# UKERC Energy Strategy Under Uncertainties

## Interactions between the Energy System, Ecosystem Services and Natural Capital

### Working Paper

April 2014

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UK Energy Research Centre UKERC/WP/FG/2014/010

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UKERC is undertaking two flagship projects to draw together research undertaken during Phase II of the programme. This working paper is an output of the Energy Strategy under Uncertainty flagship project which aims:

- To generate, synthesise and communicate evidence about the range and nature of the risks and uncertainties facing UK energy policy and the achievement of its goals relating to climate change, energy security and affordability.
- To identify, using rigorous methods, strategies for mitigating risks and managing uncertainties for both public policymakers and private sector strategists.

The project includes five work streams: i) Conceptual framing, modelling and communication, ii) Energy supply and network infrastructure, iii) Energy demand, iv) Environment and resources and v) Empirical synthesis. This working paper is part of the output from the Environment and resources work stream.

# Executive Summary

This working paper is an output of the UKERC ***Energy Strategy under Uncertainty*** flagship project which aims:

- To generate, synthesise and communicate evidence about the range and nature of the risks and uncertainties facing UK energy policy and the achievement of its goals relating to climate change, energy security and affordability.
- To identify, using rigorous methods, strategies for mitigating risks and managing uncertainties for both public policymakers and private sector strategists.

This research examines the impacts and uncertainties on ecosystem services (ES) and natural capital both within the UK and externally, relating to possible changes in power generation within the UK energy system.

It reviews the current state of evidence on the environmental impacts of generation and supply for **nuclear**, **gas**, **onshore wind**, **offshore wind** and **biomass** (domestically produced *Miscanthus* and Short Rotation Coppice as a feedstock for power generation) as these feature strongly in future energy mix scenarios through to 2030 presented in the 4th Carbon Budget. For natural gas there was also assessment of the potential consequences given wider adoption of carbon capture and storage (CCS) techniques and fracking.

The impacts on ecosystem services of each supply option were summarised in a series of matrices. Each matrix sought to describe the energy supply system under evaluation in terms of the life-cycle processes involved (rows) and their impacts on ecosystem services (columns). Life cycle stages were categorised as **upstream** (infrastructure provision**), fuel cycle** (extraction/production and processing of feedstock), **operation** (power production) and **downstream** (decommissioning). Twenty seven ecosystem services were classified as **supporting** (processes and functions), **provisioning** (nutrition, water, materials, energy), **regulation and maintenance** (wastes, flow; physical, chemical and biotic environment) and **cultural** (use and intrinsic value).

Within each matrix the different types of impact were scored (positive, neutral, negative, conflicting and unknown). Matrices were prepared for '**local**' impacts (i.e. within UK) and '**global**' impacts (i.e. impacts resulting from UK energy use arising outside of the UK).

Scores for local matrices were based on conclusions from individual research papers identified through a systematic literature review process. The global assessments stemmed from a broader appraisal of the available information and expert opinion.

Both methods had merits and limitations; both included a degree of subjectivity as allocation of scores was based on the judgement and subject knowledge of the researcher. In addition the outcome of the systematic literature review is inevitably influenced by the selection of parameters such as the type of study included (experimental/observational versus modelling or review) and the construction of search terms. However, adopting the matrix and scoring system provided a structure to the process that made analysing wide-ranging and disparate data on impacts across ecosystem impacts at different stages of energy lifecycles for different fuels, as comparable as possible.

It was notable from the systematic literature review that the body of research tended to focus on a small selection of ecosystem impacts in narrow areas of the energy life cycle. This 'clumping' of research gave rise to a further complication as different pieces of work on the same subject could reach contrasting conclusions regarding impacts, and hence scores, so a further process was needed to allocate a final score to the relevant part of the matrix. Wherever possible the score was based on the modal value (as indicative of a consensus view), but if there was a wide range of scores the final assignment represented the range of views.

The actual matrices (spreadsheets) used to record results were enormous (700 to over 1,100 data points) and finding appropriate ways to summarise the data was challenging. Data for each energy system is provided as bar and pie charts, with summarised scores in each of the four lifecycle and ecosystem service category headings. Key impacts both locally (within the UK) and globally (external to the UK) for each energy system are described.

As the global matrices were compiled on the basis of researcher/expert knowledge and a broad but general information search, in many of the matrices it was possible to allocate a likely score to the majority of cells in the matrix. As the local matrices were populated via a more in-depth analysis that produced data that was rather more specific, many of the cells in these matrices have no data and appear in the graphical representations as 'unknown'.

Across all energy types many of the upstream impacts occur mainly outside of the UK (global), and are associated with the mining, processing and importation of construction materials (e.g. concrete and steel production etc.) used to build the energy supply infrastructure. UK-based upstream impacts relate largely to the siting and construction of power stations and wind farms.

**Biomass**: The vast majority of studies identified in the systematic review related to the growth cycle of the crop (fuel cycle) though spanning a reasonably broad number of ES impacts. Negative impacts were reported on water availability; there were mixed views on the contribution of *Miscanthus* and SRC to bioremediation; positive impacts on soil and water quality, regulation of the biotic environment, pest & disease control. No local downstream impacts were identified from the literature but the global matrix records positive impacts relating to reduced water use when converting land back to conventional agriculture compared to biomass crops. This would equally apply to the UK.

**Natural Gas**: As most of the UK's gas currently comes from offshore sources most of the local impacts reported relate to the marine environment. Negative impacts associated with extraction of gas were reported for benthic organisms (urchins, copepods and sediment), mussels and sediment within the fuel cycle stage. There are also onshore negative impacts relating to emissions and pollution issues in both the fuel cycle and operational stages (processing and transmission). The global matrices for both onshore and offshore processes reflect the results in the local matrices. The positive downstream impacts in the global matrix relate to relate to decommissioning and perceived cultural benefits due to the removal of onshore and offshore infrastructure.

**CCS and fracking**: As the 4th Carbon Budget places emphasis on the introduction of Carbon Capture and Storage (CCS) in relation to the continued future use of natural gas and as the government considers wider licencing of fracking to access unconventional onshore gas resources, additional literature reviews were undertaken to provide insights into environmental impacts relating to these technologies. These reviews took an international perspective because there is not yet enough literature focused on the UK. For CCS negative impacts included leaching of the capstone and potential leakage of $CO_2$ from hydrocarbon fields or deep saline aquifers. For fracking the literature reported negative impacts on water availability, pollution of groundwater/aquifers (drinking water), leakage of methane into the atmosphere, earthquakes and impacts on the biotic environment and human health. Notably, there is also the prospect that fracking, by causing fissures, may have negative implications for CCS implementation.

**Nuclear**: The UK relies on imported uranium for nuclear power generation hence negative impacts associated with mining and other fuel cycle processes occur overseas. There are additional negative marine impacts associated with shipping, though not confined specifically to transporting nuclear fuel. Within the UK, offshore operational impacts relate to cooling water intake and discharge of waste waters and point to the generally negative impact on supporting services due to the decrease in the abundance and functioning of seabed (benthos) organisms; negative impacts on regulating services due to decreased biodiversity of particular marine organisms and negative impacts on cultural services due to harmful algal blooms and damaged benthic ecosystems. Other onshore impacts are those associated with cultural services (implications of radiation and human health), regulating services (through atmospheric regulation) and supporting services (avian mortality, terrestrial ecotoxicity).

**Onshore Wind**: As wind is a freely available resource there are no fuel cycle impacts. Upstream local impacts related mainly to mixed cultural views on wind farm development (e.g. regarding visual impacts). The literature also focused on bird and bat strikes during the operational stage.

**Offshore Wind**: A variety of local ecosystem services impacts associated with UK offshore wind were reviewed and no or negligible impacts were recorded for provisioning, regulating and cultural in the operational life cycle stage. These were predominately based on research articles investigating the impacts on fish and birds. Positive impacts were recorded for provisioning services based predominately on articles associated with increased abundance of demersal fish species, while significantly negative impacts on marine mammals during the construction upstream life cycle stage were recorded. Global impacts relate to mining/extraction and shipping of construction materials.

Impacts on **supporting**, **provisioning** and **regulating** ecosystem services were mostly associated with the **fuel cycle** and **operational** stages of energy system life cycles. The main beneficial impacts relate to offshore wind and biomass through supporting ecosystem function/atmospheric regulation, with the addition for biomass of soil and biodiversity benefits over conventional agricultural land uses. Interestingly, it notable that the largely conflicting/negative scores for **cultural** ecosystem indicators relate mostly to **upstream** and **downstream** stages of the energy systems – i.e. are associated with the built infrastructure. Information on **downstream** impacts for renewable energies was scant, presumably as the technologies are relatively new.

This project has attempted to assemble in a systematic way, a wide range of information across all life cycle stages and 27 ecosystem services, for the main energy types that feature in government plans for the future. The disappointing number of studies resulting from the systematic reviews may be due to limitations in the approach or search terms, or be indicative of a real lack of data. Studies were 'clustered' into relatively small areas of energy life cycles or related to relatively few ecosystem service indicators.

No sensitivity analysis has been applied to the results which are presented here in a simple summary form. The implicit assumption in the way the data has been summarised is that each individual impact cell is commensurate (i.e. of equal importance). Of course, this may not be true, but to include differential weighting or valuation of impacts would substantially complicate the work involved and, more importantly, is probably not merited given the currently immature state of knowledge regarding impacts on many ecosystem services.

Potential future impacts on ecosystem services are discussed in relation to potential future power generation mixes produced by the Committee on Climate Change: **ambitious nuclear**, **ambitious renewables**, **ambitious CCS** and **higher energy efficiency**. In terms of the uncertainties associated with ecosystem service impacts it is important to highlight that all four of the scenarios will have upstream consequences outside of the UK and downstream ones within it. The limited research on such impacts is therefore an issue for all four alternatives and highlights the need to further develop techniques and databases to link local consumption decisions with global consequences through identification and appraisal of supply systems. Exploring ways to rank and mitigate UK impacts on natural capital globally is also highlighted in the recent recommendations of the Natural Capital Committee (2014), so this may well be an area in which there is important scope for a common focus of energy and environmental policies.

A second important aspect of uncertainty concerns cultural ecosystem services. Issues of public acceptability are of great importance for the transformation of the UK energy system. Variations in public attitudes are central to many conflicting assessments of impacts on cultural services. It is also very apparent that there is a growing issue with respect to the introduction of fracking in the UK. Nevertheless, it is important to emphasise that public acceptability is not a static phenomenon and could well change over time.

Overall, it does not appear that any of the impacts or uncertainties regarding ecosystem services identified in this report are sufficient by themselves to obviously rule out any of the four CCC transition alternatives. More importantly, all four should also result in fewer negative impacts on ecosystem services and natural capital than the current reliance on fossil fuels such as oil or coal and would be an improvement on both the current energy generation mix and options which involved greater reliance on fracking.

# Contents

# Introduction

## Background and rationale

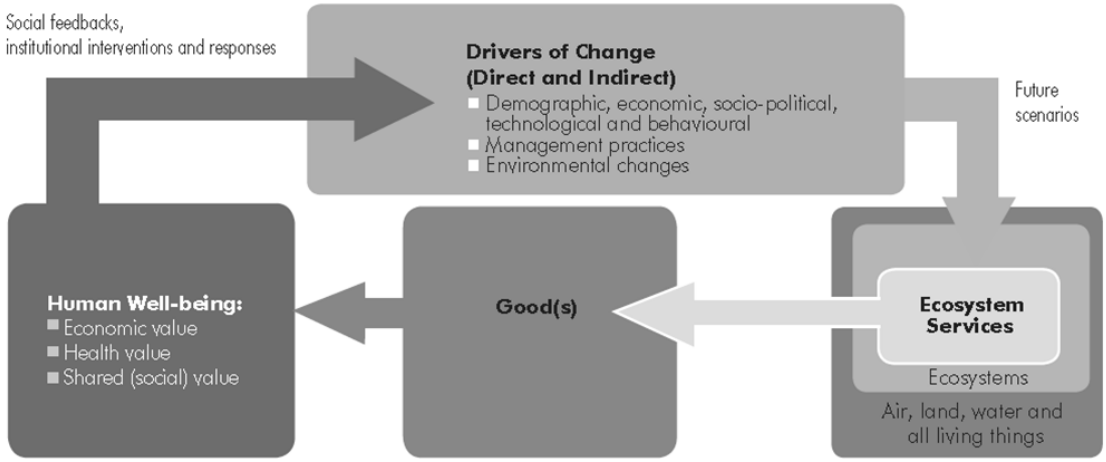
The UK government has set ambitious goals to reduce carbon emissions and transform the national energy infrastructure (HM Government, 2011a; Department of Energy & Climate Change, 2013). This will involve substantial economic, social and environmental changes that will need to occur in the presence of a series of scientific, technological, geopolitical, economic, and social uncertainties. In order to systematically address the question of risk and uncertainty in energy policy and strategy, UKERC has initiated an ambitious cross-theme flagship project, *Energy Strategy under Uncertainty*, which will draw together and extend research undertaken during Phase II of the research programme. The flagship project focuses particularly on implications for the UK and on uncertainties through to 2030. To provide a reference for the assessment of uncertainties the project also concentrates on the possible pathways discussed by the Committee on Climate Change (CCC) in their 4$^{th}$ Carbon Budget report and subsequent update (CCC, 2010; 2013a).

The research discussed in this working paper is one output from the above flagship project and examines the interactions between energy and environmental systems, particularly in terms of the impacts of possible changes in power generation within the energy system on ecosystem services and natural capital. It builds on previous UKERC research conducted as part of the *Energy and Environment* theme (particularly a Research Fund project on *Assessing the Global and Local Impacts on Ecosystem Services of Energy Provision in the UK*) and aims to provide an overview of the nature and magnitude of uncertainties regarding such interactions and impacts. The remainder of this section introduces the concepts of ecosystem services and natural capital, and then sets out the structure of the subsequent parts of this working paper.

## Ecosystem services and natural capital

Ecosystem services (ES) are commonly defined as the outputs of ecosystems from which people derive benefits (Millennium Ecosystem Assessment, 2005). As conceptualised by the UK National Ecosystem Assessment, and shown in Figure 1, ecosystem services provide goods that contribute to human well-being, while human activities in turn feedback to influence drivers of change that impact on ES (Mace *et al.*, 2011).

**Figure 1: Conceptual framework from the UK National Ecosystem Assessment.**




Source: Mace *et al.*, 2011, p.13).

There is considerable debate as to how types of ES should be categorised (e.g. de Groot *et al.*, 2002; Fisher *et al.*, 2009), but the current international CICES initiative (Haines-Young and Potschin, 2012) makes a distinction between provisioning, regulating and cultural components. Provisioning services supply goods such as food and fuel, regulating services include provision of climate or pollution control and cultural services encompass the supply of recreational or spiritual benefits. Some ES typologies also include a category of supporting services (e.g. nutrient cycling or soil formation); while others argue that they are better regarded as intermediate processes rather than final services (Fisher *et al.*, 2009). Table 1 lists different categories of ES, drawing particularly on the CICES classification.

### Table 1: Categories of ecosystem services

| Level 1 | Level 2 Description | Level 3 Description | Abbreviation |
|---|---|---|---|
| Supporting | | Processes and functions (e.g. nutrient cycling, photosynthesis) | SUP |
| Provisioning | Nutrition | Terrestrial plants and animals for food | PNT |
| | | Freshwater plants and animals for food | PNF |
| | | Marine plants, algae and animals for food | PNM |
| | Water Supply | Water for human consumption | PWH |
| | | Water for agricultural use | PWA |
| | | Water for industrial and energy uses | PWI |
| | Non-food Biotic Materials | Plant and animal fibres and structures | PMP |
| | | Chemicals from plants and animals | PMC |
| | | Genetic materials | PMG |
| | Energy | Biomass based energy | PEB |
| | | Renewable abiotic energy | PER |
| Regulation and Maintenance | Regulation of Wastes [Regulation of bio-physical environment] | Bioremediation | RWB |
| | | Dilution, filtration and sequestration | RWD |
| | Flow Regulation | Air flow regulation | RFA |
| | | Water flow regulation | RFW |
| | | Mass flow regulation | RFM |
| | Regulation of Physico-Chemical Environment | Atmospheric regulation | RPA |
| | | Water quality regulation | RPW |
| | | Pedogenesis and soil quality regulation | RPP |
| | | Noise regulation | RPN |
| | Regulation of Biotic Environment | Lifecycle maintenance, habitat and gene pool protection | RBL |
| | | Pest and disease control (incl. invasive alien species) | RBP |
| Cultural | Physical/Experiential Use of Ecosystems (environmental setting) | Non-extractive recreation | CPN |
| | | Information and knowledge | CPI |
| | Intellectual Representations of Ecosystems (of environmental settings) | Spiritual & symbolic | CIS |
| | | Non-use | CIN |

Source: based on the Common International Classification of Ecosystem Services (CICES, Version 4.1; Haines-Young and Potschin, 2012), with the addition of a 'Supporting' category. The abbreviations in the final column are referred to later in this working paper.

