UKERC Energy & Environment Theme

Bridging the gap between energy and the environment

Working Paper

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Preface

The UK Energy Research Centre (UKERC) was established in 2004 and is funded by the Research Councils UK Energy Programme. Within its second phase (2009-14), its research objectives are addressed within five broad themes, within which a number of co-ordinated, interdisciplinary projects are taking place: (1) Technology and Policy Assessment; (2) Energy and Environment; (3) Energy Supply; (4) Energy Demand; (5) Energy Systems. Two integrating flagship projects – Energy Strategies Under Uncertainty and UK Energy in a Global Context – span these themes.

This document presents key findings from research conducted within the Energy and Environment theme since 2009, when the second phase of UKERC activity began. Research within this theme has investigated the impacts associated with a range of marine and land-based energy production and greenhouse gas (GHG) mitigation technologies including bioenergy, wind, tidal, gas, nuclear and carbon capture and storage (CCS). The carbon and water footprints of these technologies have been investigated as have their social, economic and environmental impacts and their impacts on terrestrial and marine ecosystem services. A full list of research topics examined during this time and the researchers and investigators involved is listed in Annex A.

Executive summary

The environment agenda has become dominated by efforts to respond to the imminent and serious threat of climate change. Central to addressing this problem is meeting society's energy demands in an environmentally sustainable way. However, there are significant gaps in our understanding of the full implications of different energy strategies for the environment and society, both within the UK and overseas. UKERC researchers have set out to bridge this gap.

Key contributions include:

- Developing our understanding of how best to take full account of the GHG emissions associated with economic activity at a range of scales. UKERC research has influenced the way that GHG emissions are accounted for within existing policy frameworks, specifically developing and testing consumption-based GHG accounting methodologies for nations, settlements, governments, products and lifestyles.

- Adding to our knowledge of the potential of different energy technologies to meet energy generation, GHG emission and environmental targets both now and in the future. Studies have identified diverse positive and negative impacts that these energy technologies can have across their life cycles on ecosystem services and environmental, social and economic factors across a range of temporal and geographical scales.

- Utilising and developing a range of methodological approaches and tools to investigate these impacts. These include various forms of life cycle analysis (including hybrid and social), modelling, mapping, social surveys, multi-criteria decision analysis (MCA) and systematic reviews and the development of a new methodological framework for the comparative assessment of the ES impacts of different energy technologies on a local to global scale.

- Highlighting persistent issues relating to the existence, quality and accessibility of data that is necessary to take full account of impacts associated with energy technologies.

- Identifying opportunities to improve the social acceptability of energy technologies. Information about impacts and optimal locations can be used as a basis for engagement with different stakeholders and can also be used to tailor deployment decisions. This would support the increased provision of energy generation in ways that people want, maximising the use of local resources and aligning well with local or regional needs.

1. Introduction

Energy policy in the UK is driven by a desire to provide an affordable and secure energy supply while mitigating climate change by reducing GHG emissions (Department of Energy & Climate Change, 2011). A range of energy technologies is required in order to achieve this: in the short to medium term this includes natural gas and nuclear together with an increasingly important contribution from renewable energy technologies. The UK and the EU are working towards achieving 15% and 20% of energy generation from renewable sources by 2020, respectively (Department of Energy & Climate Change, 2011). While these energy technologies can make significant contributions to decarbonising the UK energy supply, they may also be associated with a diverse and complex array of positive and negative social, environmental and economic impacts, which may occur at a range of geographical and temporal scales. It is important to consider the full range of potential impacts alongside predicted gains in terms of energy supply, affordability and GHG emission reduction in order to ensure that the best decisions are made and that associated costs are predicted, minimised and mitigated against. However, our knowledge of these impacts and the extent to which different energy technologies can contribute to meeting these renewable energy targets sustainably is incomplete.

One of the gaps in our knowledge concerns the impact of energy technologies on ecosystem services[1]. It is widely recognised that the environment provides a range of services and that its degradation reduces its ability to deliver these services, leading to a range of undesirable consequences that include negative impacts on our physiological, psychological, societal and economic wellbeing. The importance of these ecosystem services is increasingly recognised, for example in reports produced by The Economics of Ecosystems and Biodiversity (TEEB) initiative, the Millennium Ecosystem Assessment (MEA) and the UK National Ecosystem Assessment (NEA). Until recently ecosystem services were not a focus of international governance, unlike climate change mitigation activity which has been driven by the Intergovernmental Panel on Climate Change (IPCC). The creation of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) in April 2012 is expected to advance the ecosystem services agenda and it is likely that the international community will increasingly be required to take action to minimise both GHG emissions and negative impacts on ecosystem services and biodiversity. It is important to explore the

[1] We use 'ecosystem service' here as a general term (following Mace *et al.*, 2012) that includes all the steps along the pathway from ecological processes to the goods derived from nature, which people value.

extent to which these goals are compatible and what the implications might be for society, the economy and the environment.

Recent UKERC research has engaged with these issues. This document presents key findings from five years of research carried out within the Energy & Environment theme, which has investigated the environmental, social and economic implications of different energy technologies with a strong focus on ecosystem services. This body of research develops the case for taking full account of the entire range of impacts associated with different energy technologies – attending to how these vary over time, across space and for different groups of stakeholders – and improving the ways in which accounting for these impacts is currently achieved. These findings and the tools developed can be used to inform decision making at different scales, from the deployment of particular energy technologies in particular places to the design of future energy mixes more broadly.

The report is structured such that individual sections can be read independently, allowing readers to access information of particular interest quickly. The next two sections showcase UKERC research findings relating to impacts associated with different energy technologies: section 2 focuses on impacts with relevance for climate change mitigation, while section 3 considers other environmental, social and economic impacts. In the course of doing this research a number of issues were brought to light, centring on persistent data gaps and the social acceptability of energy technologies: section 4 discusses these issues and suggests ways in which they may be resolved. The report concludes in section 5.

2. Climate change mitigation

The energy sector has been a major contributor to climate change: the majority of anthropogenic CO_2 emissions produced since pre-industrial times have resulted from fossil fuel combustion and cement production (68%), with land use change accounting for the remainder (IPCC, 2013, p. 9). Investing in 'decarbonising' the energy system is therefore a necessary element of climate change mitigation, which may be achieved by increasing the proportion of energy produced from renewable sources and by utilising technologies such as carbon capture and storage.

This mitigation activity is driven by a combination of international governance mechanisms and political commitments (such as the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC, adopted in 1997) and subsequent Doha Amendment (adopted in 2012)) supported by IPCC assessments. Signatory states are required to monitor progress towards meeting associated targets by submitting annual accounts of the GHG emissions produced within their territories. However, this method of monitoring does not account for all of the GHG emissions associated with that state's economic activity: in order to achieve this, an alternative approach – consumption-based emissions accounting – is required. UKERC research has developed the case for using consumption-based emissions accounting, demonstrating its utility for monitoring GHG emissions associated with economic activity at a range of scales (section 2.1).

While the development of new energy technologies is critical to ensure the reduction of GHG emissions, it is just as important to ensure that these technologies do not reduce the environment's capacity to provide climate regulation services and function as a GHG sink: currently, the ocean retains 155 GtC (28%) and 160 GtC (29%) have accumulated in natural terrestrial ecosystems (IPCC, 2013, p. 10). The introduction of particular energy technologies into particular ecosystems can negatively impact upon carbon fluxes and other biogeochemical processes that occur within them. Section 2.2 sets out how UKERC research has contributed to our knowledge of the impacts of different energy technologies on these processes.

2.1 Consumption-based emissions accounting

There are three broad ways in which it is possible to account for the GHG emissions associated with a state: in terms of territory, production and consumption. Territorial- and production-based approaches are the most similar to each other: at the national scale, territorial-based accounting includes emissions associated with industry within a particular territory and in offshore waters within its jurisdiction, excluding emissions produced in international territories; production-based accounting also includes emissions from international aviation, shipping and tourism. Consumption-based accounting takes a different approach: it considers the emissions associated with the domestic consumption of all products, regardless of whether these are produced within a nation's jurisdiction. Territorial- and production-based approaches are especially influential: international climate governance institutions such as the UNFCCC (following IPCC guidelines) use these methods in GHG emissions accounting in order to set emissions targets for industrialised countries and monitor progress in achieving those (Baiocchi and Minx, 2010; Barrett *et al.*, 2013).

According to territorial- or production-based emissions accounting, the UK would appear to have successfully reduced its GHG emissions in line with its Kyoto targets. However, studies adopting a consumption-based approach consistently reveal an increase in national GHG emissions over the same period (Barrett *et al.*, 2013; Committee on Climate Change, 2013; Scott *et al.*, 2013). This simultaneous decrease in territorial- and production-based GHG emissions and increase in consumption-based emissions in the UK is due to a combination of factors including domestic production efficiency increases, the liberalisation of the UK energy sector, the transition to a service-based economy in the UK, and increases in the consumption of imported products (especially from non-OECD countries) (Baiocchi and Minx, 2010; Scott and Barrett, 2013). Whereas all UNFCCC signatories use territorial-based accounting in their National Emissions Inventory submissions, few nations currently perform consumption-based accounting; the UK is one of the few that does (Barrett *et al.*, 2013) and may be the only one to have committed to reporting this as an official indicator (Baiocchi and Minx, 2010).

UKERC research has contributed to a growing body of evidence that supports the use of consumption-based emissions accounting. It has demonstrated that this approach, which utilises Environmentally-Extended Multi-Region Input-Output (EE-MRIO) models[2], can complement terrestrial- and production-based emissions accounting (Barrett *et al.*, 2013) and other modelling approaches, such as econometric forecasting (Wiedmann and Barrett, 2013). UKERC researchers have also demonstrated the potential that this approach has for providing policy-relevant insights for topics such as national-level footprinting or estimating the impacts of international supply chains (Barrett *et al.*, 2013; Wiedmann and Barrett, 2013). For example, consumption-based accounting has been used to show that the current focus on material efficiency in the UK Government's Sustainable Development Strategy will fail to produce sufficiently large reductions in GHG emissions to compensate

[2] EE-MRIO models have become the norm in consumption-based GHG accounting and provide a means of taking into account emissions associated with international trade.

for increasing consumption-based emissions; this could be addressed by efforts to reduce emissions embodied along international supply chains (such as the development of comprehensive product roadmaps for key product groups, greater support for behavioural change, border carbon adjustments, technology transfer and emissions trading schemes beyond the EU Emissions Trading System) in addition to the focus on improving domestic production efficiency (Baiocchi and Minx, 2010; Barrett *et al.*, 2013). Consumption-based accounting using EE-MRIO analysis has already influenced UK policy, including Defra's choice of product roadmaps included within its Sustainable Consumption and Production policy (Wiedmann and Barrett, 2013) and Defra's publication of annual consumption-based emissions accounts, generated by UKERC researchers at the University of Leeds[3].

In addition to contributing to our knowledge of the importance and suitability of consumption-based emissions accounting at the nation-state level, UKERC research has demonstrated its suitability for settlements, institutions, products and lifestyles (sections 2.1.1 to 2.1.4).

