Energy Policy 92 (2016) 181–189

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Bridging the gap between energy and the environment

Robert A. Holland [a], Kate Scott [b], Emma D. Hinton [a], Melanie C. Austen [c], John Barrett [b], Nicola Beaumont [c], Tina Blaber-Wegg [d], Gareth Brown [e], Eleanor Carter-Silk [c,d], Pierre Cazenave [c], Felix Eigenbrod [a], Kevin Hiscock [d], Tara Hooper [c], Andrew Lovett [d], Eleni Papathanasopoulou [c], Pete Smith [f], Amy Thomas [d], Rob Tickner [d], Ricardo Torres [c], Gail Taylor [a,*]

[a] *Centre for Biological Sciences, University of Southampton, Life Sciences Building (B85), Highfield Campus, Southampton SO17 1BJ, UK*
[b] *School of Earth and Environment, The University of Leeds, Leeds LS2 9JT, UK*
[c] *Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK*
[d] *School of Environmental Science, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK*
[e] *Department of Life Sciences, Imperial College London, Silwood Park Campus, Ascot SL5 7PY, UK*
[f] *Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU Scotland, UK*

HIGHLIGHTS

- Obligations for climate, biodiversity and ecosystem services must be aligned.
- Ecosystem service based assessments of energy systems can inform energy policy.
- Assessment to incorporate life cycle stages across spatial and temporal scales.
- Implications for ecosystem services differentiate between energy options.
- Pathways to decarbonisation should be identified based on such a holistic assessment.

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
20 January 2016
Accepted 25 January 2016

Keywords:
Ecosystem services
Energy
Sustainability
Life-cycle
MRIO

ABSTRACT

Meeting the world's energy demand is a major challenge for society over the coming century. To identify the most sustainable energy pathways to meet this demand, analysis of energy systems on which policy is based must move beyond the current primary focus on carbon to include a broad range of ecosystem services on which human well-being depends. Incorporation of a broad set of ecosystem services into the design of energy policy will differentiates between energy technology options to identify policy options that reconcile national and international obligations to address climate change and the loss of biodiversity and ecosystem services. In this paper we consider our current understanding of the implications of energy systems for ecosystem services and identify key elements of an assessment. Analysis must consider the full life cycle of energy systems, the territorial and international footprint, use a consistent ecosystem service framework that incorporates the value of both market and non-market goods, and consider the spatial and temporal dynamics of both the energy and environmental system. While significant methodological challenges exist, the approach we detail can provide the holistic view of energy and ecosystem services interactions required to inform the future of global energy policy.

1. Introduction

Meeting the world's energy demand over the coming century represents a major challenge for society (Foresight, 2011), increased further by the need to do so while simultaneously minimising the environmental burdens associated with energy production and use (Naik et al., 2010). Due to the contribution of energy systems to greenhouse gas emissions (Edenhofer et al., 2014), a primary driver of energy policy is identification of decarbonisation strategies, as reflected in international and regional policy (European Union, 2009; UK Parliament, 2008; UNFCCC,

* Corresponding author.
E-mail address: G.Taylor@soton.ac.uk (G. Taylor).

http://dx.doi.org/10.1016/j.enpol.2016.01.037

1998).

A range of technological and policy options for decarbonisation exist (Chu and Majumdar, 2012; Committee on Climate Change, 2013; Ekins et al., 2013) that broadly fall into five categories: (1) use of mature technologies as a bridge in the short to medium term; (2) increased energy efficiency across society; (3) increased reliance on renewable technologies; (4) refinement of existing energy systems; and (5) deployment of new technologies such as carbon dioxide capture and storage. To achieve energy decarbonisation targets such options need to be implemented in some combination rather than singly, resulting in substantial variation in the range of possible future energy pathways, as demonstrated through numerous scenario exercises (e.g. Ekins et al., 2013; International Energy Agency, 2012). While each option may contribute to decarbonising energy, each is also associated with a diverse and complex array of social, environmental and economic impacts occurring at a range of spatial and temporal scales (Gasparatos et al., 2011; Hastik et al., 2015; Papathanasopoulou et al., 2015a).

Outside the energy domain, consideration of sustainability at local, national and global scales is increasingly framed in terms of ecosystem services (Daily and Matson, 2008; Gomez-Baggethun and Ruiz-Perez, 2011). Ecosystem services is used throughout as a broad term to refer to the benefits that people derive from nature (Díaz et al., 2015a; Mace et al., 2012). Ecosystem services stem from the world's natural 'capital', which represents the stock of the earth's physical and biological resources (Sukhdev, 2010). When combined with other forms of capital (Goodwin, 2003), this give rise to final ecosystem services such as crops, timber and fresh water that provide goods of value (monetary and non-monetary) and contribute to human quality of life. The fact that ecosystem services are a function of the biophysical environment and the social and economic context in which provision occurs, means they represent an ideal metric to inform energy policy (Bateman et al., 2013; Gasparatos et al., 2011; Hastik et al., 2015; Howard et al., 2013; Ruckelshaus et al., 2013).

The main objective of this paper is to propose how knowledge of the influence of energy systems on ecosystem service provision can be used to inform energy policy. Given the strong parallels that exist with the Intergovernmental Panel on Climate Change (IPCC), we frame our discussion within the context of work being undertaken by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). The IPBES Conceptual Framework provides a theoretical model of the interactions between people and nature, so can help our understanding of the interactions between energy systems and ecosystem services. The framework describes the relationships between the natural world and humanity based on six elements (Fig. 1; Díaz et al., 2015b). Development of energy policy would be based on understanding of (i) anthropogenic assets (e.g. energy infrastructure, energy technology), the (ii) direct (e.g. anthropogenic climate change, pollution) and (iii) indirect (e.g. energy policy, business interests) drivers of pressures on (iv) nature and (v) the benefits that people derives from nature that ultimately influence (vi) human quality of life (roman numerals indicate elements depicted in Fig. 1). The importance of the IPBES Conceptual Framework is that it specifically considers both direct drivers of change (e.g. habitat loss associated a specific energy technology; Fig. 1 element ii) and their underlying cause (e.g. energy policy; Fig. 1 elements i and iii).

