant remains content that her original set of weights and rankings does meaningfully reflect her own perspective at the moment on the key issues bearing on the performance of energy options. However, she is struck that the full attention to her uncertainties at each stage in the exercise reveals that there is more scope for overlap than she had expected. Indeed, depending on the detailed assumptions and conditions, it would be entirely consistent with her appraisal to note that gas, wind or even nuclear power might possibly prove the highest ranking option.

Appendix 2. Excel Macro Program and Spreadsheets

A dedicated Excel macro program has been devised for this pilot study with the aim of quickly converting output data from the MC-Mapper software to input data for the Matlab diversity analysis program. The original version of this interface program was written by Toby Champion to a basic design by Andy Stirling and then substantively upgraded by Go Yoshizawa. In its present form, it can convert the data in two ways: as 'basic mode' and an 'advanced mode'.

The basic mode, offers a relatively convenient way for a participant to quickly get a grasp of the process as a whole. It uses a single 'Basic' worksheet in the Excel interface program. Without attending to various potentially significant details, it proceeds quite quickly to yield a provisional picture of the disparity structure and corresponding range of diverse portfolios that are implicit in the raw structure of the participant's own appraisal. In particular, it does not allow participants to add, partition or re-characterise energy options, to define additional disparity attributes, to express the natures of various kinds of portfolio interaction between options, or to conduct sensitivity analysis on key aspects of performance or diversity. The basic mode takes only 5-10 minutes, thus both offering to save time for busy participants, as well as form a good basis for the participant to return to more detailed scrutiny using the advanced mode.

The 'advanced' mode, is more time-consuming and complicated. Usually beginning with a quick run in 'basic' mode, participants go through several worksheets in the Excel interface program. First, there is the 'Options' worksheet, in which participants register detailed characterisations of the options themselves, including subordinate tranches, their constraints. Then there is the 'Disparity' worksheet, in which the participant can review the normalised performance criteria used to create a disparity structure, experiment with criteria weightings, and add any further attributes of disparity to address aspects neglected in performance appraisal. This feeds directly in to the 'Dendrogram' worksheet, which simply illustrates a picture of the disparity structure yielded by the performance appraisal and any additional disparity attributes that have been added.

The next stage is the ‘Interactions’ worksheet, which allows the participant to express the aggregate effect of various forms of positive or negative interactions between each pair of options. Finally, there is the ‘Sensitivities’ worksheet, which allows the participant or analyst to experiment with the way in which variations in the many parameters of diversity analysis lead to variabilities in the structure of the resulting portfolios. Throughout the sequence of worksheet tasks, the complexity is somewhat eased by the use of drop-down menus in the Excel interface and by assistance from (or direct mediation by) the interviewer. Aided by the overview diagram (Figure 34), the ensuing discussion here will now go through each of these methodological steps in more detail.

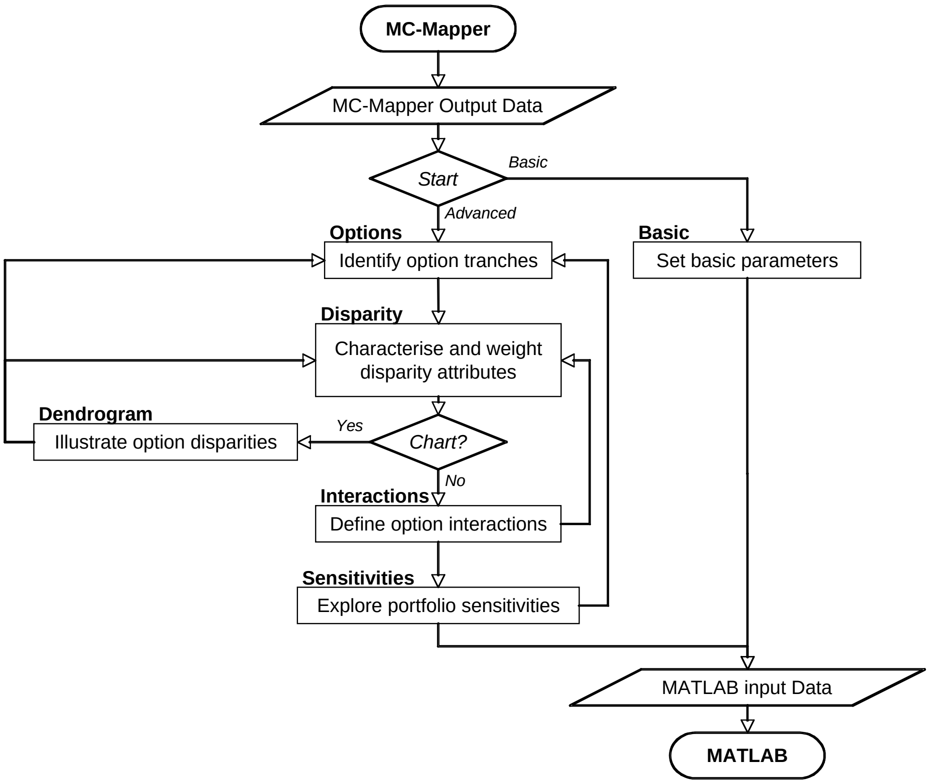


Figure 34: Flowchart of the Excel Macro Program

1. Setting Basic Parameters (Basic Sheet)

As explained above, this worksheet enables a participant to skip many steps by allowing them to concentrate only on the most essential data and the setting of basic parameters. The data required in this mode simply concern the following.