2.1.1 Settlements

Minx *et al.* (2013) combined geodemographic data[4] (from the MOSAIC consumer classification system[5]) with global production data derived from an EE-MRIO model in order to estimate the CO_2 emissions associated with different kinds of settlement in the UK. They found that most settlements were net importers of CO_2 emissions. Their analysis revealed that although there is no clear relationship between density and carbon footprint, urban settlements tend to have only slightly lower footprints than rural settlements, with much variation within each geodemographic category. Factors such as population density or rurality have little impact on the size of a settlement's carbon footprint. Socio-economic factors such as household size, education, income and car ownership accounted for some of the within-settlement variation.

[3] These statistics are available at www.gov.uk/government/publications/uks-carbon-footprint

[4] This is a means of segmenting the population according to particular characteristics, which assumes that people living near to each other are more likely to have similar characteristics than people chosen at random. This approach is long-established in marketing.

[5] MOSAIC is a geodemographic classification system that segments UK consumers at the household level into 15 groups and 66 types based on a range of socioeconomic factors. It is commercially available from Experian. See www.experian.co.uk/marketing-services/products/mosaic-uk.html

2.1.2 Institutions

Wiedmann and Barrett (2011) were commissioned by Defra to calculate the consumption-based GHG emissions associated with UK Central Government. Using an EE-MRIO, they found that 'scope 3 emissions' – that is, GHG emissions relating to the complete procurement supply chain, as defined in the Greenhouse Gas Protocol – account for 77% of Central Government's total carbon footprint. Increases in these emissions outweighed reductions in other sources of GHG emissions (specifically, direct GHG emissions and those resulting from purchased electricity, or 'scope 1' and 'scope 2' respectively). Central Government's carbon footprint is driven by the consumption of a comparatively small number of product groups which should, they argue, be the focus of sustainable procurement initiatives.

2.1.3 Products

Barrett and Scott (2012) investigated the extent to which different material efficiency strategies support the achievement of the UK's GHG emissions targets. They found that the most important strategies to both improve material efficiency and achieve large reductions in GHG emissions were related to consumer behaviour: product optimisation, product lifetime extension and dietary changes. They highlight the importance of changes to both consumption and production and the need to act in the short term in order to minimise the atmospheric accumulation of GHG emissions.

2.1.4 Lifestyles

Consumption-based accounting can also be used to estimate the direct and indirect GHG emissions associated with different lifestyle groups, which are characterised according to different quantities and types of consumption in geodemographic consumer segmentation datasets such as ACORN[6]. Baiocchi *et al.* (2010) found that the emissions associated with different lifestyle groups can vary by a factor of 2-3; that housing and transport were associated with the largest quantities of emissions; that emissions increase with income; and that emissions decrease with increasing education.

2.2 Impacts of energy technologies on the ecosystem service of climate regulation

The introduction of specific energy technologies to particular locations may impact upon the extent to which these ecosystems can deliver climate regulation. UKERC research has

[6] Like MOSAIC (see footnote 5), ACORN is a geodemographic classification system. It segments UK consumers at the postcode and neighbourhood level into 6 categories, 18 groups and 62 types based on a range of socioeconomic factors. It is commercially available from CACI. See http://acorn.caci.co.uk

investigated potential impacts in marine and terrestrial ecosystems and has demonstrated the importance of attending to the specific contexts into which energy technologies are introduced in order to maximise their GHG emissions abatement potential.

2.2.1 Carbon in the marine environment

Several energy technologies and GHG mitigation technologies – such as offshore wind farms, tidal barrages and carbon capture and storage – operate in the marine environment. Marine ecosystems make an important contribution to gas and climate regulation[7]: the continental shelf sea absorbs 30% of the anthropogenic CO_2 released into the atmosphere (Sabine *et al.*, 2004) and plays a vital role in the global CO_2 balance. Placing a value on ecosystem services such as gas and climate regulation can support decision making by assisting with balancing the benefits and trade-offs associated with different options. There are different ways in which this particular ecosystem service can be valued: valuations may be based on primary productivity, either measured *in situ* or via satellite as a proxy for direct measurement (Costanza, 1999; Mangi *et al.*, 2011; Reid, 2005); or the burial of carbon in continental shelf seabed sediments could also provide a measure of this ecosystem service. However, the data available from the UK continental shelf for quantification and hence valuation is so temporally and spatially sparse that a comprehensive assessment of this ecosystem service is yet to be achieved. UKERC research has engaged with this issue by investigating the extent to which existing data relating to commonly measured variables such as primary productivity, chlorophyll concentrations, total nitrogen (including nitrite, nitrate and ammonia), total alkalinity and air-sea CO_2 flux could be used to predict carbon burial in continental shelf seabed sediments (Carter Silk, unpublished). Using spatially-resolved biogeochemical modelling – specifically, using the European Regional Seas Ecosystem Model (ERSEM) – this study found that total nitrogen and depth measurements are good predictors of rates of carbon burial. This information and model development can be used to improve our understanding of how the marine environment sequesters CO_2 and, in turn, how the installation of marine renewable energy devices may affect the provision of this service.

Quantifying and valuing the ecosystem services provided by the marine environment is a necessary first step in order to make informed decisions that balance benefits and risks associated with different energy strategies. Carbon capture and storage, for example, could potentially result in carbon leakage in the continental shelf environment over the long term and consequently alter gas and climate regulation processes. UKERC research

[7] This has been defined as the balance and maintenance of the chemical composition of the atmosphere and oceans by marine living organisms (Beaumont *et al.*, 2008).

has investigated the impact that such leakage may have on marine ecosystems. Blackford *et al.* (2009) used a dynamic simulation model to calculate the dispersion of CO_2 from a number of hypothetical leaks following CCS in the North West European continental shelf, in order to estimate the nature and type of impacts that could result. This indicated that any CO_2 leaks were likely to be restricted both temporally and spatially: although such leaks could have catastrophic effects on local ecosystems, they would not be likely to have a significant impact on the ecosystem as a whole. Even massive leaks would have an insignificant effect compared to surface ocean acidification driven by increasing atmospheric levels of CO_2. In order to minimise the impacts of potential carbon leakage following CCS, Blackford *et al.* suggest that CCS should be sited away from ecologically sensitive areas and in areas of high natural mixing.

2.2.2 Carbon in the terrestrial environment

Although bioenergy can make an important contribution to GHG mitigation, it is also understood that under certain circumstances it may release more GHGs than it offsets (DfT *et al.*, 2012). UKERC research has contributed to our understanding of the range of factors influencing the impact of bioenergy on GHG emissions and how these factors interact.

The impact of bioenergy crop cultivation on the soil-atmosphere GHG balance (in particular relating to methane, nitrous oxide and carbon dioxide) and the hydrological cycle varies spatially and is affected by several factors, including previous land use (and associated disturbance of untilled soil and removal of previous cover), bioenergy crop type (and genotype), bioenergy crop management, topography, soil type and climate (Thomas *et al.*, 2013a, 2013b). Thomas *et al.*'s findings emphasise the importance of taking a whole agroecosystem approach to understanding the impacts of land use change associated with perennial bioenergy crop cultivation, and of matching bioenergy crops to specific sites in order to maximise GHG emissions abatement.

There is a need for robust, validated models that reliably predict the impact of short rotation coppice (SRC) crops on GHG balance: at the moment, measured data are scarce and for new crops, such data is often estimated from look-up tables and LCA databases derived from few primary data sources (Tallis *et al.*, 2013). Tallis *et al.* have developed a process-based model for SRC poplar and willow crops – ForestGrowth-SRC – which can be used to predict the impacts of a range of factors including genotype and climate on yields at a regional scale, aiding in the selection of species (and genotypes) for different sites and climates.

Economic factors are often a significant influence on the deployment of particular energy technologies in particular areas (discussed in more detail in section 3.1.3.1). UKERC research has contributed to our knowledge of the impact of economic factors on potential GHG emissions abatement for bioenergy:

- A study that combined an existing GHG balance assessment with an agent-based model found that providing direct financial support to farmers to establish bioenergy crops both improves GHG abatement potential and the cost-effectiveness of subsidies in achieving GHG emissions reductions (Alexander *et al.*, 2014). Abatement potential varied with the level of subsidy: providing 100% of establishment costs would achieve a six-fold increase in abatement potential at an increase of £1 t CO_2e^{-1} in the carbon price.

- Based on yield predictions for *Miscanthus* for Great Britain (produced using the Miscanfor model) and life cycle analysis, Wang *et al.* (2012b) found that in order to minimise both GHG emissions and economic costs, *Miscanthus* should be cultivated on land previously under arable cultivation. Transportation costs are another important factor: *Miscanthus* production is most likely to be optimal when production and power stations are in close proximity.

A separate study of the life cycle impacts of anaerobic digestion (AD) has contributed to our understanding of the potential that this form of bioenergy has for climate change mitigation, which can be achieved without impacting on existing farming routines or creating land use change (Tickner, unpublished). AD of low-energy, low-value farm-based feedstocks, such as animal slurries and manures (which are in themselves a source of GHG emissions) is not normally economically viable when they are treated alone. UKERC findings suggest that when these feedstocks are combined with small quantities of biowaste materials (treated through a 'Hub and Pod' structure[8]) and a limited quantity of purpose-grown crops, AD treatment can be economically viable[9]. This could deliver significant climate mitigation benefits (either negative- or zero-carbon emissions) within a financially viable framework that would also have a positive economic benefit at a regional scale. Initial results suggest that AD in England is under-developed both in terms of its energy generation capabilities and GHG mitigation potential.

The life cycle approach has also been used to investigate the climate mitigation potential of other energy technologies. Wiedmann *et al.* (2011) developed two different

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[8] A 'hub and pod' structure is where high-value biowastes are hygenised at a central hub. The sterilised material is then passed to local 'pods' to be anaerobically digested.

[9] Slurries and manures naturally emit methane, nitrous oxide and ammonia. However, they have very low energy content in respect of anaerobic digestion. Hence these materials are not economically viable to treat in an AD facility on their own and require supplementation with higher-energy content materials.

methodological options for hybrid life cycle assessment (hybridLCA) and were the first to apply the method to calculate emissions associated with energy generation in the UK. They showed the full global supply chain impacts of constructing off-shore wind turbines and truncation error of around 50% of emissions that results from relying on bottom-up process-based life cycle assessment data. The findings of this study provide valuable insight into the availability and robustness of approaches for informing energy and environmental policy and has since been applied to investigate the effectiveness of UK feed-in tariff (FiT) policy on reducing carbon emissions (Bush *et al.*, 2014).

3. Beyond carbon: environmental, social and economic impacts of energy technologies

Energy technologies may be associated with a range of positive and negative impacts on a host of other environmental, social and economic factors and on specific ecosystem services, not just on GHG emissions. Decision making about the proportion of the energy mix that should come from a particular technology, or concerning the deployment of particular technologies at particular sites, should be informed by detailed understandings of these impacts. There is a general acceptance of the existence of some negative impacts and the importance of avoiding, reducing or mitigating against them. For example, the concern for the sustainability of bioenergy that runs through the UK Bioenergy Strategy (DfT *et al.*, 2012) and for the avoidance of negative environmental impacts associated with tidal barrage schemes in UK estuaries (Sustainable Development Commission, 2007).Yet there remain substantial gaps in our knowledge of the nature and extent of these impacts and the conditions required to support more sustainable energy production from these sources. UKERC research has set out to address some of these important gaps in our knowledge, developing a range of tools to support both economic and environmental optimisation of the deployment of these technologies. This research has concentrated around three main energy technologies – offshore wind (section 3.1.1) and tidal energy (section 3.1.2) and bioenergy (section 3.1.3) – as well as advancing our understanding of the comparative impacts of a wider range of energy technologies over their life cycles (section 3.2).

