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A General Framework for Analyzing Diversity in Science, Technology and Society

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Contents

Abstract

This paper addresses the scope for more integrated general analysis of diversity in science, technology and society. It proposes a framework recognising three necessary but individually insufficient properties of diversity. Based on ten quality criteria, it suggests a general quantitative non-parametric diversity heuristic. This allows the systematic exploration of diversity under different perspectives, including divergent conceptions of relevant attributes and contrasting weightings on different diversity properties. It is shown how this heuristic may be used to explore different possible trade-offs between diversity and other aspects of interest, including portfolio interactions. The resulting approach offers a way to be more systematic and transparent in the treatment of scientific and technological diversity in a range of fields, including conservation management, research governance, energy policy and sustainable innovation.

Non-Technical Summary

Diversity is a topic of considerable interest in a variety of different scientific disciplines and areas of policy making – including: conservation, research and energy policy. By putting eggs in different baskets, we can foster resilience, promote innovation, avoid lock-in and groupthink and hedge uncertainty. Various methods are used to address diversity, but these are often problematic. The present paper seeks to tackle this by developing a novel general framework for thinking about diversity. It then introduces a straightforward mathematical tool that can be used to explore different viewpoints and their various implications – including crucial trade-offs between diversity and performance.

Introduction

'Diversity' is a concept that features prominently in a variety of disparate disciplines. Alongside the main focus in ecology [1,2,3], the term arises repeatedly in the physical [4], life [5] and information sciences [6], as well as in social [7], economic [8] and policy [9] studies. In particular, diversity is a prominent theme in science and technology policy [10].

That this should be so, is not unusual in itself. Whether for substantive or superficial reasons, technical terms like this are constantly being adapted to new applications. What is interesting about the concept of diversity is that, across radically different contexts, it refers repeatedly to a remarkably similar and particular set of properties. Despite much pertinent work [11,12,13,14,15,16], there is presently relatively little cross-disciplinary research on the general characterisation of diversity.

The present paper seeks to address this challenge. It begins by identifying the general properties of diversity that are common to the many contrasting fields in which it arises. It moves on to explore how these properties relate to each other and discuss the issues that emerge in trying to articulate them. It then proposes a novel general diversity heuristic with which systematically to characterise diversity across a variety of fields – and with particular reference to conservation management and technology policy. The paper ends by illustrating the practical application of this framework in examining relationships between diversity and other issues of interest.

Why is Diversity of Interest?

Before embarking on this analysis, it is worth asking why we might want to address diversity in such general terms at all? There already exists a host of specialised approaches in particular disciplines [17]. The answer here is twofold. First, it will be argued that – even in many specialist applications – well-established understandings of diversity can sometimes be circumscribed or challengeable. In such cases, a more general diversity heuristic may be useful as a reference, complement or catalyst. Second, there are fields – like science and technology policy – where diversity is prominent in discussion, but remains undefined or analytically neglected. Here, a general heuristic offers value as a means to more systematic or robust understandings.

Policy debates in many areas of science and technology yield numerous reasons for an interest in diversity. In the history, philosophy and sociology of science, interactions among a diversity of disciplinary perspectives are held to be important means to enhancing rigour [18] and creativity [19]. In research strategy, diverse portfolios offer flexibility in the face of uncertain future progress [20] and promote learning across programmes [21]. More broadly, institutional and technological diversity are seen as stimuli for innovation [22,23,24] and productivity [25]. Accordingly, it is repeatedly urged (including by *Nature* [26,27] and the Treasury [28]) that the governance of science be 'opened up' [29] to include more diverse public constituencies and interests [30]. In risk regulation, the inclusion of diverse views is likewise cited as a way to inform more robust policy decisions [31,32,33].

Similarly, in debates over precaution [34] and sustainability [35], the pursuit of diverse technology strategies is highlighted as a 'resource pool' [36] providing flexibility [37] and resilience [38] in the face of ignorance [39] and surprise [40]. This is also true in fields like energy policy, where technological and fuel diversity have long been a major focus in discussions of supply security [41,42,43,44,45]. In a world where choice among scientific and technological pathways is often a matter of intense political contention, then, diversity features both as an input and an output – pursuing a mix of strategies informed by a variety of perspectives can help accommodate otherwise irreconcilable social interests and values [46,47].

Looking at innovation more widely, diversity is a key focus of attention in economics [48,49], yielding many varieties of portfolio theory [50,51]. Less formalised notions of diversity are prominent in strategies for addressing wider challenges, like market concentration [52], institutional momentum [53], autonomy [54], entrapment [55] and lock-in [56]. Diversity is consequently a major theme in systems [57] and organisation [58] theory, bibliometrics [59], evaluation [60], engineering [61] and regional [62], development [63] and employment [64] policy. Beyond this, diversity is prominent in crucial efforts to promote religious, cultural, racial, and gender equality [65] and pluralism [66]. The concept of diversity is truly of pervasive interest.

Potential Downsides of Diversity

Of course, it must be noted that – in all these areas and despite the benefits – appeals to diversity sometimes represent little more than rhetoric [67]. Although diversity is an irreducible property of a system (rather than of its individual elements), it is repeatedly invoked in policy debates as if it were a unique quality of a particular system element or 'option' [68] – sometimes one that might actually be favoured for rather different reasons [69]. Exploiting the 'apple pie' connotations of diversity can be useful in advocating otherwise weak or marginalised positions.

Even where the benefits are substantive, it is rare indeed that diversity offers a 'free lunch' [70]. Indeed, by definition, deliberate diversification involves prioritising options that are otherwise assigned relatively low performance [71,72]. In addition, there are typically trade-offs between diversity and transaction costs [73] and with foregone benefits like accountability [74], standardisation [75] and economies of scale [76]. The value of the diversity premium [77] that is warranted in any context, will be a function of the relative performance attributed to individual options and the contributions that each makes to diversity [78]. Both are subjective judgements, offering ample scope for disagreement.

What is needed, then, is a systematic framework for exploring the implications of – and relationships between – different perspectives on the implications of diversity [79,80]. Such a framework should ideally be applicable equally across the range of contexts in which diversity is of interest. It is to this task, that the discussion will now turn.

