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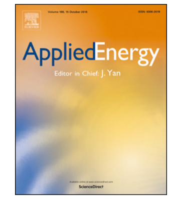

Incorporating ecosystem services into the design of future energy systems

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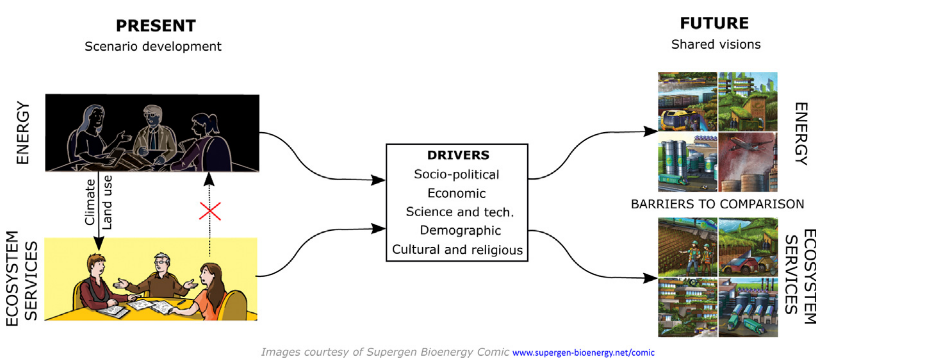
HIGHLIGHTS

- The study is a comparison of influential energy and ecosystem service scenarios.
- Across domains, scenarios exercises explore similar futures.
- There exist barriers to comparisons that limit policy relevance.
- Integration of ecosystem services would inform optimal routes to decarbonisation.

GRAPHICAL ABSTRACT



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ABSTRACT

There is increasing recognition that a whole systems approach is required to inform decisions on future energy options. Based on a qualitative and quantitative analysis of forty influential energy and ecosystem services scenario exercises, we consider how the benefits to society that are derived from the natural environment are integrated within current energy scenarios. The analysis demonstrates a set of common underlying themes across scenario exercises. These include the relative contribution of fossil sources of energy, rates of decarbonisation, the level of international cooperation and globalisation, rate of technological development and deployment, and societies focus on environmental sustainability. Across energy scenario exercises, ecosystem services consideration is primarily limited to climate regulation, food, water resources, and air quality. In contrast, ecosystem services scenarios consider energy systems in a highly aggregated narrative form, with impacts of energy options mediated primarily through climate and land use change. Emerging data and tools offer opportunities for closer integration of energy and ecosystem services scenarios. This can be achieved by incorporating into scenarios exercises both monetary and non-monetary values of ecosystem services, and increasing the spatial representation of both energy systems and ecosystem services. The importance of ecosystem services for human well-being is increasingly recognised in policy at local, national and international scales. Tighter integration of energy and ecosystem service scenarios exercises will allow policy makers to identify pathways consistent with

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international obligations relating to both anthropogenic climate change and the loss and degradation of biodiversity and ecosystem services.

1. Introduction

Anthropogenic climate change and the loss and degradation of biodiversity and ecosystem services are acknowledged as being among the most substantial challenges facing humanity in the 21st century [1]. Scenario exercises are one route to identify and explore such challenges and are increasingly utilized by governments, business and the third sector. They are intended to provide plausible, comprehensive, integrated and consistent descriptions of how the future might unfold [2]. In doing so they provide a tool to engage with stakeholders, build consensus and develop responses to challenges identified [3,4]. Given the energy sectors' contribution to total anthropogenic greenhouse gas emissions, the identification of routes to decarbonisation is central to development of energy policy at global and national scales [5], with scenario exercises widely used to examine the options that are available [4,6]. Similarly, scenario exercises have been used to explore drivers of environmental change and implications for biodiversity and ecosystem services at global [7–9] and national scales [3].

This study is motivated by the increasing recognition of the need for a whole systems approach to energy systems [10] that considers environmental, economic, technical, institutional, political and social dimensions of future options. The study examines the environmental aspect of this whole systems approach by assessing the extent to which influential energy scenario exercises have considered implications for ecosystem services. This study also considers whether there are existing ecosystem service scenario exercises that are compatible with leading energy scenarios exercises.

Throughout ecosystem services is used as a broad term to describe the benefits that humans derive from nature [11,12]. Ecosystem services are typically divided into provisioning services (e.g. food, fibre, fodder), regulating and maintenance services (e.g. water and air quality), and cultural services (e.g. spiritual and intellectual interactions) [13]. Ecosystem services stem from the world's natural capital, representing stocks of physical and biological resources [11]. It is by combining this natural capital with other forms of capital (i.e. through processing [14]) that we generate goods and services such as crops and timber, that directly contribute to human well-being. Ecosystem services can be subjected to valuation in either monetary or non-monetary terms. Incorporating values into the design of policy, such as through scenarios exercises, can exert a considerable influence on our understanding of the desirability of different policy options. For example, Bateman et al. [15] demonstrate that incorporating ecosystem service values, beyond those associated with agricultural markets, into land use planning in the UK would substantially alter decisions about optimal land use. We would highlight that valuation of ecosystem services remains a highly contested area, and it is beyond the scope of this study to detail the debate. Instead we refer reader to discussions such as those presented in [16–18] for background and methodological approaches. Our study also considers biodiversity, as defined by the 1993 Convention of Biological Diversity as the variability among living organisms, given that it is considered to both underpin many ecosystem services and to exist as a good that has value in its own right [19].