3.1 Studies of impacts associated with individual technologies

3.1.1 Offshore wind

Within Europe, the UK has access to the best offshore wind resources and is a global leader in energy generation from this source: by 2011, it had installed more than 700 wind turbines across 15 wind farms with plans for further rapid expansion in capacity; at the time of writing, over 1000 turbines have been installed in 21 offshore wind farms (OWFs) (Department of Energy & Climate Change, 2011; The Crown Estate, 2014). As such, OWFs will occupy an increasingly substantial area of coastal waters. A series of reviews conducted by UKERC researchers has contributed to our understanding of the range of environmental, social and economic impacts associated with OWF deployment, summarised in table 1.

Environmental impacts	Social and economic impacts
• Siltation inside concrete bases could support the recovery of soft sediment communities • Change in faunal communities from those associated with sand / gravel habitats to those associated with reef habitats. • Some evidence to suggest that OWFs in the UK provide a suitable habitat for brown crabs, a commercially valuable species. Could be improved by including scour protection for OWFs built on steel monopiles or building OWFs on concrete bases instead. • Increased habitat complexity around turbines could have positive impact on biomass and species richness • Physical disturbance of seabed during construction leads to increasing turbidity and may disrupt existing benthic populations • Construction noise may have negative impacts on marine mammals and fish, with less severe impacts on invertebrates • Cables may generate electromagnetic fields, potentially impacting negatively on fish navigation • Seabirds may be negatively affected, at risk of collisions with barriers including turbines and pylons • May impact higher trophic species therefore affect predation pressure	• Fish catch decreased outside OWFs during construction but recovered post-construction. OWFs have potential to act as Fish Aggregating Devices, and the creation of protected areas may eventually improve fish catch outside OWFs • May function as artificial reefs, increasing potential catch of associated species, but more likely to be associated with low commercial value benthic and nekto-benthic species rather than the high value species associated with artificial reefs • May support aquaculture due to reduced boat traffic and anchorage • Supporting multiple uses may produce positive effects in crowded coastal zone • May displace fishing (especially using towed fishing gears) into open fishing grounds, leading to increased fuel consumption and less predictable catches and with negative impacts on species richness of benthic communities, biomass and production outside OWFs, though providing opportunities for recovery inside OWFs

Table 1: Environmental, social and economic impacts identified for offshore wind developments in UKERC research. Sources: Ashley *et al.* (2014), Hooper and Austen (2014), Mangi (2013).

UKERC research has addressed a gap in our knowledge concerning the impacts of OWFs on a range of ecosystem services. A systematic review[10] conducted by Mangi (2013) revealed a paucity of published studies explicitly considering impacts on ecosystem services: the majority of studies reviewed focused on ecological and economic effects, for example fish responses to sounds emanating from OWFs and public attitudes. Mangi (2013) set out to address this knowledge deficit by estimating the potential that the range of environmental, social and economic impacts revealed in this review might have on ecosystem services (summarised in table 2).

Supporting services	Provisioning services	Regulating services	Cultural services
• reduced primary energy capture during construction • reduced nutrient cycling	• altered food provisioning from fishing activities • altered provision of habitats (e.g. artificial reefs) with potential positive impacts on fisheries	• altered coastal defence service for near-shore windfarms • altered gas and climate regulation due to changes in the pelagic food web • positive impacts on waste and heavy metal bioremediation due to increased bivalve, crab, algae and bacteria populations around turbines	• can have a positive impact on cultural heritage and identity • may have a negative impact on the aesthetic appeal of the region and the symbolic value of the sea for some

Table 2: Potential impacts of OWF on ecosystem services based on a systematic review of relevant literature. Source: Mangi (2013).

[10] Systematic reviews use replicable strategies[10] to search large bodies of literature. This approach has several advantages: the analysis addresses specific questions; results are intended to be easily interpreted by decision makers; and, due to their replicability, these reviews can be cumulatively added to as the evidence base grows (Ashley *et al.*, 2014). This methodology, which is widely used in health research, is becoming more common in environmental studies.

3.1.1.1 Offshore wind and marine protected areas

One possible benefit of OWFs is their potential to act as *de facto* marine protected areas, since the presence of artificial reef habitat combined with reduced fishing levels (where safety concerns deter fishers from using mobile, towed gears within them) could lead to positive impacts on biodiversity and improve fish catches outside the exclusion zone (Ashley *et al.*, 2014; Hooper and Austen, 2014). Ashley *et al.* (2014) conducted a systematic review of empirical studies on the effects of OWFs and comparable artificial structures (such as MREIs, shipwrecks, sea walls, oil rigs and artificial reefs) on the abundance of marine fauna and the catches and incomes of fishing activities. They found that:

- Any increase in fish populations within OWF and resultant spillover into surrounding seas may be species-specific. Crustaceans such as shrimp and brown crab and reef-associated fish species showed the largest increases in abundance and positive effect sizes in meta-analyses, whereas decreased abundance or no increase was seen for soft sediment associated species such as flatfish.

- The species that colonise may be site-specific. Positive impacts on commercial fish populations were associated with artificial reefs that have been designed specifically for habitat mitigation or fisheries, and which were deployed in areas with commercially valued reef fish. In contrast, renewable energy structures tended to be colonised by species with low commercial value which tend to be associated with hard substrata, though there was some evidence that they may enhance populations of some commercially important species such as brown crab, pollock and cod. It is not currently clear whether OWFs have the same potential for fisheries benefits as artificial reefs.

- The introduction of OWFs and MPAs is reducing the extent of fishing grounds, concentrating fishing activity (and concomitant ecosystem impacts) elsewhere and negatively impacting upon cultural and commercially important ES.

The results of Ashley et al's (2014) study suggest that on the basis of current evidence, OWFs do not necessarily support important naturally occurring habitats and species and therefore they may not meet the criteria for MPAs, although this requires further investigation.

3.1.1.2 Impacts on fishing

The rapid increase in offshore wind developments is likely to increase conflict between the sector and other users of the coastal zone, especially those involved in the fishing industry.

Empirical research conducted by Hooper (forthcoming)[11] and Ashley (2014?)[12] explored the views of fishermen and developers concerning the utilisation of these areas.

- Ashley found that fishers' views of OWFs were influenced by the kind of fishing practice that they were involved with (categorised as mobile, such as trawling, dredging, mobile nets; or static, such as potting, fixed nets, rod and line angling) and the region in which they fished.

- Static gear fishers interviewed by Ashley perceived potential benefits in terms of increases in crab and lobster while the majority of mobile gear fishers perceived limited benefits to catches and stocks from OWFs. However, those fishers participating in Hooper's study that had set pots for crab and lobster outside OWFs (none had fished within an OWF) had not been able to successfully fish those grounds because their traps had silted up.

- In Ashley's study, the co-location of OWFs and MPAs was raised as being beneficial by static gear fishers if their access to part or all of the OWF site was maintained and mobile gear fishing activity was not allowed. For mobile gear fishermen it was perceived as being beneficial only if it saved further fishing grounds outside OWFs from being designated as MPAs.

- Hooper also conducted interviews with developers and found that many were concerned about potential damage to cables, interference with maintenance operations and liability issues that could be associated with fishing within OWFs; most were of the opinion that even so, crab/lobster fishing should be permitted within OWFs, but this should be licensed rather than open access.

- Ashley found that the preferred mitigation option for the majority of mobile gear fishermen would be to deliver improved consultation with them at the earliest stage of OWF development in order to avoid siting OWFs in important fishing grounds.

3.1.1.3 Public perceptions of impacts

Public perceptions of impacts are considered within the planning process that marine renewable energy (MRE) systems are required to go through before they are deployed. At present, few studies have investigated the value that the public places on those elements

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[11] Hooper conducted interviews with fishers in South Wales, North Norfolk and the Humber and delivered a combination of interviews and an online survey with OWF developers

[12] Ashley carried out questionnaire surveys with fishers active in Liverpool Bay, Greater Wash and Greater Thames

of the marine environment that OWFs would alter. In the one empirical study of public perceptions of impacts to an ecosystem service (following OWF deployment on the German coast of the North sea) identified in Mangi's (2013) systematic review, some people indicated negative impacts to cultural ecosystem services, but these were not valued. Placing an economic value on impacts provides a way in which to consider them within a common framework and explore trade-offs more easily.

UKERC researchers have investigated public perceptions of OWF impacts in the UK and have attempted to value these. Börger and Hooper (in preparation) examined how residents of North West England and North Wales understood and ranked the relative importance of the positive and negative environmental impacts of turbines, and whether they were willing to pay increased taxes to secure an optimum OWF design. The study considered respondents' willingness to pay to secure three OWF attributes: an increase in biodiversity, a change in turbine visibility and a reduction in the impact of electromagnetic fields. Previous studies with members of the public have tended to focus on the impact of OWFs on the seascape, but findings from this study showed that people place much greater importance on the implication of OWFs for marine life than on the negative implications of turbine visibility. The results also showed that respondents were willing to pay extra costs in order to secure OWF designs that reduced the impact of electromagnetic fields or increased the biodiversity around the turbines.

3.1.2 Tidal barrages

The UK has access to 50 TWh per year of tidal energy, which constitutes just under half of the European tidal energy resource (Hammons, 1993). Tidal power is an attractive option since it is predictable, it can provide a large quantity of energy, and technologies such as tidal barrages are comparatively long-lived, lasting up to 120 years (Hooper and Austen, 2013). Although wave and tidal energy have great potential for the UK, there are few examples of these technologies in operation. Only one tidal stream turbine has so far been deployed (in Strangford Narrows, Northern Ireland) and several wave energy and tidal stream devices are being tested in Orkney at the European Marine Energy Centre, but there are no tidal range schemes active around the UK coast (Department of Energy & Climate Change, 2011).

Estuaries with a high tidal range are most suited to harnessing tidal energy, whereas straits, headlands and other areas with large tidal currents are optimal locations for free-standing tidal stream turbines (Burrows *et al.*, 2009a). Modelling studies carried out by UKERC researchers have added to our knowledge of the potential contribution that tidal barrages could make to UK energy supply by assessing the tidal power potential that major barrages in the eastern Irish Sea could provide[13] (Burrows *et al.*, 2009a, 2009b; Wolf *et al.*, 2009). Whereas previous studies have focused on identifying how to optimise power generation from individual tidal barrages, this UKERC research has considered how to optimise generation from multiple barrages, which would potentially provide a longer generation window (Burrows *et al.*, 2009b). The findings suggest that installations on eight major estuaries could meet between 10–20% of current electricity demand (Burrows *et al.*, 2009a) while five major estuary barrages on the West Coast of the UK could reliably meet approximately half of the North West of England's present electricity demand, a similar amount to that predicted to be achieved by a Severn barrage (Burrows *et al.*, 2009b). In order to provide an incremental increase in capacity while maintaining a reasonable power balance, barrages should be introduced in pairs: for example, pairing the Severn with Solway, the Wash with Morecambe Bay and the Mersey/Dee with the Humber (Burrows *et al.*, 2009a). According to the modelling undertaken in this study, ebb-mode operation in combination with baseline turbine/sluice combinations are the most cost effective (Burrows *et al.*, 2009b).