The Ubiquity of Diversity

At root, diversity is an attribute of any system whose elements may be apportioned into categories [81]. Science comprises diverse disciplines [82], compounds diverse isomers [83]; crystals diverse structures [84]; amino-acids diverse sequences [85]; phyla diverse taxa [86]; ecologies diverse species [87]; agronomies diverse crops [88]; technologies diverse forms [89], investments diverse shares [90]; products diverse attributes [91]; archaeologies diverse assemblages [92]; cultures diverse communities [93]; literatures diverse perspectives [94], networks diverse actors [95] and individuals diverse psychologies [96]. In all these areas (and others), we find ostensibly different but convergent concepts of diversity.

In many of these fields, the properties of diversity are most usefully addressed in relation to some specific empirically- or theoretically-grounded parameters that are particular to the structures of the systems in question [97]. In finance theory, for instance, the parameters of interest are the covariance coefficients reflecting past patterns in the movements of stock prices [98]. In characterising chemical diversity, fundamental combinatorial rules play crucial roles [99]. In palaeontology and conservation biology, the strictly bifurcating structure of phylogenetic trees provides a useful framework [100]. The discipline of mathematical ecology is an area in which diversity concepts have been particularly thoroughly investigated [101]. Here, a family of parametric diversity measures derive from the pervasive power law structures displayed by species-abundance distributions within and between real ecosystems [102].

Yet even in these fields where diversity is relatively well parameterised, non-parametric diversity measures are often still applied. Examples developed in ecology and applied elsewhere, include species counting [103] and various mathematical functions of the proportional representations of relevant species [104] (see Table 1). Even in some of the most mature fields of development, then, parametric measures of diversity are often substituted by more generally applicable non-parametric indices [105]. Such approaches are even more relevant in the majority of fields discussed above, where there exists no uniquely plausible parametric basis for structuring understandings of diversity.

A Common Framework

It is when viewed in a non-parametric fashion, simply as a property of the apportioning of elements or options in any system, that the remarkable similarity and particularity of interdisciplinary understandings of diversity becomes clear. In short, diversity concepts employed across the full range of sciences mentioned above, display some combination of just three basic properties. These I will call 'variety', 'balance' and 'disparity' [106]. Each is a necessary but insufficient property of diversity [107,108,109]. Though addressed in different vocabularies, each is applicable across a range of disciplines. Each is aggregated in various permutations in quantitative indices [110]. Despite the multiple disciplines and divergent contexts, there seems no other obvious candidate for a fourth important general property of diversity beyond these three [111].

Variety is the number of categories into which system elements are apportioned. It is the answer to the question: "how many types of thing do we have?" This aspect of diversity is highlighted (for instance) in the use of species-number indices in ecology [112]; the simple enumeration of firms or products in economics [113,114,115,116] or the counting of fuels or technologies in energy policy [117]. *All else being equal, the greater the variety, the greater the diversity*.

Balance is a function of the pattern of apportionment of elements across categories. It is the answer to the question: "how much of each type of thing do we have?" Analogous to statistical variance [118], this can be represented by a set of positive fractions, which sum to one [119]. Referred to as 'evenness' in ecology [120] and 'concentration' in economics [121], this is captured by the Shannon-Wiener [122], Gini [123] and Simpson [124] indices (Table 1). As the Herfindahl-Hirschman index, the latter is used in the US to regulate market share [125]. *All else being equal, the more even is the balance, the greater the diversity*.

Disparity refers to the manner and degree in which the elements may be distinguished [126]. It is the answer to the question: "how different from each other are the types of thing that we have?" It is judgements over disparity, which (often implicitly) necessarily govern the resolving of categories used to characterise variety and balance. This is addressed by an array of taxonomic indices in palaeontology [127],

conservation biology [128] and economics [129] – usually based on some form of distance measure. *All else being equal, the more disparate are the represented elements, the greater the diversity*.

Table 1: Selected non-parametric measures of diversity properties [130]

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Some General Challenges

The consequence of this threefold understanding of diversity, is a recognition that each property constitutes the other two [131]. This in turn highlights difficulties with diversity concepts and associated indices – in whatever discipline – that focus exclusively on subsets of these properties [132]. This is a matter of significant, but relatively neglected, scientific importance. The relevance is amplified by the tendency for apparently technical questions over diversity to acquire high profile policy salience – as in fields like ecological conservation [133], market regulation [134], energy policy [135] and research [136] strategies. In such areas, as we have seen, ostensibly arcane scientific questions over the definition and measurement of diversity are laden with (and conditioned by) large-scale institutional, economic and political interests [137].

Variety and balance, for instance, cannot be characterised without first considering disparity. It is on this basis that a taxonomy of elements is defined and partitioned [138]. An ecological community comprising twenty varieties of beetle is less diverse than one comprising less than twenty species drawn from different insect, reptile and mammalian taxa [139]. Likewise, an electricity system is less diverse if it comprises equal contributions from lignite, brown coal, oil and gas than if it is an equal mix of coal, nuclear and renewable energy [140]. However, a category like 'renewable energy' might itself be judged highly diverse, if it is equally apportioned into, wind, solar, hydro, tidal, biomass, landfill gas and so on. The focus of attention in each case is neither on variety nor balance, but on disparity [141]. Taking variety or balance as proxies for diversity can thus be highly sensitive to subjective construction and partitioning of taxonomies and to arbitrary linguistic conventions concerning the implicit bounding of categories.

Conversely, the relevance of disparity to diversity often depends on the pattern of apportionment across categories. Yet, such apportionment may sometimes be neglected. This is necessarily so in palaeontology, due to limited evidence on species abundance [142]. Ecological structures and the reproductive potential of germplasm can likewise make interest in genetic diversity quite independent from questions of abundance [143]. Yet problems can arise if disparity is taken as a complete representation of diversity in conservation biology. This is because, used on their

own, disparity measures fail to discriminate between species represented by viable or nonviable populations [144]. Similarly, an energy portfolio comprising a 90% contribution from one of three highly disparate resources might reasonably be judged less diverse than a portfolio comprising an equal contribution from three less disparate options [145]. This crucial feature is not addressed by understandings of diversity in terms of disparity alone. Taking disparity as a proxy for diversity ignores the balance with which a system is apportioned.