Readers are referred to Díaz et al. (2015a, 2015b) for a detailed

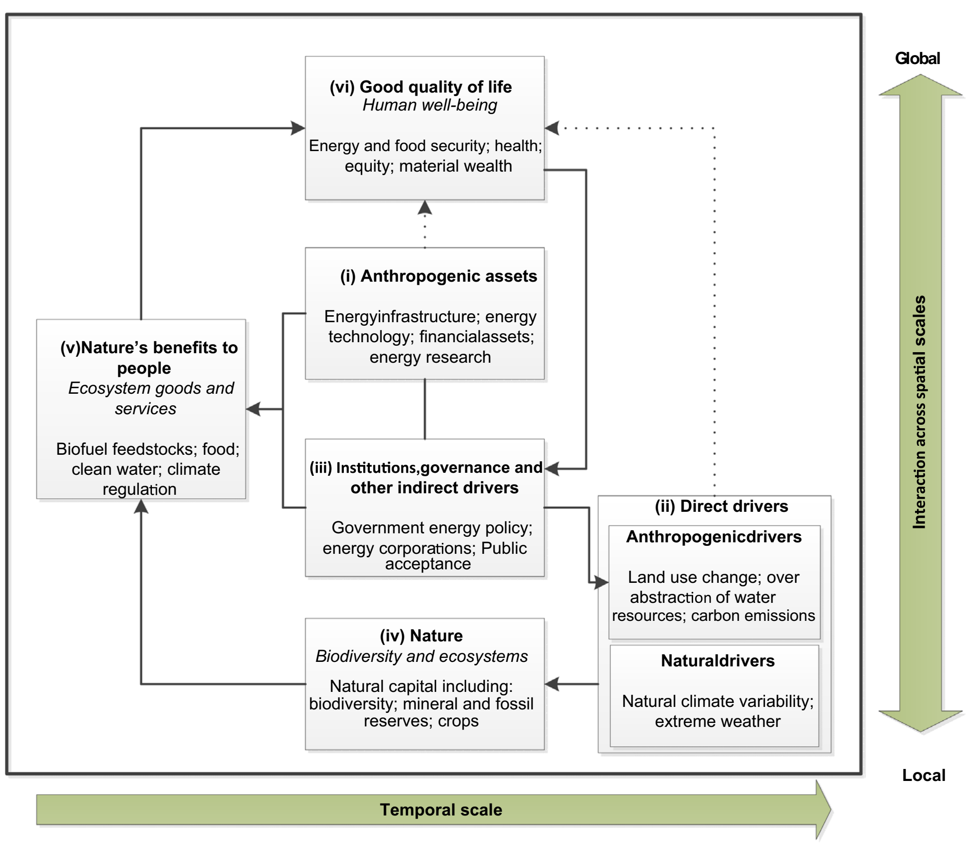

Fig. 1. Schematic of the IPBES Framework from Díaz et al. (2015a) adapted to illustrate its application for energy policy. Text in bold indicate IPBES categories, text in italics concepts from western science commonly used in policy, normal text examples of relevance to energy systems and the design of energy policy. Roman numerals refer to individual elements of the framework and cross reference with the main text.

description of the IPBES Conceptual Framework and its application, here we limit our discussion to elements of particular relevance in bridging the gap between the energy and ecosystem services communities. As such, in Section 2 we evaluate current understanding of the relationship between ecosystem services and energy systems, and so focus primarily on elements i, ii, iii and v in Fig. 1. In Section 3 we distil key elements required to assess the implications of energy technologies for ecosystem services, and in Section 4 considers how such knowledge could be implemented to guide energy policy. Ultimately, we argue that incorporation of a broader set of ecosystem services, beyond climate regulation, into the design of energy policy is essential to differentiate between energy technology options and so promote policy that selects the most sustainable pathways for the future energy system.

2. Current understanding of the interaction between energy systems and ecosystem services

Currently, evaluation of energy systems typically focuses on a suite of biophysical measures (Fig. 1 elements ii and iv). For example, recent assessments of electricity-generating pathways (Hertwich et al., 2015; Santoyo-Castelazo and Azapagic, 2014) compare indicators such as acidification and global warming potential. Such indicators provide a useful comparator to assess energy systems based on potential impact on ecological processes; however, they do not capture the spatial context within which the impacts are occurring, or the ability of the ecological system to respond. For example, land use change can be used as a proxy for negative pressures on biodiversity (Santoyo-Castelazo and Azapagic, 2014), favouring energy pathways with smaller spatial footprints. Such analysis does not incorporate underpinning ecological factors such as patterns of species distribution in relation to environmental conditions (Bateman et al., 2014; Souza et al., 2015), the vulnerability or irreplaceability of the area for biodiversity (Margules and Pressey, 2000; Turney and Fthenakis, 2011), or that certain species may benefit from the implied land or marine transitions (Ashley et al., 2014; Dauber et al., 2010; Hooper and Austen, 2014; Rowe et al., 2009). This can result in oversimplification of the true dynamics of the natural system and implications of energy technologies (Souza et al., 2015).

Beyond environmental considerations, such indicators do not capture interactions between the biophysical stocks and their value to, and ability of, society to adapt to changes in ecosystem service provision (Fig. 1 elements i, iii, v). This is a major issue as the importance of most ecosystem services is dependent on the spatial distributions of both their biophysical provision and human beneficiaries (Fisher et al., 2009; Hein et al., 2006). For example, changes in habitat structure associated with marine energy (i.e. tidal barrages, offshore wind) could enhance certain fisheries by providing species habitat (Hooper and Austen, 2014, 2013), but will only deliver ecosystem services benefits where fishermen retain access to exploit the stocks, and where an economic market for the species exists.

Beyond climate regulation, itself a key service, research at the interface of energy and ecosystem services has most prominently focused on impacts on biodiversity (Bergman et al., 2014; Rowe et al., 2009; Wiens et al., 2011), provisioning services such as food (Manning et al., 2014; Valentine et al., 2012) and fibre production (Schulze et al., 2012), regulating services such as soil, water and air quality (Gaffney and Marley, 2009; Rowe et al., 2009) and erosion control (Gregg and Izaurralde, 2010), and supporting services such as soil formation (Cowie et al., 2006; Smith et al., 2014, 2012). A number of recent studies compare different energy technologies across habitat types (Bonar et al., 2015; Hastik et al., 2015), and others have used an ecosystem service framework to examine contentious energy systems including shale gas (Souther et al., 2014), bioenergy (Gasparatos et al., 2011; Holland et al., 2015; Lovett et al., 2015), tidal barrages (Hooper and Austen, 2013), offshore wind (Mangi, 2013; Papathanasopoulou et al., 2015a), solar (Turney and Fthenakis, 2011) and nuclear (Gralla et al., 2014; Papathanasopoulou et al., 2015a). In all but a few examples, the consideration of impacts has been limited to one or a few services, and different metrics have been employed limiting our ability to make meaningful comparisons between energy systems and studies.

More fundamentally, many authors (Bonar et al., 2015; Lovett et al., 2015; Turney and Fthenakis, 2011) highlight significant gaps in understanding of interactions between energy systems and ecosystem services. Papathanasopoulou et al. (2015a, 2015b) provides one of the few examples where a consistent approach has been used to compare multiple ecosystem service impacts across different energy systems. Four main supply options (biomass, natural gas, nuclear and wind) were evaluated through the construction of impact matrices relating to detailed life cycle elements, and assessed in relation to local and global impacts on 27 ecosystem services classified using the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin, 2012). While it was possible to have many lifecycle stage/ecosystem service interactions, it was rare for the evidence base to encompass more than 10% of these. Studies primarily focused on provisioning or regulating services in the fuel cycle or operational stages. Downstream ecosystem service consequences were rarely covered, primarily due to limited experience of decommissioning upon which such evaluations could be based. Lastly, although there are *a priori* reasons for anticipating that upstream impacts associated with the mining and processing of raw materials for construction activities would be important for all energy systems, such impacts were rarely considered.