Another relevant concept is that of natural capital (NC) which can be defined as "those elements of nature which either directly provide benefits or underpin human wellbeing" (Natural Capital Committee, 2013, p.11). In essence, NC represents the stocks from which flows of ES occur and these assets in combination with other sorts of capital provide benefits which enhance human wellbeing. NC underpins all other types of capital including human capital (e.g. knowledge, time and skills), manufactured capital (e.g. factories and machines), and social capital (e.g. the quality of relationships including trust and connectedness) and so is the foundation on which economic prosperity and societal wellbeing depend (Natural Capital Committee, 2014a).

The NC and ES concepts have become very influential in environmental policy during recent years, particularly because they provide a more integrated framework for addressing many key issues and policy challenges. For instance, the Natural Environment White Paper published in 2011 states "We will put natural capital at the centre of economic thinking and at the heart of the way the way we measure economic progress nationally" (HM Government, 2011b, p.4). However, at present there are still many challenges in translating these concepts down to the level of everyday implementation (Vira *et al.*, 2011; Natural Capital Committee, 2014b).

## The scope and objectives of the research

As part of the UKERC *Energy and Environment* theme several PhD studentship and Research Fund projects have investigated the impacts of current and prospective future energy generation on other ecosystem services. These include:

- Evaluating the global impact of the UK ecological/carbon footprint of energy production/carbon abatement technologies (PhD project, University of Leeds)
- Developing tools for assessing the environmental impact of energy exploitation/carbon abatement in the marine environment and to optimise opportunities for improved sustainability (PhD project at Plymouth Marine Laboratory (PML) and University of East Anglia (UEA))
- Assessing integrated approaches to sustain and improve water and soil quality in the context of exploiting bioenergy resources (PhD project, UEA)
- Spatial mapping and evaluation of energy crop distribution in Great Britain to 2050 (Research Fund project led by University of Aberdeen, also involving researchers at the Centre for Ecology and Hydrology, Forest Research, Scottish Agricultural College, University of Southampton and UEA)
- Assessing the global and local impacts on ecosystem services of energy provision in the UK (Research Fund project led by University of Aberdeen, also involving researchers from Leeds, PML and UEA)
- A global framework for quantifying the ecosystem service impacts of oil and biofuel production (Research Fund project led by University of Southampton and Imperial College London)

Within these studies there have been a series of developments regarding methodologies and indicators to help better understand the relationships between the energy system and NC/ES, but they have also highlighted considerable uncertainties regarding such interactions (e.g. in the marine environment or in cumulative terms) and some of the dilemmas that can arise regarding conflicts in the provision of ecosystem services (e.g. food vs. fuel, land sparing vs. land sharing debates) (Phalan *et al.*, 2011; Valentine *et al.*, 2012; Bateman *et al.*, 2013).

The aim of this research was therefore to build upon insights from existing UKERC projects to provide an overview of the uncertainties regarding prospective changes in power generation within the UK energy system and interactions with ecosystem services and natural capital. The approach adopted could also be applied to materials required in other areas of the energy system e.g. smart grids or demand side technologies, but is not investigated in this study. Specific objectives were to:

- Review the current state of evidence on the environmental impacts of generation and supply for selected energy sources.
- Determine where the greatest certainties and uncertainties exist in terms of consequences for ecosystem services and natural capital.
- Place the identified uncertainties within wider classifications of risk and uncertainty such as those reviewed in Work Stream 1 of the *Energy Strategy under Uncertainty* flagship project (Davies *et al.*, 2014)
- Assess the implications of these uncertainties for the transition pathways presented in the 4th Carbon Budget, particularly whether issues regarding ecosystem services or natural capital could constrain transition options or impact upon the resilience of the energy system
- Identify where conflicts or complementarities exist between current energy policies and those regarding the provision of ecosystem services, and then consider how these interactions might change through to 2030.

The next section of this working paper describes the methodology used to assess the impacts on ecosystem services of different energy supply options. In particular, it outlines the approach to systematic review and discusses some of the issues involved in implementing such a method. Results from the reviews are then presented as a series of graphs to highlight the extent of positive or negative impacts and indicate where research effort has been focused. This material subsequently provides the basis for identifying where the greatest uncertainties exist in terms of consequences for ecosystem services, both in terms of different energy supply options and life cycle stages.

A final section discusses the implications of the findings in terms of the types of uncertainties identified, the extent to which they might have consequences for the transition pathways presented in the 4th Carbon Budget, the degree of conflict between energy polices and those concerned with the provision of other ecosystem services, and priorities for future research.

# Methodology

## Overview of approach

The broad emphasis of UK energy policy is for decarbonisation of the energy system through to 2050 by continued switch from coal to natural gas for power generation, with an increasing contribution from nuclear power and renewables (primarily onshore and offshore wind and biomass), furthered by the introduction of carbon capture and storage (CCS) to existing and future power stations (HM Government 2011a; CCC, 2013).

To reflect these pathways the energy supply sources selected for evaluation in this study were natural gas, nuclear, onshore and offshore wind and locally produced biomass (as a feedstock for power generation). These feature strongly in many scenarios of UK energy futures (e.g. Ekins *et al.*, 2013; CCC, 2013). Coal was not included as it plays a declining part in such energy mix supply scenarios to 2050 (CCC 2013a). The selected sources also encompassed both the marine and terrestrial environments and had been the subject of significant previous research in UKERC Phase II. Given current policy debates it was also decided that for natural gas there would be an assessment of the potential consequences given wider adoption of carbon capture and storage (CCS) techniques and fracking.

The impacts on ecosystem services of each supply option were summarised in a series of matrices. Each matrix sought to describe the energy supply system under evaluation in terms of the life-cycle processes involved (rows) and their impacts on ecosystem services (columns). The approach to defining life cycle stages was informed by the general framework presented in IPCC (2012) supplemented by further literature review. Ecosystem services were categorised according to the 27 Level 3 headings in Table 1 (based primarily on Haines-Young and Potschin, 2012). This resulted in the general framework shown in Table 2. Each energy supply option had a different number of life-cycle processes (see Appendix 1) so each matrix varied in the final number of cells.

**Table 2: General example of framework used to assess energy supply options**

| | Ecosystem Services | | | |
|---|---|---|---|---|
| Life Cycle Stages | Supporting | Provisioning | Regulation and Maintenance | Cultural |
| Upstream | | | | |
| Fuel Cycle | | | | |
| Operation | | | | |
| Downstream | | | | |

The matrices were compiled in several different ways. Firstly, separate matrices were developed for impacts on the terrestrial and marine environments. Secondly, a distinction was made between *local* impacts (i.e. occurring within the UK) and those which were *global* in scope (i.e. occurring outside of the UK but related to UK use of the energy). These two scales of impact were evaluated in different ways, the local impacts being evaluated through a systematic literature review process and the global ones through a 'broad-brush' approach based on researcher experience and internet-sourced general information. These two methods are discussed in further detail below. Producing separate matrices in this way made it feasible to assess whether impacts varied between the marine and terrestrial environments and by spatial scale, but for subsequent comparative purposes most of these individual matrices were amalgamated to provide an overview of a particular supply option.

Within each matrix the different types of impact were scored using the categories listed in Table 3. In the local reviews this was based on conclusions from individual research papers and in the global assessments it stemmed from an appraisal of the available information and expert opinion. During both processes there were occasions where findings were conflicting and these instances were recorded as such. It also proved necessary to find a means of summarising the large amounts of information in each matrix and for this purpose a graphical technique was employed.

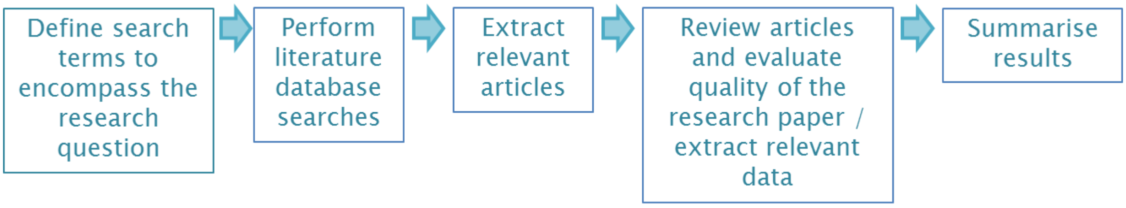
**Table 3: The categories used to score different types of environmental impacts**

| | | | |
|---|---|---|---|
| ++ | Significant positive (beneficial) impact | -- | Significant negative (detrimental) impact |
| + | Moderate positive impact | - | Moderate negative impact |
| 0 | No (or negligible) impact | +/- | Conflicting impacts |
| n/d | No data | n/a | Not applicable |
| ? | Inconclusive (Not known/direction of impact uncertain) | | |

## Implementing the systematic local reviews

Systematic reviews are widely used in health research and are becoming more common in environmental studies (e.g. Collaboration for Environmental Evidence, 2013). Implementing such a review typically involves five main stages as shown in Figure 2. The first step requires the research question to be stated and search terms relevant to each of its elements (such as type of energy technology, ecosystem service etc.) to be noted. These terms are then used to perform the database searches and are inputted into the selected search engines. Articles sourced from these searches are then examined against a list of inclusion criteria to determine whether they are relevant. All articles deemed suitable are then reviewed in full, data extracted and results summarised.

**Figure 2: The main stages in a systematic literature review**




Important advantages of the systematic review process concern replication and comparability, but the experience of conducting such reviews has highlighted a number of important issues that need to be considered. These include:

- **What types of research articles should be considered (e.g. observational, experimental, modelling, meta-analyses or reviews)?**

  All of the energy supply options were reviewed on the basis of including only *empirical studies conducted in the field or in the laboratory*, i.e. **observational** or **experimental** research. The Web of Science database was used for all searches. These decisions on scope reflected researcher judgement, library advice and the time available to complete the reviews. To assess the effect of expanding these boundaries the analysis for biomass and natural gas (onshore impacts) was extended to include ecosystem service impacts identified in **modelling studies**, and **meta-analyses** (of which there are many in relation to evaluating environmental impacts) along with **review** articles. The databases GreenFILE (biomass and gas) and Scopus (biomass only) were also searched, providing insights into the consequences of changing the search definitions. For grey literature relating to marine impacts the Aquatic Sciences and Fisheries Abstracts (ASFA) database was also consulted.

  Taking biomass and on-shore natural gas as an example, Table 4 shows the contribution of each database and each study type category to the research results. Although Web of Science returned the majority of results, the analysis indicates that including other databases does extend coverage, particularly with GreenFILE for biomass.

  The inclusion of modelling studies, meta-analyses and review articles has the benefit of allowing more search results to be included in an analysis, but because the same basic research may be cited in more than one modelling study or review article it can give rise to some double counting. Just over 61% of all articles found for biomass were modelling or review articles and 54% (including meta-analyses) for on-shore Gas (Table 4). The potential for double counting has not been addressed in Table 4 as this broader analysis was simply for comparative purposes.

The choice of databases is inevitably governed by practicality. In this study, (with the exceptions discussed above) all searches were based on ISI Web of Science, restricted to core data sets, articles from 1993 onwards (i.e. last 30 years), in English. All results presented are based only on experimental/observational studies unless otherwise mentioned.

**Table 4: Summary of articles found by database and study type for biomass and natural gas (onshore)**

| **Study Type** | **Biomass Databases queried** | | | | **Natural Gas (onshore) Databases queried** | | |
|---|---|---|---|---|---|---|---|
| | Web of Science | Scopus | GreenFILE | Total | Web of Science | GreenFILE | Total |
| EL= lab experiment | – | – | 3 | 3 | 1 | – | 1 |
| EF = field experiment | 20 | 2 | 7 | 29 | 38 | 13 | 54 |
| OB = observational | 2 | – | – | 2 | 7 | 2 | 9 |
| MA = meta-analysis | – | – | – | 0 | 27 | 5 | 32 |
| MO = modelling study | 23 | 1 | 10 | 34 | 29 | 1 | 31 |
| RV = review | 8 | 1 | 11 | 20 | 8 | 3 | 10 |
| All Articles | 53 | 4 | 31 | 88 | 110 | 24 | 134 |
| Percentage of Total | 61 | 4 | 35 | 100 | 82 | 18 | 100 |

- **Which databases should be included?**

Citation databases enable searches for references to previously published works cited by authors in their bibliographies. However, not all publications are included in these databases. It may take several years before new journals are considered suitable for inclusion in a reputable database and in addition, books and other types of publication are generally not included. As an example, the IPCC reports which provide an important synthesis of research relating to climate change and energy use are not present in Web of Science or the other databases examined in this study. Such contrasts can give rise to differences in coverage within and between disciplines. For example, databases such as Web of Science and Scopus tend to be more comprehensive in their coverage of medical and science research than social sciences or humanities (University of Washington Libraries, 2014). Table 4 indicates that research on natural gas was better represented in Web of Science than that on biomass (82% of total articles found compared with 61% for biomass). However, in any study resource constraints also apply: the greater the number of search engines included, the larger the number of articles to be sourced and appraised.

- **How should search terms be defined?**

Additional issues arise over the construction of search terms used to query a database. The descriptions of the ecosystem services under examination (Table

1) provided the basis for the terms included. Separate tables of search terms were developed for each energy type and situation (onshore/offshore). Refinement of search terms was iterative. Finding the 'Goldilocks Zone' of search terms (not too wide as to include unwanted references; not too tight as to exclude wanted references) is an art-form in itself. Table 5 gives examples of how varying a search string influenced the number of records returned. In this instance removing the broad term 'biomass' better focussed the results on papers of closer relevance to the full topic.

### Table 5: Effects of experimenting with search terms

| | Search String - Example 1 | No. of Records | Search String - Example 2 | No. of Records |
|---|---|---|---|---|
| Original | TS= ((“Biomass*” OR “biomass crop” OR “energy crop*”) AND (“Ecosystem service*” OR “Environment* impact*”)) | 1782 | TS= ((“Biomass*” OR “biomass crop” OR “energy crop*”) AND (“photosynthesis” OR “pollinat” OR “nutrient cycl*” OR “nutrient fl*” OR “nutrient loss” OR “biogeochemical cycl*”OR “nitrogen cycl*” OR “fl* of nitrogen” OR “nitrogen fl*” OR “denitrification” OR “nitr* leaching” OR “leaching of nitr*” OR “cycling of carbon” OR “carbon*” OR “primary prod*” OR “secondary prod*”)) | 48,920 |
| Revision A | TS= ((“biomass crop” OR “energy crop*”) AND (“Ecosystem service*” OR “Environment* impact*”)) | 124 | TS= ((“biomass crop” OR “energy crop*”) AND (“photosynthesis” OR “pollinat” OR “nutrient cycl*” OR “nutrient fl*” OR “nutrient loss” OR “biogeochemical cycl*”OR “nitrogen cycl*” OR “fl* of nitrogen” OR “nitrogen fl*” OR “denitrification” OR “nitr* leaching” OR “leaching of nitr*” OR “cycling of carbon” OR “carbon*” OR “primary prod*” OR “secondary prod*”)) | 402 |
| Revision B | TS= ((“biomass crop” OR “energy crop*” OR “Miscanthus*” OR “elephant grass” OR “SRC” OR “short rotation coppice” OR “wood energy” OR “energy coppice” OR “willow” OR “salix” OR “poplar”) AND ("United Kingdom" OR "UK " OR "England" OR "Scotland" OR "Ireland" OR "Wales") AND (“Ecosystem service*” OR “Environment* impact*”)) | 22 | TS= ((“biomass crop” OR “energy crop*” OR “Miscanthus*” OR “elephant grass” OR “SRC” OR “short rotation coppice” OR “wood energy” OR “energy coppice” OR “willow” OR “salix” OR “poplar”) AND ("United Kingdom" OR "UK " OR "England" OR "Scotland" OR "Ireland" OR "Wales") AND (“photosynthesis” OR “pollinat” OR “nutrient cycl*” OR “nutrient fl*” OR “nutrient loss” OR “biogeochemical cycl*”OR “nitrogen cycl*” OR “fl* of nitrogen” OR “nitrogen fl*” OR “denitrification” OR “nitr* leaching” OR “leaching of nitr*” OR “cycling of carbon” OR “carbon*” OR “primary prod*” OR “secondary prod*”)) | 73 |

## Scoring the research articles

Effects on ecosystem services and scores from the final set of articles were recorded in an impact matrix spreadsheet (see general framework in Table 2). A hypothetical example is shown in Table 6. This simplified illustration is included because the full detail of an actual analysis cannot be presented in readable form on an A4 page.

The example energy system has a total of 18 life cycle stages of which eight have local impacts (i.e. occurring within the UK) assessed by systematic literature review. Each article found by the review (Table 6a) was assessed for impacts, and the appropriate score from Table 3 was allocated to the relevant cell in the matrix (top half of Table 6b). For instance, cell 1F was assigned a negative score based on results in Article 1. The numbers of individual cell scores were then summed for broader life cycle and ES categories (see bottom half of Table 6b), then reformatted as percentages (Table 6c) and used to generate graphs (Table 6d).