Aggregation, Accommodation and Articulation

It is rare indeed that a concept as pervasive as the notion of diversity, should display such similar properties across such disparate fields. Despite the high profile attention, the scientific and policy challenges remain relatively under-explored. This is curious, since the present threefold nonparametric understanding of diversity is relatively tractable. In particular, it is striking that – for given categories of elements – all three properties are quite readily amenable to quantification: variety is an integer (enumerating categories); balance is a function of a set of fractions summing to unity (apportioning elements); and disparity a function of a matrix of distances (differentiating elements).

This said, it is difficult indeed to contemplate any single general index of diversity that could ***aggregate*** properties of variety, balance and disparity in a uniquely robust fashion. Even where these properties are already integrated in existing indices, there remain serious queries over the different weightings to apply in aggregation. This is true, for instance, of the families of 'dual concept' [146] indices used in ecology and economics to aggregate variety and balance (Table 1). The logarithm base taken in Shannon and the value of the exponent taken in Simpson-Herfindahl [147] can each have implications for the relative weightings assigned to variety and balance [148]. Yet the consequences for analysis are rarely explored in practice [149]. In short, even popular 'nonparametric' indices like these, are nonetheless parameterised at a fundamental (if implicit) conceptual level. These underlying parameter values might reasonably be varied, yielding differing pictures of diversity [150].

Beyond this problem of aggregation, there lies the further challenge of ***accommodating*** different possible understandings of disparity. Here, the picture will necessarily depend on whatever are seen as the salient dimensions of difference. In some cases, there may exist some well-established (or even objectively determined) criteria. This is the case, for instance, with taxonomies of genetic distance in evolutionary ecology, which can be assumed to display a strict branching form [151]. It is also true where differences between diverse options can usefully be reduced to a single factor such as historic covariance in financial stock [152] or fuel [153] prices. Even in these areas, however, the assumptions necessary for such parameterisation are

sometimes heroic [154,155]. Where categorisation and variance are more complex, as in Junge's [156] proposed application in psychology (Table 1), such approaches are lacking in applicability and robustness [157].

Generally speaking, notions of difference determining characterisations of diversity will depend on perspective and context. For instance, understandings of diversity in the field of conservation biology may reasonably refer not just to species abundance and genetic distance, but also to notions of ecological, agronomic or cultural value [158,159]. Likewise, notions of energy diversity may reflect contrasting criteria such as the form and provenance of fuels or equipment; geographic patterns in extraction and transport; or key features of associated infrastructures [160]. In general, these kinds of disparities in science and technology reflect complex webs of relationships, and so cannot readily be reduced to discrete branching taxonomies, as assumed, for instance, in Weitzman's index (Table 1) [161].

Beyond the aggregation of different properties of diversity and the accommodation of different perspectives on disparity, there remains a third and final challenge of *articulating* diversity with other properties of interest in analysis or evaluation. Alongside diversity, for instance, the different species or habitats constituting ecosystems may also be assessed in terms of their conservation, agronomic, socio-cultural or aesthetic landscape qualities and values. Likewise, an energy portfolio may also be assessed in terms of criteria such as operational efficacy, financial performance, security of supply, employment intensity or environmental impacts. These other aspects may to some extent be independent from diversity, but will also interlink in various ways – reflecting the structure and composition of the system and interactions between its elements. In particular, they may define many different criteria under which diversification could have positive or negative implications, of a kind that should be included in appraisal. Rather than being isolated as a narrow consideration in its own right, then, any useful framework for analysing diversity should ideally allow for ready articulation of these kinds of wider aspects.

These challenges of aggregation, accommodation and articulation conspire against aspirations definitively to capture diversity, even within a single discipline. They are all the more formidable as obstacles to a general framework for understanding diversity, of a kind that might be applicable across different empirical fields. However, this is not a challenge that is specific to the threefold characterisation of

diversity described here. Instead, it is a more pervasive problem that is intrinsic to any general notion of diversity – irrespective of whether or not this is acknowledged.

A Systematic Response

To take seriously these problems of aggregation, accommodation and articulation does not necessarily lead to a counsel of despair over the potential for systematic general characterisations – or even quantifications – of diversity. A more positive starting point is the observation that the futility of seeking to derive a single definitive diversity ***index***, need not preclude the possibility of a flexible general ***heuristic***. Like an index, a heuristic may be quantitative. But rather than aiming to measure diversity in some unconditional objective fashion, it offers an explicit, systematic basis for exploring sensitivities to the assumptions conditioning aggregation, accommodation and articulation.

For any particular perspective on the appropriate weightings for variety and balance and the salient dimensions of disparity, such a heuristic would behave as an index. It would accommodate different views on the salient attributes of disparity, aggregate these with consideration of variety and balance and allow systematic articulation with important system-level properties other than diversity. For applications involving a range of perspectives, this heuristic would allow systematic comparisons to be made between the implications of contending judgements. In other words, a heuristic characterisation of diversity aims to combine the rigour, transparency and specificity of quantification with the applicability, flexibility and symmetry of qualitative approaches. The real challenge lies in achieving this, whilst minimising the introduction of further complexity and contingency.

No existing diversity index addresses all three properties of variety, balance and disparity in an unproblematic way. However – based partly on criteria applied to the treatment of these individual diversity properties by researchers such as Hill [162], Laxton [163], Pielou [164], Weitzman [165] and Solow and Polasky [166] – a series of non-trivial requirements are quite readily developed. One such set of desirable features of a general diversity heuristic (Δ) that help explicitly to address challenges of aggregation, accommodation and articulation as defined here, are as follows:

1. ***Scaling of variety:*** Where variety is equal to one, Δ takes a value of zero [167].

2. ***Monotonicity of variety:*** Where elements are evenly balanced and equally disparate, Δ increases monotonically with variety [168].

3. ***Monotonicity of balance:*** For given variety and disparity, Δ increases monotonically with balance (ie: Δ is maximal for equal representation) [169].

4. ***Monotonicity of disparity:*** For given variety and balance, Δ increases monotonically with the aggregate disparity between elements [170].

5. ***Scaling of disparity:*** Where aggregate disparity is zero (ie: where all elements are effectively identical), Δ takes a value of zero [171].

6. ***Open accommodation:*** Δ symmetrically accommodates any perspective on salient dimensions of difference under which elements can be differentiated [172].

7. ***Insensitivity to partitioning:*** For any given perspective on taxonomy, Δ is insensitive to alternative partitionings of elements into categories [173].