	Note	step	individaual	intermittency	carbon reduction	rapid dispatch
Nuclear		0.000	0.30	0	0	0
LNG		0.000	0.20	0	0	0
Coal+CCS		0.000	0.15	0	0	0
Oil		0.000	0.05	0	0	0
Coal		0.000	0.15	0	0	0
Hydro		0.000	0.05	0	0	0
Waste		0.000	0.08	0	0	0
Wind		0.000	0.08	0	0	0
Solar PV		0.000	0.05	0	0	0
Solar Thermal		0.000	0.02	0	0	0
Geothermal		0.000	0.01	0	0	0
Biomass		0.000	0.02	0	0	0
Ocean Energy		0.000	0.01	0	0	0
LNG+CCS		0.000	0.01	0	0	0
			Maximum	1.00	1.00	1.00

Figure 35: Constraints Section

First, there is the 'step scale' that is characteristic of each option (i.e. the minimum unit size in which that option is available). This is entered using the orange-shaded cells in the Basic sheet (as illustrated in Figure 35). It is expressed as a proportion of the portfolio mix as a whole, under whatever metric is held to be most relevant (whether capacity, output, investment – in this case it is approached in terms of output). The value will typically be high for nuclear power but small for wind. For example, if an evaluator estimates that the installation of a nuclear power plant contributes to 1% of the total electricity generation from all energy sources in the issued region, the evaluator should fill "0.01" in the "step" cell for the nuclear option.

Second, there are the constraints that are held to apply to the contributions of individual energy options. This is entered using the lavender-shaded cells in the Basic sheet (Figure 35). This represents the maximum extent to which the option can contribute to the total electricity generation. In order not to overly constrain or confound the dynamics of the optimisation process in the later diversity analysis, it is advisable to make only the most measured use of this 'constraints' parameter – for instance reflecting concrete physical resource limits rather than less tangible social, political and cultural aspects.

Third, there are constraints acting on the contributions of groups of options (for instance, concerning the collective contribution that is acceptable from intermittent renewables). This is entered using the green-shaded cells in Basic sheet (as illustrated in Figure 35). For the purposes of the present pilot study, intermittency, carbon emissions reduction and rapid dispatch were suggested in advance as possible collective constraints. If, for example, a participant wishes to set an upper limit for energy options with high carbon dioxide emissions in order to forestall global warming, an upper system contribution is set in the separate row of green cells alongside the word "*Maximum*" at the bottom of the block of green cells (Figure 35). The options to which this collective constraint applies are then each indicated by entering "1" in the corresponding green columns cells above. This field thus allows only the binary entries, 0 or 1.

Fourth, the only other parameters that need to be specified in this Basic mode involve a series of 'housekeeping' issues to do with the plotting of diagrams and the configuring of the diversity heuristic. These inputs from the Basic worksheet are shown in Figure 36 below.

minDelta	0.1
maxDelta	100
nDeltas	500
deltaScale	log
alpha	1.0
beta	1.0

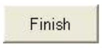
Figure 36: Basic Parameters Section

There is also the option of setting the values taken by the terms 'alpha' and 'beta' in the Stirling diversity heuristic, which reflect different prioritisations of diversity attributes (though the default values of alpha = beta = 1 serves as a representative diversity index).

The rose-shaded cells are used to frame the plotting of the diversity-optimal portfolios. The first two set the minimum ("minDelta") and maximum ("maxDelta") values to be used for the parameter 'delta' (δ), a scaling coefficient which expresses the trade-off between performance and diversity. The third rose-shaded cell ("nDeltas") determines the number of values that are plotted for δ, which determines the resolution of the range of portfolios. In other words, all possible conditionally optimal portfolios from those that maximise value due to aggregate performance of individual elements at the point of minDelta, to those that maximise value due to portfolio interactions and system diversity at the point of maxDelta. In the fourth rose-shaded cell ("deltaScale"), the participant or analyst may enter the form of the plot required for displaying the range of diversity-optimal portfolios – either on a linear or a logarithmic scale.

Finally, the lavender-shaded cells in this section (Figure 36) allow the participant or analyst to enter the values for the exponents used in the Stirling diversity heuristic, α ("alpha") and β ("beta"). These give the relative emphasis placed in the characterisation of diversity, on the subordinate properties of disparity (and associated variety) and balance. Values of $\alpha = \beta = 0$ yield a pure index of variety. Values of $\alpha = 1$; $\beta = 0$ yield a pure measure of disparity. Values of α =

0; β = 1 yield a generic index of balance. Values of α = β = 1 yield a generic index of diversity. Shifting values of alpha and beta between 0 and 1 collectively addresses all possible relative weightings on variety, balance and disparity. The default values used throughout this pilot exercise were those of the generic index (α = β = 1).

Having reviewed these entries in the Basic worksheet and satisfied themselves that the inputs are sufficient for a provisional run, the participants then click the 

button and the program automatically creates an Excel file comprising the input data for the Matlab diversity analysis program. The calculation process embedded in this worksheet automatically converts performance scores (which are loaded from the MC-Mapper output data in the form of Excel worksheet) into disparity attributes. The process does not allow re-sorting, adding, duplicating and deleting energy options, adding disparity attributes, changing interaction coefficients and conducting sensitivity analysis. Therefore all interaction coefficients are fixed as 1 and the median value is taken from the performance score.