3.1.2.1 Potential impacts of tidal barrages

Estuaries are prime locations for tidal barrages but they also tend to be important sites for conservation: the Solway Firth, Morecambe Bay, Dee, Mersey, Severn estuaries contain species and habitats protected under international legislation such as the EU Habitats and Birds Directives and the Ramsar Convention (Hooper and Austen, 2013). It is especially important to understand the potential environmental impacts that deploying tidal barrages in UK estuaries might have. UKERC researchers have contributed to this endeavour by reviewing published and grey literature, including empirical studies of existing barrages around the world (Hooper and Austen, 2013), and modelling potential impacts. Table 3 summarises a range of environmental, social and economic impacts identified in this research.

[13] These papers relate to the same project, which combined 0D with 2D modelling. 0D modelling was used to investigate the impact of turbine characteristics and operational mode on power production, taking into account the hydraulics of flow through the turbine and considering tidal range. Two programs were developed to achieve this: 'Turgency', which produces the power and outflow against head characteristics of a given turbine; and 'Generation', which integrates these turbine characteristics into a modelled barrage scheme. In contrast, the 2D model (Adcirc) uses an unstructured grid to model hydrodynamic effects either side of the barrage in detail.

Environmental impacts	Social and economic impacts
• Increased availability of hard substrate for colonisation • Reduced turbidity leads to increases in primary productivity, which can benefit filter feeders • Ecosystem can recover to some extent from some negative changes over time • Loss of intertidal habitat (mudflats, salt-marshes) with negative impacts on waders and wildfowl • Build-up of contaminants • Increased eutrophication risk • Obstruction of passage of migratory fish; collision risk to fish and marine mammals • Altered sedimentation regime and bottom stress due to currents and waves can lead to changes to benthic communities • Short term loss of marine species associated with construction and particular operating regimes	• Improved road and rail links across barrage • Potential increased water access including commercial navigation and recreation during certain modes of operation • Improved conditions for recreation upstream • Potential increase in tourism • Increased local employment • Sea defense, with flood risk protection extending up-river • Some may consider barrages an aesthetic improvement • Increased submersion time could provide additional feeding opportunities to shellfish (cockles, mussels) fisheries, provide opportunities for aquaculture and benefit shellfish predators • Erosion and outfall restriction can increase local flood risk • Increased average water level inside the basin could reduce groundwater flows and have a negative impact on land drainage • Navigation restrictions • Decreased wellbeing due to changes to seascape, noise • Potential loss of historic sites in intertidal areas • Disruption to local services (e.g. transport) during construction

Table 3: Environmental, social and economic impacts associated with tidal barrages, as identified in UKERC research. Sources: Burrows *et al.* (2009b), Hooper and Austen (2013), Wolf *et al.* (2009).

Since so few tidal energy schemes have been deployed, modelling studies are particularly important for both predicting impacts and estimate uncertainty around these predictions. UKERC researchers have been at the forefront of demonstrating the potential that unstructured hydrodynamic models have for this purpose.

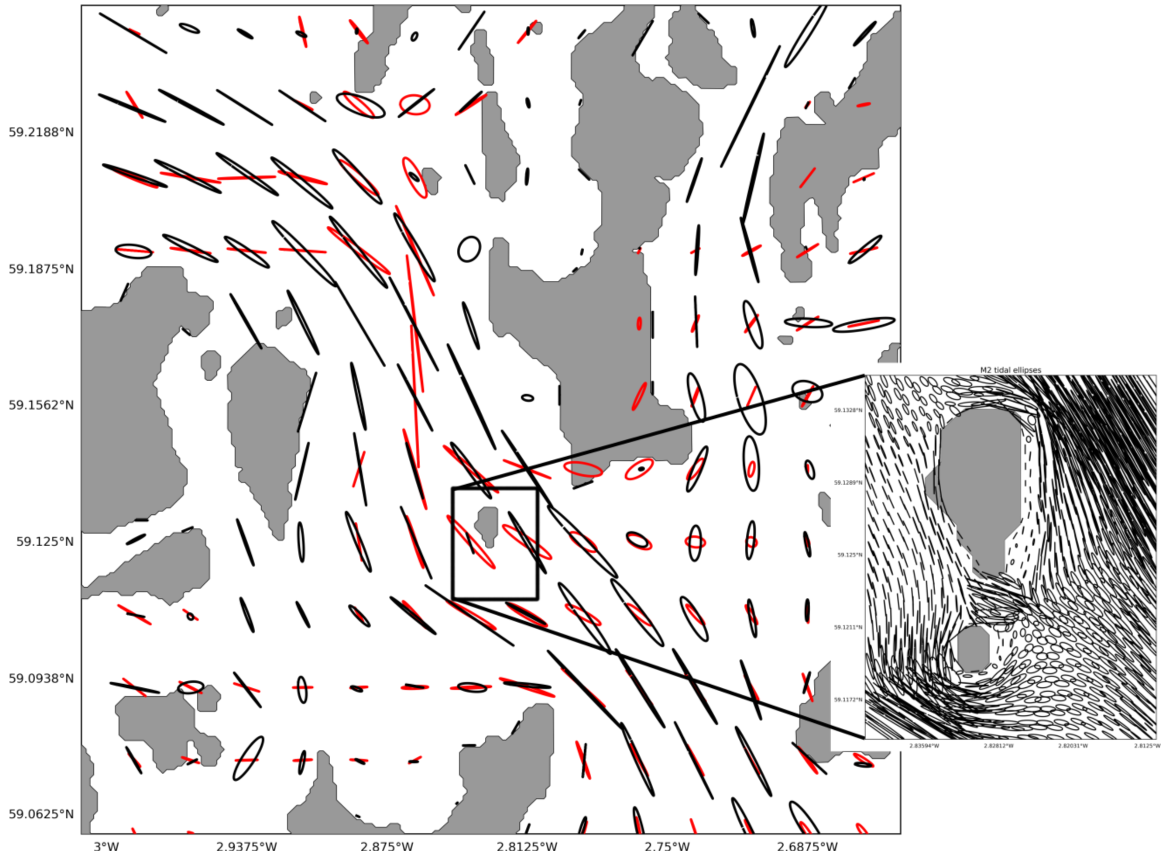

Figure 1: Subsampled comparison of the derived M2 tidal ellipses from the FVCOM unstructured model (black) of the EMEC tidal turbine test site in the Fall of Warness (Scotland) with the equivalent ellipses from the POLCOMS regularly gridded model output (red). The unstructured grid shows significant difference in the orientation of the flow due to its flexible grid resolution in areas where it is required. The zoomed section shows the calculated ellipses at the full unstructured grid resolution. Source: Pierre Cazenave

Torres and Cazenave (unpublished) have investigated the potential of the Finite Volume Coastal Ocean Model (FVCOM), which uses 3D unstructured grids, to accurately model coastal hydrodynamics. This research has shown how unstructured grids are better able to represent coastlines through the flexible distribution of grid resolution, where shallow areas, areas of interest or areas of complex flow can be represented at 10-200m resolution while areas far from the coast can be represented at 20km resolution. Compared against observed data[14], the unstructured grids were able to predict current directions and velocity

[14] FVCOM outputs were compared against forty-one coastal tide gauges from the National Tide and Sea Level Facility (NTSLF), with coincident ADCP and High Frequency (HF) radar off the north Cornish coast and with open ocean current meter data from the British Oceanographic Data Centre (BODC). The modelled

with high accuracy; they were also better able to resolve current direction than the equivalent outputs from the regularly gridded models investigated[15], due to improved coastal representation and increased resolution near the coast. These findings demonstrate that unstructured hydrodynamic models are well-suited to examining local and far-field impacts associated with marine renewable energy extraction, where resolution can be increased in target areas.

Unstructured grid models can be coupled with ecological models in order to reduce uncertainty associated with ecosystem impacts of marine energy harvesting such as on primary productivity, benthic organisms and species at higher trophic levels (Hooper and Austen, 2013). UKERC researchers have coupled FVCOM with PML's marine ecosystem model, the European Regional Seas Ecosystem Model (ERSEM) (Blackford *et al.*, 2009), in order to develop a novel modelling system capable of resolving ecological scales that has not been previously available to the UK ecosystem modelling community. This coupled hydrodynamic-ecosystem model retains all of ERSEM's present capabilities, including variable stoichiometry, bacterial processes, comprehensive food web dynamics, explicit benthic biogeochemistry and detailed carbon chemistry suitable for ocean acidification and carbon capture and storage studies.

A combined modelling approach has been used to investigate the impacts of proposed barrage developments. Wolf *et al.* (2009) predicted the likely environmental impacts on north-west UK estuaries associated with five potential tidal barrages in the eastern Irish Sea. Although the findings suggest that there would likely be no significant change in the location of tidal fronts in the Celtic and Irish Seas, these barrages would be likely to result in a range of other changes. There may be significant change in tidal amplitude, which would be particularly prominent at the coast of Northern Ireland and would increase coastal flooding risk. Tidal ranges would probably reduce around potential barrage sites with

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surface elevations and velocities were found to compare well to the observations, with a mean correlation coefficient across the tide gauge data within the domain of 0.76. Comparison of the M_2 and S_2 tidal ellipses derived from FVCOM at 249 locations against ellipses from current meter observations shows M_2 amplitudes are within an average (median) of 12cm and phases within 6° degrees across the domain. The temporal and spatial distribution of the modelled current vectors when compared with the HF radar-derived vectors shows the model is reproducing the spatial variability in the sea surface currents. This is confirmed by comparison with the in situ ADCP data collected in tandem with the HF radar data.

[15] This study compared outputs from FVCOM with published POLPRED harmonics derived from a shelf-scale regularly gridded POLCOMS model.

greatest decreases within impounded basins, leading to the loss of intertidal habitats such as mudflats and salt-marshes and concomitant negative impacts on bird populations. Further, changes to bottom stress for each potential barrage will impact upon benthic habitats, with impacts depending on the site in question. Their findings suggest that local impacts could be reduced by using a dual-mode (ebb and flood generation) scheme with more turbines than the lowest-cost option, which would retain more of the present tidal range within a basin than alternatives.

3.1.2.2 Valuing the impacts of tidal barrages

Very little is known about the value of environmental impacts associated with tidal barrages: UKERC research has set out to address this gap in our knowledge. Hooper (2014) has investigated the value of environmental impacts associated with tidal barrages, taking Taw Torridge estuary in North Devon as a case study and carrying out face-to-face and online questionnaires with a range of stakeholders (members of the public from North Devon and Wellington (Somerset) and marine science experts and other academics from Plymouth) using contingent valuation, the analytic hierarchy process and a choice experiment. Hooper found a positive willingness to pay (WTP) amongst participants, indicating that members of the public derive benefits from estuarine mudflats to the extent that they are willing to sacrifice income in order to reduce habitat loss. The research conformed to economic theory, as the factors with the most influence on WTP were income, gender, and level of environmental concern. WTP was influenced more by exposure to environmental goods rather than understanding of them: expertise in marine science was not a significant predictor of WTP, in contrast to participation in certain coastal activities and level of environmental concern. The WTP elicited in the choice experiment used in this study was not significantly different from that elicited by the contingent valuation, suggesting that the value was a robust reflection of WTP. Importantly, the findings of this study suggest that people with a particular concern for the environmental good in question are more likely to express a WTP for the good itself, while those who are less concerned may be more likely to be paying for the 'warm glow' of supporting a good cause.