8. ***Parsimony of form:*** Δ is as uncomplicated in structure and parsimonious in form as necessary to fulfil the above conditions.

9. ***Explicit aggregation:*** Δ permits explicit aggregation of variety, balance and disparity, by reflecting divergent contexts or perspectives using weightings.

10. ***Ready articulation:*** Δ allows unconstrained articulations of diversity with other salient properties of the system as a whole or of its individual elements.

A General Diversity Heuristic

No established diversity index satisfies all these criteria. Yet, there is one relatively straightforward quantitative heuristic, which is not specifically discussed in the literature reviewed thus far (Table 1), but which does offer a starting point [174]. This is the sum of pairwise disparities, weighted in proportion to contributions of individual system elements (***D***):

$$\boldsymbol{D} = \sum_{ij(i\neq j)} d_{ij}.p_i.p_j \qquad [1]$$

where: p_i and p_j are proportional representations of elements i and j in the system (balance), and d_{ij} is the degree of difference (disparity) attributed to elements i and j. The summation is across the half-matrix of $((n^2-n)/2)$ non-identical pairs of n elements $(i\neq j)$. In the special case where all d_{ij} are equal (scaleable to unity), ***D*** reduces to half Gini (Table 1). In the special case where one element dominates the system $(p_i \rightarrow 1)$, ***D*** is a member of the family of measures introduced by Polasky and Solow (Table 1).

In the absence of definitive parametric understandings of system structure, the simplest way to conceive of disparities between elements, is as a distance between points in disparity space [175]. Each perspective will yield a unique ***n***-dimensional disparity space, representing judgements over the salience of ***n*** different attributes of system elements. Attributes can be rated in cardinal, interval or binary yes/no terms. Here, a Euclidean ***n***-space offers the most parsimonious and generally applicable framework. With suitable normalisation and weighting, the relative magnitudes of the resulting distances can be scaled to reflect divergent notions of specific disparities or different geometries in disparity space [176]. In particular, a Euclidean ***n***-space involves less restrictive assumptions and greater consistency than the ultrametric space required by the Weitzman index (Table 1) [177,178].

It is readily demonstrated that this heuristic, ***D***, complies with criteria (1) to (7). Compliance with criterion (8) remains a matter of judgement, but it is difficult to imagine a solution to these criteria that is simpler or more parsimonious. As to criterion (9), this raises a final notable feature of ***D***, that can be illustrated by introducing just two further terms:

$$\Delta = \sum_{ij(i\neq j)} (d_{ij})^{\alpha}.(p_i.p_j)^{\beta} \qquad [2]$$

If exponents α and β are allowed to take all possible permutations of the values 0 and 1, this yields four variants of the heuristic Δ. Each of these usefully captures one of the four properties of interest: variety, balance, disparity and diversity (Table 2).

Table 2: Four variants of Δ and their relationship with diversity properties
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Shifting the value of exponent α between 0 and 1 yields further variants of Δ, collectively addressing all possible relevant weightings on balance and variety/disparity. Of these, the reference case, **D** (α = β = 1) does the same job as other widely used non-parametric measures like Gini, Shannon and Simpson, but with the major additional feature that it also captures disparity. Unlike the disparity measures proposed by Weitzman or Solow and Polasky (Table 1), Δ also addresses variety and balance. Unlike the measure proposed by Junge [179] (Table 1), Δ accommodates radically divergent perspectives on disparity and is relatively parsimonious in form. An entirely novel feature of Δ, is that it systematically addresses alternative possible aggregations of these subordinate properties, according to perspective and context.

Articulating Diversity with Other System Properties

This leaves unaddressed only criterion (10) concerning the articulation of diversity with other relevant system-level properties. As already mentioned, diversity is rarely a free lunch in decision making. Whether in fields like conservation management, research strategy or energy policy, the total value of any system will be a function not only of system diversity but of other properties of the system and its individual elements. In economics, for instance, diversity may provide an effective response to challenges like hedging ignorance, fostering innovation, mitigating lock-in and accommodating pluralism. But it will often require some compromise on other aspects of performance – like cost, equity, environment or ethics. There will typically be constraints on the contributions of individual elements and portfolio effects resulting from their interactions [180].

In conservation management, Solow and Polasky show how their own proposed disparity function (Table 1) can be adopted in a utilitarian fashion, articulating the value of ecological diversity with that attached to other possible evaluative criteria, such as possible medical applications that may be discovered in relation to individual species [181]. Other ecological system properties might also be included in this way, perhaps to address the importance of trophic webs or the value of keystone species [182]. In this vein, for example, Karr's index of biotic integrity articulates – with explicit subjectivity – further system-level considerations of ecological and biological health [183].

In these terms, then, the value assigned under a given perspective to any particular system under specific conditions ($V\{S\}$) can be expressed as the sum of the value due to the aggregate performance of individual system elements ($V\{E\}$) and an incremental value attached to irreducible portfolio-level properties including diversity ($V\{P\}$). If the net implications of diversity are adverse, then $V\{P\}$ can be negative.

$$V\{S\} \quad = \quad V\{E\} \ + \ V\{P\} \qquad\qquad [3]$$

Long experience in the field of decision analysis [184] shows that – just as divergent notions of difference can be represented as co-ordinates in an *n*-dimensional Euclidean disparity space – so divergent valuations of individual system elements can be represented as co-ordinates in an *m*-dimensional Euclidean performance space [185].