2. Identifying Option Tranches (Options Sheet)

This worksheet allows modifications to the characterisation of energy options as originally defined for the purposes of appraisal in the MC-Mapper software. In short, it allows the re-sorting, adding, duplicating and deleting of energy options. The sheet therefore revisits the constraint values, which are automatically mirror-copied from the Basic sheet, where these have already been entered. However, the participant can also set new values under each of these parameters in the Options sheet, in which case, these will automatically be mirror-copied to the Basic sheet, as soon as this is opened.

The form of the raw MC-Mapper appraisal data that is imported in the Options sheet is illustrated in the following table (Table 3). The table contains lowest and highest values of performance scores and performance weightings.

Table 3: MC-Mapper Output Data Field

	Criterion **1**		Criterion **2**		…	Criterion **c**		…	Criterion **n**	
Weighting					…	$w_c^{performance}$		…		
Option **1**			2	4						
Option **2**			4	6						
…			1 S_2^{min}	7						
Option **i**			3	8	…	$\underline{S}_{ic}$	$\overline{S}_{ic}$	…		
…			6	9 S_2^{max}						
Option **m**			5	6						

$\underline{S}_{ic}$: lowest value of the performance score for option **i** and criterion **c**

$\overline{S}_{ic}$: highest value of the performance score for option **i** and criterion **c**

$w_c^{performance}$: performance weighting for criterion **c**

The lowest and highest performance scores for each option under each criterion are transferred in their raw form from MC-Mapper into the light yellow and yellow -shaded cells respectively in the "Options" sheet (Table 4). Each performance score interval is represented as follows.

$$S_{ic} = [\underline{S}_{ic}, \overline{S}_{ic}]$$

For the calculation of disparity, the median of the performance score interval is calculated as follows and displayed in beige-shaded cells of the "Options" sheet (Table 4).

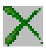
$$S_{ic}^{med} = (\underline{S}_{ic} + \overline{S}_{ic})/2$$

Criteria weightings are also imported into beige-shaded cells, this time moved for ease of representation to the bottom of the table (Table 4).

Table 4: Performance Data Field in the Options Sheet

	Criterion 1			…	Criterion **c**			…	Criterion **n**		
Option 1	2	1	3								
Option 2	3	1	5								
…											
Option **i**	3.5	3	4	…	S_{ic}^{med}	$\underline{S}_{ic}$	$\overline{S}_{ic}$	…			
…											
Option **m**	3.5	2	5								
Weighting				…	$w_c^{performance}$			…			

Options can be re-sorted in this sheet by clicking the up-arrow  and down-arrow  icons positioned at the upper-left corner of the worksheet when the relevant option name is selected by the cursor. When clicking the up-arrow icon, the selected option goes up and is exchanged for the option located immediately above. A new option can be added by clicking the icon  at the top in the set of icons. A dialog box appears and requires the operator to enter the option name. Data for steps, collective constraints, and performance scores are set as a default at 0. Data for individual constraints are set as a default at 1.

All data for an option shown in this worksheet (i.e. individual steps, option constraints and performance scores) can be duplicated by clicking the second icon  from the top, but only when the name of the option to be duplicated is selected. This duplication function can be used to break options down into "tranches". New tranches will have the same performance as their parent option, but may have different steps and/or constraints, or even lower or higher performance values under certain criteria. All data for an option can be deleted by clicking the cross icon  at the third from the top, where the name of the relevant option is selected.

The purpose of this worksheet is to allow detailed re-examination of the way in which options are characterised and partitioned, as well as to permit consideration of step-sizes, individual constraints and collective constraints in option contributions.

3. Characterising and Weighting Disparity Attributes (Disparity Sheet)

This worksheet takes the form of a matrix containing two differently-shaded cells. Those shaded beige colour display normalised performance score values from the Options sheet. The normalisation renders the overall ranks equal for all options, but preserves the proportional contributions to these ranks from different performance criteria. In this way, it contains the disparity structures that are embedded in these scores, without introducing bias due to the fact that certain options rank better overall than do others. Default weights for each of these normalised criteria for the purpose of characterising disparity, are set at 50, but can be changed in subsequent analysis. Also displayed in this characterisation matrix (using light green cells) are columns for entering a series of further disparity attributes and corresponding weightings. The weights for all these disparity attributes can be altered using vertical slider controls displayed under the matrix.

It appears from this pilot exercise that many participants experience difficulty in discriminating between the idea of characterising disparity and that of appraising performance. The option of adding further disparity attributes (in the light green cells) is therefore not often taken. In such cases, the disparity structures employed in diversity analysis are yielded entirely by the implicit disparities in the MCM appraisal data.