3. Key elements for integration of ecosystem services within energy systems assessment

From the studies highlighted in the previous section, it is possible to distil key elements that are required when assessing the implications of energy system for ecosystem services (Fig. 2). Firstly, assessment must include consideration of a broad range of ecosystem services to properly account for impacts. This should be undertaken using a consistent framework that ensures comparability between technologies, and that the full range of both market (e.g. crops, timber) and non-market (e.g. cultural value, recreation) ecosystem services are considered (Bateman et al., 2011). CICES (Haines-Young and Potschin, 2012) represents a candidate classification framework as it has been developed to support work on environmental accounting within the European Union and the United Nations Statistical Division (European Commission et al., 2013)

Secondly, analysis must consider the ecosystem service implications across all stages of the life cycle of energy systems. An extensive review of life cycle assessments of energy systems from a carbon perspective identifies reliance of renewable energy technologies on existing fossil fuel infrastructure for material extraction, fabrication, assembly, delivery and so forth (Edenhofer et al., 2014, 2011). This suggests that the implications for ecosystem services of different energy technologies share similarities at certain stages, from the extraction of raw materials to operation and decommissioning (Fig. 3). Policy must be based on identifying and understanding these similarities and critical differences between energy systems. For example bioenergy and petroleum production may have different land requirements for the production/extraction of the primary energy, but will share similarities in

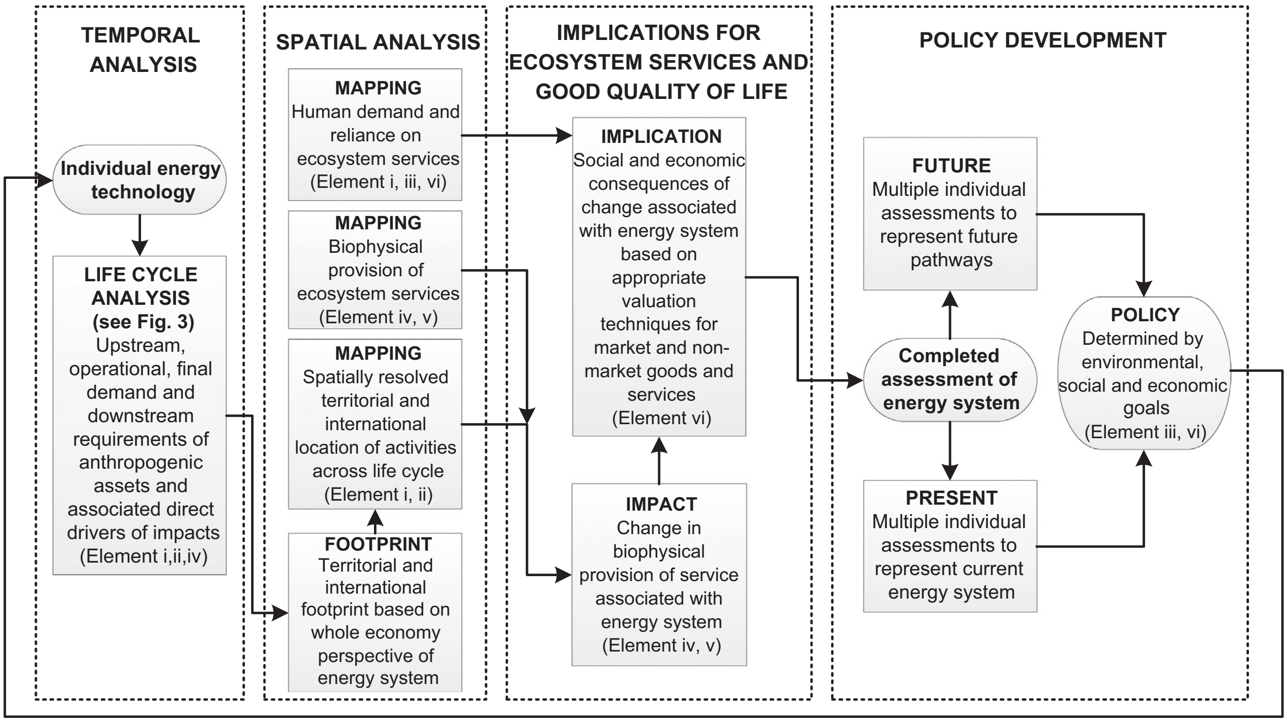

Fig. 2. Elements of assessment of energy systems and ecosystem services. Ecosystem services should be based on a standard classification scheme such as CICES that includes both market and non-market goods. Roman numerals refer to elements in Fig. 1.