## Table 6: Hypothetical example of literature review output and matrix scoring process

a) Literature review output (cell reference indicates life cycle stage and ES indicator). Note that some articles (e.g. Article 3) produced multiple scores

| Article | Cell Reference | Score |
|---|---|---|
| Article 1 | 1F | – |
| Article 2 | 5D | 0 |
| Article 3 | 8D , 8H | – , – |

b) Inputting and summarising scores

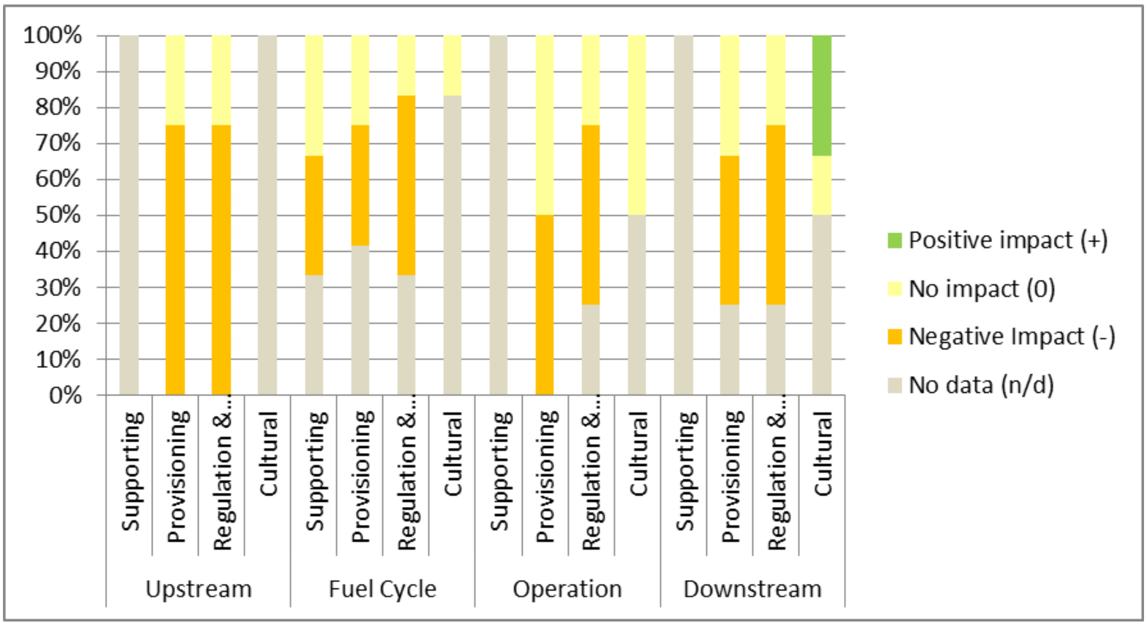
| Life Cycle Stages | | Local | Ecosystem Services | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Supporting | Provisioning | | | | Regulation and Maintenance | | | | Cultural | |
| | | | A | B | C | D | E | F | G | H | I | J | K |
| Upstream | 1 | Y | n/d | – | – | 0 | – | – | 0 | – | – | n/d | n/d |
| | 2 | | | | | | | | | | | | |
| | 3 | | | | | | | | | | | | |
| | 4 | | | | | | | | | | | | |
| Fuel Cycle | 5 | Y | – | n/d | – | 0 | n/d | 0 | 0 | n/d | 0 | n/d | 0 |
| | 6 | Y | 0 | – | n/d | 0 | 0 | n/d | 0 | – | – | n/d | n/d |
| | 7 | Y | n/d | – | n/d | n/d | – | n/d | 0 | n/d | 0 | n/d | n/d |
| Operation | 8 | Y | n/d | 0 | 0 | – | – | n/d | 0 | – | – | 0 | n/d |
| | 9 | | | | | | | | | | | | |
| | 10 | | | | | | | | | | | | |
| | 11 | | | | | | | | | | | | |
| | 12 | | | | | | | | | | | | |
| | 13 | | | | | | | | | | | | |
| | 14 | | | | | | | | | | | | |
| Downstream | 15 | Y | n/d | n/d | – | – | 0 | n/d | 0 | – | – | n/d | + |
| | 16 | Y | n/d | n/d | – | – | – | n/d | 0 | – | – | n/d | 0 |
| | 17 | Y | n/d | n/d | 0 | 0 | 0 | n/d | 0 | – | – | n/d | + |
| | 18 | | | | | | | | | | | | |
| Stages relevant at local scale | | 8 | | | | | | | | | | | |
| **Sum of Scores:-** | | | **Supporting** | **Provisioning** | | | | **Regulation and Maintenance** | | | | **Cultural** | |
| Upstream – n/d | | | 1 | | | | | | | | | 2 | |
| Upstream – – | | | | 3 | | | | 3 | | | | | |
| Upstream – 0 | | 1 | | 1 | | | | 1 | | | | | |
| Upstream – + | | | | | | | | | | | | | |
| Fuel Cycle – n/d | | | 1 | 5 | | | | 4 | | | | 5 | |
| Fuel Cycle – – | | | 1 | 4 | | | | 6 | | | | | |
| Fuel Cycle – 0 | | 3 | 1 | 3 | | | | 2 | | | | 1 | |
| Fuel Cycle – + | | | | | | | | | | | | | |
| Operation – n/d | | | 1 | | | | | 1 | | | | 1 | |
| Operation – – | | | | 2 | | | | 2 | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Operation – 0 | 1 | | 2 | 1 | 1 |
| Operation – + | | | | | |
| Downstream – n/d | 3 | 3 | 3 | 3 | 3 |
| Downstream – – | | | 5 | 6 | |
| Downstream – 0 | | | 4 | 3 | 1 |
| Downstream – + | | | | | 2 |
| Total life cycle and ES combinations at local scale | 8 | 8 x 1 ES = 8 | 8 x 4 ES = 32 | 8 x 4 ES = 32 | 8 x 2 ES = 16 |

c) Reformatting scores to prepare for graphical display

| **Life Cycle** | **ES Category** | **No data (n/d)** | **Negative Impact (–)** | **No impact (0)** | **Positive Impact (+)** |
|---|---|---|---|---|---|
| Upstream | Supporting | 1 (100%) | | | |
| | Provisioning | | 3 (75%) | 1 (25%) | |
| | Regulation and Maintenance | | 3 (75%) | 1 (25%) | |
| | Cultural | 2 (100%) | | | |
| Fuel Cycle | Supporting | 1 (33%) | 1 (33%) | 1 (33%) | |
| | Provisioning | 5 (42%) | 4 (33%) | 3 (25%) | |
| | Regulation and Maintenance | 4 (33%) | 6 (50%) | 2 (17%) | |
| | Cultural | 5 (83%) | | 1 (17%) | |
| Operation | Supporting | 1 (100%) | | | |
| | Provisioning | | 2 (50%) | 2 (50%) | |
| | Regulation and Maintenance | 1 (25%) | 2 (50%) | 1 (25%) | |
| | Cultural | 1 (50%) | | 1 (50%) | |
| Downstream | Supporting | 3 (100%) | | | |
| | Provisioning | 3 (25%) | 5 (42%) | 4 (33%) | |
| | Regulation and Maintenance | 3 (25%) | 6 (50%) | 3 (25%) | |
| | Cultural | 3 (50%) | | 1 (17%) | 2 (33%) |

d) Graph of row percentages from Table 6c




Evaluating the articles inevitably involves some judgements on the part of the researcher undertaking the review. Benefits (e.g. regarding greenhouse gas amelioration) may be relative (e.g. gas is 'better' relative to coal; biomass is 'better' relative to gas or peat). In addition, articles may indicate a general direction of impact, but it is difficult to decide whether the impact is 'significant' (i.e. + + or – –) or 'moderate' (i.e. + or –). For example, according to a paper by Christian and Riche (1998, p.131) "The results show that *Miscanthus*, once established, can lead to low levels of nitrate leaching and improved groundwater quality compared to arable crops." In this case the score allocated was a '+' for moderate water quality regulation during the growth cycle. As a rule, for biomass, unless the paper mentioned 'significant' either in words or statistically, the impact was scored as 'moderate'. In the case of gas a score of '– –' was generally attached to major impacts involving substantial volumes of un-remediated potential pollutants, whereas '–' was reserved for anything less. Scores of '+/–' were quite rare and assigned to only to situations such as where a balance between the pollution caused and a naturally occurring bio-remediation was reported. A larger choice of possible scores would have been unhelpful since it would have simply exacerbated the inevitable subjectivity of the process.

Throughout the review of articles care was taken to score only the impacts reported in a study and not inferred consequences. For example, in relation to gas extraction, 'produced water' is water trapped in underground formations that is brought to the surface along with oil or gas that requires large-scale storage, treatment and disposal. A study on the topic of large-scale storage and remediation of sodic co-produced waters also clearly implies the requirement for a storage area and so adds to the land-take associated with the site (i.e. habitat loss) and similarly, probable impacts on soil health. However, if such impacts were not expressly discussed by the study, they were not scored. Conversely, where an article mentioned some effect that fell within the scope of the study the result was added to the matrix even if this information was not the focus of the paper e.g. "it is estimated that a trillion litres of sodic co-produced waters are a bi-product of production from this site annually …".

For some research it was quite straightforward to identify to which cell in the matrix a score should be assigned (e.g. the Christian and Riche example given previously). In the case of biomass, for example, the vast majority of the research was concerned with the growth cycle of the crop, with some additional studies on wider impacts e.g. on landscape, on loss of land for food production, and others on the comparative benefits over fossil fuels. For all of the energy supply options relatively little research was found on upstream impacts associated with infrastructure (e.g. construction of power stations) or downstream issues such as decommissioning because there is currently little experience of such activities.

This 'clumping' of research gave rise to a further complication as different pieces of work could reach contrasting conclusions regarding impacts, and hence scores, so a further process was needed to allocate a final score to the matrix. Wherever possible the score was based on the modal value (i.e. the most frequently occurring value) – as indicative of a consensus view, but if there was a wide range of scores the final assignment represented the range of views (e.g. – / +). For many cells the degree of agreement was in the range 60% to 80%, but there were also cases where grouping research article results to fit within individual matrix cells hid certain impacts. One example was in the biomass matrix in terms of atmospheric regulation services where the overall greenhouse gas benefits of biomass crops resulted in predominantly positive scores. However, the subsequent modal assignment masked research on other emissions relating to biomass crops – e.g. volatile organic compound emissions from *Miscanthus* and short rotation coppice willow (Copeland *et al.*, 2012) with negative impacts. Since the degree of consensus is a useful indicator of the uncertainty associated with such environmental impact assessments there are tables in the Results section summarising the levels of agreement identified, though it should be noted that these values are dependent on how the matrix cells are defined and the literature considered (e.g. only experimental and observational studies or also modelling and review papers).

## Implementing the global 'broad-brush' assessments

Global impacts associated with the energy technologies were based on researcher knowledge and general literature reviews, verified by experts. The process included firstly identifying which of the life cycle stages and their activities would have predominately global impacts, i.e. those which occur outside of UK borders. Each lifecycle stage was then considered with respect to the 27 types of ecosystem services and an impact score assigned. These scores followed the definitions listed in Table 3, i.e. impacts were considered to be significantly negative/positive, moderately negative/positive, no/negligible, inconclusive or conflicting impacts.

Consultation with experts outside the research team, but from within the host institutions or involved in other elements of the UKERC Energy and Environment theme was used to verify the resulting assessments. The merit of this approach was that a wider range of impacts could be covered quite quickly, but unlike the systematic reviews it was not possible to make any assessment of the degree of consensus underpinning the evaluations.

In this consultation/expert review process, three experts were identified based on their knowledge and experience. Each expert was contacted and once they had accepted the invitation, an information pack was sent to them by email. The pack consisted of three documents. The first document explained what the research aimed to achieve, the role of the expert in the review process, the steps needed to be completed, and a description of the two remaining documents: the global ecosystem service impacts matrices and the scoring justification document. The global ecosystem service impacts matrices contained the completed matrices for each of the technologies and a description of the scoring impacts used. The scoring justification document explained the reasoning behind each of the scores recorded in the matrices.

Reviewers were asked to review the impact matrices in-conjunction with the justification document and to note whether they agreed or disagreed with the impacts stated. Provision was made both in the matrices and in the justification document for the experts to note their opinion. The experts were also asked to comment on whether any impacts had been missed in the assessment, what in their opinion would be the possible impact and what would be the reasoning. On completion of the review, the documents were returned to the corresponding researchers and the experts’ comments incorporated into the findings where appropriate.

# Results

## Local and global impacts of different supply options

A very large number of graphs were generated from the matrices showing on-shore and off-shore impacts at local and global scales. With one exception, in the final presentation of these graphs, on and offshore impacts have been combined as they are simply different dimensions of the same energy production system. In the case of wind however, onshore and offshore wind were considered sufficiently different systems, and are also distinguished in possible future pathways (e.g. CCC, 2013), that it was decided to present them separately.

The final graphs for local (within UK) impacts, derived from the systematic literature reviews are all presented on the basis of observational/experimental studies only. For some on-shore supply options there are also data based on all categories of study (i.e. including modelling and review studies) and these are referred to as appropriate in the discussion that follows.

As previously noted, the actual matrices (spreadsheets) used to record results were enormous and finding appropriate ways to summarise the data was challenging. Table 7 gives an indication of the scale of the task undertaken.

### Table 7: Matrix dimensions and papers contributing to systematic reviews

| | Biomass | Natural Gas On/Offshore | Nuclear On/Offshore | Wind Onshore | Wind Offshore |
|---|---|---|---|---|---|
| All life cycle stages identified (global and local) | 31 | 43 | 32 | 30 | 30 |
| Overall matrix size (no. of cells) | 837 | 1,161 | 864 | 810 | 810 |
| Local life cycle stages subject to systematic review | 30 | 42 | 25 | 26 | 26 |
| No. of cells relevant to systematic literature review | 810 | 1,134 | 675 | 702 | 702 |
| Experiment/observation studies | | | | | |
| No. of articles found | 34 | 61 / 14 | 9 / 17 | 8 | 21 |
| No. of scores from articles | 43 | 31/ 65 | 16 / 27 | 17 | 41 |
| No. of cells populated | 12 | 7 / 8 | 17 / 9 | 8 | 7 |
| All studies | | | | | |
| No. of articles found | 88 | 134 * | - | - | - |
| No. of scores from articles | 202 | 103 | - | - | - |
| No. of cells populated | 59 | 10 | - | - | - |

* some not found to be useful on further scrutiny

The discussion that follows examines the key findings for each energy type in turn and assesses the degree of consensus on the direction of impacts revealed by the research studies contributing to the local systematic reviews. This is followed by a comparison of the key impacts across all energy systems.

In the presentation of results that follows the large areas in the local impacts graphs shown as ‘unknown’ reflects the narrow focus of scores drawn from experimental/ observational research, whereas the global impacts graphs have fewer ‘unknowns’ due to the ability of the compiler to extrapolate from generalised knowledge.

## Biomass

Figure 3 shows the results of a) the assessment of impacts on ecosystem services occurring within the UK as indicated by the systematic literature review and b) impacts on ecosystem services external to the UK as indicated by the ‘broad-brush’ approach. The life cycle table for biomass (Figure 3c) shows there were 31 lifecycle stages, 30 of which were relevant at the local scale and 6 at the global scale.

### *Local impacts*

No upstream local impacts were identified from the literature review, but there will inevitably be impacts associated with the construction of power stations that were not picked up by this method. The vast majority of studies related to the growth cycle of the crop (i.e. only one or two stages within the fuel cycle category), though spanning a reasonably broad number of ES impacts compared with studies for other energy systems. This is particularly the case when examining experimental/ observational studies only. Negative impacts were reported on water availability; there were mixed views on the contribution of *Miscanthus* and SRC to bio-remediation; positive impacts on soil and water quality, regulation of the biotic environment, pest and disease control.

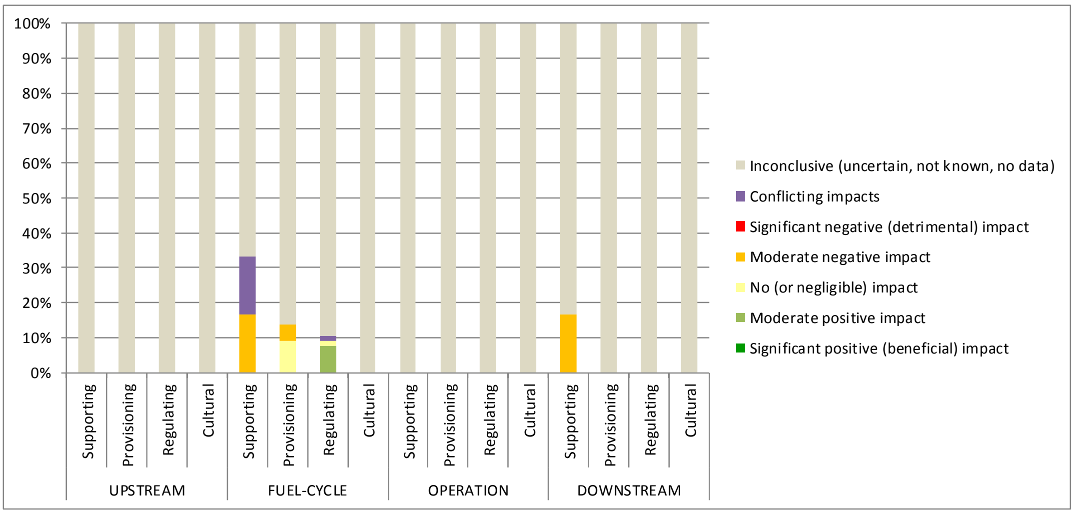
The inclusion of modelling studies adds scores relating to greenhouse gas emission savings compared to other energy systems (see the difference within the operational section of the graph in Figure 4) and those regarding issues of land-take, the food *vs* fuel debate and cultural concerns such as visual impacts (see Figure 4). There are no downstream local impacts relating to decommissioning as this is a new technology and relevant experience on land reversion post biomass crop does not appear to have been reported yet.