In more technical terms, the analysis of disparity is undertaken in the Disparity sheet in the Excel file in the following fashion. As discussed earlier, the raw performance scores imported from MC-Mapper may be represented as follows (see Table 3):

$$S_c^{min} = min\{\underline{S}_{1c}, \cdots, \underline{S}_{mc}\} \quad \text{where } \ 1 \le i \le m$$
$$S_c^{max} = max\{\overline{S}_{1c}, \cdots, \overline{S}_{mc}\}$$

For the purpose of appraising performance, scores and weights are normalised (as they are in MC-Mapper) as shown below:

$$s_{ic} = S_{ic}^{norm} = \frac{S_{ic} - S_c^{min}}{S_c^{max} - S_c^{min}}$$
$$w_c = w_c^{norm} = \frac{w_c^{performance}}{\sum_{c=1}^{n} w_c^{performance}}$$

Whilst the overall performance rank for each option is given (as explained above) as the sum of these weights and scores, it is the performance 'sub-rank' for each option under each criterion that is employed in further normalising these scores to yield disparity attribute values. These sub-ranks can be expressed as follows.

$$r_{ic} = w_c \times s_{ic}$$

This further normalisation of performance scores to derive disparity attributes is conducted in the following fashion:

$w_c^{disparity}$: disparity weighting for criterion **c**
D_{ic} : disparity attribute for option **i** and criterion **c**

$$D_{ic} = \frac{w_c^{disparity} s_{ic}}{\sum_{c=1}^{n} w_c^{disparity} s_{ic}}$$

Table 5: Disparity Data Field in the Disparity Sheet

	Attribute 1	…	Attribute c	…	Attribute n	Attribute n+1	…	Attribute N
Option 1			0.4					
Option 2			0.5 D_c^{max}					
…								
Option i		…	0.3 D_{ic}	…			…	
…			0.1 D_c^{min}					
Option m			0.2					
Weighting		…	$w_c^{disparity}$	…			…	

As mentioned above, cells for additional disparity attributes and their corresponding weightings are shaded in light green in the Disparity sheet (Table 5). In this worksheet the participant can add new attributes (attribute n+1 to attribute N) and their weightings for the further characterisation of energy options.

In the Matlab program, disparity is addressed as the squared Euclidean distance between different options, represented as co-ordinates in the space defined by their corresponding disparity attributes as displayed in the Disparity worksheet.

$$d_{ij} = \sqrt{\sum_{c=1}^{n} (w_c^{disparity})^2 (D_{ic} - D_{jc})^2}$$

4. Illustrating Option Disparities (Dendrogram Sheet)

This worksheet shows a dendrogram, which reflects the degree of disparity between different options, according to the disparity attributes that have been entered into the Disparity worksheet. This 'tree diagram' helps the participant grasp how individual energy options are clustered together in the 'disparity space' defined by the various attributes. As a default, the dendrogram is calculated using Ward method, or squared Euclidean distances.

It is important to recognise that this constitutes just one (arguably the most appropriate) of a number of clustering methods that might be used to represent the complex multidimensional distribution of disparities in a simple two-dimensional tree structure. The representation is thus not perfect, and loses information when compared to the original multi-dimensional distribution itself. It is the full set of disparity data that is employed in the diversity analysis itself, however, with the dendrogram simply providing a convenient visual guide to the underlying structure. In particular, this simple graphical representation helps the individual participants reflexively to understand the structure of option disparities that is implicit in their performance appraisal.

Following the construction of the dendrogram a dialog box appears which allows, options to be re-ordered in all worksheets in the same sequence. Aside from this final step, the Dendrogram worksheet is simply for information – not requiring any deliberate data entry or modification.

5. Defining Option Interactions (Interactions Sheet)

This worksheet allows the participant to determine the interaction term in the full portfolio equation. Represented as ι_{ij}, this is an additional parameter to reflect the effect on system value of synergies or tensions between elements **i** and **j**. The net positive or negative effect of a range of different possible interactions is expressed as a marginal departures from a default of unity ($\iota_{ij} = 1 \pm \partial\iota$). For most systems $\partial\iota << 1$.

The inputs for this purpose are made in a half matrix of pale blue –shaded cells (Table 6). These are pre-set with a default value of 1 (indicating no net interaction). The diversity analysis method provides no definitive way objectively to determine the magnitude of this value. Instead, it simply reflects the product of expert deliberation over factors such as system interactions, operational factors, industrial relationships, economies of scale and scope and so on.

For an array of **m** options, the table in this worksheet (Table 6) shows a half-matrix of **m** by **m-1**. The number of values that may be determined in this way is thus m(m-1)/2. Typically, only a small sub-set (if any) of these are judged to be relevant by the participant.

Table 6: Option Interactions Data Field in the Interactions Sheet

	Option 1	Option 2	…	Option i	…	Option m-1
Option 1						
Option 2	1.0					
…						
Option i	1.0	ι_{i2}				
…						
Option m-1	1.0	$\iota_{(m-1)2}$		$\iota_{(m-1)i}$		
Option m	1.0	ι_{m2}		ι_{mi}		$\iota_{m(m-1)}$

6. Exploring portfolio sensitivities (Sensitivities sheet)

This final worksheet helps the participant or analyst to perform sensitivity analysis on the main parameters determining the structure of the diverse portfolios. Since both the disparity structures and the performance profiles are governed by the MCM performance appraisal – and these are represented as ranges – the sensitivity analysis focuses on the effect of taking different specific values with these ranges. It begins by displaying the median values for these ranges, as used as defaults in the diversity analysis. By moving sliders presented in this sheet we can change any performance score from the lowest value (pessimistic) to the highest value (optimistic) accommodated in the performance appraisal for each energy option. We can also perform the same sensitivity analysis with respect to performance criteria (rather than options) – with sliders provided to test the effect of changed criteria scores and weightings. In this way, the three kinds of sliders allow consideration of the systematic effects of optimism or pessimism across different options or criteria.