3.1.3 Bioenergy

Bioenergy can be used to provide heat, electricity and transport fuel in addition to providing a disposal route for some wastes. It has some advantages compared to other sources of renewable energy: it can provide a more continuous supply, and the variety of types of biomass that can be used provide a degree of energy security (DfT *et al.*, 2012). At present, 3% of total UK primary energy consumption is provided by bioenergy, mostly from imported biomass; recent government estimates suggest that it could contribute 8-11% of total primary energy demand by 2020 and 12% by 2050, and that energy crops and agricultural residues are expected to account for the greatest growth in the supply of UK biomass (DfT *et al.*, 2012). Bioenergy has been supported by a range of policy interventions including the Renewable Obligation Order 2005, which supported the development of combined heat and power (CHP) plants, dedicated biomass burners and large-scale co-firing (Rowe *et al.*, 2009). Although incentives target power plant investors and farmers, growth in the market has been slower than anticipated. UKERC research has engaged with this issue, investigating how bioenergy production can be made economically and environmentally optimal and how supply and demand may be matched both in the present and under future climates, developing tools by which to assess this at high levels of spatial resolution (section 3.1.3.1). It has also contributed to our knowledge of the environmental and socioeconomic impacts associated with bioenergy production (section 3.1.3.2).

3.1.3.1 Supply and demand

Lovett *et al.* (2014) have mapped the potential area of land in Great Britain that is suited to and potentially available for perennial bioenergy crop cultivation. Although previous spatial studies of perennial bioenergy crops in Great Britain exist, these tend to be limited in terms of their consideration of interactions between factors such as farm economics, national-level supply and demand and changes in yield under predicted climate change. Lovett *et al.*'s study was the first step in a more holistic analysis that sets out to provide a 'whole system' perspective, taking into account a range of factors that would affect the distribution of cultivation[16]; here, rather than simply excluding land within protected areas, Lovett *et al.* took the novel approach of using thresholds of land cover naturalness scores. After applying several constraints, between 8.5 and 9 M ha (or 37-40% of land area) was found to be potentially suited to bioenergy crop cultivation, just over 7 M ha of which is in Britain (6.5 M ha in England and 0.5 M ha in Wales) (figure 2). This estimate includes land suited to food production. However, even if only land that was not of the highest value for food production (i.e. Grade 4 or 5 agricultural land) was used, this would meet current policy aspirations to 2020. Economic considerations may be a strong influence on whether or not this planting is achieved.

[16] Data sources included in the GIS analysis include the presence of urban areas, main roads, rivers, lakes, existing woodland, natural and semi-natural habitats, slopes greater than 15%, high organic carbon soils, designated areas, National Parks and Areas of Outstanding Natural Beauty, cultural heritage sites, landscape naturalness, existing plantings of energy crops and agricultural land classification.

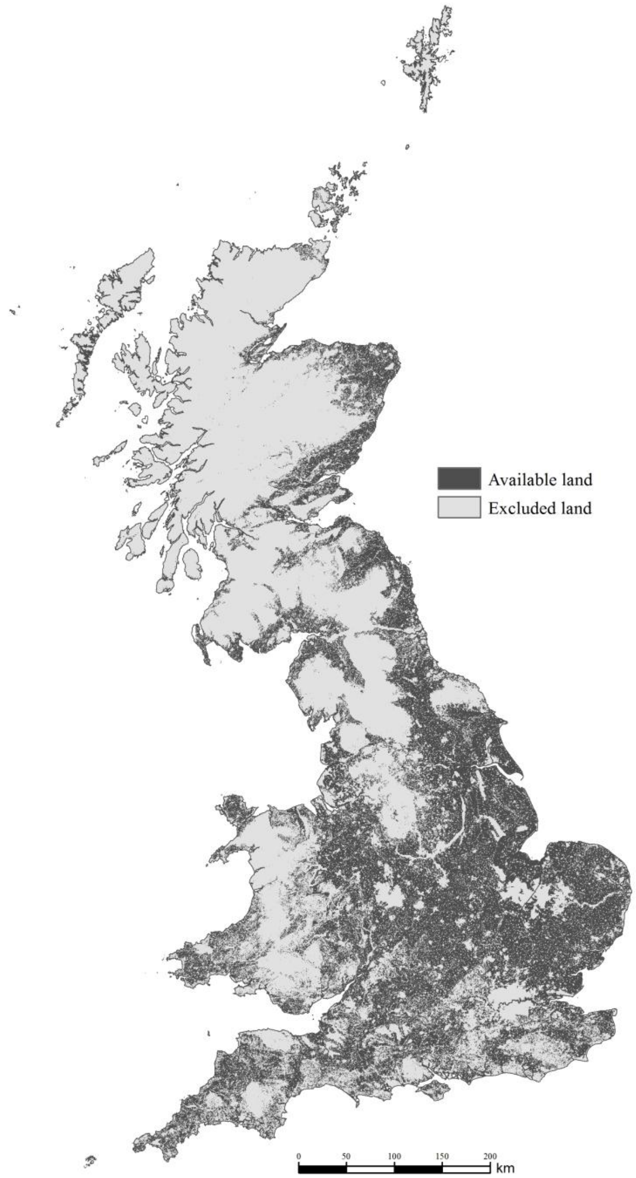

Figure 2: Land potentially available for bioenergy crop production identified by Lovett *et al.* (2014). Source: Andrew Lovett

In addition to the quantity of land available for cultivation, it is important to understand the potential yield of different bioenergy crops under different conditions in order to improve our understanding of potential supply. Estimates of potential yield can contribute to the development of robust landscape-scale scenarios that can be used to identify optimal crop mixtures at the catchment scale.

- In Pogson *et al.*'s (2012) study of the impact of collections of meteorological and soil factors on Miscanfor, a crop growth model calibrated for *Miscanthus giganteus*, it was found that collections of factors influence yield in ways that are unpredictable on the basis of single factors. On this basis they argue for investigating collections of factors rather than single factors in studies of crop growth. Since soil water parameters were found to have a significant impact on yield, Pogson *et al.* recommend that soil texture should be preserved as far as possible and soil properties monitored in order to avoid detrimental effects on crops arising from drier conditions associated with climate change.

- Tallis et al (2013) have demonstrated the suitability of ForestGrowth-SRC for predicting yield and water usage of short rotation coppice (SRC) willow and poplar across the UK, though predictions were less accurate for shallow soils or high clay contents. Predictions made using ForestGrowth-SRC were compared with empirical data from 7 trial sites (studied in detail), supplemented with data from 25 other, more diverse, sites. This study produced the first ever high resolution UK map of regional short rotation coppice (SRC) willow yield using a process-based model. High yield regions for SRC poplar and willow were identified in the north and the west of the UK, and SRC poplar was found to have a higher water use efficiency than willow at similar yields.

- In a separate study, this time focused on Great Britain and considering a wider range of perennial bioenergy crops, Hastings *et al.* (2014) investigated the potential yield of *Miscanthus*, SRC willow and poplar and short rotation forestry (SRF) poplar, aspen, black alder, European ash, Sitka spruce and silver birch, for current and predicted future climates (to 2050). Based on predictions made using a combination of process-based models (MiscanFor, ForestGrowthSRC) and an empirical-based model (ESC-CARBINE), mean yields for SRF poplar and *Miscanthus* increase while the yield for SRC poplar remains constant and the yield for SRC willow declines slightly under the medium emissions scenario (UKCP09). In both current and future climates, SRC willow had the lowest and SRF poplar the highest potential yields. Using GIS, these predicted yields were mapped at 1km^2 resolution. The highest yields for different bioenergy crops were found in different regions: for *Miscanthus* this occurred in the south west, for SRC willow and poplar highest yields were found in the north west, whereas the midlands and south east supported the highest yields of SRF poplar. This changes over time: areas where SRF poplar and *Miscanthus* yields are highest increase in size while areas where yields of SRC poplar and willow are the highest decrease, particularly in drier eastern areas. These findings suggest that a mix of feedstock types and management strategies are most likely to maximise the potential energy production from bioenergy crops across Great Britain, where species and management strategies should be optimised for different regions. It also demonstrates the important contribution that SRF poplar can make to bioenergy supply, particularly since it is a crop which tends not to be grown on high quality agricultural land and so does not compete directly with food crop cultivation. . The modelling framework developed in this study will be useful for predicting the performance of new genetic material as it is developed, so helping to select the best variant for the prevailing environmental conditions.

Predicting energy demand is of paramount importance to bioenergy supply. UKERC research has shown that CHP is the most efficient way to produce energy from bioenergy crops but in order to produce energy cost effectively, it is important to locate CHP plants close to both feedstock production and end users. At present, energy demand data is only available at limited spatial resolution, which is inadequate for the purposes of planning the optimal locations of CHP plants and bioenergy crop cultivation. Research by Taylor *et al.* (2014) has addressed this issue by predicting the spatial distribution of energy demand from buildings in Great Britain – specifically, demand for heat and non-heating electricity – at 1km^2 resolution from the present to 2050 using two scenarios developed by UKERC, 'low carbon' and 'additional policies'. These maps show concentrations of demand in urban areas, and both climate scenarios show a decrease in future heat demand in the domestic sector over time, associated with the predicted widespread take up of high efficiency heat pumps.

UKERC research has for the first time set out to match supply and demand for bioenergy crops in a series of studies which have focused on particular bioenergy crops – *Miscanthus* and SRC willow – at different scales (England, Great Britain, UK), utilising a range of methodologies including mapping, modelling and life cycle analysis (see table 4).