### *Global impacts*

The global matrix includes generalised information relating to upstream impacts concerning construction materials and activities (concrete and steel production), and further details relating to fuel cycle impacts (e.g. greenhouse gas emission benefits and provisioning ecosystem service benefits). There are no global operational impacts as greenhouse gas emissions from combustion of the crops in UK power stations are treated as local impacts offset by growth of the crops. Downstream positive impacts relate to reduced water when converting land back to conventional agriculture compared to biomass crops. (This was not recorded from the literature review but would equally apply to the UK).

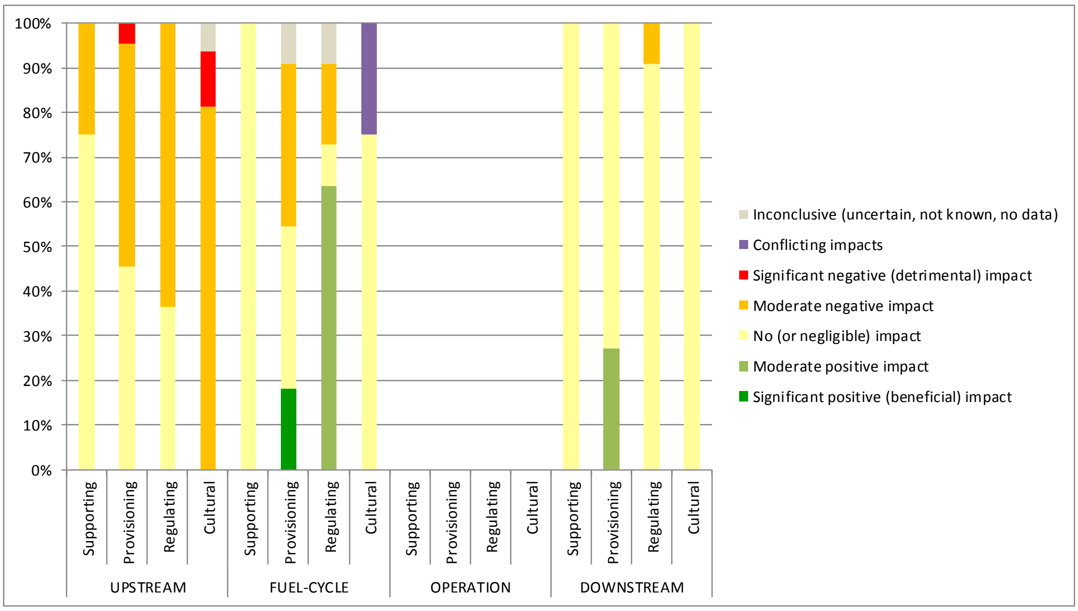
## Figure 3: Impacts on ecosystem services of biomass (*Miscanthus*/short rotation coppice willow) production and use in the UK

a) Local impacts (within the UK)




Method for local chart: systematic literature review - 30 lifecycle stages (observational/experimental studies only)

(b) Global impacts (occuring outside of the UK but relating to UK use of this energy type)




Method for global chart: researcher knowledge / broad internet infomation search - 6 lifecycle stages.

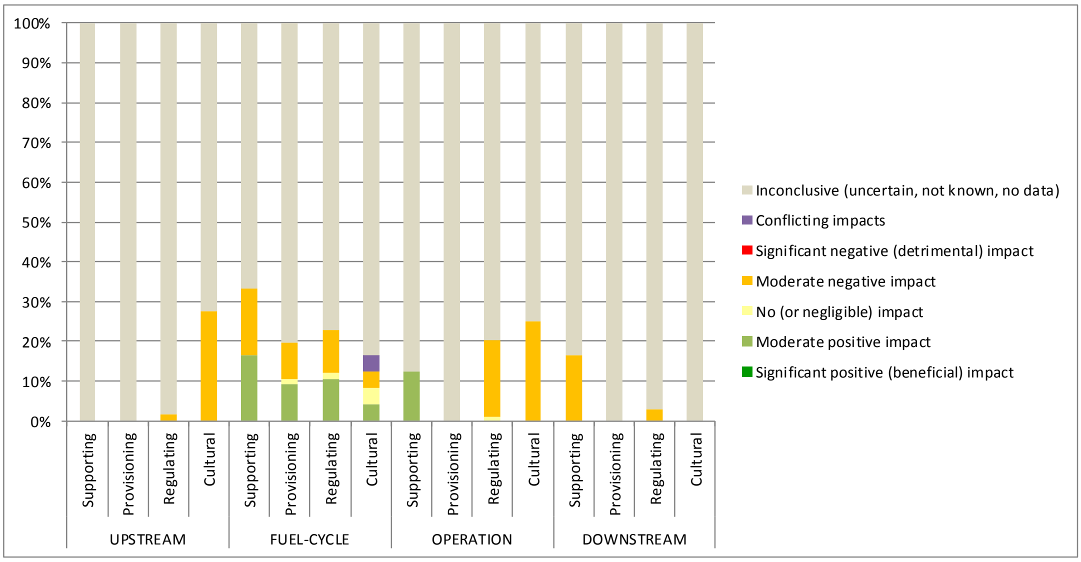
c) Life cycle stages

| | | Upstream | Fuel Cycle | Operation | Downstream | Total | Local Matrix | Global Matrix |
|---|---|---|---|---|---|---|---|---|
| Local | | 7 | 5 | 8 | 5 | 25 | 25 | |
| Local/Global * | | 3 | 1 | 0 | 1 | 5 | 5 | 5 |
| Global | | 1 | 0 | 0 | 0 | 1 | | 1 |
| Total | 31 | 11 | 6 | 8 | 6 | 31 | 30 | 6 |

* these appear on both matrices

## Figure 4: Biomass systematic review including modelling and review papers

Local impacts (within the UK)




Method for local chart: systematic literature review – 30 lifecycle stages (all studies i.e. including modelling and reviews)

### *Research consensus*

As previously discussed, scores allocated to a particular cell in the local impact matrix could be based on a single study, or might be the consensus view (modal score) from several references. The degree of agreement on the magnitude and direction of impact between studies (i.e. % of studies contributing to the modal score) provides an insight into how certain the body of research is regarding that particular impact.

Table 8 provides this data for the experimental/observational studies that contribute to the results shown in Figure 3a. Note that the inclusion or exclusion of certain types of study (e.g. modelling or review papers) has a bearing on the modal score. In the case of cell reference RWB14 in Table 8 there were a relatively large number of studies investigating the bioremediation potential of short rotation coppice. These studies varied in scale, duration, method and detail, with contrasting findings. Consequently there were a wide range of scores with a smaller number of studies (18%) having the modal score.

**Table 8: Biomass systematic review: multi-reference score consistency**

| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference. | Consensus Impact Score | Total No. of Scores | Percentage Agreement |
|---|---|---|---|---|---|
| *Fuel Cycle* | | | | | |
| Supporting | Process-function | SUP13 | - | 1 | |
| | Process-function | SUP14 | - / + | 4 | 50% |
| Provisioning | Water | PW(all) | - | 1 | |
| | Energy | PEB(fuel cycle) | 0 | 1 | |
| Regulating | Bioremediation | RWB14 | - / + | 11 | 18% |
| | Dilution wastes | RWD14 | 0 | 1 | |
| | Atmospheric Reg. | RPA14 | + | 5 | 60% |
| | Soil quality | RPP14 | + | 5 | 80% |
| | Water quality | RPW14 | + | 1 | |
| | Reg. Biotic Env | RBL14 | + | 10 | 80% |
| | Pest/disease | RBP14 | + | 2 | 100% |
| *Downstream* | | | | | |
| Supporting | Process-function | SUP31 | - | 1 | |
| Total no. of scores | | | | 43 | |

## Natural gas

Both on-shore and off-shore technologies were reviewed with respect to their terrestrial and marine impacts. Figure 5 shows the combined results of a) the assessment of impacts on ecosystem services occurring within the UK as indicated by the systematic literature review and b) impacts on ecosystem services external to the UK as indicated by the 'broad-brush' approach. The lifecycle table for natural gas in Figure 5c shows there were 43 lifecycle stages, 42 of which were relevant at the local scale and 27 at the global scale.

### *Local impacts*

As there were no specific studies relating to ecosystem impacts of onshore gas infrastructure there are no details relating to upstream impacts, although as with biomass, there must inevitably be impacts relating to power station construction. There are some onshore impacts relating to processing and transmission; the focus of the studies obtained in the systematic review related to emissions or pollution issues in fuel cycle and operational stages. For this energy source no greater breadth of results was obtained through the addition of modelling studies.

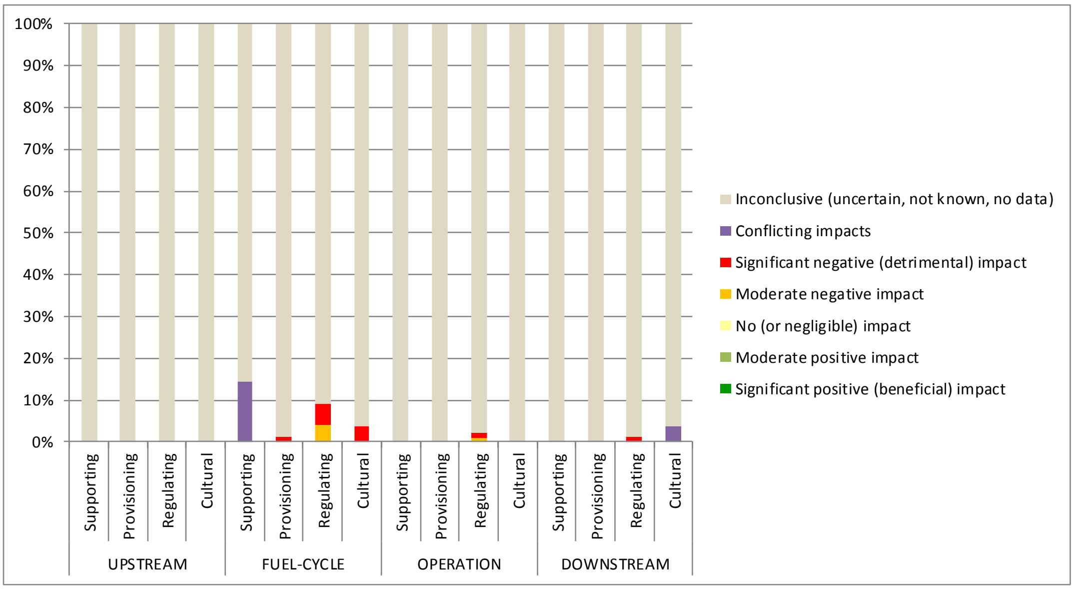
With respect to the gas extraction in UK waters, there is a dominance of negative impacts for the provisioning, regulating and cultural services. These results are based on the effects the extraction of gas has on benthic organisms (urchins, copepods and sediment), mussels and sediment within the fuel cycle stage. There are also conflicting results for supporting services in the fuel cycle stage and cultural services in the downstream stage.

### *Global impacts*

Again, the global matrix includes generalised information relating to upstream construction materials (concrete and steel production) and processes – particularly associated with the transportation and mining of the materials needed to construct the offshore rigs. Fuel cycle impacts relate to the extraction, processing and transmission of gas. There are no global operational impacts as the focus of this study was the impacts of operation within the UK. Operational greenhouse gas emissions have been treated as a local impact and are hence not included in the global matrix. Downstream impacts relate to decommissioning and perceived cultural benefits due to the removal of onshore and offshore infrastructure. However there is an assumed overall negative impact on the provisioning, regulating, cultural and supporting services

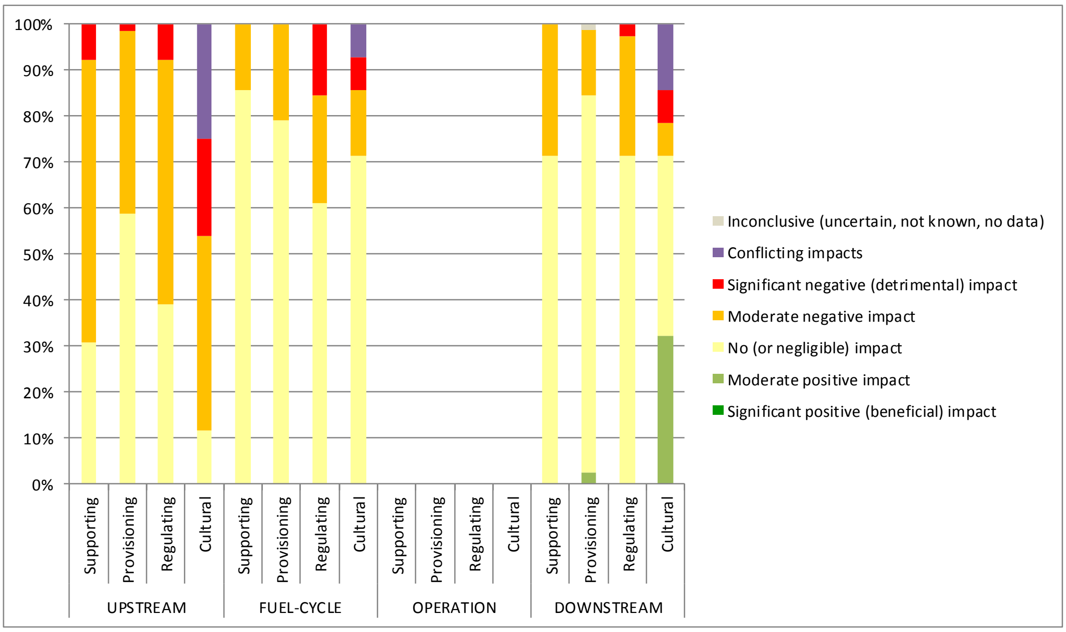
## Figure 5: Impacts on ecosystem services of natural gas production and use in combined-cycle gas-fired power stations in the UK

a) Local impacts (within the UK)




Method for local chart: systematic literature review – 42 lifecycle stages (observational/experimental studies only)

b) Global impacts (occuring outside of the UK but relating to UK use of this energy type)




Method for global chart: literature review / broad internet information search – 27 lifecycle stages.

c) Life cycle stages

| | | Upstream | Fuel Cycle | Operation | Downstream | Total | Local Matrix | Global Matrix | |
|---|---|---|---|---|---|---|---|---|---|
| Local | | 7 | 0 | 9 | 0 | 16 | 16 | | |
| Local/Global | | 12 | 7 | 0 | 7 | 26 | 26 | 26 | * these appear on both matrices |
| Global | | 1 | 0 | 0 | 0 | 1 | | 1 | |
| Total | 43 | 20 | 7 | 9 | 7 | 43 | 42 | 27 | |

*Research consensus*

Table 9 shows the results of the literature reviews for onshore and offshore gas and where multiple scores exist for a particular impact area, the degree of agreement between studies. Atmospheric pollutants were the focus of the onshore studies whilst offshore studies concentrated more on impacts of gas extraction on the marine benthos (including sea urchins, copepods, macro-fauna and sediment), fish and pelagic animals (such as turtles) with a relatively high degree of agreement in the direction and magnitude of impact between studies.

**Table 9: Gas systematic review: multi-reference score consistency**

| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference. | Consensus Impact Score | Total No. of Scores | Percentage Agreement |
|---|---|---|---|---|---|
| **Onshore** | | | | | |
| *Fuel Cycle* | | | | | |
| Regulating | Reg. Biotic Env. | RBL26 | -- | 1 | |
| | Atmospheric Reg. | RPA21 | -- | 10 | 70% |
| | | RPA26 | -- | 1 | |
| | | RPA27 | - | 1 | |
| | Soil quality | RPP26 | - | 2 | 100% |
| | Water quality | RPW26 | - | 1 | |
| Operational | | | | | |
| Regulating | Atmospheric Reg. | RPA28 | - | 15 | 60% |
| Total no. of scores | | | | 31 | |
| **Offshore** | | | | | |
| *Fuel Cycle* | | | | | |
| Supporting | Process-function | SUP22 | ++/-- | 16 | 88% |
| Provisioning | Nutrition | PNM22 | -- | 9 | 88% |
| Regulating | Physi-Chem Env | RPR22 | -- | 8 | 75% |
| | Reg. Biotic Env. | RBL22 | -- | 16 | 50% |
| Cultural | Cultural | CUL22 | -- | 8 | 86% |
| Downstream | | | | | |
| Supporting | Process-function | SUP38 | ? | 1 | |
| Regulating | Physi-Chem Env | RPR38 | -- | 2 | 100% |
| Cultural | Cultural | CUL38 | ++/-- | 5 | 80% |
| Total no. of scores | | | | 65 | |

## Observations on carbon capture and storage (CCS) and fracking

Since continued use of natural gas as a greenhouse-gas-generating fossil fuel is attracting considerable debate with regard to mitigation measures such as CCS, and conversely, as various governments are also seeking to exploit previously unreachable reserves by the process of fracking, it seemed appropriate to carry out further systematic reviews to gain insights into the potential future impacts of these activities. These reviews took an international perspective because there was not enough literature focused on the UK. Table 10 summarises the results for CCS.