The importance of our study is that the international community has obligations to address climate change (e.g. the Paris Agreement), and the loss of biodiversity and ecosystem services (e.g. Aichi Biodiversity Targets [20]). With the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), a body with a similar remit to the Intergovernmental Panel on Climate Change (IPCC), the importance of biodiversity and ecosystem services will move up the policy agenda. We would argue that this will have substantial implications for energy scenario exercises. A review of the history of influential (that is scenarios that have shaped policy) energy scenario exercises [10] demonstrates a changing focus through time in response to international agreements and concerns. In the 1970s and 1980s scenario exercises addressed questions around energy security, primarily taken to mean a stable supply of affordable oil [21]. The Chernobyl accident in 1986 saw scenarios emerge that considered an end to nuclear energy [10]. The late 1980s and early 1990s saw a focus on renewable energy to address nitrogen oxide and sulphur oxides [10]. Since the 1992 UN Framework Convention on Climate Change and the 1997 Kyoto protocol, a primary focus of energy scenario exercises has been identification of routes to address climate change [10]. Indeed, one could draw parallels between the history of scenario exercises and the evolving definition of energy security. Four decades ago energy security was focused on security of supply [21]. From the 1980s this definition has evolved to the current form that recognises "availability, affordability, technological development, sustainability and regulation" as important factors that determine energy security [22].

As evidence of the negative implications for human wellbeing and the economy associated with the loss of biodiversity and ecosystem services is presented to governments, we argue that the environmental implications of energy pathways beyond climate change will become increasing important in shaping energy policy. For this reason those groups involved in the development of energy scenarios must begin to incorporate ecosystem services within their work. This study represents an initial step in this process. We present for the first time a comparison of scenarios produced by practitioners working in the energy and the ecosystem service domains. We compare the scope, methodology, key drivers and implications of 40 individual energy and ecosystem services scenario exercises. A subset of 10 scenario exercises are quantitatively analysed, and a typology of scenarios developed to describe correspondence across the energy and ecosystem service domains. We consider the implications of our findings from the perspective of those involved in the development and use of energy scenarios to inform policy.

2. Material and methods

2.1. Selection of scenarios

Given the number of scenario exercises that exist, the study focussed on two spatial scales, global and UK. At the global scale, the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) represent two organisation with a common goal of providing independent scientific advice to support development of multilateral environmental agreements [23]. Decisions emerging from COP21 (Paris), the Aichi Biodiversity Targets [20], and work such as the Millennium Ecosystem Service Assessment [12] indicate the relevance of considering scenario exercises conducted at this scale. At the national scale, the UK has been a leader in establishing a legally binding set of carbon budgets [24], and in the integration of ecosystem services within policy, informed by exercises such as the UK National Ecosystem Assessment [25]. With reference to energy scenarios, as an example of such integration the UK Government's Climate Change Act [26] and Carbon Plan [27] consider policy options that addresses climate change should be identified that appropriately recognise the value of nature [27].

Energy scenarios selected for the current study were those produced and used by key organisations in policy, strategy and research i.e. by bodies with some recognised responsibility and authority [28]. A number of recent reviews of UK and global energy scenarios have been carried out by the UK Energy Research Centre (UKERC) and others [10,29–31], therefore it was not necessary to repeat such an exercise. From these reviews, analysis was conducted on; (i) scenarios that have been used to inform UK and global policy debates and decision-making about future energy systems; (ii) diversity, so that scenarios from government (including government agencies), industry, academic and the third sector were included; (iii) for cases where organisation produce annual or regular scenarios, only the most recent ones as of May 2015 were included unless previous versions differ substantially in scope.

As no previous work on ecosystem service scenarios had been conducted within UKERC, a standard Rapid Evidence Assessment Protocol [32] was employed to identify candidate scenario exercises. Keyword searches of the Thompson Reuters Web of Knowledge and Elsevier Science Direct databases were performed using Boolean combinations of terms relevant to ecosystem services, as defined under the Common International Classification of Ecosystem Services (CICES) version 4 [33] (see Supplementary Online Material). This initial search returned 45,046 references. These were firstly filtered for relevance based on their title. The full text of retained search results was retrieved, and a second stage of filtering conducted based on the abstract. During this second filtering stage the sole criterion for retention was that the study considered ecosystem service scenarios. We considered studies to be relevant if they encompassed individual or multiple services. Scenario studies that considered other environmental factors of relevance to the provision of ecosystem services, for example scenarios of future land use change or biodiversity loss, were also retained. The full text of the remaining 338 references was filtered based on the same criteria as used in the review of abstracts, resulting in a pool of 74 candidate studies. Cross referencing these studies to identify duplication in underlying scenarios resulted in a list of 34 potential scenario studies of relevance at the UK and global scale. Of these we were unable to locate documentation in 12 cases. The remaining candidate scenario exercises were compared against a number of existing reviews [3,7,34,35] conducted by domain experts. Final scenario exercises were selected for analysis (see Supplementary Online Material) that meet the same criteria of influence and diversity used to select energy scenarios (see i – iii previous paragraph). We stress that with the proliferation of energy and ecosystem service scenario exercises over the last few decades the aim of this study was not to analyse a comprehensive set of all published studies, but rather a representative set of those that can be considered authoritative and mainstream.

2.2. Analysis of relationship between scenarios

Across the 40 energy and ecosystem service scenarios exercises identified, factors such as differences in time horizon and lack of quantification of the energy system resulted in 10 scenario exercises being selected for subsequent analysis. Together these 10 scenario exercises described 38 individual scenarios out to 2050. For each, we extracted the percentage contribution of coal, gas, oil, biomass and other (non-fossil sources) to the energy mix in 2050. A review of the narratives of each individual scenario was then carried out to capture the emphasis on decarbonisation (scored low/high), the availability of carbon capture and storage technology (scored yes/no), the role of energy efficiency (low/high) and worldview (national/global).