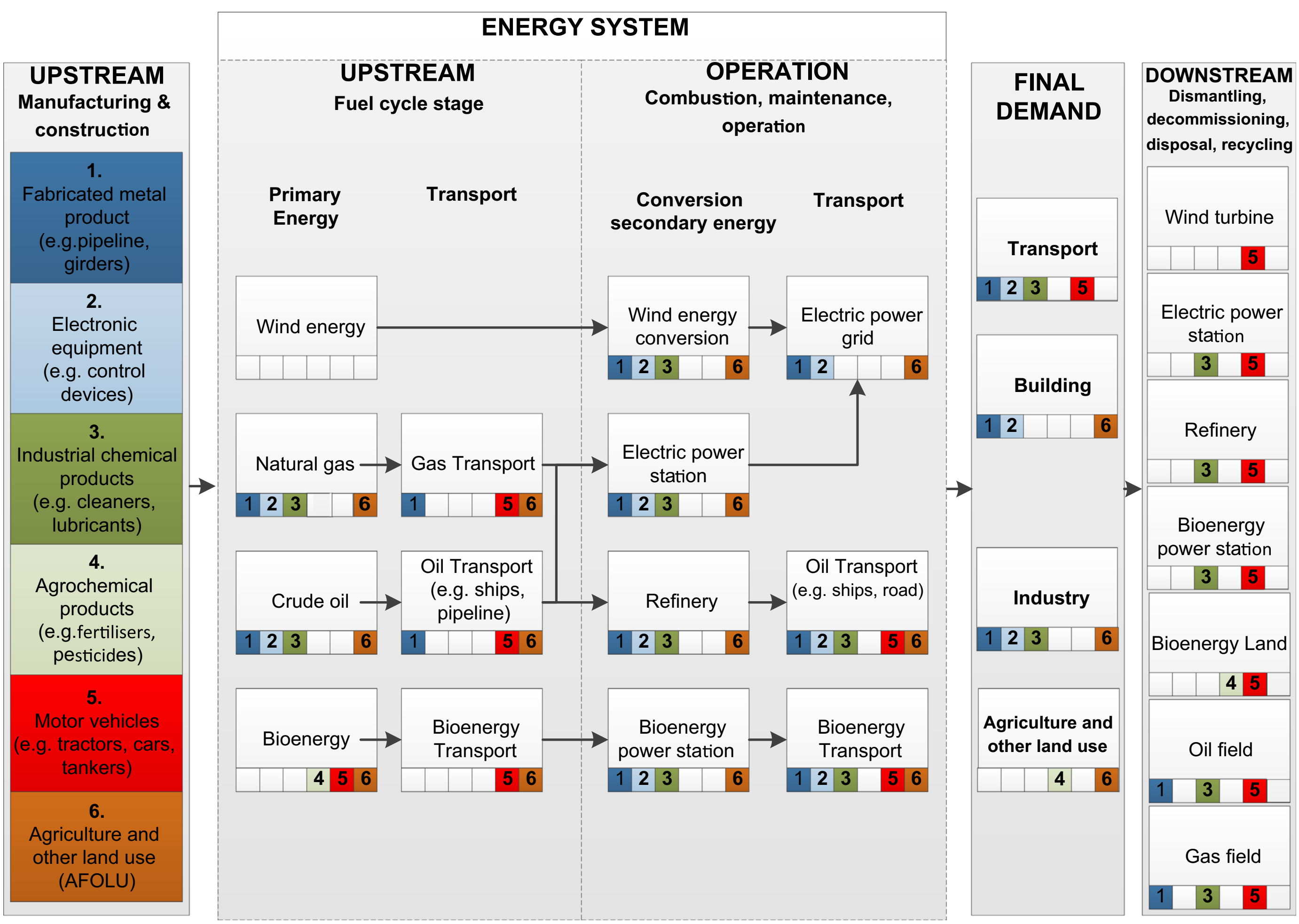

Fig. 3. Illustrative diagram showing different energy systems can have shared requirements for resources throughout their life cycle (adapted from Edenhofer et al. (2014, 2011)).

terms of infrastructure requirements for conversion and distribution of secondary energy (Fig. 1 elements i, iii; Fig. 3). Even where similarities exist, differences can also express themselves in terms of the spatial extent of impacts (e.g. total land use change) and through temporal dynamics (e.g. length of time of operation) and the interaction between the two.

Thirdly, assessment of the desirability of specific energy technologies must consider mismatches between the temporal and spatial scales over which ecosystem services and energy systems operate (Fig. 1 elements ii, iii). The ecological impact of energy systems tend to manifest at the local level, while energy policy is designed at the national and global level. For example Allison et al. (2014) discusses the difficulty in balancing deployment of zero or low carbon energy technologies to address the long term global threat to species posed by climate change against more immediate but localised impacts. Given predictions of loss of biodiversity due to climate change over the long term, policy might choose localised near term negative impacts as a mechanism to secure long term survival of species. By contrast, in certain systems impacts of climate change are predicted to be a less significant driver of loss of species and ecosystem function than current anthropogenic threats (Kuemmerlen et al., 2015; Tedesco et al., 2013), such that energy policy might be more weighted towards ameliorating near term local impacts. Understanding such spatial and temporal dynamics is key to identifying the most desirable energy options, balancing both short and long term and both local and global considerations.

Finally, assessment must consider both the territorial and international dimensions of energy systems. Analysis focussed on greenhouse gas emissions (Barrett et al., 2013; Hertwich and Peters, 2009; Peters et al., 2011) demonstrates that an increase in the volume and structure of international trade in recent decades has resulted in a transfer of net emissions from developed (consumer) nations to less developed (producer) nations (Peters et al., 2011). This indicates that the apparent success of industrialised countries in decreasing domestic emissions has been offset by an increase in emissions embodied in imports (Kanemoto et al., 2014). Using similar analytical approaches, whole economy studies demonstrate that consumption and globalisation are putting pressure on water resources (Holland et al., 2015; Lenzen et al., 2013), land-use (Weinzettel et al., 2013; Yu et al., 2013), material use (Wiedmann et al., 2015) and biodiversity (Lenzen et al., 2012) globally. Such "telecoupling" (Liu et al., 2013) of natural and human system must be incorporated into assessments of energy systems to fully understand the implications of energy technologies, and ascertain whether certain options generate an ecological deficit (Kroll et al., 2012) in regions separate from where final demand for energy resides and which may lack the adaptive capacity to cope with loss of ecosystem services. For example Holland et al. (2015) developed a methodology to trace localised freshwater consumption resulting from global energy supply chains, and to start to understand where the associated freshwater consumption was detrimental to the livelihoods of the local population. This can reduce the risk of selecting energy pathways associated with drought prone and water-vulnerable areas. Accounting for such displaced impacts remains a difficult problem. Its resolution is central to the paradigm shift that is required for appropriate consideration of a wide range of ecosystem services and how they are linked to the international trade of technologies, products and services that underpin the delivery of global energy supplies.

4. Implementing an ecosystem services framework in energy policy decisions

The challenges to implementing an ecosystem service assessment framework in an energy policy context are considerable and fall into two distinct categories; methodological and institutional. Many of the methodological challenges are not unique to the energy sector and include well-documented issues of sparse data for many ecosystem services and their valuation (Naidoo et al., 2008; Ruckelshaus et al., 2013). Initiatives such as The Economics of Ecosystems and Biodiversity (Sukhdev, 2010) make a strong case for incorporating the economic value of the full range of ecosystem services within the decision making process. However, designing policy based on valuation of the broad range of ecosystem services has its difficulties, particularly in creating meaningful valuations and comparisons of market and non-market goods, the provision of which may change through time (Bateman et al., 2013, 2011). A particular challenge is identifying the different societal groups that may benefit from different ecosystem services, as values are qualitative and context-specific, and winners and losers may be unevenly distributed across space, time and different stakeholder groups (Fig. 1 element vi; Brooks et al., 2014). In addition to these well-documented difficulties, quantifying the ecosystem service impacts of energy technologies must be disaggregated according to the components of their life cycle (Fig. 3).

A major institutional challenge to fully incorporating ecosystem services into energy policy is identified by Pittock (2011) who notes conflation of energy and climate policy, with discussion around energy currently incorporating information about only a few (predominantly regulating and provisioning) services. There is fragmentation across the policy landscape with climate and energy often considered by bodies separate from those that are relevant for other environmental considerations. For example, statutory bodies in UK exhibit such a division (i.e. Dept. of Energy and Climate Change, Dept. of Environment, Food and Rural Affairs), as do organisations collating evidence at the international level (IPCC, IPBES).

Fragmentation of the policy landscape may express itself most visibly in tensions that exist between environmental and energy policy. A prominent example of this is provided in relation to biofuels (Gasparatos et al., 2011; Mohr and Raman, 2013; van der Horst and Vermeylen, 2011) which have been promoted as a mechanism for energy security and independence, and reducing greenhouse gas emissions from the transport sector. Critics have identified a number of unintended consequences associated with broader sustainability ideals in relation to some production practices of first-generation feedstocks. For example, the release of carbon from land-use change (Fargione et al., 2008; Searchinger et al., 2008; Smith and Searchinger, 2012), increasing pressure on land and water resources (De Fraiture et al., 2008), and economic pressures that may have contributed to food insecurity for vulnerable populations (Phalan, 2009; Pimentel et al., 2009). As understanding has developed, analyses considering environmental (Manning et al., 2014; Rowe et al., 2009), social (van der Horst and Vermeylen, 2011) and economic (Bauen et al., 2010) aspects of biofuel production has emerged that provides a more nuanced understanding of biofuel pathways. This has identified more sustainable biofuel options such as the use of non-food crops, grown on land unsuitable for food production (Gelfand et al., 2013; Lovett et al., 2014; Valentine et al., 2012). Despite the biofuel industry being represented by a diverse range of technologies, feedstock types and production methods that could deliver positive outcomes for the environment and society, historic controversy arising through failure to consider wider environmental and social considerations has led to policy uncertainty, reduced levels of investment and slowed uptake of advanced feedstocks (Berti and Levidow, 2014; Boucher, 2012).