The dimensions of this space represent any set of m performance criteria, each weighted to reflect their respective importance [186]. As with disparity, the selection, characterisation and scaling of these criteria will vary across context and perspective [187]. Although it is difficult to justify any single approach to aggregating performance across perspectives, decision analysis has shown that any single perspective can be uniquely captured by means of the following expression for the overall value attached to the performance of individual system elements $V\{E\}$:

$$V\{E\} \quad = \quad \sum_i \sum_c (w_c.s_{ic}).p_i \qquad\qquad [4]$$

where s_{ic} is the value attached to the performance of element i under criterion c; w_c is a scalar weighting reflecting the relative importance of criterion c (under the perspective and context in question) and p_i is (as in equations [1] and [2]), the proportional representation of element i in the system. It follows from equation [2] that the corresponding value attached to irreducible portfolio-level properties including diversity ($V\{P\}$), can then be expressed follows:

$$V\{P\} \quad = \quad \delta.\Delta'$$

$$= \quad \delta.\sum_{ij(i\neq j)} (d_{ij})^\alpha.(p_i.p_j)^\beta.\iota_{ij} \qquad\qquad [5]$$

where Δ' represents an augmented form of the diversity heuristic Δ given in equation [2], which includes an additional term to reflect portfolio interactions (ι_{ij}). This is an array of scalar multipliers exploiting the pairwise structure of Δ' to express the effect on system value of synergies or tensions between elements i and j, respectively, as marginal positive or negative departures from a default of unity ($\iota_{ij} = 1 \pm \partial\iota$: for most systems $\partial\iota<<1$). This serves as a means to capture a variety of system-level properties that – like diversity – are irreducible to individual elements. The coefficient δ scales expressions of portfolio value to render them commensurable with aggregate values of individual options in equation [4]. For positive assessments of portfolio value, $0 < \delta < \infty$. From equations [3], [4] and [5], we therefore obtain the following heuristic system-level articulation ($V\{S\}$) of the value attached to diversity together with that assigned to other portfolio properties ($V\{P\}$) and to the performance of individual system elements ($V\{E\}$).

$$V\{S\} \quad = \quad \sum_i \sum_c (w_c.s_{ic}).p_i + \delta.\sum_{ij(i\neq j)} (d_{ij})^\alpha.(p_i.p_j)^\beta.\iota_{ij} \qquad [6]$$

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It is in $V\{S\}$ that we have a means to address the final criterion (10) developed above, in that a diversity heuristic should allow systematic unconstrained articulation of diversity with alternative characterisations of other salient properties of the system as a whole.

The interest of the heuristic $V\{S\}$, lies not in any attempt to derive some unconditional 'optimal' balance between the performance of individual elements, system interactions and diversity. Instead, with sensitivity analysis, $V\{S\}$ can be used systematically to explore different possible perspectives and assumptions concerning the contributions of these components to overall system value. For each perspective on the performance and interactions of individual elements, their disparities, the aggregation of diversity properties and the scale of the performance-diversity trade-off, there exists a particular apportionment of elements that yields some maximum overall value. By varying δ between zero and infinity, resolving the set of p_i which give a maximal value for $V\{S\}$ yields a continuum of all possible conditionally optimal systems. These range (respectively) from those that maximise value due to aggregate performance of individual elements (low δ), to those that maximise value due to portfolio interactions and system diversity (high δ).

Figure 1:   schematic relationship between habitat diversity and other aspects of landscape value

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For schematic data provided in an electronic Annex [A], Figure 1 presents an illustration of this heuristic usage of $V\{S\}$. These data reflect one hypothetical perspective on the challenges associated with finding an appropriate balance between diversity and other aspects of landscape value in conservation management [188]. Here the focus of attention is not directly on species diversity, but on the contributions that might be made to this end by habitat diversity in the landscape [189]. This bears in mind that certain individual habitats may be seen to hold greater intrinsic conservation value than others and that there exist other economic, socio-cultural and aesthetic criteria for informing decisions over landscape management [190].

Consider for the sake of illustration, a schematic case in which each of a series of habitat types (A,B,C,D) offer viable options across a discrete, contiguous landscape

for which long-term land-use policy commitments are being made subject to a consultative process at a particular point in time. Under one hypothetical perspective, these habitats are mutually distinguishable under a set of four disparity attributes: *(i)* commercially managed mixed woodland; *(ii)* low-input mixed arable farming with wide field margins; *(iii)* close-grazed bryophyte-rich grassland and *(iv)* low-intensity grazing of wildflower meadows. Depending on the perspective, it is these kinds of attribute which might constitute the distance metric (d_{ij}) in applying the heuristic Δ' in equation [6].

Criteria applied in the evaluation of the individual habitat types might include a number of general ecological considerations, values attached to particular endangered species endemic to each habitat, the internal biodiversity of the habitat itself, as well as economic revenues for sustaining local livelihoods, aesthetic and cultural-historical issues (of relevance also in indirect tourism revenues) [191]. These constitute the basis for the performance measures (s_{ic}) and their respective weightings (w_c) in equation [6]. Even if one of the four habitat types is evaluated much more positively than others, there may nonetheless be a benefit in sustaining habitat diversity as a means to support certain species and communities spanning different habitats and to address the conservation value of 'mosaics' as well as other landscape-scale economic and socio-cultural issues [192]. Likewise, some system-level aspects of landscape value will derive from the presence of particular combinations of habitats – and their interfaces – in the mix [193]. These constitute the basis, respectively, for the diversity coefficient (δ) and the interaction term (ι_{ij}) in equation [6]. For the purposes of the present illustrative exercise, the perspective in question is assumed to favour an aggregation of diversity properties in equation [6], in which both α and β take a value of 1 (thus $\Delta = \boldsymbol{D}$ in equations [1] and [2]).

Figure 1 displays the sort of outcome that can readily be derived from these kinds of input, as a heuristic articulation of the overall value attached to individual habitats with that deriving from their interactions and from diversity in the landscape. The shaded areas represent the composition of an optimal frontier (obtained using iterative optimisation procedures provided in Matlab software), maximising $V\{S\}$ for this dataset at varying values of δ (equation [6]). It shows the way in which the proportion of the landscape assigned to each of the four schematic habitat types (vertical axis –

p_i, p_j in equation [6]) varies as progressively greater weight is attached to maintaining a diversity of habitats (horizontal axis – δ in equation [6]). The vertical dotted line shows the value of δ at which $V\{E\} = V\{P\}$ (equation [3]).

Of course, for the purposes of exposition, the present example is highly stylised. It is very simple and omits many important features – such as those relating to the geographical structure of the landscape in question [194]. However, by repeating such an exercise iteratively as a way of exploring the implications of different assumptions or interpretations of uncertainty, this heuristic framework may therefore be used to assist the formulation of individual perspectives or to inform effective deliberation between contending disciplinary or stakeholder positions on this kind of decision over habitat diversity in the landscape.