The relationship between energy and ecosystem service scenarios was quantitatively examined using a self-organizing map (SOM) [36]. This technique maps high-dimensional data onto a two-dimensional regular grid of nodes preserving the topological and metric relationship of the original data [37,38]. In the current study the SOM grid provides a visualisation with which to understand the relationships between scenarios [36]. In the first stage of the analysis an on-line (stochastic) relational version of the SOM algorithm [37,38], as implemented in the SOMbrero package [39] of R was used. The relationship between each of the 38 individual scenarios was represented within a dissimilarity matrix calculated using Gower's coefficient [40], expressed as a dissimilarity. The use of Gower's coefficient accounts for the mix of data types. The SOM was trained using 50,000 iterations, and representation of the relationships between scenarios assessed using two measures of quality. Firstly, the topographic error represents that average frequency in which a scenario is assigned to a neighbouring node within the grid during training, and not the grid node to which it is finally assigned. Secondly, the quantization error represents the average distance of observations to the winning grid node to which the SOM algorithm assigns them [39]. In our analysis low values for the topographic error (0.02) and quantization error (0.04) indicate good representation of the relationship between scenarios within the SOM.

The second stage of the analysis sought to further group scenarios to identify emergent themes. To achieve this, hierarchical cluster analysis was performed on the dissimilarity matrix describing the relationship between individual scenarios. This returned a dendrogram tree with each branch representing a grid node within the SOM (Fig. 1A). The overall shape of this dendrogram tree represents the relationship between grid nodes. To achieve grouping of similar scenarios, the dendrogram tree was cut to derive a set of "super-clusters" referred to subsequently as scenario families. The point at which the dendrogram

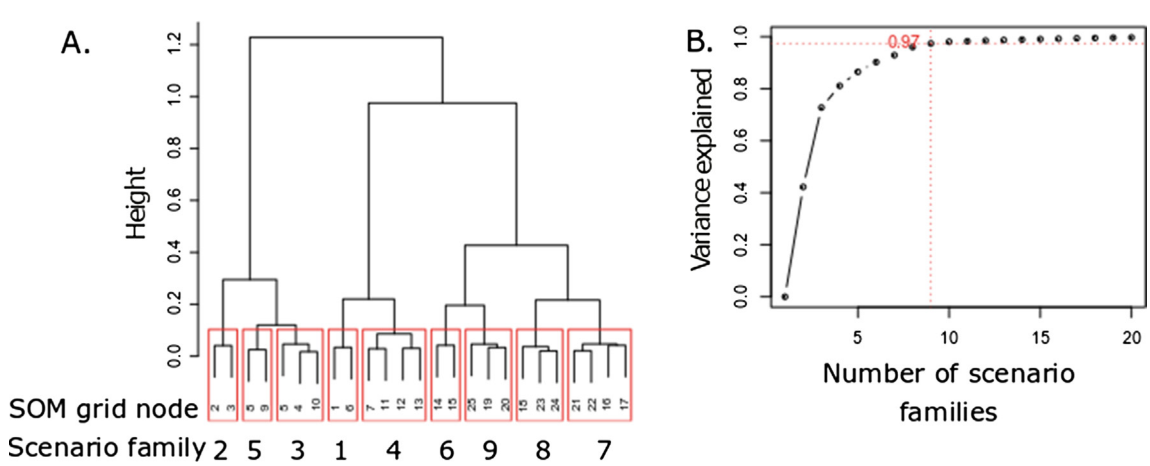

Fig. 1. Relationship between SOM grid nodes and grouping into scenario families. This is represented as a dendrogram tree (A) derived from the dissimilarity matrix describing the relationship between SOM grid nodes 1–25. Red boxes indicate grouping of SOM grid nodes into scenario families. These scenario families were derived using the elbow criterion (B) that cut the dendrogram tree to achieve a balance between the number of superclusters and the variance that is explained. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tree was cut, and hence the number of scenario families that are derived was based on the elbow criterion implemented in the GMD package of R [41] (Fig. 1B).

In the final stage of the SOM analysis, the quantitative criteria used to establish the number of scenario families within the SOM allowed further aggregation to represent the relationship between families based on the overall shape of the dendrogram tree. Exploiting this property it was possible to develop a typology of four themes that encompass the nine scenario families and 38 individual scenarios (Table 2).

3. Results

3.1. Overview of scenario exercises

In total it was possible to access the text of 18 scenario exercises of relevance to energy systems. These are summarised in aggregate within Table 1, with individual summaries provided for each scenario exercise in Supplementary Tables S6 and S7. Exploration of changes in the energy system that are consistent with greenhouse gas emission reduction targets was used to define the scope of 11 of the 18 energy scenario exercises. These scenarios explore the associated technological and infrastructure requirements, business strategies, policy frameworks, and social and economic implications of changes in the energy sector necessary to meet emission reduction targets (Table S6). These scenario exercises also commonly present a counterfactual scenario where emission reduction targets are not met. The scope of the remaining seven exercises was defined by the commissioning bodies in relation to energy security. As discussed in the introduction, the current definition of energy security can be taken to consider factors relating to availability, affordability, technological development, sustainability and regulation [22]. Therefore, reductions in greenhouse gas emissions are considered within these scenario exercises within the context of sustainability, but this was not the primary scope of the exercise. Across 17 of the 18 exercises, quantitative modelling was used to inform scenario development. There is some limited evidence that environmental obligations beyond emission reduction targets are integrated into the development of scenarios (Table S7). Across the 18 exercises considered, seven explicitly address environmental implications primarily relating to the food-energy-water nexus and air quality [24,42–44].