Such controversy speaks to a wider point about public acceptability (Fig. 1 element iii), an important influence on acceptance of energy policy (Devine-Wright, 2005; Ekins, 2004; Parkhill et al., 2013; Walker et al., 2007). In the UK people tend to be largely supportive of renewable energy technologies and there is evidence that the public wants and expects change in how energy is supplied, used and governed (Parkhill et al., 2013). Yet there has been widespread local opposition towards some renewable energy developments (particularly wind and biomass) due to concerns about impacts at the local level, such as the environmental and aesthetic impacts of land use change and distributive injustice (Devine-Wright, 2005; Gross, 2007; Upham and Shackley, 2006; Walker et al., 2010; Wüstenhagen et al., 2007). Integrating ecosystem services into local energy planning processes could allow informed decisions as to the trade-offs that different stakeholder groups are willing to accept, and the kinds of benefits they consider most important (Börger et al., 2014a, 2014b; Hooper et al., 2014; Howard et al., 2013) taking into account the longer term dynamics of the environment under climate change. Combined with spatial targeting, such a strategy could help to identify deployment strategies with likely positive outcomes, potentially bolstering the reputation of energy technologies.

A key requirement for uptake of an ecosystem service based framework for analysing energy systems will be to convince the private sector of the feasibility of such an approach. Meeting this challenge will require incorporating emerging partnerships and approaches being developed by ecosystem service researchers in fields ranging from climate change mitigation (e.g. Bateman et al., 2015), to those working on embedding such an approach within standard corporate accounting (Kareiva et al., 2015). A significant first step toward integration of ecosystem services within energy policy could be through scenario exercises. These are used globally as a basis for policy, planning and investment decisions by government and industry. For example, future energy scenarios have been developed by the UK government within their Renewable Energy Road Map (Department of Energy and Climate Change, 2011) and by The Committee on Climate Change (2015) in its carbon budgets, and there are a number of notable global examples including the World Energy Outlook (International Energy Agency, 2015) and the New Lens Scenarios (Royal Dutch Shell, 2013). Globally, the IEA have taken an initial step towards integrating water resources (International Energy Agency, 2012) into consideration of future scenarios, acknowledging the role of water as a critical factor affecting energy systems. For governments and businesses, information on ecosystem service implications of energy pathways would provide policy-relevant insights for future planning. Within scenarios, projected changes in ecosystem service provision under contrasting energy pathways would allow consideration of the implications of differing plausible technological, economic and social pathways, and form a central part of the exploration of which options are most desirable. As energy systems become increasingly geared towards decarbonisation, implications of different energy options for ecosystem services beyond climate regulation will represent a key factor that differentiates between pathways, and thus the desirability of specific policy options.

While acknowledging the challenges, integration of ecosystem services into energy policy presents opportunities for informing governments, industry, third sector organisations and individual consumers. Climate regulation, which is more advanced in policy making than ecosystem services, has become increasingly evident in stakeholder decision making. However, this has been supported by government departments dedicated to energy and climate policy and a legal framework founded on carbon, renewable energy and energy efficiency targets. There are standardised methods to account for carbon emissions, both within and outside national borders, and mandatory emissions reporting globally. Even so, climate policy has yet to become widespread across all actors. By drawing on advancements in climate regulation, enhancing interactions between the energy and ecosystem service communities could identify desirable energy pathways that align national and international obligations for both decarbonisation (Edenhofer et al., 2014) and halting the loss of biodiversity and degradation of ecosystem services (Convention on Biological Diversity, 2012).

5. Conclusions and policy implications

Concurrent with development of tools and policy to examine and address climate change there is a growing understanding and ability to assess the provision and importance of ecosystem services for human well-being. The bridging of these two domains is central to achieving a secure and sustainable future. The IPBES Conceptual Framework (Fig. 1), provides a unifying structure within which this can be achieved. In this paper we have highlighted some of the key elements that are essential to, and which could arise from, such an integrated assessment. Consideration of ecosystem services within an energy context clarifies the full consequences of a given energy system or pathway, enabling the benefits and costs in social, economic and environmental terms to be objectively assessed and transparently presented, and thus contribute to the development of informed energy policy.

Threats to ecosystem services represent a key impact of climate change identified by the IPCC (2014) and the Millennium Ecosystem Assessment (2005). Given the contribution of energy systems to greenhouse gas emissions, identifying pathways that reduce emissions is critical for the maintenance of ecosystem services on which humanity depends. Formal establishment of the interaction between energy systems and ecosystem services in governance processes is required so that both are enshrined in the relevant policy and management practices to address both near term (e.g. land/sea use, overexploitation) and future (e.g. climate change) threats. To enable decision makers to analyse which energy pathways are most beneficial to society, assessment methods need to be developed that consider the ecosystem service impacts of large-scale shifts to a low carbon energy infrastructure within a consistent framework allowing cross comparison between options.

Substantial research challenges remain for practitioners. These include: (1) Static life cycle analyses of individual energy systems that often focus on a handful of environmental impacts without tracing the implications for provision of ecosystem services on which society depends; (2) Energy system models that generally say nothing about impacts to ecosystem services beyond greenhouse gas emissions nor outside the focal country; (3) Increasing displacement of production from the point of consumption with little current understanding of the connection between the location of impact with the energy demand driving it, making reliable assessment of the impact energy demand has on distant communities competing for natural resources near impossible; (4) Achieving macro-level analysis of global energy systems while maintaining a high spatial resolution relevant for most ecosystem services; and (5) integrating research from a number of disciplines such as ecology, energy modelling, vulnerability and adaptation. Despite such challenges the research highlighted here suggests that the elements of such an integrated assessment are beginning to coalesce and can provide the holistic view of energy and ecosystem services interactions that is required to inform the future of global energy policy.

Acknowledgements

This work was supported by the UK Energy Research Centre Phase 2, under its Energy and Environment theme Grant Number NE/J005924/1 and NE/G007748/1.

References

Allison, T.D., Root, T.L., Frumhoff, P.C., 2014. Thinking globally and siting locally – renewable energy and biodiversity in a rapidly warming world. Clim. Change 126, 1–6. http://dx.doi.org/10.1007/s10584-014-1127-y.

Ashley, M.C., Mangi, S.C., Rodwell, L.D., 2014. The potential of offshore windfarms to act as marine protected areas – a systematic review of current evidence. Mar. Policy 45, 301–309. http://dx.doi.org/10.1016/j.marpol.2013.09.002.

Börger, T., Beaumont, N.J., Pendleton, L., Boyle, K.J., Cooper, P., Fletcher, S., Haab, T., Hanemann, M., Hooper, T.L., Hussain, S.S., Portela, R., Stithou, M., Stockill, J., Taylor, T., Austen, M.C., 2014a. Incorporating ecosystem services in marine planning: the role of valuation. Mar. Policy 46, 161–170. http://dx.doi.org/10.1016/j.marpol.2014.01.019.

Börger, T., Hattam, C., Burdon, D., Atkins, J.P., Austen, M.C., 2014b. Valuing conservation benefits of an offshore marine protected area. Ecol. Econ. 108, 229–241. http://dx.doi.org/10.1016/j.ecolecon.2014.10.006.