**Table 10: Systematic review results for carbon capture and storage (CCS)**

| | | | Modelling/Review Studies | | | Experimental/Obs. Studies | | |
|---|---|---|---|---|---|---|---|---|
| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference | Consensus Impact Score | Total No. of Scores | % Agree | Consensus Impact Score | Total No. of Scores | % Agree |
| *Operation* | | | | | | | | |
| Regulation | Atmospheric Regulation | RPA33 | +/- | 28 | 0 | +/- | 5 | |
| | Soil quality | RPP33 | -- | 1 | | - | 2 | 100% |
| | Water quality | RPW33 | - | 13 | 54 | +/- | 2 | |
| | Regulation Biotic. Env. | CPN33 | + | 1 | | | | |
| Cultural | Cultural | RBL33 | - | 6 | 67 | | | |
| Total no. of scores | | | | 49 | | | 9 | |

A total of 32 articles were found. Eight of these were experimental or observational. The remaining 24 were modelling studies, meta-analyses or reviews. The articles produced a total of 58 scores, but these related to only five impact areas.

Beyond biological methods for the sequestration of $CO_2$, industrial scale 'carbon capture' refers to the chemical or physical sequestration of $CO_2$ that results from the burning of fossil fuels. There are three main types of technology for carbon capture: pre-combustion, post-combustion and oxyfuel (burning of the fuel in pure oxygen to convert all waste gas to $CO_2$ and water vapour). There are two main options for carbon storage: conversion to mineral carbonates that have lengthy periods of environmental stability (Khoo *et al.*, 2011), or storage in deep geological formations (Davison, 2007; Yousef and Najjar, 2008). Deep ocean storage is no longer being considered as it increases the problem of ocean acidification. Transportation of the $CO_2$ to storage would be by pipeline or in liquid form by ship.

Although a variety of techniques for carbon capture have been used in the oil and chemical sectors over many years, large scale commercial CCS applied to UK power generation does not currently exist. The government is working with industry to support the development of CCS in the UK for deployment in the 2020s, for example, through the UK Storage Appraisal Project (UKSAP) (overseen by the Energy Technologies Institute and the Crown Estate). This project has developed an online database (www.co2stored.co.uk) with detailed information on around 600 potential $CO_2$ storage sites in depleted offshore oil and gas reservoirs and saline aquifers around the UK.

Several insights were provided by the literature review regarding both the implementation of CCS elsewhere in the world, and potential environmental impacts associated with this technology. The findings suggest that since the process of carbon capture and storage essentially form an on-cost to power generation (van der Zwaan, 2011), the least-cost generation and capture solutions have tended to be favoured which, at this time, appears to be carbon capture from gas-fired generation plants (Davison, 2007), and $CO_2$ injection into hydrocarbon fields or deep saline aquifers (Davison, 2007).

As the objective of CCS is the long-term removal of a greenhouse gas, prevention from leaking back into the atmosphere must essentially be guaranteed for geologic time-periods. It is currently uncertain whether any solution can guarantee such a conclusion, with a 10% leak-back from some repositories being estimated on timescales of only a few hundred years. There are additional concerns that leaching of the gas-impervious top-rock beneath which the $CO_2$ is to be contained (termed the 'capstone') may accelerate this leakage (Geloni *et. al.*, 2011). Overall, the key point from Table 10 is that the current literature shows no consensus on the atmospheric regulation benefits of CCS.

With respect to fracking a total of 19 articles were found and the impacts are summarised in Table 11. Six of the papers were experimental or observational. The remaining 13 were modelling studies, meta-analyses or reviews. The articles produced a total of 52 scores, relating mostly to impacts on groundwater/aquifers. Interestingly, there was some difference between the modal scores for modelling or review studies and experimental/observational papers, with the latter consistently reporting more strong negative impacts than the former.

**Table 11: Systematic review results for fracking**

| | | | Modelling/Review Studies | | | Experimental/Obs. Studies | | |
|---|---|---|---|---|---|---|---|---|
| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference | Life Cycle Stage/ ES Group | ES Type | ES Cell Reference | Life Cycle Stage/ ES Group | ES Type | ES Cell Reference |
| *Fuel Cycle* | | | | | | | | |
| Supporting | Process-function | SUP21 | - | 1 | | | | |
| Provisioning | Water | PWH21 | 0 | 5 | 60% | -- | 5 | 80% |
| | Water | PWA21 | 0 | 6 | 50% | -- | 5 | 80% |
| | Water | PWI21 | 0 | 6 | 50% | -- | 5 | 80% |
| Regulating | Water flow | RFW21 | | | | -- | 1 | |
| | Atmospheric regulation | RPA21 | - | 3 | 67% | | | |
| | Water quality | RPW21 | 0 | 6 | 50% | -- | 6 | 67% |
| | Regulation Biotic Env. | RBL21 | -- | 2 | 100% | -- | 1 | |
| Total no. of scores | | | | 29 | | | 23 | |

In the USA there is growing concern over overlap between sites identified for carbon storage that are also potentially suitable for fracking. Shale formations, the target of fracking operations, have low permeability and make good capstone. Elliot & Celia (2012) found that whilst carbon storage capacity in deep saline aquifers in the USA was large, up to 80% of that capacity has overlap with potential shale-gas production areas.

Since fracking is specifically designed to cause fissures in capstone rock through which the liberated gas can flow into collection pipes, it could render potential $CO_2$ storage sites useless. It seems unlikely that sufficient intact voids will remain available to hold all the $CO_2$ produced since fracking is growing in popularity due to its lower-than-standard extraction costs. This could have implications for CCS implementation, including in the UK, though potentially to a lesser extent as it appears that shale/coal reserves that are being assessed for potential fracking are onshore whereas many potential storage sites are offshore.

Fracking is said to have made available gas reserves beneath mainland USA (the subject of almost all papers identified) to meet the country's complete needs at today's consumption rates for the next 45 to 180 years leading to a situation where the financial returns generated by such extraction opportunities appear to already be attracting defenders of otherwise seemingly counter-intuitive arguments in terms of generated pollution. There will be a relationship between the volume of gas extracted for combustion and the $CO_2$ recovered and if capstones are being fracked by preference – then this is perhaps a cause for some thought.

Since fracking is designed to widen or create new fissures in the geologic formations in which it is used – it clearly causes constructional changes in rocks to which it applied (Cornet, 2012). Concerns are growing that one result of this disturbance is that methane from the fracked strata is finding a direct route into otherwise previously intact aquifers (Jackson *et al.*, 2013). There appears to be accumulating evidence that this is that case (e.g. Batley and Kookana; 2012; Warner *et. al.*, 2013), and that pollution of some aquifers is occurring as a direct result of the fracking process. Warner *et al.* (2013) report that of 51 drinking-water wells tested above a fracked deposit there were 32 with elevated levels of methane relative to 'natural' expectations. Jackson *et al.* (2013) noted that 82% of the drinking water wells they tested showed increased methane levels, with these being six times higher than expected in wells within 1 km of fracking operations.

The free release into the atmosphere of methane (the largest component of natural gas) from fracked reserves is estimated to contribute between an additional 30% to 100% of the amount released by conventional extraction methods, with 3.6% to 7.9% of all gas extracted by fracking escaping to the atmosphere (Howarth *et al.*, 2011). It is readily calculated, therefore, that of the USA's newly accessible 45 years' worth of methane, between 1.62 and 3.55 years' worth of its total annual consumption will be vented, unburnt, into the atmosphere over the lifetime of these wells. Methane is estimated as being 20 times more active as a greenhouse gas than $CO_2$ (Weinhold, 2012) so such changes would have considerable consequences for atmospheric regulation.

Additionally, a wide variety of chemicals in substantial volumes are injected into a well during the fracking process (Pelley, 2003; Shariq, 2013). These chemicals perform various functions from keeping generated fissures open (through granular introductions), through to improving the rapidity with which gas flows (Shariq, 2013). There are also considerable implications for water resources, with one reserve alone being cited as using the equivalent of 9% of the entire water supply required by the city of Dallas for the same 12 month period (McBroom *et al.*, 2012). Of the substantial cocktail of chemicals injected into reserves (50,000 to 350,000 gallons) (Pelley, 2003) only between 25% and 61% of these are ever recovered for surface reprocessing (Pelley, 2003). The unrecovered chemicals are then, in some circumstances, positioned to migrate into aquifers often located above the reserves (Flewelling and Sharma, 2014). Concerns have been expressed by health professionals regarding patients potentially ingesting such contaminants through their water supply (Rafferty and Limonik, 2013). A number of known carcinogenic chemicals were banned from use following their discovery in the recovered waste waters from fracking processes (Batley and Kookana, 2012) with other chemicals used being known to be significantly injurious to human health (Finkel and Law 2011).

Finally, fracking is recognised as having the potential to cause earthquakes (Cornet 2012). Information on the magnitude of such earthquakes and reports of any environmental damage caused by them was not found in this review, but it was noted that the greatest risks tend to follow the completion of the injection processes and the subsequent pressure reductions in the reserve (Cornet 2012).

## Nuclear

The impacts of nuclear energy on the terrestrial and marine environment were considered in this review and the results combined. Figure 6 shows the results of a) the assessment of impacts on ecosystem services occurring within the UK as indicated by the systematic literature review, and b) impacts on ecosystem services external to the UK as indicated by the 'broad-brush' approach. The life cycle table for nuclear energy in Figure 6c shows that there were 32 lifecycle stages, 25 of which were relevant at the local scale and 11 at the global scale.

### *Local impacts*

Local impacts identified by the literature review revealed terrestrial upstream impacts relating to the excavation of construction sites and operational impacts related to water intake and discharge of wastes. There are no local fuel cycle impacts as the uranium is mined outside of the UK. The results of the review highlight that the ecosystem services mostly impacted are those associated with cultural services (implications of radiation and human health), regulating services (through atmospheric regulation) and supporting services (avian mortality, terrestrial ecotoxicity).

With respect to marine impacts the articles reviewed pointed to the generally negative impact on supporting services due to the decrease in the abundance and functioning of seabed (benthos) organisms; negative impacts on regulating services due to decreased biodiversity of particular marine organisms and negative impacts on cultural services due to harmful algal blooms and damaged benthic ecosystems.

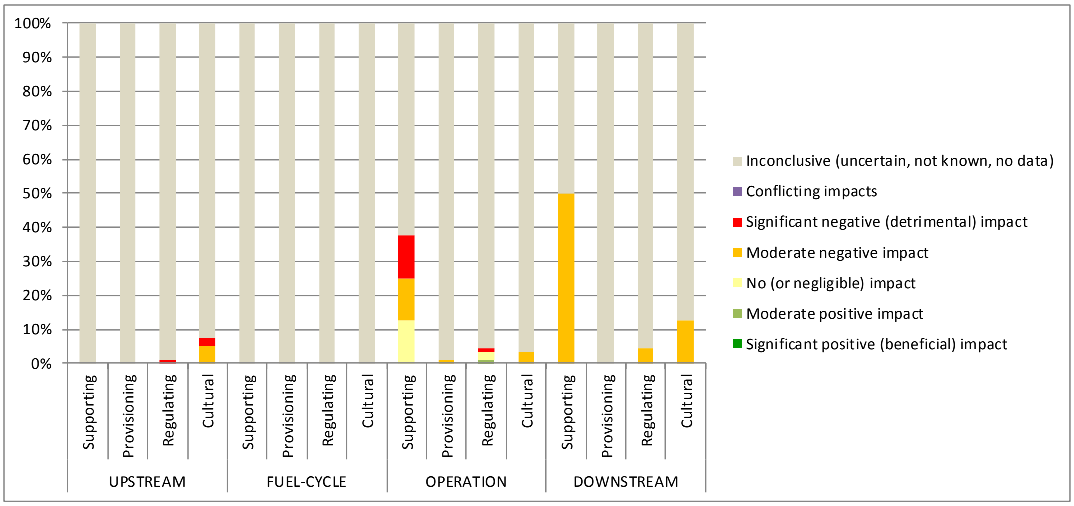
### *Global impacts*

The negative terrestrial upstream impacts relate to the mining, processing and transport of construction materials and many of the scores are common to the global matrices for onshore and offshore gas, biomass and onshore and offshore wind.

The global marine impacts are predominately negative impacting on all four broad groups of ecosystem services. These are due to associated water transport pollution negatively affecting the waters, dredging of foreign ports damaging benthic communities, ship collisions with cetaceans and invasive species being introduced through ballast waters. Additionally, further damage can be inflicted on marine organisms due to the discharge of waste waters and antifouling chemicals from ships. In countries where construction materials such as iron ore, aluminium and graphite are mined, tailings deposited offshore could damage natural marine habitats through smothering benthic communities and decreasing the ability of some marine organisms to photosynthesise.

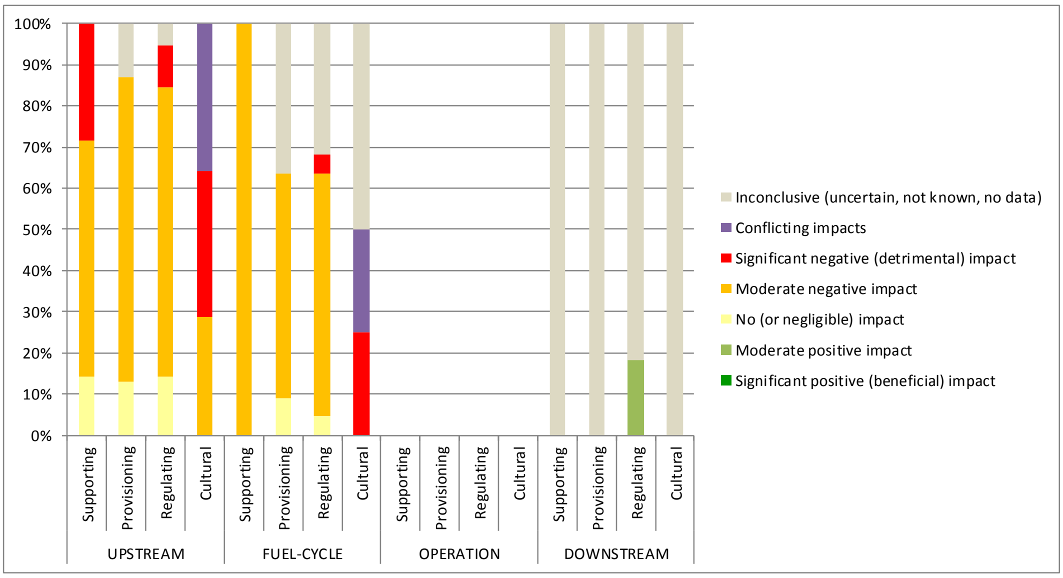
## Figure 6: Impacts on ecosystem services of nuclear energy generation in the UK

a) Local impacts (within the UK)




Method for local chart: systematic literature review – 25 lifecycle stages (observational/experimental studies only)

b) Global impacts (occuring outside of the UK but relating to UK use of this energy type)




Method for global chart: literature review / broad internet infomation search – 11 lifecycle stages.

c) Life cycle stages

| | | Upstream | Fuel Cycle | Operation | Downstream | Total | Local Matrix | Global Matrix | |
|---|---|---|---|---|---|---|---|---|---|
| Local | | 7 | 1 | 8 | 5 | 21 | 21 | | |
| Local/Global | | 3 | 0 | 0 | 1 | 4 | 4 | 4 | * these appear on both matrices |
| Global | | 4 | 2 | 0 | 1 | 7 | | 7 | |
| Total | 32 | 14 | 3 | 8 | 7 | 32 | 25 | 11 | |

*Research consensus*

Table 12 shows the results of the systematic review for onshore and offshore nuclear energy production in terms of the degree of agreement between studies. For many impacts there are insufficient scores to calculate consensus measures but where this can be done there are limited levels of agreement for several categories of cultural service where public opinion is divided (e.g. regarding the siting of nuclear power stations).