In total it was possible to access the text of 22 scenario exercises of relevance to ecosystem services. As with the energy scenarios, these ecosystem services scenario exercises are summarised in aggregate within Table 1, and a more detailed individual summary is provided in Supplementary Tables S8 and S9. Ecosystem service scenario exercises vary in scope from those that examine a single ecosystem service [8,45] to those that consider multiple services [3,12,46] (Table S8). Biodiversity loss, climate change, water and food security emerge as core focal areas, together with land-use change that can be linked to alteration in the provision of ecosystem services through multiple mechanisms [1,12,47]. Reflecting a pattern in the broader ecosystem services literature, cultural services are rarely considered featuring only in scenarios specifically designed to take a holistic view across ecosystem service categories [3,12,46]. Fifteen of the ecosystem service scenarios exercises explicitly consider energy pathways, six define their own energy pathways, with the remaining nine exercises using energy pathways derived from independent climate and energy studies that consider a limited number of environmental factors beyond greenhouse gas emissions. For example, a number of ecosystem service scenario exercises draw on IPCC Special Report Emissions Scenarios (SRES) [2]. These SRES are constructed based on consideration of environmental policies relating to air quality and agricultural production, primarily in terms of greenhouse gas emissions. Across the 15 ecosystem service scenario exercises, energy systems are commonly represented in a highly aggregated form, typically as oil, coal, gas, biomass and non-fossil sources [48,49]. Energy systems may also be represented as global trends as opposed to considering country or region specifics [3].

3.2. Relationship between energy and ecosystem services scenarios

As stated in the methods, of the 40 energy and ecosystem service scenario exercises identified and described in Section 3.1. it was only possible to extract empirical data from 10 exercises representing 38 individual scenarios. The relationship between these 38 individual scenarios is visualised within a SOM grid (Fig. 2) with those scenarios that are closest together on the grid considered to be most similar [50]. To illustrate, the grid node labelled nine in Fig. 2 contains scenarios that correspond to a "reference" state. Specifically, these are from

Table 1
Summary of scenario exercises used in this review. Percentage values refer to the number of studies that had each of the characteristics identified. Those in italics were quantitatively analysed using a self-organising map to examine the relationship between individual scenarios.

Ecosystem service scenario exercises	Exercise characteristics
Global environment outlook 5 [1]; *Global environment outlook 4* [48]; Environmental Outlook [92]; Business in the world of water [93]; *Global scenarios group* [94]; *Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM)* [49]; EURuralis [95]; *Millennium Ecosystem Assessment* [12]; Foresight Food and Farming [96]; Global Europe 2050 [97]; CLIMSAVE [98]; *ALARM* [8]; Natural England Environment in 2060 [46]; Looking ahead to 2050 [99]; Agrimonde [100]; PRELUDE [101]; UKCIP02 [102]; *UK National Ecosystem Assessment* [3]; Global Biodiversity Outlook 3 [45]; AFMEC (Alternative future scenarios for marine systems) [103]; Net benefits [103]; Foresight Land Use Futures [47]	**Funder:** Government (including intergovernmental) 95.5%, Business 4.5%, Academic 4.5%, NGO 13.6% **Target audience:** Government 81.8%, Business 100%, NGO 95.5%, Public 31.8% **Approach:** Quantitative 81.8%, Qualitative 86.4% **RANGE ACROSS SCENARIOS** **Emission by 2050:** 4.7 to 80.83 GtC-eq yr **Decarbonisation as focus:** 55.3% **GGR removal technologies:** 60.6% **Energy efficiency as measure:** 66.7% **Globalised world:** 63.2%
Energy scenario exercises	Exercise characteristics
UKERC Global Energy Scenarios [51]; Transition Pathways & Realising Transition Pathways [104]; Foresight Scenarios: Powering our Lives [105]; *CLUES* [106]; Infrastructure Transitions Research Consortium [107]; *Energy 2050* [51]; Transition Pathways for Hydrogen [108]; *Shell New Lens Scenarios* [42]; National Grid Future Energy Scenarios [109]; The CCC 5th Carbon Budget [24]; CCC 4th Carbon Budget (2013 revision) [44]; Carbon Plan [27]; Project Discovery [110]; The Economics of Climate Change Policy in the UK [43]; *World Energy Scenarios* [111]; World Energy Outlook 2015 [112]; The outlook for energy, a view to 2040 [113]; ETI Scenarios [114]	**Funder**: Government (including intergovernmental) 38.8%, Business 33.3%, Academic 27.7%, NGO 5.5% **Target audience**: Government 50%, Business 44.4%, NGO 0%, Public 11.1% **Approach**: Quantitative 94.4%, Qualitative 44.4% **RANGE ACROSS SCENARIOS** **Emission by 2050:** 19 to 80.44 GtC-eq yr **Decarbonisation as focus:** 68.2% **GGR removal technologies:** 70.0% **Energy efficiency as measure:** 84.1% **Globalised world:** 84.6%