Barrett, J., Peters, G., Wiedmann, T.O., Scott, K., Lenzen, M., Roelich, K., Le Quéré, C., 2013. Consumption-based GHG emission accounting: a UK case study. Clim. Policy 13, 451–470. http://dx.doi.org/10.1080/14693062.2013.788858.

Bateman, I.J., Mace, G.M., Fezzi, C., Atkinson, G., Turner, K., 2011. Economic Analysis for Ecosystem Service Assessments. Environ. Resour. Econ. 48, 177–218. http://dx.doi.org/10.1007/s10640-010-9418-x.

Bateman, I.J., Coombes, E., Fitzherbert, E., Binner, A., Bad'ura, T., Carbone, C., Fisher, B., Naidoo, R., Watkinson, A.R., 2015. Conserving tropical biodiversity via market forces and spatial targeting. Proc. Natl. Acad. Sci. 112, 7408–7413. http://dx.doi.org/10.1073/pnas.1406484112.

Bateman, I.J., Harwood, A.R., Abson, D.J., Andrews, B., Crowe, A., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R., Hulme, M., Kontoleon, A., Munday, P., Pascual, U., Paterson, J., Perino, G., Sen, A., Siriwardena, G., Termansen, M., 2014. Economic Analysis for the UK National Ecosystem Assessment: synthesis and scenario valuation of changes in ecosystem services. Environ. Resour. Econ. 57, 273–297. http://dx.doi.org/10.1007/s10640-013-9662-y.

Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., Andrews, B., Binner, A., Crowe, A., Day, B.H., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R., Hulme, M., Kontoleon, A., Lovett, A.A., Munday, P., Pascual, U., Paterson, J., Perino, G., Sen, A., Siriwardena, G., Soest, D., van Termansen, M., 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. Science 341, 45–50. http://dx.doi.org/10.1126/science.1234379.

Bauen, A.W., Dunnett, A.J., Richter, G.M., Dailey, A.G., Aylott, M., Casella, E., Taylor, G., 2010. Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresour. Technol. 101, 8132–8143. http://dx.doi.org/10.1016/j.biortech.2010.05.002.

Bergman, M.J.N., Ubels, S.M., Duineveld, G.C.A., Meesters, E.W.G., 2014. Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone. ICES J. Mar. Sci. J. Cons. 193. http://dx.doi.org/10.1093/icesjms/fsu193.

Berti, P., Levidow, L., 2014. Fuelling expectations: a policy-promise lock-in of UK biofuel policy. Energy Policy 66, 135–143. http://dx.doi.org/10.1016/j.enpol.2013.09.044.

Bonar, P.A.J., Bryden, I.G., Borthwick, A.G.L., 2015. Social and ecological impacts of marine energy development. Renew. Sustain. Energy Rev. 47, 486–495. http://dx.doi.org/10.1016/j.rser.2015.03.068.

Boucher, P., 2012. The role of controversy, regulation and engineering in UK biofuel development. Energy Policy 42, 148–154. http://dx.doi.org/10.1016/j.enpol.2011.11.058.

Brooks, E.G., Smith, K.G., Holland, R.A., Poppy, G.M., Eigenbrod, F., 2014. Effects of methodology and stakeholder disaggregation on ecosystem service valuation. Ecol. Soc. 19, 18.

Chu, S., Majumdar, A., 2012. Opportunities and challenges for a sustainable energy future. Nature 488, 294–303. http://dx.doi.org/10.1038/nature11475.

Committee on Climate Change, 2013. Fourth Carbon Budget Review – Technical Report. Sectoral Analysis of the Cost-effective Path to the 2050 Target. Committee on Climate Change, London, UK.

Convention on Biological Diversity, 2012. COP 10 Decision X/2 Strategic Plan for Biodiversity 2011–2020. Convention on Biological Diversity.

Cowie, A.L., Smith, P., Johnson, D., 2006. Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? Mitig. Adapt. Strateg. Glob. Change 11, 979–1002. http://dx.doi.org/10.1007/s11027-006-9030-0.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.M., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, S.T., Asfaw, Z., Bartus, G., Brooks, L.A., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y., Zlatanova, D., 2015a. The IPBES Conceptual Framework — connecting nature and people. Curr. Opin. Environ. Sustain. 14, 1–16. http://dx.doi.org/10.1016/j.cosust.2014.11.002.

Díaz, S., Demissew, S., Joly, C., Lonsdale, W.M., Larigauderie, A., 2015b. A Rosetta Stone for nature's benefits to people. PLOS Biol. 13, e1002040. http://dx.doi.org/10.1371/journal.pbio.1002040.

Daily, G.C., Matson, P.A., 2008. Ecosystem services: from theory to implementation. Proc. Natl. Acad. Sci. USA 105, 9455–9456. http://dx.doi.org/10.1073/pnas.0804960105.

Dauber, J., Jones, M.B., Stout, J.C., 2010. The impact of biomass crop cultivation on temperate biodiversity. Glob. Change Biol. Bioenergy 2, 289–309. http://dx.doi.org/10.1111/j.1757-1707.2010.01058.x.

De Fraiture, C., Giordano, M., Liao, Y., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10, 67.

Department of Energy and Climate Change, 2011. Renewable Energy Roadmap. Department of Energy and Climate Change, London.

Devine-Wright, P., 2005. Local aspects of UK renewable energy development: exploring public beliefs and policy implications. Local Environ. 10, 57–69. http://dx.doi.org/10.1080/1354983042000309315.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C., 2011. Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, UK, Special report of the intergovernmental panel on climate change.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C., von Zwickel, T., Minx, J., 2014. Climate Change 2014: Mitigation of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Ekins, P., 2004. Step changes for decarbonising the energy system: research needs for renewables, energy efficiency and nuclear power. Energy Policy 32, 1891–1904. http://dx.doi.org/10.1016/j.enpol.2004.03.009, Energy Policy for a Sustainable Energy Future.

Ekins, P., Keppo, I., Skea, J., Strachan, N., Usher, W., Anandarajah, G., 2013. The UK Energy System in 2050: Comparing Low-Carbon, Resilient Scenarios.

European Commission, Organisation for Economic Co-operation and Development, United Nations, World Bank, 2013. System of Environmental-Economic Accounting 2012. Experimental-Economic Accounting, White cover publication. ed..

European Union, 2009. DIRECTIVE 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 140, 16–45.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238. http://dx.doi.org/10.1126/science.1152747.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. http://dx.doi.org/10.1016/j.ecolecon.2008.09.014.

Foresight, 2011. The Future of Food and Farming. The Government Office for Science, London, Executive Summary.

Gaffney, J.S., Marley, N.A., 2009. The impacts of combustion emissions on air quality and climate – from coal to biofuels and beyond. Atmos. Environ. 43, 23–36. http://dx.doi.org/10.1016/j.atmosenv.2008.09.016.

Gasparatos, A., Stromberg, P., Takeuchi, K., 2011. Biofuels, ecosystem services and human wellbeing: putting biofuels in the ecosystem services narrative. Agric. Ecosyst. Environ. 142, 111–128. http://dx.doi.org/10.1016/j.agee.2011.04.020.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., Robertson, G.P., 2013. Sustainable bioenergy production from marginal lands in the US Midwest. Nature 493, 514–517. http://dx.doi.org/10.1038/nature11811.