To substantiate the more general applicability of this heuristic framework, Figure 2 provides one further schematic illustration in the rather different, but currently highly topical, field of energy policy [195]. Here, the interest lies in constructing a mix of generating technologies at the level of an electricity system like that of the UK, such as to reconcile different possibilities and perspectives in the economic, environmental, energy security and wider social performance of the supply mix [196]. Disparities here may be conceived in terms of the nature and origins of the fuels and technologies concerned, as well as salient features of their respective institutional, commercial or socio-political contexts [197]. Positive and negative economic, organisational and operational synergies between different technologies inform the modelling of interactions. Certain options are tightly constrained in terms of the available resource, or display reductions (from learning or scale) or increases (from depletion) in costs or impacts as the contributions rise. For illustrative data on all these aspects provided in electronic Annex [B], Figure 2 shows – for a particular hypothetical perspective – how the resulting conditionally optimal electricity portfolios vary as greater or lesser priority is placed on diversity.

Low values of δ in Figure 1 may 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 may imply that 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. Again, the value of this kind of heuristic framework, is as a means more explicitly and systematically to inform analysis under individual perspectives, and to provide a basis for more effective and transparent deliberation between contending positions.

Figure 2: illustrative performance-diversity trade-offs for UK energy portfolios
INSERT ABOUT HERE

Conclusion

The present paper has outlined a framework for interdisciplinary analysis of diversity. The discussion began by noting many different reasons for an interest in diversity, not least in high profile areas of science and technology policy. Here, diversity offers a means to promote innovation, hedge ignorance, mitigate lock-in and accommodate pluralism. It offers one important strategy for achieving qualities of precaution, resilience and robustness that are central to sustainability.

To these ends, the paper identifies a general framework for understanding diversity in a range of different contexts and specialisms. This involves recognition of diversity as a function of three necessary but individually insufficient properties: variety, balance and disparity. Existing nonparametric diversity indices address only subsets of these three properties, and/or raise questions over their underlying assumptions.

By reference to ten quality criteria, the paper proposes a novel general diversity heuristic, D. A more general formulation ($\varDelta$), serves not just as a heuristic for diversity, but for each of the three subordinate properties, thus permitting systematic exploration of different possible weightings on variety, balance and disparity. As such, $\varDelta$ may prove applicable in any fields in which diversity is presently discussed, irrespective of whether it has been definitively parameterised.

One way of using this heuristic, is systematically to explore relationships between diversity and other aspects of portfolio performance. For instance, the framework might be used to elicit perspectives on likely performance and salient differences between contending research and development programmes, energy technology investments or habitat types in conservation management. By allowing exploration of trade-offs between diversity and performance – including consideration of system constraints and interactions – this offers a means to frame more effective policy deliberation. Similar applications suggest themselves in other areas, like ecological analysis, research governance, innovation policy, urban planning, agricultural strategy and regional development. Indeed, the approach seems applicable anywhere where there is an interest in analysing system diversity – particularly as a means to promote more inclusive, precautionary, resilient and sustainable applications of science and technology.

Table 1: Selected non-parametric measures of diversity properties [198]

Property Addressed	Name	Form
variety	Category Count [199]	N
balance	Shannon Evenness [200]	$\dfrac{-\sum_i p_i \ln p_i}{\ln N}$
disparity	Weitzman [201] Solow & Polasky [202]	$\max_{i \in S}\{\mathbf{D}_W(S \setminus i) + \mathbf{d}_W(i, S \setminus i)\}$ $\boldsymbol{f}(\mathbf{d}_{ij})$
variety / balance	Shannon [203] Simpson [204] Gini [205]	$-\sum_i p_i \ln p_i$ $\sum_i p_i^2$ $1 - \sum_i p_i^2$
variety / balance / disparity	Junge [206]	$\left(\dfrac{\sigma}{\mu \cdot \sqrt{n-1}}\right)\cdot\left(\dfrac{1}{\sqrt{N}}\right)\cdot\left(\sqrt{N-1} - \sqrt{N\Sigma_i p_i^2 - 1}\right)$

Notation	*Interpretation*
N	number of categories of elements
ln	logarithm (usually natural)
p_I	proportion of system comprised of category i
n	number of attributes displayed by elements
σ	standard deviation of attributes within categories
μ	mean of attributes within categories
$\boldsymbol{f}(\mathbf{d}_{ij})$	function of distance in disparity space between categories i and j
$\mathbf{D}_W(S)$	aggregate disparity of system S
$\mathbf{d}_W(i, S \setminus i)$	distance in disparity-space between category i and nearest remaining element in S if i is excluded

Table 2: Four variants of Δ and links with diversity properties and measures

Property	α	β	[eq.2]: Δ =.	Equivalents [cf: Table 1]	Interpretation
variety	0	0	$\sum_{ij} d_{ij}^{0}$	$(N^2 - N)/2$	scaled variety
balance	0	1	$\sum_{ij} p_i . p_j$	[Gini] / 2	balance-weighted variety
disparity	1	0	$\sum_{ij} d_{ij}$	[Solow & Polasky]	disparity-weighted variety
diversity	1	1	$\sum_{ij} d_{ij} . p_i . p_j$	**D**	balance and disparity weighted variety