Focus	Methodology	Findings
Miscanthus in England (Thomas *et al.*, 2013b)	• GIS-based assessment of bioenergy potential within existing energy systems • Assessed the spatial distribution of potential supply of local feedstock (excluding unsuitable land) alongside the spatial distribution of efficient demand forms (co-firing, industrial and large-demand CHP sites, residential / district heating CHP) under a series of scenarios	• Of the 2,521,996 ha available for cultivation, 79% are within 25km of potential end users and 96% are within 40km. Potential energy generation exceeds the 2020 target for biomass generation in the UK for both radii. • The north east and central England have greatest potential for co-firing locally grown *Miscanthus*. Co-firing has potential for expansion; investing in plant adaptations for co-firing at over 10% capacity could significantly increase biomass generation if feedstock is sourced from up to 40km, but would have less impact if sourcing with 25km. • Local *Miscanthus* feedstock cannot meet all potential demand from district heating (DH), in part due to low potential for cultivation close to areas with high population density. Cultural factors may limit potential for DH in the UK. • Different forms of demand tend to cluster; it may be necessary to make allocation decisions based on comparative efficiency and GHG mitigation potential.
Miscanthus in Great Britain, supplied at optimal cost (Wang *et al.*, 2012a)	• Developed a demand-driven optimization energy crop supply model that can be used to identify both the optimal locations and capacity of biomass production (most existing models focus on just the optimal locations of facilities) and associated carbon emissions for a range of bioenergy crops and energy production technologies • Used this model to identify the best means by which to supply *Miscanthus* in Great Britain at optimal cost, taking into account the spatial distribution of predicted yield, potential cost of energy production via CHP and potential sale price of the resultant energy	• Optimal results are achieved if one CHP plant is located in each region • Location of CHP plants is strongly influenced by CHP cost • CHP cost is strongly influenced by production costs and (to a lesser extent) investment costs • The sale price of *Miscanthus* only influences the quantities sold when it is close to CHP cost

Focus	Methodology	Findings
SRC willow and *Miscanthus* in Great Britain (Alexander *et al.*, 2014)	• Mapping exercise • Matching supply with demand and taking into account economic considerations associated with bioenergy crop production and with the consumption of resultant energy	• Areas of economic bioenergy crop cultivation do not always overlap with those in which yield may be highest: for example, areas of the North West of England are economic in terms of SRC willow and Miscanthus cultivation despite not having the highest potential yield. • Since transportation of bioenergy feedstocks is associated with high financial costs and GHG emissions, it is desirable to locate bioenergy crop cultivation in close proximity to power plants. On this basis, power plants should be located within or close to regional concentrations of economic bioenergy crop cultivation; however, investors build power plants only where there is already a sufficient supply. • The optimal case would involve a network of smaller CHP plants, which differs to the present situation where bioenergy crops are co-fired in large conventional power plants.
SRC willow and *Miscanthus* in Great Britain, potential to meet demand for electricity and heat up to 2050 (Wang *et al.*, 2014)	• Economic optimization model described in Wang *et al.* (2012a) was used to model how demand could most profitably be met using these crops, predicting optimal locations and power plant capacities • Combined with process-based terrestrial biogeochemistry models (MiscanFor and ForestGrowth-SRC) to estimate yields • Mapped optimal supply and demand to 1km resolution	• SRC and Miscanthus could provide 62% of total electricity demand and 66% of total heat demand, not taking into account existing land use or farm-scale economic constraints • Areas with highest potential yield are not necessarily the same as areas where it is economically most optimal to cultivate these crops. For *Miscanthus,* highest yields are achieved in Wales, north west and south west England but the most economically optimal areas are in the south and midlands. For SRC willow, highest yields occur in the south of Scotland, Wales and north west England, but the most economically optimal areas are mostly in Scotland, the midlands and parts of the south • The spatial distribution of demand for electricity and heat, of potential yields and of potential locations of CHP plants determine the optimal spatial distribution of bioenergy crop cultivation, where yield is expected to change with the changing climate

Table 4: A summary of the approaches taken and the findings of UKERC research that has investigated how best to match supply with demand for different bioenergy crops.

3.1.3.2 Understanding the impacts of bioenergy

Increasing bioenergy production in the UK is likely to involve an increase in the cultivation of perennials, specifically a combination of rhizomatous grasses and trees for short rotation coppice and forestry. In most cases this would entail land use change with associated impacts on regulating, provisioning, supporting and cultural ecosystem services. Table 5 summarises a range of environmental, social and economic impacts discussed in UKERC research.

Environmental impacts	Social and economic impacts
• Altered interactions with the hydrologic, carbon and nitrogen cycles with impacts on hydrology and gaseous composition of soil and air – the extent to which this positive or negative depends on crop type, previous land use (more benefits compared to prior arable cultivation; fewer if replacing natural or semi-natural habitats), management regime (especially tillage) • Fewer agrochemical inputs (pesticides, fertilisers) required for perennial bioenergy crops compared to arable food crops, with potential to reduce N_2O emissions and improve local water quality • Employing no till management of perennial bioenergy crops can produce a CO_2 sink, reduce soil erosion, improve soil texture and fertility, increase soil water-holding capacity and reduce farm machinery fuel consumption • Greater farm-scale biodiversity for perennial bioenergy crops compared to arable crops • Short rotation coppice (SRC) can provide phytoremediation for contaminated soil and water • Any carbon storage associated with no till perennial cultivation may not offset carbon released due to land use change • No till management may stimulate microbial activity and consequently, N_2O emissions (varies with site-specific factors) • Possible increased water use for SRC compared to arable crops	• Landscape impacts: visual impacts associated with short rotation coppice (SRC) and *Miscanthus* cultivation include obstructing views, obscuring landscape features, rapid changes associated with harvesting, impacts on scenic quality

Table 5: The range of impacts associated with bioenergy crop cultivation discussed in UKERC research. Sources: Rowe *et al.* (2009), Tallis *et al.* (2013), Thomas *et al.* (2013b), Holland et al (in review), Lovett *et al.* (2014)

UKERC research has improved our understanding of the range of impacts associated with bioenergy production and the utility of different means of evaluating them. Thomas *et al.* (2013a) evaluated a range of methods to estimate the environmental impacts of land use change for perennial energy crops, in particular impacts on carbon, nitrogen and water cycling. Taking a multi-criteria decision analysis approach, Thomas *et al.* (2013a) applied criteria identified from the literature on impacts associated with land use change to identify which whole agroecosystem models are most suitable for estimating these impacts. Their findings indicate that DNDC, DayCent, Expert-N, ECOSSE, Ecosys, WNMM and ANIMO were the most appropriate for predicting impacts for a range of crop types, regions and resolutions and that of these, WNMM, DayCent and DNDC had been applied over the widest geographical range. A systematic review of the literature on bioenergy production from second generation feedstocks was conducted in order to highlight opportunities for the conversion of existing arable and marginal land for production. The provision of many ecosystem services in these systems could be enhanced by second generation bioenergy feedstocks (Holland *et al.*, in review). However, the study provides only general indications of the range of impacts that energy production can have on ecosystem services provision. As has been demonstrated by Lovett *et al.* (2014), to fully understand the options available it is important to consider the context in which feedstock production will take place.

Research carried out within UKERC has also made an empirical contribution to our understanding of the socioeconomic impacts associated with biofuels. As biofuels are a diverse range of energy technologies that encompass many different feedstocks and forms of production their impact on ecosystems and society will be dependent on the context in which they are produced. Wegg (unpublished) used the Social Life Cycle Assessment (SLCA) framework to identify impacts associated with sugarcane bioethanol production for transport fuel across the supply chain from the site of production in Sao Paulo, Brazil to consumers in the UK, by conducting interviews with individuals from diverse stakeholder groups that are directly affected. The distribution of positive and negative socioeconomic impacts was not as expected, with more positive impacts in the producer region and more negative impacts for consumers:

- ***Residents within the producer region***: Local people benefited from the presence of the mill[17] mainly because of its long history of sugarcane production for both the food and fuel industries and the considerable levels of corporate social responsibility practiced. The mill has contributed to the local area's economic development as well as the provision of community services including education, health, leisure activities, transport infrastructure and housing. The commitment to

[17] The Usina Sao Joao in Araras, Sao Paulo, Brazil

improved levels of sustainability and employment standards, driven by national and international initiatives associated with the production of this biofuel, has also resulted in improved environmental conditions locally. Stakeholder groups thought to be largely negatively affected were smaller-scale producers (who find it harder to compete and invest in measures to meet higher level sustainability criteria) and the least-educated workers in the industry.

- *UK consumers*: It is assumed that many UK consumers are unaware of their existing consumption of bioethanol in mandatory unleaded petrol blends. Those that are aware raised concerns including: (1) compromised consumer ethics due to the inability to select whether or not to consume bioethanol within their purchases of unleaded petrol, the lack of labelling and the inability to identify fuels meeting higher level sustainability criteria (thus achieving more positive social, economic and environmental impacts); (2) potential damage to car engines and infrastructures associated with higher proportions of bioethanol in fuel blends and associated costs (which are likely to hit people on lower incomes and in rural areas the hardest); (3) difficulty in steering policy and funding towards alternative sustainable transport initiatives, regarded as more socially acceptable and which may provide wider benefits to the economy and more sustainable outcomes (such as domestic production including local level production of biofuels from agricultural and food wastes); and (4) the extent to which reliance on imported bioethanol may realistically improve UK energy security for the transport sector.

This study highlights the potential that this type of bottom-up, participatory approach can have for improving sustainability assessments of energy technologies. Such methodologies can complement desk-based and quantitative life-cycle assessments by providing more holistic and rounded understandings of the social and environmental impacts relating to an energy technology's use. This methodology can be used as the basis for assessments and information-gathering for any type of energy technology, whether those affected in producer regions are in the same geographical location as its consumers or elsewhere, linking well with consumption-based accounting methods and ideals. Further, this kind of approach has the potential to increase the social acceptability of particular energy technology installations since the results of detailed studies of impacts in a local area can be used as the basis for knowledge-sharing, promoting the likely positive impacts and engaging stakeholders around possible negative effects. It can also be used to inform decision-making processes, tailoring actions, projects and policies to address these issues, adapting existing practices and, consequently, advancing more sustainable socio-economic or environmental outcomes.

3.2 Comparing the impacts of multiple energy technologies

UKERC researchers working on the Global Impacts project (Project 5, see Annex A) have investigated the impacts of a range of energy technologies (specifically, onshore and offshore wind; onshore and offshore gas; nuclear; and biomass) on the services provided by marine and terrestrial ecosystems for each stage of the life cycle. This study considered impacts on provisioning, regulating, supporting and cultural ecosystem services – such as those considered in the UK National Ecosystem Assessment, the Millennium Ecosystem Service Assessment and the Common International Classification of Ecosystem Services (CICES) – and constitutes the first such study that considers life cycle impacts on more than a limited set of ecosystem services.

A systematic review of published results on the local impacts of these energy technologies was conducted and the findings were categorised into the following impact groups: significant positive/negative, moderate positive/negative, no/negligible impact, conflicting and inconclusive. These local impacts were mapped onto the lifecycle stages for each technology and were predominately concentrated in the operational and decommissioning stages. Using expert opinion global ES impacts were also documented across each technology's life cycle, specifically those associated with upstream (mining, transportation), fuel cycle (processing and delivery of fuel), and downstream (deconstruction and decommissioning) stages of the technologies (see table 6).