Gomez-Baggethun, E., Ruiz-Perez, M., 2011. Economic valuation and the commodification of ecosystem services. Prog. Phys. Geogr. 35, 613–628. http://dx.doi.org/10.1177/0309133311421708.

Goodwin, N.R., 2003. Five Kinds of Capital: Useful Concepts for Sustainable Development. Tufts University, Medford, MA.

Gralla, F., Abson, D.J., Møller, A.P., Lang, D.J., von Wehrden, H., 2014. The impact of nuclear accidents on provisioning ecosystem services. Ecol. Indic. 41, 1–14. http://dx.doi.org/10.1016/j.ecolind.2014.01.027.

Gregg, J.S., Izaurralde, R.C., 2010. Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock. Biofuels 1, 69–83. http://dx.doi.org/10.4155/bfs.09.8.

Gross, C., 2007. Community perspectives of wind energy in Australia: the application of a justice and community fairness framework to increase social acceptance. Energy Policy 35, 2727–2736. http://dx.doi.org/10.1016/j.enpol.2006.12.013.

Haines-Young, R., Potschin, M., 2012. CICES Version 4: Response to Consultation. Centre for Environmental Management, University of Nottingham.

Hastik, R., Basso, S., Geitner, C., Haida, C., Poljanec, A., Portaccio, A., Vrščaj, B., Walzer, C., 2015. Renewable energies and ecosystem service impacts. Renew. Sustain. Energy Rev. 48, 608–623. http://dx.doi.org/10.1016/j.rser.2015.04.004.

Hein, L., van Koppen, K., de Groot, R.S., van Ierland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57, 209–228. http://dx.doi.org/10.1016/j.ecolecon.2005.04.005.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environ. Sci. Technol. 43, 6414–6420.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J. D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-