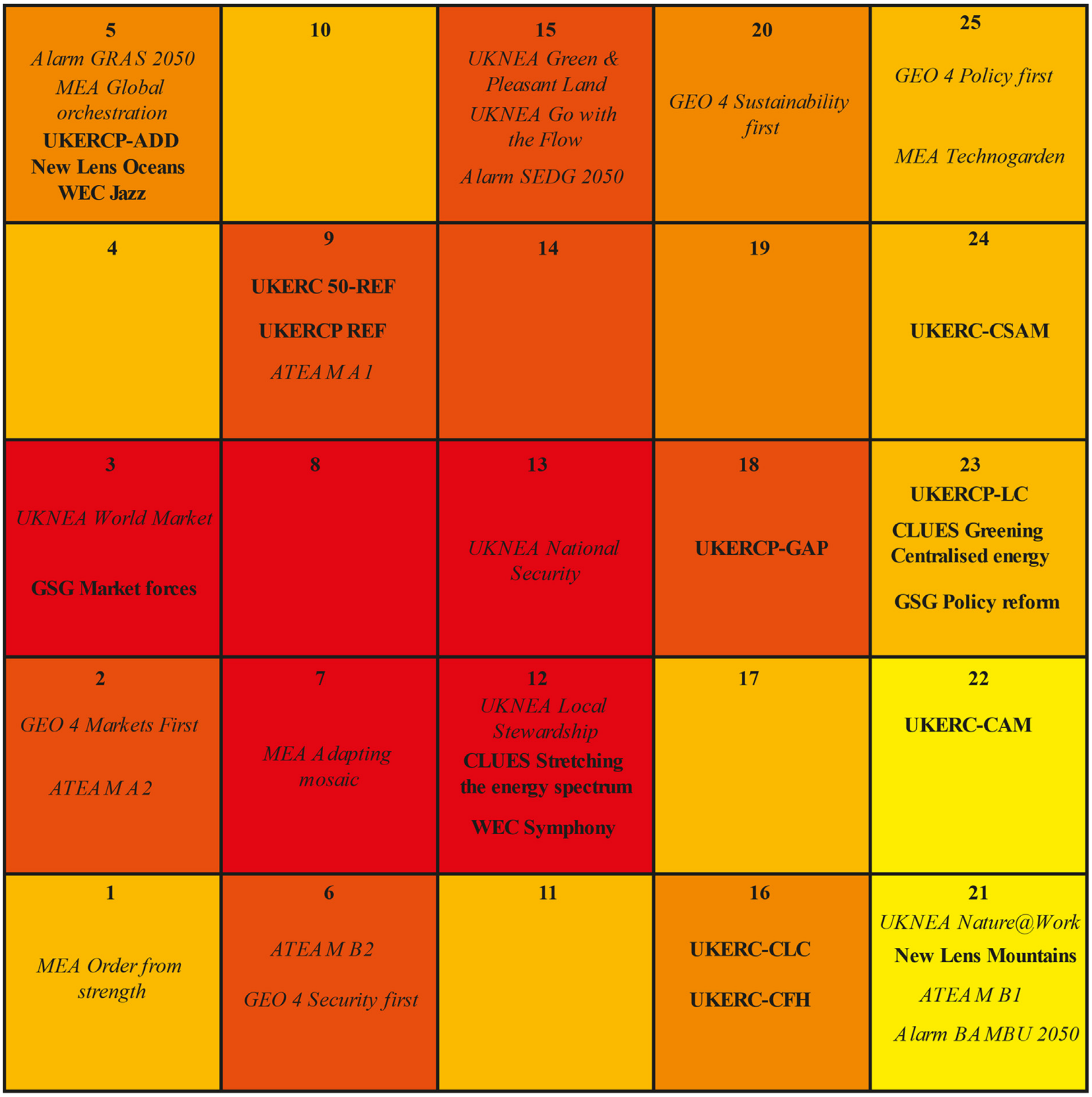

Fig. 2. Self-organising map (SOM) representing the relationship between individual energy and ecosystem services scenarios. Individual grid cells in the diagram represent a node in the SOM (numbered 1–25) to which the algorithm assigns a scenario/s based on their similarity to others. Colour gradient from yellow to red indicates increasing distance between prototypes and their neighbours. Energy scenarios are indicated in bold text and ecosystem services scenarios in italics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

UKERC scenario exercises conducted in 2008 and 2013 [51], and the Advanced Terrestrial Ecosystem Analysis and Modelling [49] A1 scenario. These scenarios can be broadly summarised as being those where fossil sources of energy remain a central component of the energy mix. This is consistent with the use of a reference narratives within scenarios exercises to represent the world in 2050 based on current conditions, policy frameworks, and/or the trajectory of change under business as usual or as might be usual assumptions. Such a reference scenario provides a comparative state for other scenarios that, for example, explore options for decarbonisation or energy security.

In the second stage of the SOM analysis, quantitative criteria were used to group the 25 SOM grid nodes into nine scenario families [39] (Fig. 3). For example, grid node 2 and 3 (Fig. 2) were grouped into a single family containing scenarios where economic growth is prioritised above climate and broader environmental considerations. For each of the nine families, a review of the storylines associated with the individual scenarios was used to develop an overarching narrative that captures central idea explored by the scenario family (Table 2). The relative contribution of different sources of energy within each scenario family is summarised in Fig. 4. To aid interpretation, the shape of the dendrogram tree (Fig. 1A) was used to group these nine scenarios families into four broad themes (Table 2).

4. Discussion

4.1. Alignment of scenario exercises

The distribution of scenarios with the SOM indicates that the energy and ecosystem service exercises considered in the current study are exploring comparable visions of the future out to 2050. This is quantitatively demonstrated by mixing of individual energy and ecosystem services scenarios across grid nodes in the SOM (Fig. 2). When aggregated into scenario families, seven of the nine contain individual scenarios from both energy and ecosystem service domains (Fig. 3).

Fig. 3. Relationship between energy and ecosystem services scenarios represented as nine scenario families. Grid squares of the same colour belong to the same family. Energy scenarios are indicated in bold text and ecosystem services scenarios in italics.

This further demonstrates that the scenario exercises are considering comparable visions of the future out to 2050. The exception to this is scenario families 6 and 9, that were grouped under the theme of "sustainable development in reformed markets" (Table 2). These scenario families contain only individual scenarios from the ecosystem service domain. Reading the narratives associated with the scenarios indicates that they are closely aligned to scenario families 7 and 8, grouped under the theme of decarbonisation (Table 2; families 7 and 8). Separation is driven by the assumption of higher future reliance on biomass, limited availability of carbon capture and storage technology, and a greater emphasis on the role of gas (Fig. 4) in scenarios families 6 and 9.