Figure 1: **schematic relationship between habitat diversity and other aspects of landscape value**
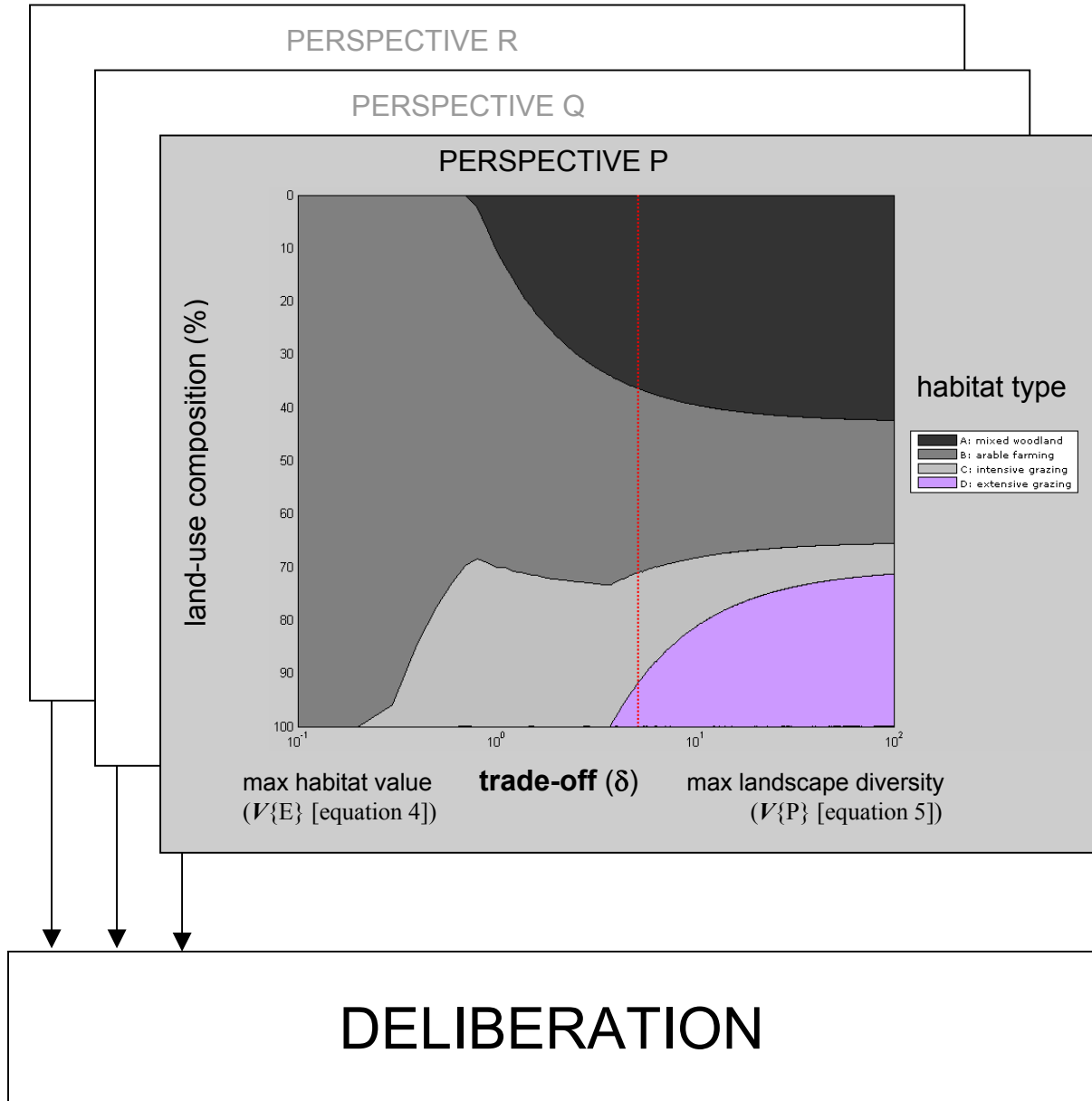
Figure 2: illustrative performance-diversity trade-offs for UK energy portfolios
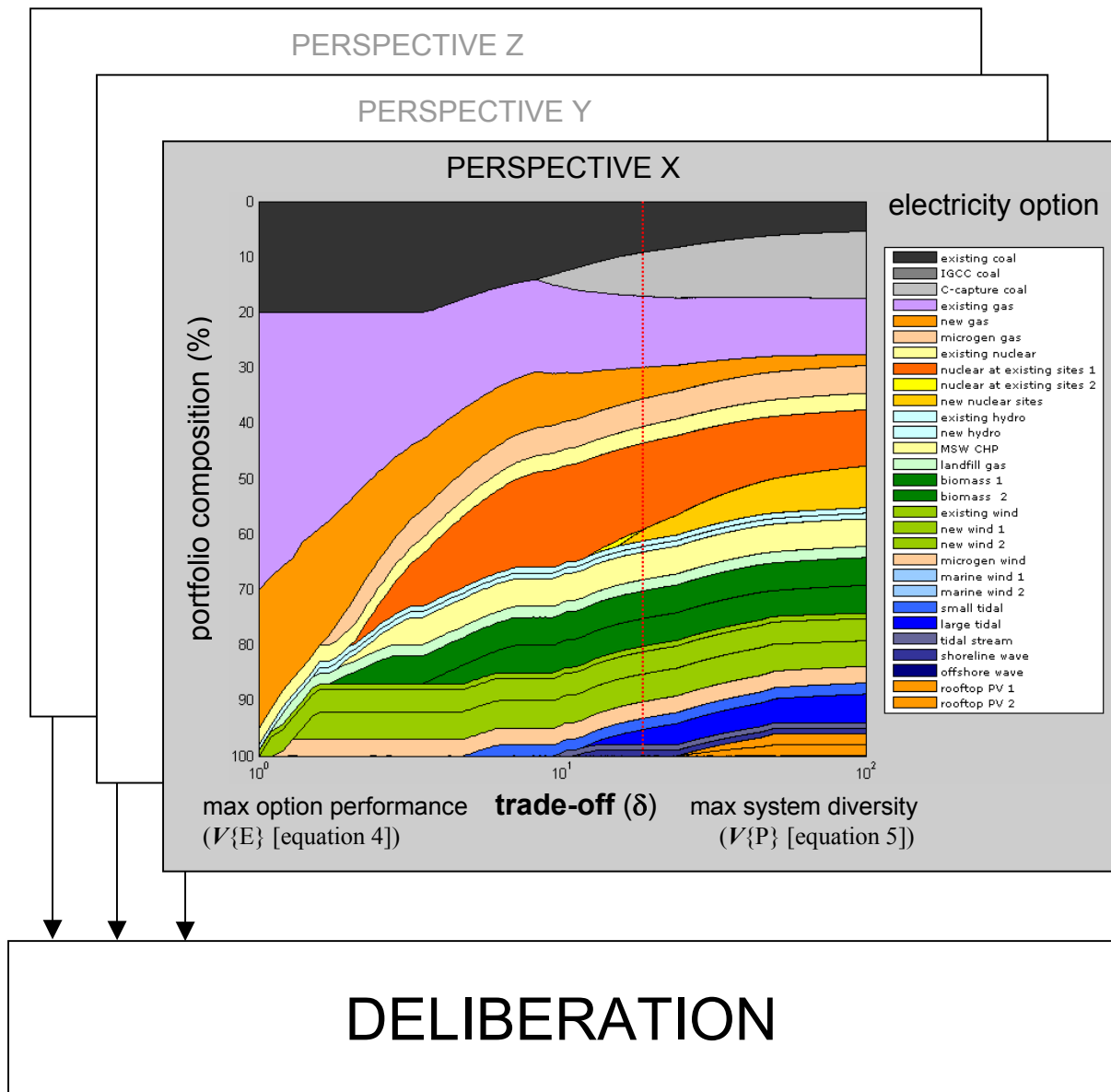
Electronic Annex A: Illustrative Data for Analysis of Habitat Diversity (Figure 1)