**Table 12: Nuclear systematic review: multi-reference score consistency**

| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference. | Consensus Impact Score | Total No. of Scores | Percentage Agreement |
|---|---|---|---|---|---|
| **Onshore** | | | | | |
| *Upstream* | | | | | |
| Cultural | Cultural | CUL10 | 0/- | 1 | |
| | | CUL11 | 0/- | 1 | |
| *Operation* | | | | | |
| Supporting | Process-function | SUP20 | 0/- | 1 | |
| Regulating | Atmospheric Reg. | RPA18 | + | 1 | |
| Cultural | Cultural | CUL20 | ? | 1 | |
| | | CUL21 | 0/- | 1 | |
| *Downstream* | | | | | |
| Supporting | Process-function | SUP22 | - | 1 | |
| | | SUP27 | - | 1 | |
| | | SUP28 | - | 1 | |
| Regulating | Atmospheric Reg. | RPA22 | - | 1 | |
| | | RPA27 | - | 1 | |
| | | RPA28 | - | 1 | |
| Cultural | Cultural | CUL22 | - | 1 | |
| | | CUL27 | 0 | 1 | |
| | | CUL28 | 0/- | 2 | 100% |
| Total no. of scores | | | | 16 | |
| **Offshore** | | | | | |
| *Upstream* | | | | | |
| Supporting | Process-function | SUP14 | - | 1 | |
| Regulating | Atmospheric Reg. | RPA14 | -- | 1 | |
| Cultural | Cultural | CUL14 | -- | 5 | 60% |
| *Operation* | | | | | |
| Supporting | Process-function | SUP20 | -- | 10 | 60% |
| | | SUP21 | 0 | 1 | |
| Provisioning | Nutrition | PNM21 | - | 2 | 100% |
| Regulating | Atmospheric Reg. | RPA20 | 0 | 1 | |
| | Atmospheric Reg. | RPA21 | -- | 1 | |
| | Reg. Biotic Env | RBL20 | 0 | 5 | 60% |
| Total no. of scores | | | | 27 | |

## Onshore Wind

Figure 7 shows the results of a) the assessment of impacts on ecosystem services occurring within the UK as indicated by the systematic literature review and b) impacts on ecosystem services external to the UK as indicated by the 'broad-brush' approach. The life cycle table for wind in Figure 7c shows there were 30 lifecycle stages, 26 of which were relevant at the local scale and 10 at the global scale. There are no fuel cycle (i.e. production/processing) life cycle stages as this is a freely available natural resource. Additionally, as this is a relatively new technology, there is no information on downstream (i.e. decommissioning) impacts.

### *Local impacts*

Research on ecosystem impacts identified by the literature review covered only a few of the lifecycle stages. Upstream impacts related mainly to mixed cultural views on wind farm development (e.g. regarding visual impacts). Several papers also focused on bird and bat strikes during the operational stage. The modelling studies identified in the literature review reflected the benefits of this energy type in respect of greenhouse gas emission reductions – obviously something that is unlikely to produce a 'measured' experimental study and hence is not included in the experimental/observation only graph.

### *Global impacts*

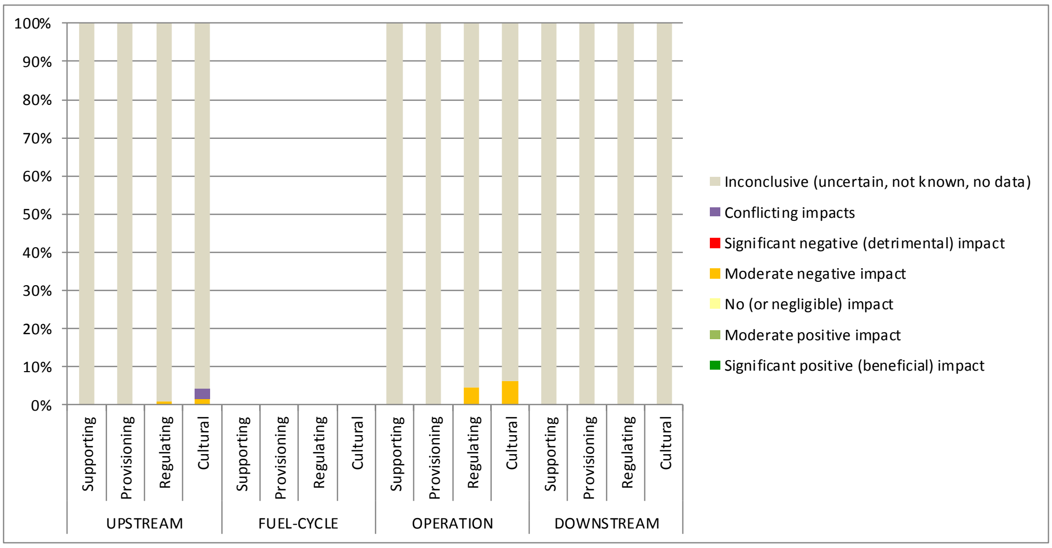
The onshore upstream impacts mainly relate to the mining and processing of construction materials (e.g. concrete and steel) and subsequent production and transport of components.

### *Research consensus*

Table 13 shows the degree of agreement between studies relating to impacts of onshore wind production and use. The lower percentage agreement in relation to cultural indicators reflects the range of public views both for and against onshore wind farms.

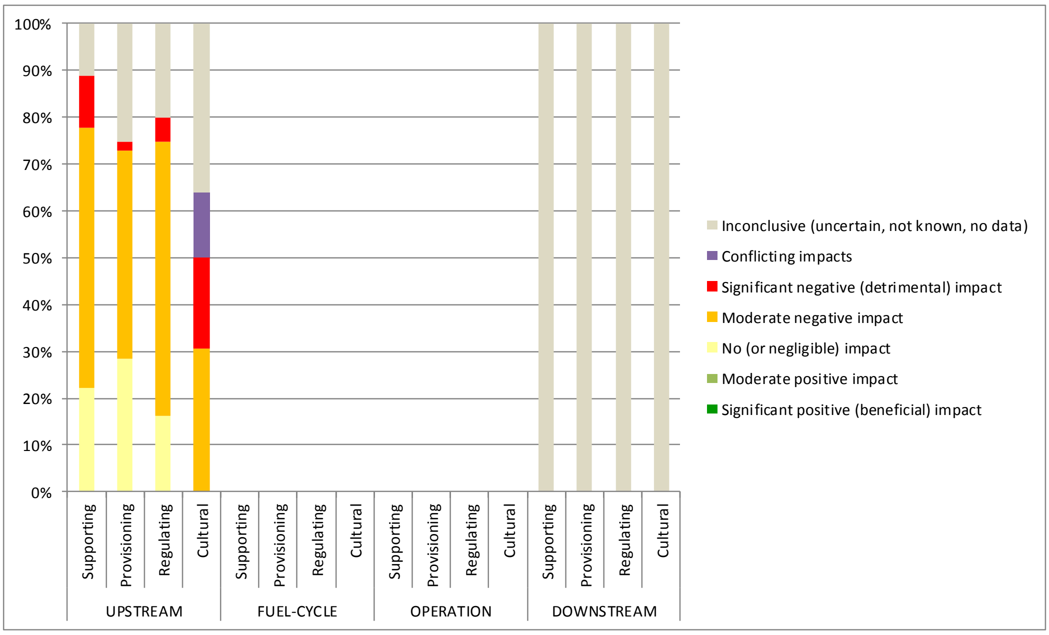
## Figure 7: Impacts on ecosystem services of onshore wind energy generation in the UK

a) Local impacts (within the UK)




Method for local chart: systematic literature review – 26 lifecycle stages (observational/experimental studies only)

b) Global impacts (occuring outside of the UK but relating to UK use of this energy type)




Method for global chart: literature review / broad internet infomation search – 10 lifecycle stages

c) Life cycle stages

| | | Upstream | Fuel Cycle | Operation | Downstream | Total | Local Matrix | Global Matrix | |
|---|---|---|---|---|---|---|---|---|---|
| Local | | 12 | 0 | 4 | 4 | 20 | 20 | | |
| Local/Global | | 5 | 0 | 0 | 1 | 6 | 6 | 6 | * these appear on both matrices |
| Global | | 4 | 0 | 0 | 0 | 4 | | 4 | |
| Total | 30 | 21 | 0 | 4 | 5 | 30 | 26 | 10 | |

Table 13: Onshore wind systematic review: multi-reference score consistency

| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference. | Consensus Impact Score | Total No. of Scores | Percentage Agreement |
|---|---|---|---|---|---|
| *Upstream* | | | | | |
| Regulating | Reg. Biotic Env | RBL18 | - | 1 | |
| | | RBL20 | - | 2 | 100% |
| Cultural | Cultural | CIN20 | +/- | 4 | 50% |
| | | CIS20 | - | 3 | 100% |
| | | CPI20 | +/- | 2 | 50% |
| *Operation* | | | | | |
| Regulating | Reg. Biotic Env | RBL23 | - | 2 | 100% |
| | Noise | RPN23 | - | 1 | |
| Cultural | Cultural | CIN23 | - | 2 | 100% |
| Total no. of scores | | | | 17 | |

## Offshore Wind

Figure 8 shows the results of a) the assessment of impacts on ecosystem services occurring within the UK as indicated by the systematic literature review and b) impacts on ecosystem services external to the UK as indicated by the 'broad-brush' approach. The life cycle table for wind in Figure 8c shows that there were 30 lifecycle stages, 26 of which were relevant at the local scale and 10 at the global scale. Again, there are no fuel cycle (i.e. production/processing) life cycle stages as this is a freely available natural resource.  Also, as this is a relatively new technology, there is no information on downstream (i.e. decommissioning) impacts.

### *Local impacts*

A variety of marine ecosystem service impacts associated with offshore wind were reviewed and no or negligible impacts were recorded for provisioning, regulating and cultural in the operational life cycle stage. These were predominately based on research articles investigating the impacts on fish and birds. Positive impacts were recorded for provisioning services based predominately on articles associated with increased abundance of demersal fish species, while significantly negative impacts on marine mammals during the construction upstream life cycle stage were recorded and translated into negative impacts on cultural services.

### *Global impacts*

The global marine impacts presumed to be associated with offshore wind farms are based on similar thinking to that involved in deriving the global marine impacts associated with nuclear. In general, it was assumed that there are negative upstream impacts due to widening and deepening of ports in foreign countries which destroys benthic communities, discharge of pollution, waste waters and antifouling agents from ships which have negative effects on marine ecosystems. Furthermore, invasive species introduced into foreign natural waters are often destructive for local marine organisms and can subsequently impede the functioning of ecosystem services.

*Research consensus*

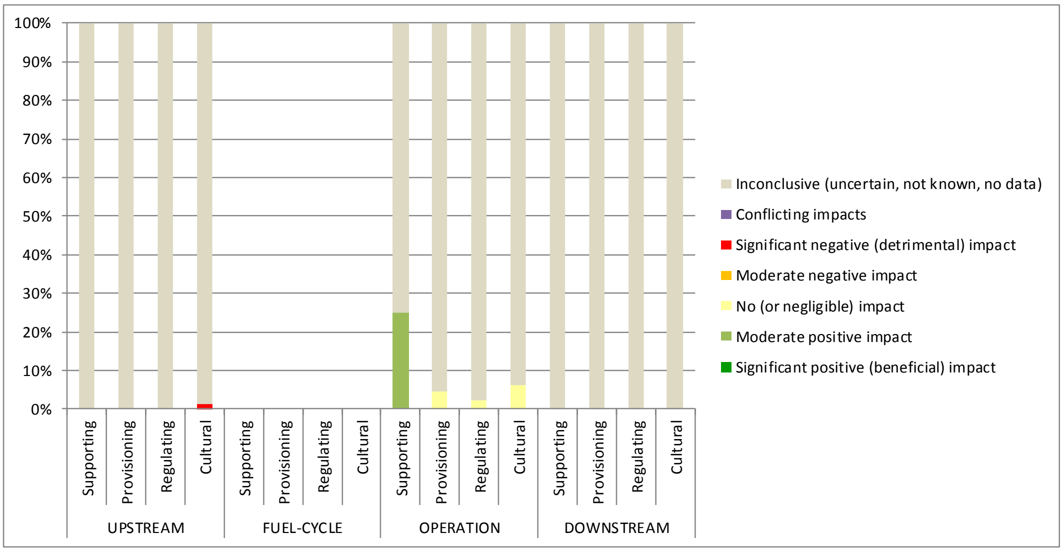
Table 14 shows the degree of agreement between studies relating to impacts of onshore wind production and use. Again, there tend to be lower levels of agreement for cultural than other categories of ecosystem services.

**Table 14: Offshore wind systematic review: multi-reference score consistency**

| Life Cycle Stage/ ES Group | ES Type | ES Cell Reference. | Consensus Impact Score | Total No. of Scores | Percentage Agreement |
|---|---|---|---|---|---|
| *Upstream* | | | | | |
| Supporting | Process-function | SUP20 | ? | 1 | |
| Cultural | Cultural | CUL20 | -- | 8 | 50% |
| *Operation* | | | | | |
| Supporting | Process-function | SUP23 | + | 3 | 66% |
| Provisioning | Nutrition | PNM23 | 0 | 3 | 66% |
| | Materials | PMP23 | 0 | 6 | 66% |
| Regulating | Reg. Biotic Env | RBL23 | 0 | 6 | 50% |
| Cultural | Cultural | CUL23 | 0 | 14 | 29% |
| Total no. of scores | | | | 41 | |

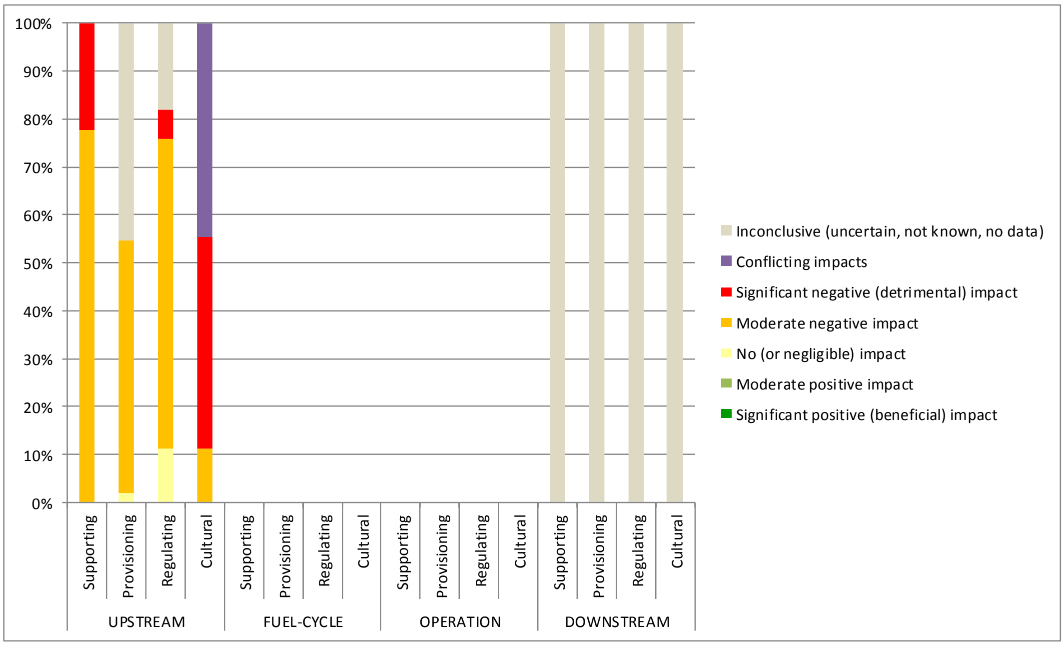
## Figure 8: Impacts on ecosystem services of offshore wind energy generation in the UK

a) Local impacts (within the UK)




Method for local chart: systematic literature review – 26 lifecycle stages (observational/experimental studies only)

b) Global impacts (occuring outside of the UK but relating to UK use of this energy type)




Method for global chart: literature review / broad internet infomation search – 10 lifecycle stages

c) Life cycle stages

| | | Upstream | Fuel Cycle | Operation | Downstream | Total | Local Matrix | Global Matrix | |
|---|---|---|---|---|---|---|---|---|---|
| Local | | 12 | 0 | 4 | 4 | 20 | 20 | | |
| Local/Global | | 5 | 0 | 0 | 1 | 6 | 6 | 6 | * these appear on both matrices |
| Global | | 4 | 0 | 0 | 0 | 4 | | 4 | |
| Total | 30 | 21 | 0 | 4 | 5 | 30 | 26 | 10 | |

## Comparative assessment of impacts across energy systems

The analysis that follows draws on the data presented in the previous sections, summarising across all energy systems, in order to examine whether impacts differ between energy systems, whether they are more prevalent at particular stages in the energy life cycle or fall more heavily on particular ecosystem services. Pie-charts are used to provide graphical summaries with complementary tables and text.

### *Key impacts across life cycle stages*

Local impacts are summarised in Figure 9 and Table 15, while Figure 10 and Table 16 perform the same role for the global analysis. The pie-charts (Figures 9 and 10) represent the number of cells in the impact matrix relevant to the scale (local/global) and life cycle stage (life cycle elements x ecosystem service indicators). The numbers shown below and to the right of each pie-chart indicate this number of cells. Tables 15 and 16 describe the key impacts identified.

As previously indicated, specific information on upstream and downstream ecosystem impacts associated with construction and decommissioning of the built infrastructure (e.g. power stations) in the UK associated with each energy system was scant in the literature obtained through the systematic review. Hence the vast majority of cells in the local matrices/graphs are recorded as 'inconclusive'. There is some work on nuclear decommissioning largely due to concerns regarding the disposal of nuclear waste and decommissioning of the nuclear power stations. Wind energy is too new for there to be published evidence on downstream impacts, while upstream negative impacts associated with this technology are predominantly cultural and reflect opposition or conflicting views to the development of wind farms.

Upstream impacts external to the UK (Table 16) relate mainly to extraction and processing of the raw materials required for buildings or other infrastructure (iron ore, limestone, sand and gravel). Negative impacts both within the UK and externally in the fuel cycle and operational stages relate mainly to pollutant issues. Whilst greenhouse gas emissions arising during the operational stage are a global concern, in this analysis they have been considered within the local reviews.

## Figure 9: Local impacts summary – energy life cycle

The pie-charts represent the number of cells in the impact matrix relevant to the local scale and life cycle stage (life cycle elements x ecosystem service indicators). The numbers shown below and to the right of each pie-chart indicate this number of cells.