The comparability of scenarios across the energy and ecosystem services domains is further supported by a review of the associated storylines (Table 2). This identifies common narrative threads including; (i) the relative contribution of fossil sources of energy (Fig. 4); (ii) the drive towards decarbonisation; (iii) the level of international cooperation and globalisation; (iv) the degree of technological development and deployment, particularly in relation to increased energy efficiency and the availability of low carbon technologies and; (v) the degree to which governments and individuals are concerned with environmental sustainability.

In broad terms, the distribution of individual scenarios in the SOM (Figs. 2 and 3) and the shared theme (Table 2), reflect a common methodological approach across scenario exercises. When conducting scenario exercises practitioners will often use dichotomous axes, for example to consider the emphasis on decarbonisation and degree of globalisation. Of the scenarios analysed in the current study a number used more complex approaches, such as morphological analysis (e.g. [3]). These still produced individual scenarios that are consistent with those produced in other studies that took a simpler approach. The finding of shared storylines across scenario exercises agrees with previous work by van Vuuren et al. [7], who identified six scenario families through a qualitative reading of global environmental assessment studies. As with the scenario families that we derive, scenario families presented in Vuuren et al. [7] are differentiated through the rate of economic development, the level of market reform, the emphasis on

Table 2
Themes and scenario families derived from quantitative analysis of 38 individual energy and ecosystem services scenarios.

Decarbonisation
Scenario family 7: Scenarios within this scenario family represent varied approaches to tackling recognised environmental problems. A range of factors from changes in economic growth to technological solutions lead to reduction of greenhouse gas emissions. **Scenario family 8:** Scenarios within this scenario family envisage a world of international cooperation and a narrative based on routes to decarbonisation and to address environmental problems. This is achieved through technological and policy changes. For the energy sector there is considerable uncertainty about the mix of technologies that will emerge, although there will be focus on non-fossil sources of energy as well as greater end-use energy efficiency.
Sustainable development and reformed markets
Scenario family 6: In these scenarios there is a focus on expansion of global markets in conjunction with an increase in sustainability. The environment is often managed with a view to realising societal benefits such that there may be some trade-offs between economic and environmental goals. Although there may be a varying pace of technological development, it is often geared towards improving sustainability and as such there is considerable development in renewable energy. **Scenario family 9:** Scenarios within this scenario family have an environmental focus coupled with economic growth. There is promotion of emerging technologies and a high level of international cooperation to tackle global problems. This leads to the deployment of energy systems with a focus on efficiency and reduction in environmental impact.
Regional priorities
Scenario family 1: These scenarios consider decreasing globalisation at least initially, providing impetus for nations to manage and exploit local resources. This benefits a number of ecosystem services where economic imperatives provide incentive to invest in sustainable use. This local focus means that energy policy is based on efficiency and local availability of energy resources. This leads some countries to increase their use of fossil resources and others to diversify their supply toward renewables. **Scenario family 4:** A world of increasing regionalisation, although with a global outlook that allows convergence of some policy objectives between countries. Use of national resources is prioritised leading to a move towards sustainable resource management for those services that society values the most. Pressures on global energy resources leads to energy policy focused on exploitation of local resources, with technological solutions used to address associated environmental problems.
Economic growth in conventional markets
Scenario family 2: Common features of scenarios in this scenario family are an increasing role of business in shaping society and a belief that markets will be able to tackle emerging environmental problems. Although there may be increasing free trade across the world, resource scarcity may drive national and local difference in energy use and lead to protectionism. A common theme is increased environmental degradation as profits are maximised. **Scenario family 3:** These scenarios represent a globalized world where economic growth is seen as a key objective. There is abandonment or weakening of much environmental legislation but where environmental damage is seen to have a substantial negative effect on economic growth, restoration and preventative measures are taken. As international consensus on the social and economic impact of climate change is reached the continued use of conventional and unconventional fossil fuels is coupled with some low carbon technologies such as carbon capture and storage. **Scenario family 5:** Scenarios here represent a globalized world of fossil fuel use that might be thought to be closest to the current trajectory that we are on, taking into account current and likely future goals and legislation. Consideration of climate change by governments and businesses is significant, but it is not until the impacts of climate change become obvious that serious attention is given to what might be done. At this point adaptation becomes much more important as the world is already committed to significant climate change.

sustainability, and the degree of globalisation. Differences between our scenarios families and those in van Vuuren et al. [7] are attributable to (i) the inclusion of energy scenarios and details of the energy system in the current study (as opposed to just environmental scenarios in [7]); (ii) the influence of a greater number of individual scenarios in the current study and; (iii) methodologically to the use of quantitative criteria to cluster individual scenarios into families within the current study.

The alignment of scenarios within the SOM also reflects a common underlying set of assumptions, with quantitative aspects of both energy and ecosystem service scenario exercises based on drivers that fall into five categories [3,12]; socio-political; economic; science and technology; cultural and religious; demographic. Within each of these categories scenario development may draw on a shared pool of drivers. For example, where population projections are used in models they are likely derived from the work of demographers in a few institutions that project a range of between 7 and 11 billion people in 2050 [12]. A review of environmental integrated assessment models by Harfoot [52] suggests that projected changes in the provision of ecosystem services over coming decades could influence these underlying modelling assumptions. To illustrate, a number of recent energy scenarios have considered the influence that changes in water resource availability associated with climate change will have on energy pathways [53] through imposition of physical limits on the use of certain technologies (e.g. by insufficient cooling water being available). In such examples, limits on water would be expected to also influence irrigated agriculture [54], and coupled with other factors such as changes in soil quality [55] under certain climate trajectories could lead to substantial regional impacts on food production. This in turn will influence the demographic and economic variables that are used as inputs to energy system models, and so may undermine internal modelling assumptions used in the development of energy scenarios.