Habitat types		Disparity attributes				Performance Criteria						Habitat Interactions			
		mixed woods	arable farms	intensive grazing	extensive pasture	Rare species 1	Rare species 2	Rare species 3	Economic value	Sustainable livelihood	Aesthetic value	A: mixed woods	B: arable farms	C: intensive grazing	D: extensive pasture
	Weightings	4.0	2.0	1.0	1.0	4.0	2.0	2.0	12.0	4.0	2.0	4.0	2.0	4.0	2.0
A: mixed woods		4.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0			
B: arable farms		0.0	2.0	0.0	0.0	0.5	0.0	0.5	1.0	0.0	0.0	1.0	1.0		
C: Intensive grazing		0.0	0.0	1.0	0.0	0.0	0.5	1.0	0.5	1.0	0.0	**1.2**	1.0	1.0	
D: extensive pasture		0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.5	0.5	1.0	1.0	1.0	1.0

Electronic Annex B: Illustrative Data for Analysis of Energy Diversity (Figure 2)

#	Energy options	fraction of system	centralised	fossil fuel	concentrated fuel chain	concentrated labour	concentrated equipment	specialist infrastructure	offshore engineering	aero-turbine engineering	hydro-turbine engineering	combustion engineering	nuclear engineering	semi-cond. engineering	heat integration	waste integration	household integrated	dispatch restrictions	new sites	special regulations	emissions regulation	generic sensitivities	engineering cost	carbon emissions	wider environment	security: long term	security: reliability	land use issues	system operation	public acceptability	military vulnerability
	Weightings		48.0	24.0	12.0	12.0	12.0	12.0	9.0	6.0	6.0	6.0	12.0	6.0	6.0	6.0	12.0	12.0	12.0	12.0	6.0	6.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	existing coal	0.20	1.0	1.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.0	0.9	0.2	0.1	0.9	0.8	0.8	1.0	0.7	0.5
2	IGCC coal	0.80	1.0	1.0	0.5	0.5	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.9	0.3	0.3	0.9	0.9	0.9	0.8	0.7	0.5
3	C-capture coal	0.80	1.0	1.0	0.5	0.5	1.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	1.0	0.0	0.7	0.8	0.4	0.9	0.8	0.9	0.8	0.8	0.5
4	existing gas	0.50	1.0	1.0	0.5	1.0	0.5	0.0	0.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.9	0.5	0.5	0.6	0.9	1.0	1.0	1.0	0.5
5	new gas	1.00	1.0	1.0	1.0	0.5	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.5	0.0	0.0	0.0	0.5	0.0	1.0	0.0	0.9	0.6	0.6	0.5	0.9	0.9	1.0	0.9	0.5
6	microgen gas	0.05	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0	0.0	1.0	0.0	0.7	0.7	0.6	0.5	0.8	1.0	0.9	1.0	1.0
7	existing nuclear	0.03	1.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	0.0	1.0	1.0	0.1	0.6	0.7	1.0	1.0	0.3	0.0
8	nuclear current sites 1	0.20	1.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0	0.8	1.0	0.2	0.6	0.8	1.0	0.9	0.1	0.0
9	nuclear current sites 2	0.20	1.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	0.5	1.0	1.0	1.0	0.7	1.0	0.2	0.5	0.8	0.9	0.8	0.1	0.0
10	new nuclear sites	0.40	1.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.6	1.0	0.2	0.5	0.8	0.8	0.8	0.0	0.0
11	existing hydro	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.8	0.8	0.6	0.7	0.9	0.8	1.0
12	new hydro	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.7	1.0	0.6	0.8	0.6	0.6	0.9	0.6	1.0
13	MSW CHP	0.05	0.0	0.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	1.0	0.0	0.7	1.0	0.4	0.7	0.6	0.9	0.3	0.4	1.0
14	landfill gas	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.7	1.0	0.9	0.4	0.5	1.0	0.9	0.9	1.0
15	biomass 1	0.05	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0	0.7	1.0	0.6	0.7	0.5	0.5	0.6	0.6	1.0
16	biomass 2	0.05	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0	0.7	1.0	0.5	0.7	0.5	0.4	0.5	0.6	1.0
17	existing wind	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	1.0	1.0	0.7	0.9	0.4	0.4	0.4	0.6	1.0
18	new wind 1	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.7	1.0	0.6	0.9	0.5	0.3	0.3	0.6	1.0
19	new wind 2	0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.7	1.0	0.5	0.9	0.5	0.2	0.2	0.6	1.0
20	microgen wind	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.7	1.0	0.5	0.9	0.5	0.2	0.2	0.6	1.0
21	marine wind 1	0.05	0.5	0.0	1.0	0.5	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.7	1.0	0.7	0.9	0.6	0.7	0.6	0.8	1.0
22	marine wind 2	0.05	0.5	0.0	1.0	0.5	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.6	1.0	0.7	0.9	0.6	0.6	0.5	0.8	1.0
23	small tidal	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.0	0.0	0.0	0.6	1.0	0.4	0.9	0.2	0.3	0.4	0.3	0.5
24	large tidal	0.10	1.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.0	0.0	0.0	0.6	1.0	0.4	0.9	0.2	0.3	0.4	0.3	0.0
25	tidal stream	0.01	0.0	0.0	0.0	0.5	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.4	1.0	0.7	0.9	0.4	1.0	0.4	0.9	1.0
26	shoreline wave	0.01	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.5	1.0	0.7	0.9	0.4	0.8	0.4	0.7	1.0
27	offshore wave	0.05	0.5	0.0	0.0	1.0	1.0	1.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.9	0.9	0.2	1.0	0.4	0.9	1.0
28	rooftop PV 1	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.1	1.0	0.8	0.9	0.9	1.0	0.4	0.6	1.0
29	rooftop PV 2	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.1	1.0	0.8	0.9	0.9	1.0	0.4	0.6	1.0

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