LIFE CYCLE ECOSYSTEM SERVICE IMPACTS				
	Upstream stage (construction, mining)	*Fuel cycle stage (extraction, processing and transportation of feedstock)*	*Operation stage (generation of electricity)*	*Downstream stage (dismantling and decommissioning)*
Gas (onshore and offshore)	Predominantly negative impacts on marine and terrestrial ecosystem services (ES) for both onshore and offshore gas.	Predominantly negative marine ES impacts for offshore gas especially in cultural services, but negligible for terrestrial ES for onshore gas.	Some negative impacts in terms of regulating services (e.g. GHG emissions).	Negative impacts for offshore gas across all marine ES, however, negligible and is some instances positive for terrestrial ES for onshore gas.
Nuclear	Negative for supporting and cultural marine ES connected with the construction of intake and discharge tunnels and shipping of fuel, yet a negligible to negative impacts for terrestrial ES.	Some onshore ES impacts are negative, while for marine ES the majority are negative.	Negative for marine ES impacts, while onshore shows some positive impacts on regulating services.	Positive impacts on terrestrial regulating services.
Biomass	Negligible to negative impacts on all terrestrial ES except cultural services where the majority of impacts are negative.	Negligible for terrestrial supporting, mix of negative and positive for provisioning, mainly positive for regulating and negligible for cultural.	Moderate negative impacts in terms of regulating and cultural services (e.g. GHG emissions and visual intrusion).	Moderate positive impacts on provisioning services, negligible impacts on other services.
Wind (onshore and offshore)	Negative across all marine and terrestrial ES associated with onshore and offshore wind.	[not applicable]	Positive impacts in marine supporting services and negligible for remaining marine ES	Little information is known at present of the impacts associated with the dismantling of onshore and offshore wind turbines.

Table 6: Impacts on ecosystem services associated with different energy technologies over the life cycle

Results from this study[18] have fed into an additional study on 'Interactions between the Energy System, Ecosystem Services and Natural Capital' that was undertaken as part of the UKERC flagship project 'UK Energy Strategy under Uncertainty' (Dockerty *et al.* 2014). Specifically, these results are being applied to:

- Determine where the greatest uncertainties exist regarding the environmental impacts of generation and supply for selected future energy sources
- Place these uncertainties within wider classifications of risk and uncertainty
- Identify where conflicts or complementarities exist between current energy policies and those regarding the provision of ecosystem services
- Assess how these interactions might change in the future and whether issues regarding natural capital and ecosystem services could constrain transition options or impact upon the resilience of energy systems

The consumption based techniques developed and demonstrated for GHG emissions have been built upon to examine the ecosystem services impacts of a range of energy technologies beyond climate regulation. Researchers at the University of Southampton and University of Leeds have developed the MRIO approach to examine impacts of energy technologies on water resources. The model allows global and UK water consumption of water resources associated with different energy sectors to be described and mapped at sub-national resolution. In doing so the model provides decision makers with information on the implications of different energy sectors for water resources, and by extension human wellbeing. Ongoing work coordinated by UEA and Leeds is also using these techniques to understand land use change and associated ecosystem services impacts. More broadly, work carried out under Project 6 of the energy and environment theme has incorporated life-cycle thinking into a generalizable framework that links energy technologies to impacts on ecosystem services. This allows decision makers to understand the implications of different energy policies and assess trade-offs between action to address climate change and other environmental considerations.

[18] See:

- Holland, R., Scott, K., Wegg, T., Beaumont, N., Papathanasopoulou, E. and Smith, P. (2015). Energy Production and Ecosystem Services. Chapter submission for UKERC Global Energy book.
- Papathanasopoulou, E., Holland, R., Dockerty, T., Scott, K., Wegg, T., Beaumont, N., Sünnenberg, G., Lovett, A., Smith, P. and Austen, M. (2015). Energy and ecosystem service impacts. Chapter submission for UKERC Global Energy book.

4. Persistent issues

In the course of undertaking this research, persistent issues relating to the existence, availability or quality of data on impacts were identified (discussed in section 4.1) in addition to issues around how information about impacts tend to be communicated (discussed in section 4.2).

4.1 Data gaps

At present, the environmental impacts of energy technologies are not always properly evaluated: there are issues around the suitability of existing monitoring (4.1.1), the availability of data (section 4.1.2), inconsistencies between datasets (4.1.3) and the appropriate validation of models (4.1.4). In order to enable the sustainable implementation of energy technologies and GHG mitigation technologies and minimise environmental impacts, these issues should be addressed and, specifically, more rigorous monitoring and validation procedures must be built into environmental management.

4.1.1 Inadequate monitoring

Regulations associated with renewable energy deployment require some degree of monitoring, but UKERC researchers have found that this can be lacking. For example, there is no universal or EU-wide requirement for the prediction of impacts of land use change for bioenergy projects, such that some kinds of impacts (e.g. relating to carbon and nitrogen fluxes) may be included more often than others (e.g. evapotranspiration). Also, although IPCC guidelines do exist for GHG emissions associated with land use change in general and impacts associated with nitrogen inputs, their application is variable: typically, the least data intensive approach is taken (Thomas *et al.*, 2013a).

Monitoring associated with OWF deployment can also be problematic. Reviews carried out by Mangi (2013) and Hooper and Austen (2014) found that this monitoring may:

- Be of variable quality and precision
- Involve variable survey designs, monitoring equipment and sampling techniques, some of which may be inappropriate
- Incorporate limited or no baseline information for specific OWF sites
- Involve small sample sizes
- Include no controls

- Either not carry out repeat surveys, or these may be carried out by different contractors using different methods, such that it is not possible to identify change over time
- Involve statistical analyses that are not always consistent or correct
- Focus on individual factors (e.g. species) but not interactions between them
- Not always include commercially important species such as crabs and lobsters, or the hard substrate habitats where they are likely to be found

There is a need for detailed monitoring that utilises improved, standardised survey designs and sampling techniques; includes baseline studies and studies post-construction, carried out over extended periods across different seasons; and that takes account of a wider range of impacts including detailed studies of changes in community structure and impacts on commercially important species and the habitats that they favour (Ashley *et al.*, 2014). Environmental impact assessments should be improved by considering not just direct social and economic impacts but also impacts on the environment by considering impacts on ecosystem services and the value of their benefits, enabling the comparison of these different impacts in the same units (Mangi, 2013).

4.1.2 Inadequate data availability

In many cases, there is insufficient data available from which to adequately assess impacts associated with the deployment of energy technologies. The systematic review of the local and global ecosystem service impacts associated with a range of energy technologies discussed in section 3.2 highlighted the sparse availability of empirical data from which to draw definitive conclusions, finding that the majority of studies use models to predict impacts or comprise reviews. This review study also found that significant gaps exist in our knowledge of particular impacts associated with particular stages of the life cycle for particular energy technologies. Research activity should focus on addressing these gaps.

To focus on one energy technology, there is inadequate data available at sufficiently high resolution and quality to monitor the impact of OWFs on ecosystem services and, consequently, to appropriately value them. Studies of the impacts of OWFs have only been undertaken for a limited number of sites and only for 1-2 years post-deployment, which is partly attributable to the comparatively short time since they have been introduced into the marine environment (Ashley *et al.*, 2014). There is also insufficient data at appropriate spatial scales to adequately value impacts on food provisioning services delivered by the marine environment; in order to do this it would be necessary to produce high resolution, high quality data on the size of catches, the value of landings, where the landed fish were caught and the number of people employed in the fishing industry (Mangi, 2013). Data gaps also exist concerning impacts associated with the displacement of fishing activity, impacts on cultural ES at appropriately high levels of disaggregation, and impacts on gas and climate regulation following OWF deployment (Ashley *et al.*, 2014; Mangi, 2013).

4.1.3 Inconsistencies between datasets

Data collection and policy implementation relating to energy technologies often differs between devolved administrations in the UK. Gaining access to data from different agencies can be time-consuming and there can be inconsistencies between different datasets. This can require further time-consuming work in order to get the data into a comparable form so that they can be used together or even lead to the exclusion of some datasets. For instance, in Lovett *et al.*'s (2014) study of potential land availability for perennial bioenergy crop cultivation, considerable effort was required to compile consistent datasets for England, Scotland and Wales (i.e. Great Britain) but Northern Ireland data was excluded from consideration due to such difficulties. In order to facilitate analysis of impacts and resource potential for more than one country, standardised approaches to dataset production should be implemented.

4.1.4 Inadequate validation of models

Modelling studies are undoubtedly a useful and informative approach to understanding impacts associated with energy technologies, especially when – as with tidal barrages in the UK – there is little empirical evidence available. It is imperative to validate models well, but UKERC researchers have discovered that there is still a need to validate some models for at least some applications. The lack of a systematic evaluation of the uncertainty in predictions for resource potential and impacts is a significant issue, especially for industry and government investment.

Gaps were found in model validation for renewable energy technology deployment in both terrestrial and marine environments. Thomas *et al.*'s (2013a) comparison of a range of agroecosystem models that could be used to predict ecosystem impacts following land use change for bioenergy cultivation identified a need for further research in order to establish the applicability of each of these models for both arable and perennial crops, for a range of climates (dry, cool and temperate) and a range of locations. At the moment, only some of this validation has been done for some of the models. In addition, the limited data available relating to below ground processes for bioenergy crops, which is due in part to the difficulty of measuring this reliably, has serious implications for the extent to which it is possible to precisely and accurately model the impact of bioenergy crop cultivation on GHG balances (Tallis *et al.*, 2013).

In the marine environment, numerical modelling has seen fast development over the last two decades and it is increasingly being used for the evaluation of marine energy extraction impacts on the whole marine system, yet large gaps remain for reliable energy resource modelling (Black & Veatch, 2005). For example, there are still only a small number of energy resource assessment models that account for the devices in the marine environment and their feedback on the resource (Wolf *et al.*, 2009). The gaps are more critical when considering the evaluation of all factors (physical and ecological) contributing to the environmental footprint of MRE devices. Current assessments of hydro-environmental impacts generally focus on relatively small modelling domains (i.e. areas of sea), ignoring the potential for cumulative impacts of large and very large arrays of MRE devices and with simplistic array parameterisation that fails to capture the complex energetic impacts of marine energy extraction. The combination of short term and larger scale changes to the marine environment can affect multiple aspects of physical and chemical oceanography (e.g. Neill *et al.*, 2009), with potential effects on primary productivity and the entire trophic chain. These can combine to modify the connectivity between stretches of coast with implications for marine planning and management of MPAs and Marine Conservation Zones. Overall, there is an urgent need for (i) more accurate predictions of marine energy resources, (ii) assessment of the impact of installations on the marine environment (physical and ecological), and (iii) measures of uncertainty. While UKERC has taken steps to develop the necessary framework and modelling tools, these need to be implemented to perform a thorough assessment. The use of a model ensemble approach would constitute a critical step towards providing reliable predictive tools for improved decision-making.

4.2 Improving the acceptability of energy technologies

Public acceptability can be an important influence on whether or not energy technologies are deployed in particular places (Devine-Wright, 2007, 2005a, 2005b; Ekins, 2004; Parkhill *et al.*, 2013). People tend to be largely supportive of renewable energy technologies and there is evidence that the British 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 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, 2005b; Gross, 2007; Toke, 2005; Upham and Shackley, 2006; Walker *et al.*, 2010, 2007; Warren *et al.*, 2005; Wüstenhagen *et al.*, 2007). This section considers ways in which information about impacts (section 4.2.1) and the ways in which lay publics are engaged (section 4.2.2) could be improved to support increasing levels of public acceptability for energy technologies.

4.2.1 Information

At least in part, problems of social acceptability can be due to an information deficit. The discourse around energy technologies tends to emphasise energy security, economic growth and GHG emissions; 'ecosystem services' and related terms rarely feature, which might be expected to make them seem less important. A lack of familiarity with, and understanding of, ecosystem services could also mean that lay publics may be inclined to place less value on them.