(1) Vertical sliders for eliciting scoring sensitivity by performance criteria
(2) Horizontal sliders for eliciting scoring sensitivity by option
(3) Vertical sliders for eliciting weighting sensitivity by performance criteria

Cells displaying the magnitude of the sensitivity factor in each case are shaded yellow-brown and labelled "*Sensitivity*". For ease of reference by the participant or analyst, the correspondingly modified values for the scores and weightings are displayed in the associated beige-shaded cells.

Table 7: Portfolio Sensitivities Data Field in the Sensitivities Sheet

	Criterion 1	…	Criterion **c**	…	Criterion **n**	Overall		*Sensitivity*
Option 1								
…								
Option i		…	$S_{ic}(\chi_i, \chi_c)$	…		$S_i^{overall}$		χ_i
…								
Option **m**								
Sensitivity		…	χ_c	…				
Weighting		…	$w_c(\chi_c^w)$	…				
Sensitivity		…	χ_c^w	…				

For ease of calculation, it is the median of the performance score range that is adopted as a default in the diversity analysis. This sensitivity analysis thus enables the participant or analyst to examine to what extent uncertainty in performance score affects the composition of the final series of diversity-optimal portfolios. In other words, it shows how portfolio composition responds to the uncertainty expressed in the appraisal of the energy options. This is represented as follows in Table 7:

χ_c : performance sensitivity for criterion **c**
χ_c^w : weighting sensitivity for criterion **c**

The sensitivity analysis for options extends the performance score from lowest value to the highest value, based on the weighted minimum and maximum scores under each criterion respectively. In other words, the lowest end of the sensitivity scale should correspond with assigning the lowest value in the performance score interval for each option under that criterion. Likewise, the highest end of the sensitivity scale should correspond with assigning the highest value in the performance score interval for each option under that criterion. The weightings in either event remain unchanged.

This sensitivity analysis is structured on a scale from 0 to 100. If the performance sensitivity for a given option or criterion is 0, then the relevant performance score takes the lowest value in the associated range yielded in appraisal. If the sensitivity is 100, the performance score takes the highest value in this range. If the sensitivity is 50, the performance score takes the median value, which is the default used in the diversity analysis. The performance sensitivity by option and by criterion function individually.

$$S_{ic}(\chi_i, \chi_c) = \underline{S}_{ic} + \frac{\sqrt{\chi_i \chi_c}}{100}(\overline{S}_{ic} - \underline{S}_{ic})$$

$$S_{ic}^{norm}(\chi_i, \chi_c) = \frac{\underline{S}_{ic} + \frac{\sqrt{\chi_i \chi_c}}{100}(\overline{S}_{ic} - \underline{S}_{ic}) - S_c^{min}}{S_c^{max} - S_c^{min}}$$

By contrast with this, the sensitivity analysis of weightings is independent of the scoring ranges. Here, the sensitivity analysis explores a difference between lowest and highest weighting amounting to a total factor of one order of magnitude. In other words, the lowest end of the weighting sensitivity scale corresponds with the product of the normalised weight and reciprocal root ten. Likewise, the highest end of the weighting sensitivity scale corresponds with the product of the normalised weight and root ten. In performing this sensitivity analysis, all other criteria weights are preserved *ceteris paribus* – i.e. with the original normalised values. In other words, only the values for the selected criterion are changed, and the new set of weightings subsequent to the selected sensitivity value for the chosen criterion, are then re-normalised to sum to one.

$$w_c(\chi_c^w) = \frac{w_c^{performance}}{\sum_c w_c^{performance}}\left(\sqrt{10}\right)^{\frac{\chi_c^w}{50}-1}$$

$$w_c^{norm}(\chi_c^w) = \frac{w_c(\chi_c^w)}{\sum_c w_c(\chi_c^w)}$$

For ease of reference by the participant or analyst, the overall performance score yielded by the sensitivity multipliers for each option under each criterion are also displayed in this sheet. This displays the option that is thereby attributed the highest overall performance score. It is this option that will be dominant in diversity analysis at the performance-maximising extreme of the range of diversity-optimal portfolios.

$$S_i^{overall} = \sum_c w_c(\chi_c^w) S_{ic}(\chi_i, \chi_c)$$

The normalised performance rank **r** with sensitivity is calculated as follows.

$$r_{ic} = w_c^{norm}(\chi_c^w) \times S_{ic}^{norm}(\chi_i, \chi_c)$$

$$v_{portfolio} = \sum_i \sum_c r_{ic} p_i + \delta \sum_{ij(i \neq j)} d_{ij} \iota_{ij} p_i p_j$$

When the sensitivity analysis is completed, the participant and / or analyst should check through the worksheet as whole. As a final stage in the diversity analysis process, it is wise to make a unique file containing all the relevant data settings. For this purpose, it is possible to select “Make datafile” from the “Appraisal” menu in the top menu bar.

A pop-up dialog box will also at this stage provide the option of changing the default set of colours that are used in the Matlab program to display the ranges of diversity-optimal portfolios. This will be useful, where the neighbouring options are coloured inconveniently, or where it wished to highlight or associate different kinds of option by means of colour. The colours are also displayed at the left-hand side of option names in the Sensitivities worksheet.