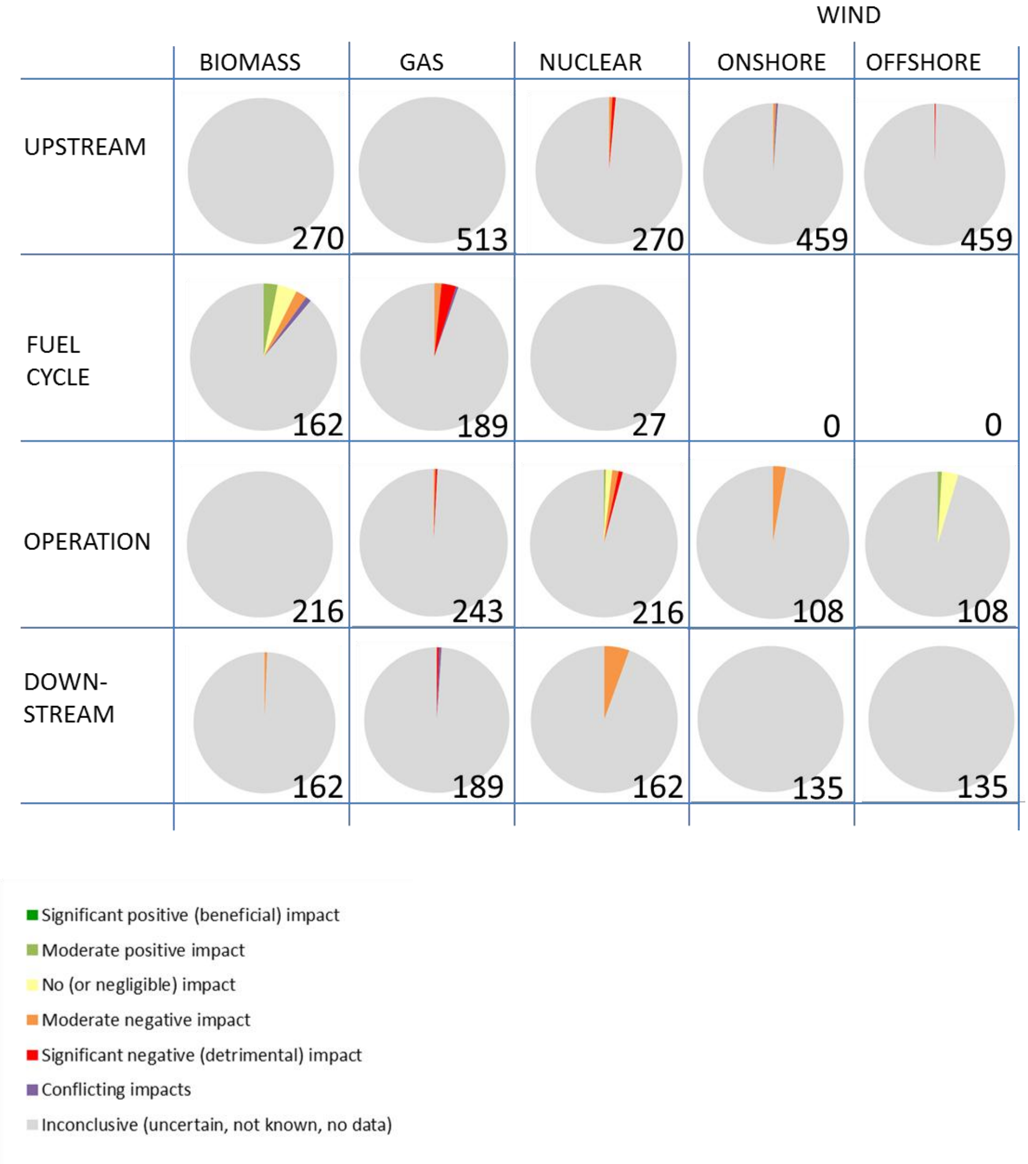


Table 15: Local impacts summary (areas of focus of experimental/observational research literature)

| | Biomass | Gas | Nuclear | Wind | |
|---|---|---|---|---|---|
| | | | | Onshore | Offshore |
| **Upstream** (infrastructure provision) | No data | No data | Impacts relating to excavation of construction site. | Mixed response to wind farm development (visual impact etc). | Negative response to wind farm development (visual impact etc). |
| **Fuel Cycle** (extraction /production and processing of feedstock) | Impacts cover a wide number of ES indicators focussing on the growth cycle of the crop. Greenhouse gas offset during growth cycle. | Impacts relate to emissions or pollution issues. **[Potential future negative impacts on land integrity and aquifers from fracking]** | No data [no uranium mining in UK – potential impacts exist relating to processing/ enrichment of uranium] | N/a | N/a |
| **modelling studies**, and **meta-analyses** | None recorded [note- impacts reported from modelling studies and reviews but not experimental or observational research] | Impacts relate to offshore rigs; emissions or pollution issues, displacement of species. **[Potential future mitigation through CCS?]** | Impacts relating to water intake and discharge of wastes. Greenhouse gas emissions savings (compared to fossil fuels). | Mixed response to wind farm development (visual impact etc). Impacts relating to bird and bat strikes. | Greenhouse gas emissions savings (compared to fossil fuels). |
| **Downstream** (de-commisioning) | Increased greenhouse gas emissions on reversion of land to conventional agriculture. | Impacts relating to transportation and dismantling of gas rigs. Restoration of marine habitats. | Impacts relating to plant demolition and storage of intermediate level waste (ILW). | No data [Technology too new for downstream impacts?] | No data [Technology too new for downstream impacts?] |

■ Negative ■ Positive ■ Conflicting

**Figure 10: Global impacts summary – energy life cycle**

The pie-charts represent the number of cells in the impact matrix relevant to the global scale and life cycle stage (life cycle elements x ecosystem service indicators). The numbers shown below and to the right of each pie-chart indicate this number of cells.

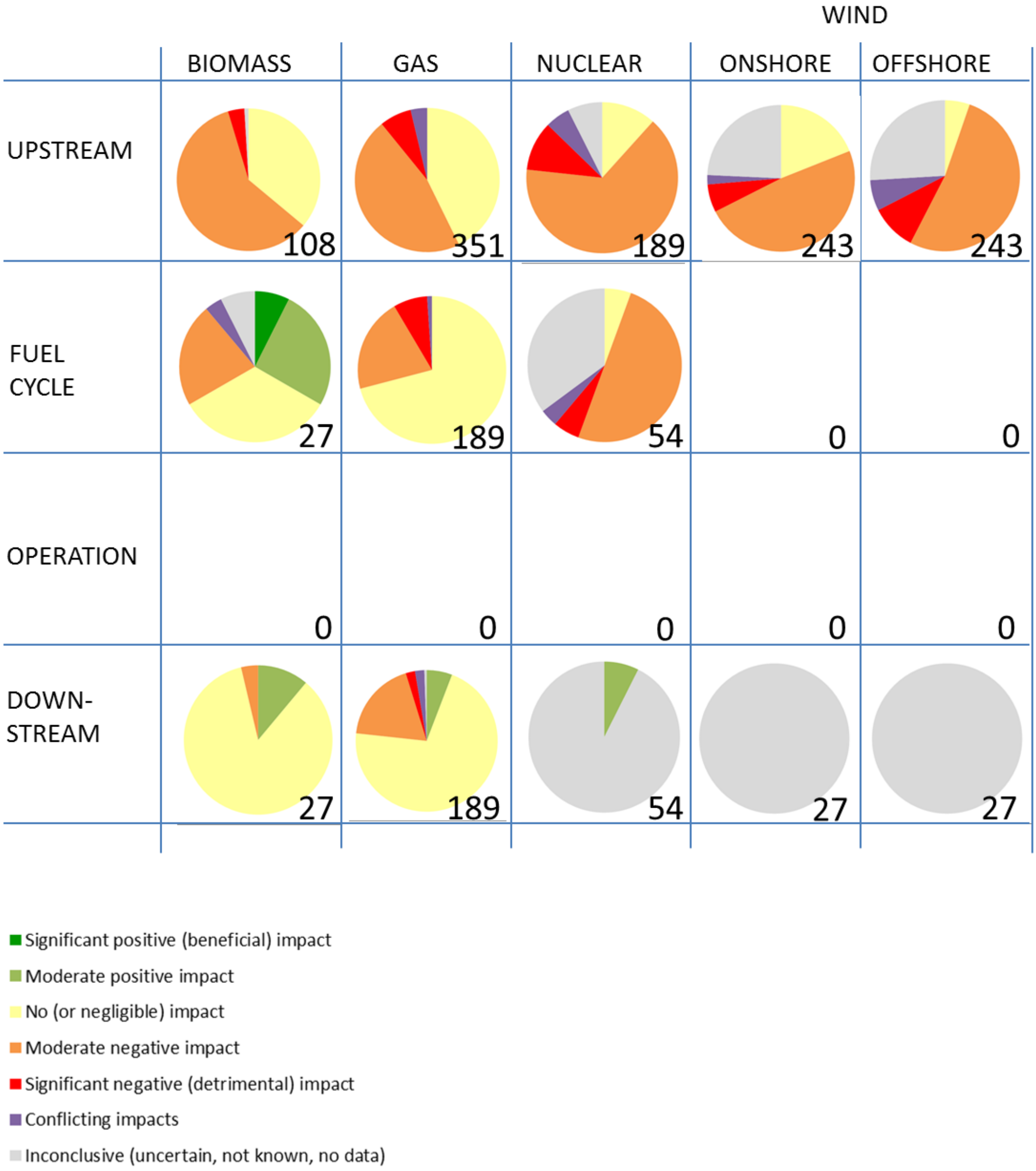


Table 16: Global impacts summary (areas of focus from generally available information)

| | Biomass | Gas | Nuclear | Wind | |
|---|---|---|---|---|---|
| | | | | Onshore | Offshore |
| **Upstream** (infrastructure provision) | Impacts associated with dredging/ mining/ processing construction materials, shipping and transport | Impacts associated with dredging/ mining/ processing construction materials, shipping and transport | Impacts associated with dredging/ mining/ processing construction materials, shipping and transport | Impacts associated with dredging/ mining/ processing construction materials, shipping and transport | Impacts associated with dredging/ mining/ processing construction materials, shipping and transport |
| **Fuel Cycle** (extraction /production and processing of feedstock) | Greenhouse gas offset during growth cycle. Biomass based energy = 'provisioning ES' [relating to country of origin of *Miscanthus* feedstock] | Impacts relate to offshore rigs; emissions or pollution issues, displacement of species. | Impacts associated with mining, processing and transportation of fuel. | N/a | N/a |
| **Operation** (power production) | N/a | N/a | N/a | N/a | N/a |
| **Downstream** (de-commissioning) | Reduced water use when converting land back to conventional agriculture. | Onshore impacts relate to perceived cultural benefits due to the removal of infrastructure. | Reclamation/restoration of uranium mining site. | No data<br><br>[Technology too new for downstream impacts?] | No data<br><br>[Technology too new for downstream impacts?] |

■ Negative ■ Positive ■ Conflicting

*Key impacts across ecosystem services*

Figures 11 and 12 present pie-charts that summarise the key impacts within the four main categories of the ecosystem services used in the preceding discussion for each energy system assessed. Again, the values shown alongside each pie-chart indicate the number of relevant cells from the impact matrices.

**Figure 11: Local impacts summary – ecosystem services**

The pie-charts represent the number of cells in the impact matrix relevant to the local scale and life cycle stage (life cycle elements x ecosystem service indicators). The numbers shown below and to the right of each pie-chart indicate this number of cells.

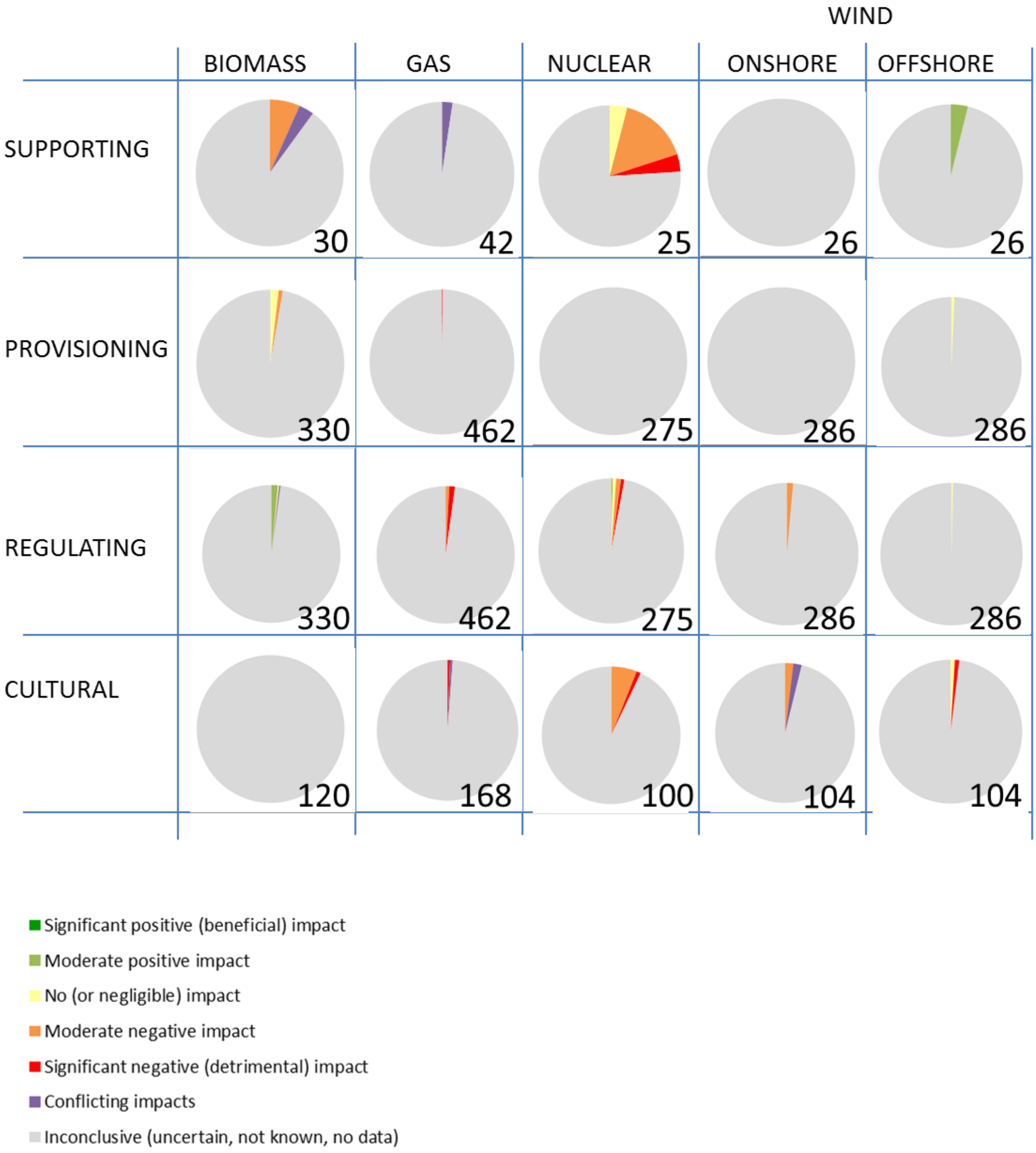



Table 17 complements Figure 11. It draws from previous tables in this report and shows the consensus score and associated percentage agreement for those impact areas where the systematic literature review identified three or more references.