4.2. Representation of the energy system

In collating data for analysis it became apparent that energy and ecosystem service scenario exercises represent the energy system at differing levels of technological detail. At the level of individual scenarios those developed within the energy domain were often richer with up to 19 individual energy supply technologies considered in some exercises. This compares with ecosystem service scenario exercises that consider a maximum of 9 supply technologies. The reason for this difference is ultimately down to the aims of the commissioning body. As discussed, decarbonisation and energy security define the scope of all the energy scenario exercises considered. As such representation of technological options will be desirable to address the questions posed by the commissioning body. This contrasts with ecosystem service scenarios where the implications of energy systems are predominantly mediated through projected impacts on climate or land-use [1,9]. In ecosystem service scenario exercises, description of the energy system may simply focus on the balance of fossil to non-fossil sources of energy, and the use of land for production of biomass as these factors will be the primary drivers of impacts on ecosystem services.

From the perspective of energy scenario development, a range of plausible energy technologies and pathways consistent with narratives of decarbonisation and energy security are available. There may be substantial advantages in incorporating consideration of ecosystem services into scenario development. Low carbon sources of energy include a wide portfolio of technologies associated with a diverse and complex array of social, environmental and economic impacts occurring at a range of spatial and temporal scales [56–60]. Taking advantage of the rich technological data available in energy system models and incorporating a broader set of ecosystem service impacts could help differentiate between low carbon sources of energy beyond projected changes in greenhouse gas emissions. Given the dominance of quantitative modelling as a tool in energy scenario exercises it may be that the "optimal" solutions that meet targets within a particular scenario would no longer be optimal if a more diverse set of ecosystem service criteria were included. For example, for a given location consideration of implications for ecosystem services such as water resources, pest and disease control, carbon sequestration, and biodiversity could differentiate between energy technologies such as utility-scale solar energy [61] and wind arrays [62] beyond differences in carbon emissions alone [63,64].

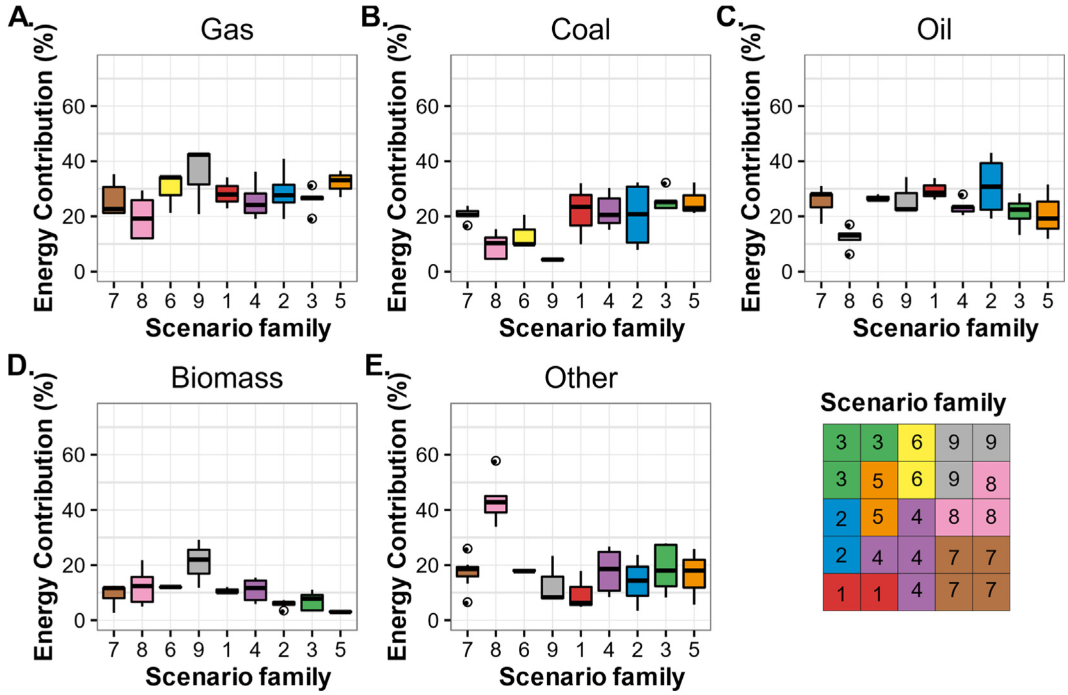

Fig. 4. Boxplots representing the per cent contribution of (A) gas, (B) coal, (C) oil, (D) biomass and (E) other (non-fossil sources) to the energy mix in 2050 for each scenario family. Plots are ordered in line with the themes in Table 2; Decarbonisation (Scenario family 7–8); Sustainable development and reformed market (Scenario family 6,9); Regional Priorities (Scenario family 1,4); Economic growth in conventional markets (Scenario family 2,3,5).

4.3. Operationalizing ecosystem services in energy scenario exercises

Integration of ecosystem services into energy system models might readily be achieved within existing scenario exercises and using existing quantitative tools. Scenarios such as those that fall within the "economic growth in conventional markets" theme (see Table 2), could incorporate monetary value of those ecosystem services for which markets exist (e.g. provisioning services such as food, fibre, etc.) into their modelling framework. This would allow comparison of the broader economic implications of different energy strategies and may help differentiate between energy technologies.

A more substantial methodological challenge for such integration is associated with scenarios such as those highlighted in the "sustainable development in reformed markets" theme (Table 2). Here identifying desirable energy technologies would be contingent on prioritisation of ecosystem services that exists outside traditional markets or have non-use value [65]. For such non-market ecosystem services, initiatives such as The Economics of Ecosystems and Biodiversity (TEEB) [11] and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) tool [66] have begun to address this challenge by developing approaches to valuation and representation of ecosystem services that can be incorporated into scenario exercises.