The Excel macro program produces as an output the file “data.xls” and overwrites the corresponding file located as default in the folder “C:/MCMdiversity/mainline”. This output file contains performance data, disparity data, interaction data and basic parameters, for all of which values are set in the Excel program.

Matlab is a numerical and computing environment and programming language. The fundamental part of the Matlab optimisation code was written by Toby Champion based on an original basic format by David Waxman and modified with minor additions by Go Yoshizawa. All output figures generated by the portfolio analysis are illustrated in Appendix 3.

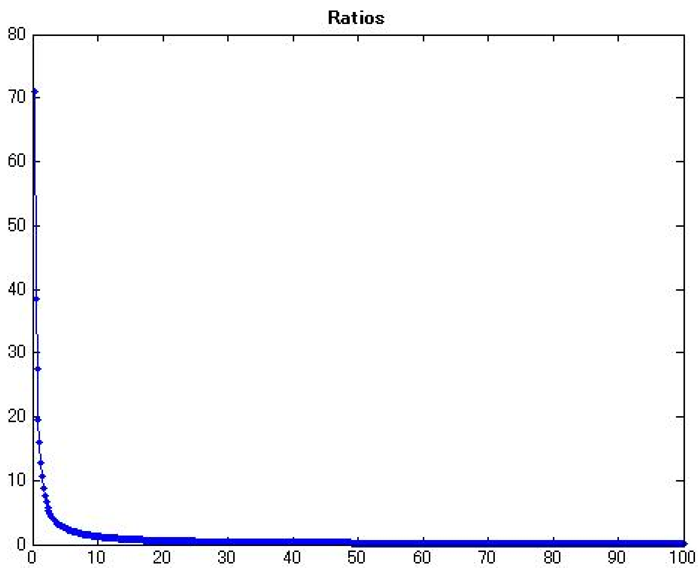
Appendix 3. Matlab Program Output Figures

The Matlab program produces the following seven output figures.

- Figure 1 is a graph entitled "Ratios", which displays on the x-axis the values taken by δ, the coefficient which scales diversity against performance in the diversity optimisation equation. This is plotted against a y-axis displaying the product $V\{E\}/V\{P\}$. This reflects the ratio between the two main components of portfolio value as also characterised in the diversity optimisation equation.

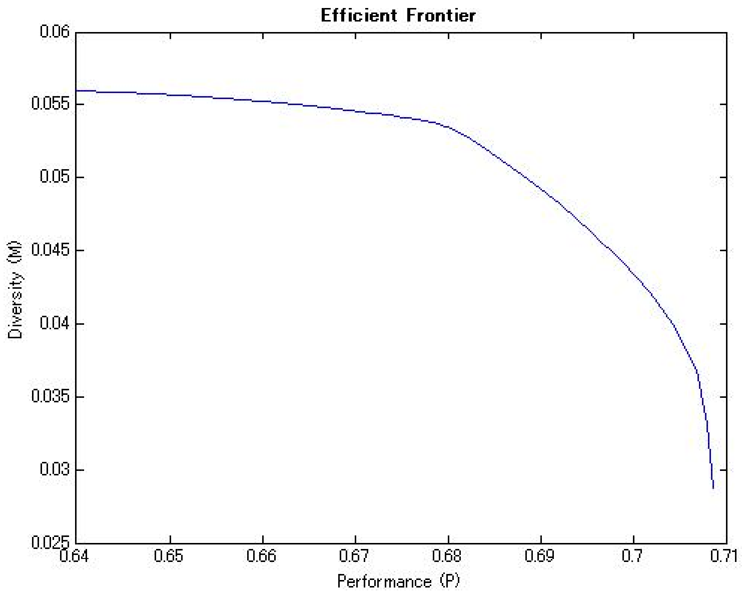
$$V\{S\} = V\{E\} + V\{P\} = \sum_i \sum_c (w_c \cdot S_{ic}) \cdot p_i + \delta \cdot \sum_{ij(i \neq j)} (d_{ij})^\alpha (p_i \cdot p_j)^\beta \cdot \iota_{ij}$$

Here, V{E} is the aggregate portfolio value due to the sum of the performance of the individual options and V{P} is the corresponding value due to portfolio diversity. This provides one way to show the relative scale (and identify any interesting features) in the relationship between these two key components of portfolio value.