carbon technologies. Proc. Natl. Acad. Sci. 112, 6277–6282. http://dx.doi.org/10.1073/pnas.1312753111.
Holland, R.A., Scott, K.A., Florke, M., Brown, G., Ewers, R.M., Farmer, E., Kapos, V., Muggeridge, A., Scharlemann, J.P.W., Taylor, G., Barrett, J., Eigenbrod, F., 2015. Global impacts of energy demand on the freshwater resources of nations. Proc. Natl. Acad. Sci. 112, E6707–E6716. http://dx.doi.org/10.1073/pnas.1507701112.
Hooper, T., Austen, M., 2013. Tidal barrages in the UK: ecological and social impacts, potential mitigation, and tools to support barrage planning. Renew. Sustain. Energy Rev. 23, 289–298. http://dx.doi.org/10.1016/j.rser.2013.03.001.
Hooper, T., Austen, M., 2014. The co-location of offshore windfarms and decapod fisheries in the UK: constraints and opportunities. Mar. Policy 43, 295–300. http://dx.doi.org/10.1016/j.marpol.2013.06.011.
Hooper, T., Cooper, P., Hunt, A., Austen, M., 2014. A methodology for the assessment of local-scale changes in marine environmental benefits and its application. Ecosyst. Serv. 8, 65–74. http://dx.doi.org/10.1016/j.ecoser.2014.02.005.
Howard, D.C., Burgess, P.J., Butler, S.J., Carver, S.J., Cockerill, T., Coleby, A.M., Gan, G., Goodier, C.J., Van der Horst, D., Hubacek, K., Lord, R., Mead, A., Rivas-Casado, M., Wadsworth, R.A., Scholefield, P., 2013. Energyscapes: linking the energy system and ecosystem services in real landscapes. Biomass Bioenergy 55, 17–26. http://dx.doi.org/10.1016/j.biombioe.2012.05.025.
International Energy Agency, 2012. World Energy Outlook 2012. IEA, Paris, France.
International Energy Agency, 2015. World Energy Outlook 2015. IEA, Paris, France.
IPCC, 2014. Summary for Policy Makers. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Kanemoto, K., Moran, D., Lenzen, M., Geschke, A., 2014. International trade undermines national emission reduction targets: new evidence from air pollution. Glob. Environ. Change 24, 52–59. http://dx.doi.org/10.1016/j.gloenvcha.2013.09.008.
Kareiva, P.M., McNally, B.W., McCormick, S., Miller, T., Ruckelshaus, M., 2015. Improving global environmental management with standard corporate reporting. Proc. Natl. Acad. Sci. 112, 7375–7382. http://dx.doi.org/10.1073/pnas.1408120111.
Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29, 521–535. http://dx.doi.org/10.1016/j.landusepol.2011.07.008.
Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N., Jähnig, S.C., 2015. An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. Freshw. Biol. 60, 1443–1458. http://dx.doi.org/10.1111/fwb.12580.
Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112. http://dx.doi.org/10.1038/nature11145.
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecol. Econ. 94, 78–85. http://dx.doi.org/10.1016/j.ecolecon.2013.06.018.
Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Cesar, R., Lambin, E.F., Li, S., et al., 2013. Framing sustainability in a telecoupled world. Ecol. Soc. 18, 26.
Lovett, A., Sünnenberg, G., Dockerty, T., 2014. The availability of land for perennial energy crops in Great Britain. GCB Bioenergy 6, 99–107. http://dx.doi.org/10.1111/gcbb.12147.
Lovett, A.A., Dockerty, T.L., Papathanasopoulou, E., Beaumont, N.J., Smith, P., 2015. A framework for assessing the impacts on ecosystem services of energy provision in the UK: an example relating to the production and combustion life cycle of UK produced biomass crops (short rotation coppice and Miscanthus). Biomass Bioenergy 83, 311–321. http://dx.doi.org/10.1016/j.biombioe.2015.10.001.
Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol. Evol. 27, 19–26. http://dx.doi.org/10.1016/j.tree.2011.08.006.
Mangi, S.C., 2013. The impact of offshore wind farms on Marine Ecosystems: a review taking an ecosystem services perspective. Proc. IEEE 101, 999–1009. http://dx.doi.org/10.1109/JPROC.2012.2232251.
Manning, P., Taylor, G., Hanley, M.E., 2014. Bioenergy, food production and biodiversity – an unlikely alliance? GCB Bioenergy 7 (4), 570–576. http://dx.doi.org/10.1111/gcbb.12173.
Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405, 243–253. http://dx.doi.org/10.1038/35012251.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington DC, USA.
Mohr, A., Raman, S., 2013. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Energy Policy 63, 114–122. http://dx.doi.org/10.1016/j.enpol.2013.08.033.
Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R.E., Lehner, B., Malcolm, T. R., Ricketts, T.H., 2008. Global mapping of ecosystem services and conservation priorities. Proc. Natl. Acad. Sci. USA 105, 9495–9500. http://dx.doi.org/10.1073/pnas.0707823105.
Naik, S.N., Goud, V.V., Rout, P.K., Dalai, A.K., 2010. Production of first and second generation biofuels: a comprehensive review. Renew. Sustain. Energy Rev. 14, 578–597. http://dx.doi.org/10.1016/j.rser.2009.10.003.
Papathanasopoulou, E., Beaumont, N., Hooper, T., Nunes, J., Queirós, A.M., 2015a. Energy systems and their impacts on marine ecosystem services. Renew. Sustain. Energy Rev. 52, 917–926. http://dx.doi.org/10.1016/j.rser.2015.07.150.
Papathanasopoulou, E., Holland, R.A., Dockerty, T., Scott, K., Blaber-Wegg, T., Beaumont, N., Taylor, G., Sunnenberg, G., Lovett, A., Smith, P., Austen, M.C., 2015b. Scenario impacts on ecosystem services. Global Energy: Issues, Potentials, and Policy Implications. Oxford University Press, Oxford, UK.
Parkhill, K., Demski, C., Butler, C., Spence, A., Pidgeon, N., 2013. Transforming the UK Energy System: Public Values, Attitudes and Acceptability, synthesis report.
Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. 108, 8903–8908. http://dx.doi.org/10.1073/pnas.1006388108.
Phalan, B., 2009. The social and environmental impacts of biofuels in Asia: an overview. Appl. Energy 86, S21–S29. http://dx.doi.org/10.1016/j.apenergy.2009.04.046.
Pimentel, D., Marklein, A., Toth, M.A., Karpoff, M.N., Paul, G.S., McCormack, R., Kyriazis, J., Krueger, T., 2009. Food versus biofuels: environmental and economic costs. Hum. Ecol. 37, 1–12. http://dx.doi.org/10.1007/s10745-009-9215-8.
Pittock, J., 2011. National Climate Change Policies and Sustainable Water Management: conflicts and synergies. Ecol. Soc. 16 (2), 25.
Rowe, R.L., Street, N.R., Taylor, G., 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renew. Sustain. Energy Rev. 13, 271–290. http://dx.doi.org/10.1016/j.rser.2007.07.008.
Royal Dutch Shell, 2013. New Lens Scenarios: A shift in perspective for a world in transition.
Ruckelshaus, M., Doney, S.C., Galindo, H.M., Barry, J.P., Chan, F., Duffy, J.E., English, C. A., Gaines, S.D., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J., Talley, L.D., 2013. Securing ocean benefits for society in the face of climate change. Mar. Policy 40, 154–159. http://dx.doi.org/10.1016/j.marpol.2013.01.009.
Santoyo-Castelazo, E., Azapagic, A., 2014. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. J. Clean. Prod. 80, 119–138. http://dx.doi.org/10.1016/j.jclepro.2014.05.061.
Schulze, E.D., Korner, C.I., Law, B.E., Haberl, H., Luyssaert, S., 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. Glob. Change Biol. Bioenergy 4, 611–616. http://dx.doi.org/10.1111/j.1757-1707.2012.01169.x.
Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319, 1238–1240. http://dx.doi.org/10.1126/science.1151861.
Smith, J., Nayak, D.R., Smith, P., 2012. Renewable energy: avoid constructing wind farms on peat. Nature 489, 33. http://dx.doi.org/10.1038/489033d.
Smith, J., Nayak, D.R., Smith, P., 2014. Wind farms on undegraded peatlands are unlikely to reduce future carbon emissions. Energy Policy 66, 585–591. http://dx.doi.org/10.1016/j.enpol.2013.10.066.
Smith, K.A., Searchinger, T.D., 2012. Crop-based biofuels and associated environmental concerns. Glob. Change Biol. Bioenergy 4, 479–484. http://dx.doi.org/10.1111/j.1757-1707.2012.01182.x.
Souther, S., Tingley, M.W., Popescu, V.D., Hayman, D.T., Ryan, M.E., Graves, T.A., Hartl, B., Terrell, K., 2014. Biotic impacts of energy development from shale: research priorities and knowledge gaps. Front. Ecol. Environ. 12, 330–338. http://dx.doi.org/10.1890/130324.
Souza, D.M., Teixeira, R.F.M., Ostermann, O.P., 2015. Assessing biodiversity loss due to land use with Life Cycle Assessment: are we there yet? Glob. Change Biol. 21, 32–47. http://dx.doi.org/10.1111/gcb.12709.
Sukhdev, P., 2010. The economics of ecosystems and biodiversity. Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. TEEB, [S.l.].
Tedesco, P.A., Oberdorff, T., Cornu, J.-F., Beauchard, O., Brosse, S., Dürr, H.H., Grenouillet, G., Leprieur, F., Tisseuil, C., Zaiss, R., Hugueny, B., 2013. A scenario for impacts of water availability loss due to climate change on riverine fish extinction rates. J. Appl. Ecol. 50, 1105–1115. http://dx.doi.org/10.1111/1365-2664.12125.
The Committee on Climate Change, 2015. The Fifth Carbon Budget: The Next Step Towards a Low-carbon Economy. Committe on Climate Change, London, UK.
Turney, D., Fthenakis, V., 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renew. Sustain. Energy Rev. 15, 3261–3270. http://dx.doi.org/10.1016/j.rser.2011.04.023.
UK Parliament, 2008. Climate change act 2008.
UNFCCC, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations, New York, NY.
Upham, P., Shackley, S., 2006. Stakeholder opinion of a proposed 21.5 MWe biomass gasifier in Winkleigh, Devon: implications for bioenergy planning and policy. J. Environ. Policy Plan. 8, 45–66. http://dx.doi.org/10.1080/15239080600634144.
Valentine, J., Clifton-Brown, J., Hastings, A., Robson, P., Allison, G., Smith, P., 2012. Food vs. fuel: the use of land for lignocellulosic next generation' energy crops that minimize competition with primary food production. Glob. Change Biol. Bioenergy 4, 1–19. http://dx.doi.org/10.1111/j.1757-1707.2011.01111.x.
van der Horst, D., Vermeylen, S., 2011. Spatial scale and social impacts of biofuel production. Modelling environmental, economic and social aspects in the Assessment of Biofuels. 35, pp. 2435–2443. doi:10.1016/j.biombioe.2010.11.029.
Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 35, 2683–2691. http://dx.doi.org/10.1016/j.enpol.2006.12.001.
Walker, G., Hunter, S., Devine-Wright, P., Evans, B., Fay, H., 2007. Harnessing Community Energies: explaining and evaluating community-based localism in renewable energy policy in the UK. Glob. Environ. Politics 7, 64–82. http://dx.doi.org/10.1162/glep.2007.7.2.64.
Walker, G., Devine-Wright, P., Hunter, S., High, H., Evans, B., 2010. Trust and community: exploring the meanings, contexts and dynamics of community renewable energy. The Role of Trust in Managing Uncertainties in the Transition

to a Sustainable Energy Economy, Special Section with Regular Papers. Energy Policy, 38, pp. 2655–2663. http://dx.doi.org/10.1016/j.enpol.2009.05.055.
Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Global Environ. Change 23, 433–438.
Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112 (20), 6271–6276. http://dx.doi.org/10.1073/pnas.1220362110.
Wiens, J., Fargione, J., Hill, J., 2011. Biofuels and biodiversity. Ecol. Appl. 21, 1085–1095.
Yu, Y., Feng, K., Hubacek, K., 2013. Tele-connecting local consumption to global land use. Global Environ. Change 23, 1178–1186. http://dx.doi.org/10.1016/j.gloenvcha.2013.04.006.