For those services with non-market values, such as biodiversity, another possible route to address the challenge of integration is provided by energy system models that already consider greenhouse gas emissions as an exogenous constraint on energy pathways [30]. Future energy system models could incorporate similar exogenous constraints relating to biodiversity and other non-use ecosystem services designed to be consistent with scenario narratives. Ultimately, as demonstrated by Bateman et al. [15] in the context of land use, it will be necessary to incorporate a suite of ecosystem services with both market and non-market values into the development of energy scenarios.

Beyond issues of valuation, integration of ecosystem services into energy scenario exercises is also challenging due to the need to address spatial context in relation to ecosystem services provision. Energy systems models have historically been either aspatial or highly spatially aggregated to global, regional (e.g. Europe) or country scales. Such spatial aggregation will limit understanding of the implication of different energy options for the provision of many ecosystem services. For example Hertwich et al. [67] utilises a Life Cycle Assessment Approach to compare fossil and non-fossil sources of energy across two scenarios. Comparisons were based on metrics relating to greenhouse gas emissions, water resources, air quality and land use. While the authors conclude that consideration of these multiple metrics would favour a future energy scenario more heavily reliant on non-fossil sources of energy, the analysis is at a highly aggregated global scale. At local scales the use of a Life Cycle Assessment and more complex environmental modelling techniques will be more informative for energy policy. For example Kostevšek et al. [68] describes the development of an "ecosystem model" of energy systems with a strong emphasis on environmental impacts. The authors consider that their model may be most applicable for local decision making, where environmental indicators based on an LCA approach will resonate. This is important as ecosystem services are known to exhibit complex spatial patterns and be highly context dependent [17,65]. For example, while certain energy technologies might have a high demand for water resources, it is by putting such demand within the context of water security that we can understand the desirability of specific energy pathways [69]. If the technology were to be deployed in an area with high water security, then the desirability of the specific energy technology should be judged by other criteria for example implications for biodiversity, climate, or recreational value. Such an approach is demonstrated, again at local scale, by Martinez-Hernandez et al. [70] who were able to incorporate a detailed set of environmental indicators into consideration of the water-food-energy nexus. In doing so the authors were able to inform re-development of an ecotown in the UK in a way that considered interdependencies across the techno-environmental system. Their holistic approach identified pathways that met 100% of electric demand while simultaneously improving the provision of ecosystem services including food and biomass production, and carbon capture.

Current understanding of the spatial distribution of ecosystem services is patchy globally, with good coverage in some regions (e.g. UK;

Europe) and for some services (e.g. crops; water resources) [71]. The emerging emphasis on spatial richness in energy system models (e.g. [72,73]) could address the issue of context by incorporating the distribution of ecosystem services where data is available, and then optimising the energy system to meet targets that are consistent with scenario storylines. Given its land use footprint and our understanding of the impact of agriculture on the environment, work on the relationship between bioenergy and ecosystem services is perhaps at the forefront of exploring such integration [56,73–77]. However, other examples exist such as for wind energy, in terms of its impact on the landscape [62,78–80] and fisheries [81].

We note that our understanding of the relationship between energy system and ecosystem services often relates to the operational phase of the energy technology. Recent reviews of the implications of energy systems for ecosystem services [82–86] suggest there is a lack of evidence to understand the implications of many forms of energy for biodiversity and ecosystem services, particularly at the commissioning and decommissioning stages of the life cycle. Given the multidecadal timelines over which scenario exercises are carried out, improving our understanding at these phases is critical.

Finally, scenario analysis and the modelling that supports it must recognise the increasing interconnectedness of the world, such that decisions made at local and national scales will have international implications. This has been demonstrated in the context of greenhouse gas emissions where the last few decades have seen a transfer of net emissions from developed (consumer) to less developed (producer) countries [87]. Similarly findings have also been reported for land use [88] and biodiversity [89]. Examples relating to water resources and energy [69,90] demonstrate that input-output analysis and associated techniques can help to quantify the international implications of local and national energy choices. Integrating such techniques into scenario development, and including ecosystem service indicators, would further inform the desirability of specific energy pathways.

5. Conclusion

The concept that ecosystem services are essential for human well-being is increasingly accepted and embedded in policy at local, national and global scales [16,91]. As such, exploring the implications of energy systems for ecosystem services, and the way in which ecosystem services could inform decisions about the desirability of different energy options, will have strong resonance with decision makers. We would argue that the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services will mean that government are increasingly likely to consider the implications of energy systems for ecosystem services, and that the energy scenarios community must be ready to address this challenge.

The analysis of influential energy and ecosystem service scenarios exercises presented here indicates that practitioners working across energy and ecosystem service domains are considering a comparable set of futures. This represent a good starting point to consider methods to integrate ecosystem services thinking into energy scenario exercises. However, qualitative and quantitative analysis of scenario exercises across domains presented here indicates that energy scenarios exercises; (i) consider only a limited number of ecosystem services, primarily relating to food production, water resources and climate regulation; (ii) do not consider possible future changes in the natural environment and energy systems and the implications that this could have for energy modelling assumptions; (iii) are highly spatially aggregated limiting understanding of implications for ecosystem services provision which is often highly context dependent. Such barriers limit the ability of energy scenario exercises to identify future challenges and formulate responses to pressure on ecosystem services associated with transition to a low carbon economy.

The implication of these conclusions is that it is not possible to simply bring together existing, albeit compatible, energy and environmental scenarios exercises. This leads to implications for research and policy. For research, further work is required to better reflect environmental issues in energy scenario narratives and to quantify (though not necessarily in monetary terms) environmental and ecosystem service impacts of, and influence on, energy system scenarios. For policy, a holistic consideration of the influence of energy pathways on ecosystem services that exist both within and outside markets could help to identify pathways that deliver routes to decarbonisation while simultaneously maximising the benefits that people derive from nature.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.04.022.

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