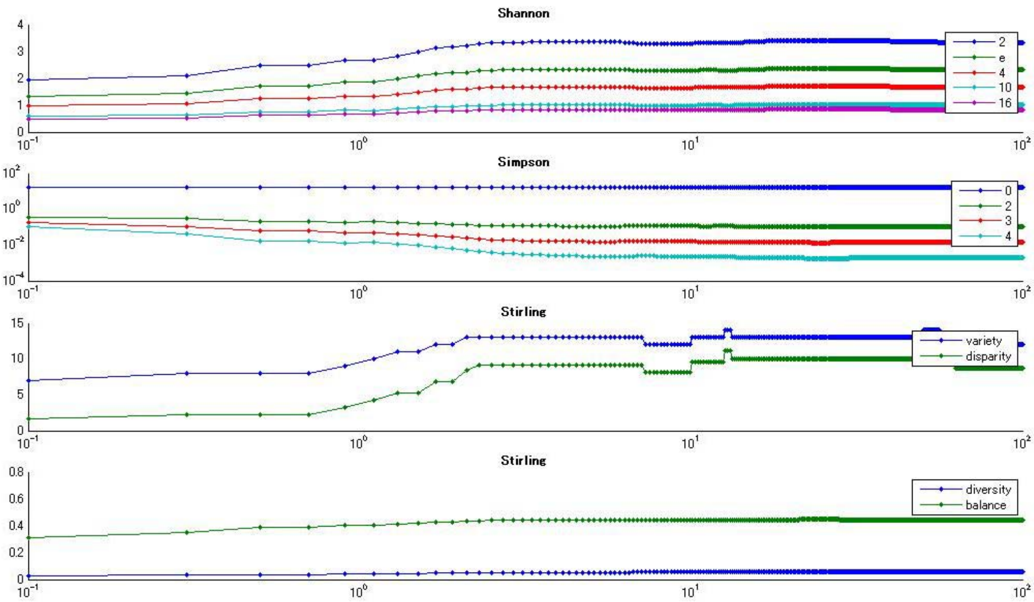


- Figure 2 is a graph entitled "Efficient Frontier". This shows on the x-axis the aggregate portfolio value due to the sum of the performance of the individual options (V{E}) against a y-axis displaying the value due to portfolio diversity (V{P}). This shows as a 'Pareto frontier' the co-ordinates of those portfolios that display either a maximum value due to portfolio diversity or a maximum value due to option performance. Portfolios plotted below this curve are inefficient in one or other respect. It is this curve which provides the source for the range of diversity-optimal portfolios, which form the centre for analysis (See under Figure 19 below).

  By displaying the shape of the efficient frontier in this way, we gain another view of the relative scale of the two main components of portfolio value as characterised in the portfolio optimisation term This also provides a convenient way to identify interesting features in the trade-off between these two parameters. Where the frontier displays loops or saw-tooth features, for example, there is an indication of an underlying difficulty in the optimisation process, which can be addressed by checking the input parameters.

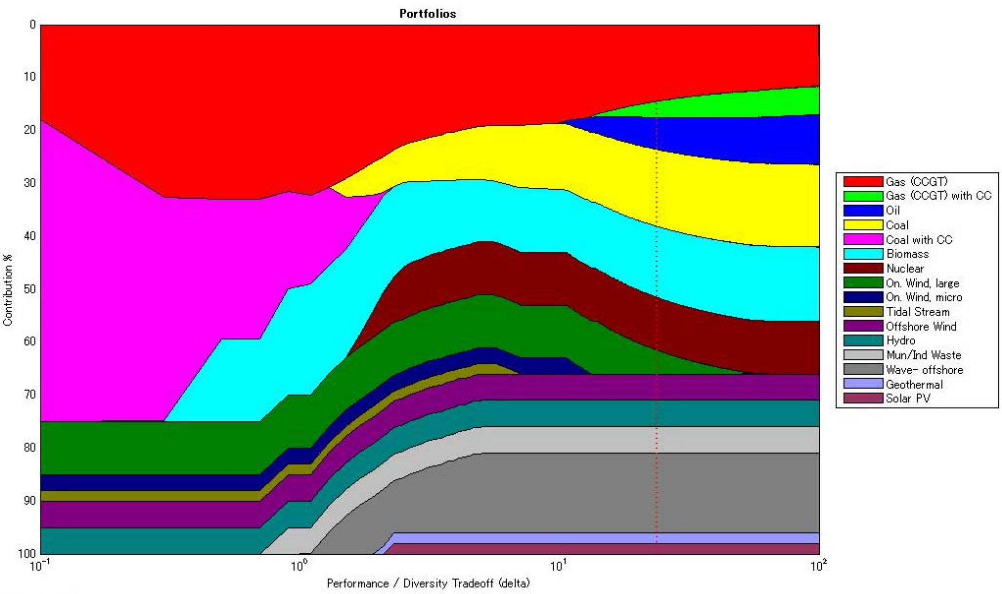


- Figure 3 is titled “Indices”, generating four graphs displaying on the y-axis various diversity-indices; namely the Shannon index, Simpson index, Stirling index for variety and disparity, and Stirling index for balance and diversity. All the graphs are plotted with the performance/diversity trade-off term δ on the x-axis, to index the position along the range of diversity-optimal portfolios as drawn from the efficient frontier.