Lay publics may be sceptical about the extent to which energy technologies deliver the benefits that are claimed for them and desire access to evidence that can assist in their ability to make informed choices about trade-offs (Parkhill *et al.*, 2013; Rowe *et al.*, 2009). However, sound, impartial, up-to-date, clearly communicated information about the full range of impacts – both positive and negative – may not be readily available. Detailed analyses of likely impacts at different scales, such as those discussed in sections 2 and 3, can go some way towards addressing this gap, if research findings are communicated to lay publics in forms that are easily accessible.

Greater attendance to localised impacts relating to particular energy technologies could lead to changed perceptions of an entire energy technology. For example, high-level debate about biofuels has been characterised by controversy and opposition, leading to much policy uncertainty in the sector. This controversy can be attributed in part to the nature of the information about biofuels that has been disseminated, which does not always reflect the considerable diversity amongst feedstocks and practices within the system that determines the extent to which particular biofuels can achieve sustainable outcomes. However, UKERC-funded research conducted by Wegg (UEA, discussed in section 3.1.3.2) found a surprising level of support for biofuels amongst interviewees under certain circumstances. Biofuels produced locally from genuine wastes were particularly popular as these were associated with a range of local benefits including improved energy security; economic development through learning, skills and employment; and greater efficiencies through the provision of more locally sustainable solutions.

4.2.2 Public engagement

Engaging with lay publics should not solely consist of efforts to inform about those impacts identified and defined by experts such as academics, policymakers and industry representatives. Instead, two-way communication can support improved social acceptability of energy technologies. There is already growing interest in participatory and deliberative methods to explore the extent to which different aspects of the marine environment are valued by different stakeholder groups, the results of which can feed into multi-criteria decision analysis (Mangi, 2013). Findings from social life cycle assessments, such as the investigation into socioeconomic impacts across the supply chain for biofuel production discussed in section 3.1.3.2, can bring to light impacts at the local level but also identify the basis for any concerns. This kind of approach can help to bring potential ecosystem impacts into focus not just for those communities likely to be affected, but also for those seeking to install particular technologies in those particular places. In combination with improved monitoring and data sharing (discussed in section 4.1), this could support both lay publics and experts in making informed choices about the acceptability of particular trade-offs, enabling developers to provide locally tailored solutions that may be both more acceptable to local communities and realise more positive impacts. In order to achieve this strong interdisciplinary partnerships are required, bringing together social, natural and physical scientists, communication specialists and members of local communities, including community-level intermediaries such as skilled local facilitators or 'green ambassadors' of different kinds.

Local scale approaches such as this could impact positively on public engagement in energy futures, supporting a progression from consultation to local partnerships, co-management, supply and profit share (Devine-Wright, 2005b). However, this would require flexible and tailored support at all levels and increased support from the government (Hargreaves *et al.*, 2013; Seyfang *et al.*, 2013a). The social and economic benefits of community energy go beyond sustainable energy. People get involved with community energy schemes for a range of reasons including community development and empowerment, increased local resilience, social inclusion and cohesion, tackling fuel poverty and saving money, economic regeneration or gaining skills and creating jobs locally (Seyfang *et al.*, 2013b). Building these opportunities into the design of sustainable energy technologies alongside the provision of information about potential ecosystem service impacts is therefore likely to promote higher levels of social acceptance and engagement, providing an opportunity to promote learning about ecosystem services as well as a range of other benefits.

There may therefore be important benefits to be gained from improving the ways in which we communicate about ecosystem services and building the outcomes of public engagement more systematically into sustainability appraisals. Public engagement should seek to support effective communication between local communities and other stakeholders, sharing information that is clear, concise, accessible and delivered in a range of ways. Public engagement exercises could be tailored to address local concerns and should be characterised by two-way communication, informed by research into likely ecosystem service impacts at the local level. Where the deployment of energy technologies responds to these concerns, there is increased potential to improve social acceptability of these technologies both locally and further afield, which would support efforts to reach the UK and EU targets for renewable energy production.

5. Conclusions

UKERC research has demonstrated the need to use full assessments of the implications of different energy strategies on local, national and global ecosystem services when designing policy. In order to do this successfully, the following areas are highlighted for future action:

- It is widely acknowledged that GHG emissions are a global problem requiring coordinated effort from global communities. UKERC research points towards this being the same for other ecosystem services. Energy and environment policy must be designed to reflect this. Furthermore, the creation of the Intergovernmental Platform on Biodiversity and Ecosystem Services in 2012 suggests that the international community may be required to place greater emphasis on the need to balance the impacts of energy technologies on ecosystem services alongside those on GHG emissions.

- Ecosystem service impacts are often indirect or not immediately apparent, temporally or spatially. Consequently, they are less likely to be recognised (especially in the marine environment, where they are even less apparent). Better tools are needed to support decision-making, enabling informed choices to be made on the trade-offs between impacts in the present and impacts in the future. In part, this will involve establishing what the potential consequences would be of not taking action to protect ecosystem services in the present and estimating associated levels of risk. Tools such as scenario development that address key issues (e.g. financial costs, food security, flood risk) can help but it is important that assessments are made across the whole system.

- There are gaps in the extent to which ecosystem service impacts are currently monitored and the availability of existing data to the research community. Open data is essential in order to be able to achieve a comprehensive understanding of impacts. Robust monitoring frameworks are required with stronger regulation to enforce their use and the sharing of resultant data.

- At present, messages about ecosystem service impacts have not been refined in order to ensure that they are easily understood by non-experts across multiple stakeholder groups. A clear and consistent vocabulary is required. Messages should be tailored for clarity to different audiences in order for them to be able to make informed choices, for example regarding their support for individual technologies, investments or their willingness to pay to avoid the risk of negative consequences if no action is taken. Support is also necessary for better communication between stakeholders.

- Given the success of raising awareness of GHG emissions and getting action to address them it is useful to ask what can be learned from this and applied to other environmental and ecosystem service impacts.
- There is considerable scope for improving the degree to which bottom up, participatory approaches are used within life-cycle assessments. This would bring forward information relating to the social impacts of particular technologies, enhance datasets concerning their impacts – both positive and negative – and help shape policies across public and private sectors, which would likely increase levels of social acceptance and take-up.

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Annex A: Projects, investigators and researchers

Project 1: Evaluation of the global impact of the UK's carbon footprint

Led by:	John Barrett (Leeds)
Co-investigators:	Jan Minx (formerly Stockholm Environment Institute), Tommy Wiedmann (formerly SEI)
Researchers:	Anne Owen (Leeds)

Project 2: Development of tools for assessing the environmental impact of energy exploitation / carbon abatement in the marine environment and optimisation of opportunities for improved sustainability

Led by:	Mel Austen (PML)
Co-investigators:	Nicola Beaumont (PML), Tobias Börger (PML), Pierre Cazenave (PML), Jason Holt (NOC), Tara Hooper (PML), Corinne Le Quere (UEA), Alex Souza (NOC), Ricardo Torres (PML), Judith Wolf (NOC)
Researchers:	Matthew Ashley (PML), Eleanor Carter Silk (UEA, PML), Phillip Hall (NOC), Andy Lane (NOC), Stephen Mangi (PML)

Project 3: Development of tools for assessing integrated approaches to sustain and improve water and soil quality in the context of exploiting bioenergy resources

Led by:	Kevin Hiscock (UEA)
Co-investigators:	Alan Bond (UEA), Jason Chilvers (UEA), Andrew Lovett (UEA), Jane Powell (UEA), Gill Seyfang (UEA)
Researchers:	Amy Thomas (UEA), Rob Tickner (UEA), Tina Wegg (UEA)

Project 4: Spatial mapping and evaluation of energy crop distribution in Great Britain to 2050 *

Led by: Pete Smith (Aberdeen)

Co-investigators: Eric Casella (Forest Research), Jon Finch (CEH), Steven Firth (Loughborough), Andrew Lovett (UEA), Dominic Moran (SAC), Gail Taylor (Southampton), Simon Taylor (Loughborough)

Researchers: Peter Alexander (SAC), David Allinson (Loughborough), Iwona Cisowska (CEH), Trudie Dockerty (UEA), Astley Hastings (Aberdeen), Jon Hillier (Aberdeen), James Morison (Forest Research), Mohammed Quddus (Loughborough), Gilla Sünnenberg (UEA), Mat Tallis (Southampton), Chao Wang (Loughborough), Shifeng Wang (Aberdeen)

Project 5: Assessing the global and local impacts on ecosystem services of energy provision in the UK *

Led by: Pete Smith (Aberdeen)

Co-investigators: Mel Austen (PML), John Barrett (Leeds), Nicola Beaumont (PML), Andrew Lovett (UEA)

Researchers: Trudie Dockerty (UEA), Tara Hooper (PML), Gilla Sünnenberg (UEA), Joana Nunes (PML), Eleni Papathanasopoulou (PML), Ana Queiros (PML), Kate Scott (Leeds), Shifeng Wang (Aberdeen)

Project 6: A global framework for quantifying the ecosystem service impacts of oil and biofuel production *

Led by: Felix Eigenbrod (Southampton)

Co-investigators: Rob Ewers (Imperial), Val Kapos (UNEP WCMC), Ann Muggeridge (Imperial), Jorn Scharlemann (Sussex), Gail Taylor (Southampton)

Researchers: Gareth Brown (Imperial), Liz Farmer (WCMC), Rob Holland (Southampton), Kate Scott (Leeds)

Project 7: Complete analysis of the UK energy system using a hybrid I-O LCA framework

Led by: John Barrett (Leeds)

Co-investigators: Tommy Wiedmann (formerly SEI)

Researchers: Adolf Acquaye (formerly SEI), Kuishang Feng (formerly SEI), Kate Scott (Leeds)

Project 8: Interactions between the Energy System, Ecosystem Services and Natural Capital, part of Uncertainties Flagship project

Led by: Andrew Lovett (UEA)

Co-investigators: Nicola Beaumont (PML)

Researchers: Trudie Dockerty (UEA), Eleni Papathanasopoulou (PML)

*Note: Projects marked with a * were funded by UKERC's Research Fund.*

Annex B: Acronyms

AD	anaerobic digestion
CCS	carbon capture and storage
CEH	Centre for Ecology & Hydrology
CHP	combined heat and power
CICES	Common International Classification of Ecosystem Services
CO_2	carbon dioxide
DH	district heating
EE-MRIO	environmentally extended multi-region input-output model
ERSEM	European Regional Seas Ecosystem Model
ES	ecosystem services
FiT	feed-in tariff
FVCOM	Finite Volume Coastal Ocean Model
GHG	greenhouse gas
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle analysis
MCA	multi-criteria decision analysis
MEA	Millennium Ecosystem Assessment
MPA	Marine Protected Area
MREI	marine renewable energy installation
NEA	UK National Ecosystem Assessment
NOC	National Oceanographic Centre
OWF	offshore wind farm
PML	Plymouth Marine Laboratory
POLCOMS	Proudman Oceanographic Laboratory Coastal Ocean Modelling System
SAC	Scottish Agricultural College
SLCA	social life cycle analysis
SRC	short rotation coppice

SRF	short rotation forestry
TEEB	The Economics of Ecosystems and Biodiversity initiative
UKERC	UK Energy Research Centre
UNFCCC	United Nations Framework Convention on Climate Change
WTP	willingness to pay

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