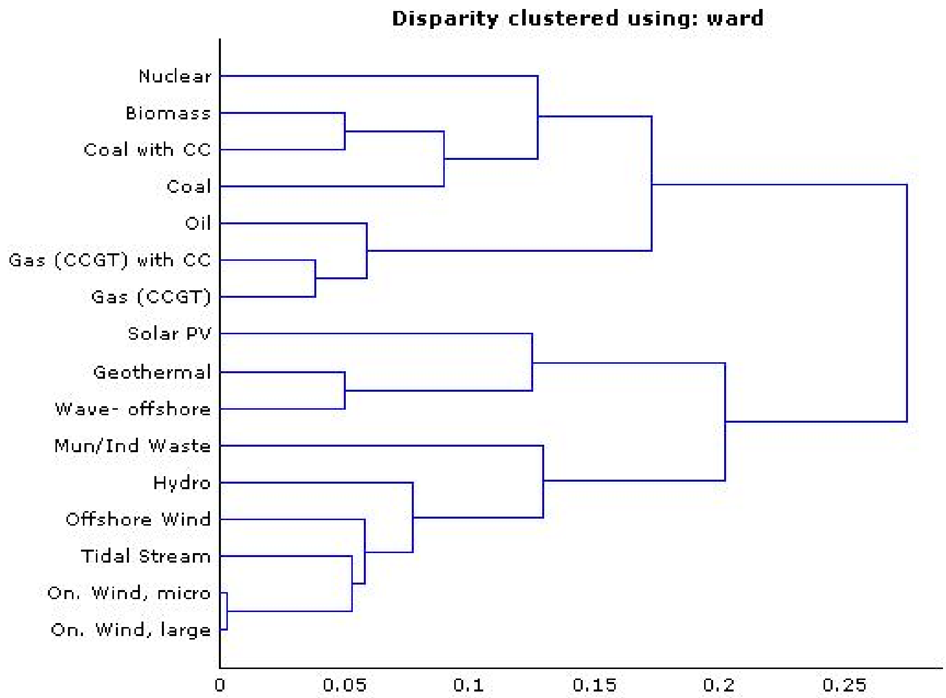


- Figure 4, titled “Portfolios”, is the principal useful output of this program. It graphs on the y-axis the percentage contribution to the overall mix drawn from each defined energy option. This is the composition of the diversity-optimal portfolios drawn from the Pareto efficient frontier shown in Figure 2. It is indexed on the x-axis it with the performance-diversity trade-off for each portfolio (δ).

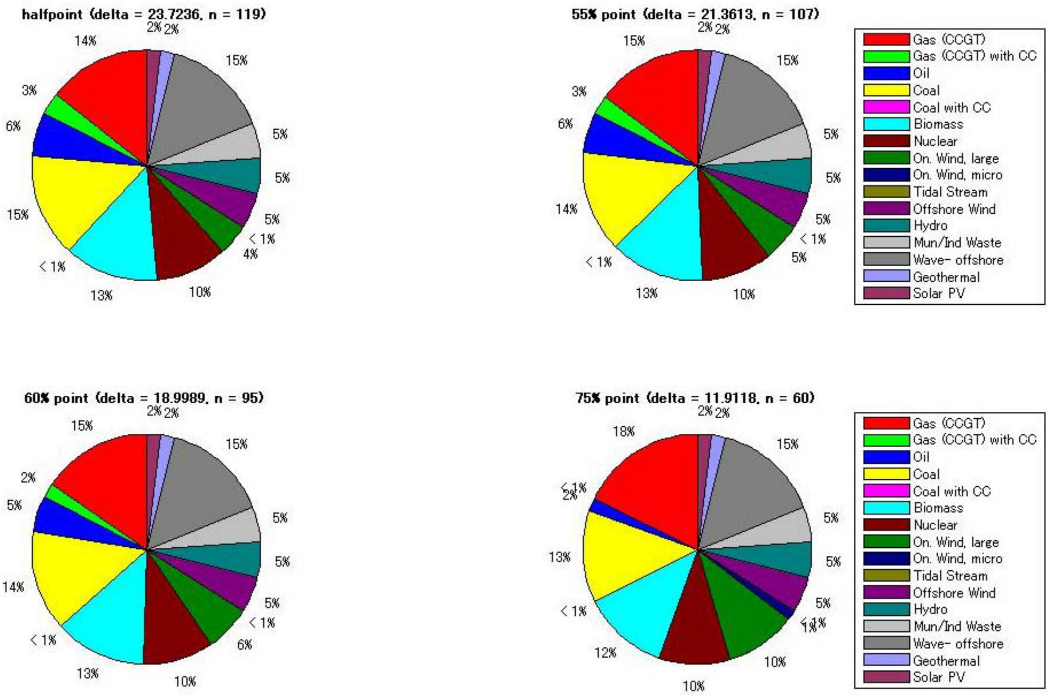
  This is the graphic that is referred to in the text as the ‘range of diversity-optimal portfolios’. The value of δ at which the portfolio value due to option performance (V{E}) is equal to that due to portfolio diversity (V{P}) is indicated with a red vertical dashed line. Low values of δ in this range express high confidence in performance appraisals of individual technologies, with little concern over deep uncertainties to which diversity is a reasonable response. Likewise, low values of δ imply that a priority is attached to maximising this performance, rather than the other benefits of diversity (in fostering innovation, mitigating lock-in or accommodating pluralism). High values of δ, on the other hand, reflect a dominant interest in these benefits of diversity, with little concern over the resulting compromises on performance.



- Figure 5, titled “Dendrogram”, uses the same algorithms and metrics as the clustering procedure selected in the Excel interface program, and therefore displays the same picture of the underlying disparity structure. The only difference is that the vertical ordering of the energy options is reversed.



- Figure 6 is titled "PieCharts" and is newly introduced for this pilot study. This figure has four pie charts of percentage contribution of individual energy options at the performance-diversity half point, 55% point (performance : diversity = 55 : 45), 60% point and 75% point. These charts provide participants with a clearer representation of portfolio compositions along a typically-favoured interval of the diversity-performance trade-off, of a kind that is normally held to yield realistic levels of diversity in the energy mix.



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