Table 17: Local impacts summary for ecosystem services (key impact areas – degree of agreement from experimental/observational research literature)

| | | | | Wind | |
|---|---|---|---|---|---|
| | Biomass | Gas | Nuclear | Onshore | Offshore |
| **Supporting** (processes and functions) | −/+ (50%) [FUEL CYCLE] | −−/++ (88%) offshore [FUEL CYCLE] | −− (60%) offshore [OPERATION] | | + (66%) [OPERATION] |
| **Provisioning** (nutrition, water, materials, energy) | | | | | |
| Nutrition | | −− (88%) offshore [FUEL CYCLE] | | | 0 (66%) [OPERATION] |
| Materials | | | | | 0 (66%) [OPERATION] |
| **Regulation and Maintenance** (wastes, flow, physical, chemical & biotic environment) | | | | | |
| Regulation of wastes | −/+ (18%) [FUEL CYCLE] (bioremediation) | | | | |
| Atmospheric Regulation | + (60%) [FUEL CYCLE] | −− (70%) [FUEL CYCLE] − (60%) [OPERATION] | | | |
| Water quality | | −− (75%) offshore [FUEL CYCLE] | | | |
| Soil quality | + (80%) [FUEL CYCLE] | | | | |
| Reg. Biotic Env | + (80%) [FUEL CYCLE] | −− (50%) offshore [FUEL CYCLE] | 0 (60%) offshore [OPERATION] | | 0 (50%) [OPERATION] |
| **Cultural** (use and intrinsic value) | | −− (86%) offshore [FUEL CYCLE] −−/++ (80%) offshore [DOWNSTREAM] | −− (60%) offshore [UPSTREAM] | −/+ (50%) [UPSTREAM] − (100%) [UPSTREAM] | −− (50%) [UPSTREAM] 0 (29%) [OPERATION] |

Note: Includes only consensus scores from three or more studies

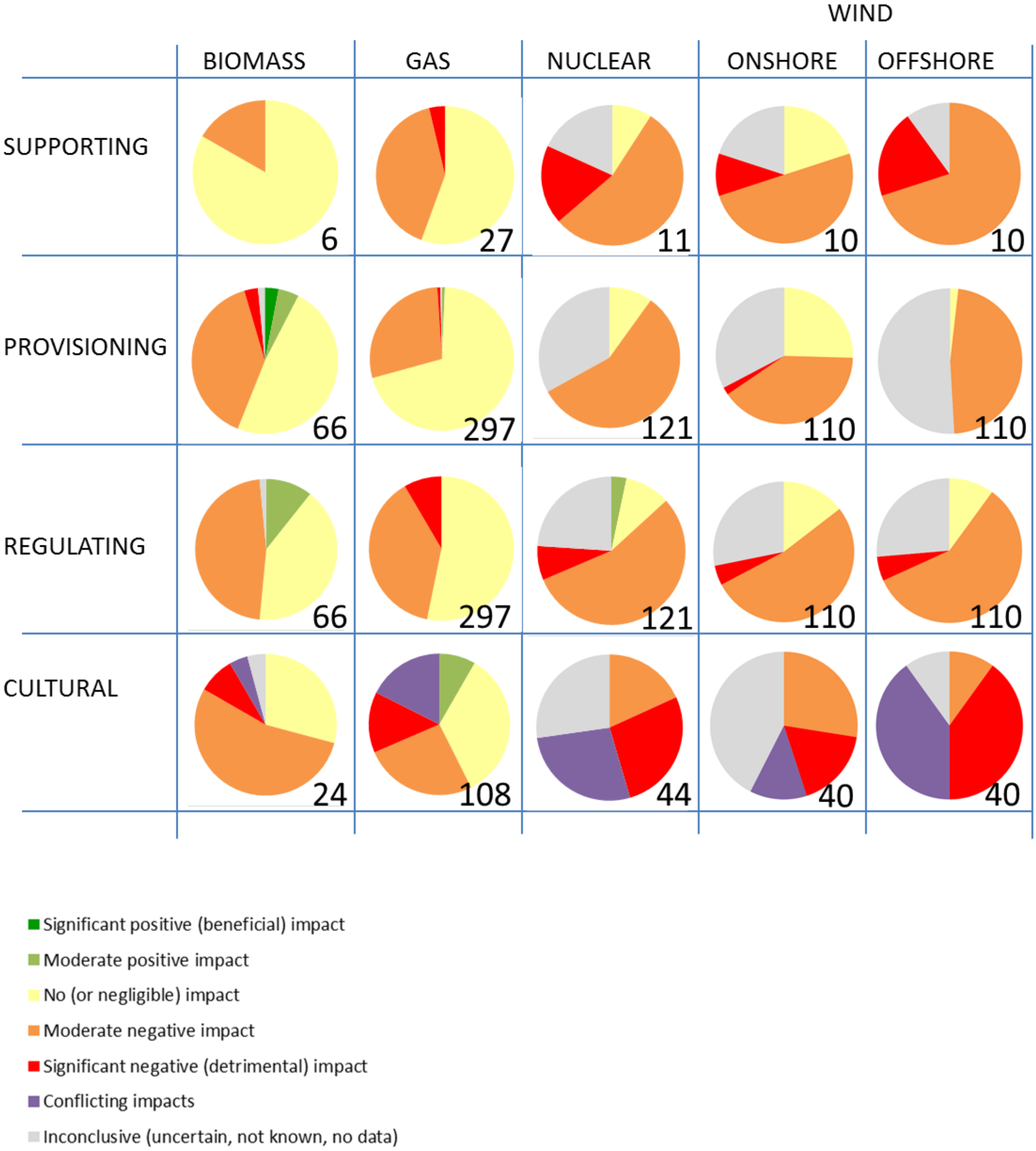
■ Negative ■ Positive ■ Conflicting ■ No/negligible impact

Table 17 shows that research into impacts on supporting, provisioning and regulating ecosystem services has been mostly associated with the fuel cycle and operational stages of energy system life cycles. Where levels of agreement with consensus scores can be evaluated they are commonly in the 60 to 80% range, though in some cases reflect common conclusions regarding mixed impacts. The main beneficial impacts relate to offshore wind and biomass through supporting ecosystem function/atmospheric regulation, with the addition for biomass of soil and biodiversity benefits over conventional agricultural land uses. Interestingly, it notable that the largely conflicting/negative scores for cultural ecosystem indicators relate mostly to upstream and downstream stages of the energy systems – i.e. are associated with the built infrastructure, which corresponds with the findings of a recent UK study of public attitudes to energy crops (Dockerty *et al.*, 2012).

Global scale impacts on ecosystem services are summarised in Figure 12. There is a predominance of negative impacts on supporting and regulating services for most of the energy systems, with conflicting impacts being particularly prominent for cultural services. This again reflects variations in public attitudes towards many types of energy generation infrastructure.

**Figure 12: Global impacts summary – ecosystem services**

The pie-charts represent the number of cells in the impact matrix relevant to the global scale and life cycle stage (life cycle elements x ecosystem service indicators). The numbers shown below and to the right of each pie-chart indicate this number of cells.



# Discussion

The discussion that follows first presents some comments on the benefits and limitations of the methods used in this evaluation. It then relates the results of the evaluations to broader definitions and classifications of uncertainty. Subsequently the implications of the findings for future energy supply transitions are evaluated through a focus on some of the possible pathways outlined in the recent 4th Carbon Budget review.

## Comments on the review and scoring methods

The main benefit of using a systematic review approach in a study comparing ecosystem impacts across different energy systems is in providing a framework that is transparent and replicable. It should be noted, however, that the methodology for a systematic literature review does not necessarily produce a *comprehensive* literature review. The articles identified by this form of investigation are influenced by what is included in the search terms and also by what literature is actually present in a particular database. Overall the approach is well-suited to areas of research (e.g. medical) asking quite specific research questions (e.g. causes of falls in elderly people), but it is harder to ensure comprehensive data capture when considering a broad topic such as this one, comparing the impacts of several energy life cycles across 27 ecosystem services. For the review to work well it is also necessary to have comprehensive databases of the relevant literature and for that literature to itself be reasonably extensive. One important feature of the reviews undertaken in this study was to highlight where research to date has been focused, but it was also very evident that large areas of the full impact matrices remained unpopulated.

Systematic literature review based solely on observational or experimental data makes obvious sense for health related studies, where this approach is widely used, in order to gather 'evidence-based' results. For environmental science and the evaluation of environmental impacts the experience of this study is that such a focus can be too narrow, particularly in terms of the types of impacts identified. In much environmental research the 'precautionary principle' is an important concept and it is common for relatively small numbers of experimental/ observational studies to be scaled up through modelling techniques to assess potential overall impacts. Without the inclusion of modelling studies it is quite possible for local matrices to be under-represented with respect to '+' or '-' scores. For example, greenhouse gas savings are generally assessed in the literature through statistical/modelling work rather than observation or experimental research.

The global matrices are more likely to include a score for such types of impacts because they are based on 'expert judgement'. Consequently these matrices included scores for many more parts of the energy life cycles. This may make the global results appear more comprehensive than the local ones (i.e. fewer 'inconclusive' scores), but it is simply a reflection of the approach taken. It is also important to note that the 'expert judgement' method as implemented here does not allow the degree of consensus on impacts to be evaluated (except through confirmation of scores by expert reviewers). The extent to which this can be done is again dependent on the available literature, but results such as those summarised in Table 17 do provide useful indicators of the confidence that can be placed in assessments of impacts.

A final point that needs to be made about both the local and global matrices is that the results are very dependent on how the framing categories, in this case of life cycle elements and ecosystem service indicators, are defined. This is particularly true when the scores are aggregated into the types of graphical representations shown in Figures 3 to 12 because the implicit assumption in the percentage calculations is that each individual impact cell is commensurate (i.e. of equal importance). Of course, this may not be true, but to include differential weighting or valuation of impacts would substantially complicate the work involved in such assessments and, more importantly, is probably not merited given the currently immature state of knowledge regarding impacts on many ecosystem services.

## Types of uncertainties

An important objective of this study was to determine where the greatest certainties and uncertainties exist in terms of consequences for ecosystem services of generation and supply of selected energy systems. There is a whole body of work relating to the development of typologies of uncertainty (e.g. see Davies *et al.*, 2014). 'Uncertainty' has many definitions, but basically relates to a lack of complete deterministic knowledge of a particular subject (Sigel *et al.*, 2010; Davies *et al.*, 2014). Identifying how knowledge is lacking has led to a number of typologies that attempt to classify the ways in which uncertainty may arise. For example, Skinner *et al.* (2014) present a typology with three main components – (i) nature of the uncertainty (i.e. epistemic due to present imperfect knowledge or aleatory arising from the randomness of natural and human systems), (ii) location of the uncertainty (e.g. language, data precision, extrapolation etc.) and (iii) level or severity of the uncertainty (confidence, probability or total ignorance).

It was not feasible within the resources for this project to directly relate individual positive/negative impact scores to an uncertainty typology, although it is potentially feasible to assess research papers identified during a systematic review against such a classification (e.g. Skinner *et al.*, 2014) to identify what types of uncertainty are associated with a particular field of literature. However, drawing on the example of Skinner's typology, the main areas of uncertainty highlighted by this work are:

*A lack of studies – especially experimental work*
The paucity of studies resulting from the systematic reviews may be due to limitations in the approach or search terms, or be indicative of a real lack of data. Studies were 'clustered' into relatively small areas of energy life cycles or related to relatively few ecosystem service indicators.

*An incomplete view of life cycles*
Studies tended to focus on impacts during the fuel cycle and operational stages and there is little information available on upstream impacts specific to energy types.

*A lack of experience*
Similarly, with some of the newer technologies, such as wind, it appears that there is little information on the potential impacts that may arise when existing infrastructure and generation capacity is decommissioned. As a consequence, there is currently greater uncertainty regarding the downstream elements of life cycles.

All three of these examples are essentially *epistemic* sources of uncertainty (i.e. relating to our knowledge of the impacts) where there is some prospect that they could be reduced through additional research. However, there is also an *aleatory* element (i.e. dependent on chance) in that the inherent randomness of natural and human systems challenges the identification of environmental impacts and is reflected in even the agreement scores for well-established areas of natural science research rarely exceeding 80% (Table 17).

In terms of differences between energy supply systems the results in Table 7 imply that there is more published literature on local impacts in the UK for gas and biomass than nuclear or onshore/offshore wind. This is also reflected in some higher levels of consensus regarding impacts in Table 17, particularly for gas. Nevertheless the differences between energy systems are not great and the contrasts in knowledge between life cycle stages appear to be more pronounced than those regarding generation options.

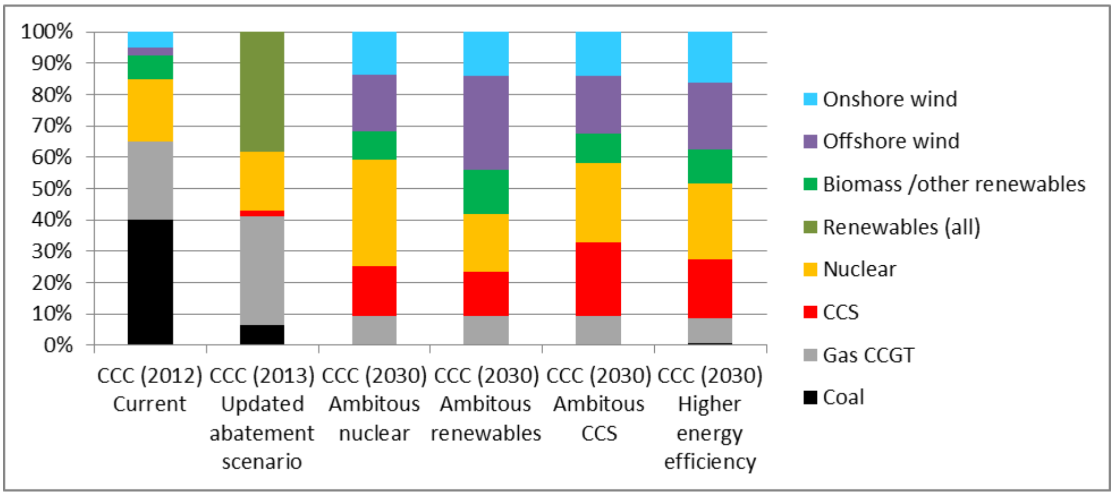
## Implications for transition pathways in the 4$^{th}$ Carbon Budget

The Committee on Climate Change (CCC) is tasked by the government with producing five-year carbon budgets to help achieve the reduction in greenhouse gas emissions of at least 80% from 1990 levels by 2050 as enshrined in the Climate Change Act. The first four carbon budgets are set in law and the UK is currently in the second carbon budget period (2013-17).

The government's vision for 'decarbonising' the future energy supply was set out in 'The Carbon Plan' (HM Government, 2011a). In relation to the generation of electricity, the focus is on three main low-carbon sources – renewable power, nuclear power, and coal and gas-fired power station fitted with CCS (HM Government, 2011a). The power sector gave rise to 27% (156 $MtCO_2$-e) of UK total greenhouse gas emissions by source in 2010 and the plan expects that by 2050 emissions from this sector need to be close to zero, despite a rising demand for electricity of between 30% and 60% (HM Government 2011a).

Recent alternatives regarding potential future power generation mixes reviewed by the CCC are shown in Figure 13. The government has not set explicit targets for particular energy sectors, but aims to develop a low carbon technology combination involving CCS, renewables and nuclear (HM Government 2011a).

**Figure 13: Scenarios of current and potential future power generation mixes**




Derived from: Column 1 CCC (2013b); Column 2 CCC (2010); Columns 3 – 6 CCC (2013a).

With the move away from coal and introduction of CCS to continuing fossil fuel use what are going to be the future issues with the nuclear/renewable energy sources that more reliance is placed upon? Will such a transition reduce ecosystem service impacts compared to the current situation? The government's own plan highlights concerns relating to the availability of sustainable biomass – will it be scarce or abundant? Will wind, CCS or nuclear be the cheapest method of generating large-scale low carbon electricity? (HM Government 2011a).

In addition, with an indication that the current government is minded to support the development of fracking, and hence presumably an increasing use of gas compared to the transition pathways (which seems at odds with the intentions of its own Carbon Plan), will these alternatives need to be rethought? With increased gas extraction will the plan for continued 'decarbonisation' place more reliance on CCS technologies?

Insights on within-UK impacts from the analysis in this report are relatively tightly focussed; in the case of biomass, for example, the research focus has been mostly on the growth cycle of the crops. If home-grown biomass is to expand, impacts will be largely UK-based. The same applies to on-shore wind. With conventional gas and nuclear more of the impacts will occur elsewhere in the world where the fuels are extracted. The degree of environmental impact will therefore relate to how well regulated these industries are and the sensitivity of specific local ecosystems. The analysis presented here provides information on the potential nature and direction of effects but, as noted earlier, does not try to distinguish the relative magnitudes of impacts. The extent of ecosystem service impacts is often context specific.

In the following paragraphs each of the CCC alternative power sector scenarios for reaching 50g$CO_2$/kWh by 2030 is discussed in terms of implications for ecosystem services. This leads on to a consideration of the ecosystem service uncertainties associated with the scenarios.

### *Ambitious nuclear*

Impacts in the UK will relate to public acceptability of expansion of the nuclear industry and development of new power stations; effects arising from the use and pollution of cooling water including on marine organisms and the disposal of radioactive waste. However, the land-take is relatively small (e.g. compared to the ambitious renewables scenario) and apart from a nuclear catastrophe, there are obviously greenhouse gas benefits. Impacts outside the UK will depend on the imported sources of the raw materials (such as concrete and steel) used in construction activities, and also of uranium feedstock as the UK is completely dependent on imports from Canada, Australia and Africa.

### *Ambitious renewables*

Again, impacts in the UK will relate to public acceptability of additional built infrastructure (biomass power stations and wind turbines), landscape issues, and potentially the 'food v fuel' debate. Research suggests that there is potential to expand the area of land under biomass crops considerably without significantly compromising food supply, possible biodiversity benefits and greenhouse gas savings, but possible negative impacts on water availability (Karp *et al.*, 2009; Rowe *et al.*, 2009; Lovett *et al.*, 2014). With wind power the land-take is limited by the increasing emphasis on offshore development, but the structures pose a hazard to bats and birds. Offshore turbines can potentially be beneficial to marine biodiversity by providing artificial reefs, though more research on long-term effects is needed. Impacts of imported biomass have not been considered in this study. There are numerous sources of imported biomass from palm residues to olive pits (Defra, 2007) and the sustainability of transporting these over large distances is questionable. At present such sources are largely being imported to meet co-firing targets in coal-fired power stations. With a move away from coal the requirement for these imports may well reduce in future.

### *Ambitious CCS*

This scenario involves the greatest continuing use of fossil fuels. The introduction of CCS will obviously bring greenhouse gas benefits, but if the source of gas switches from conventional sources which are largely external to the UK to within-UK fracked sources, there is the potential for additional negative impacts, particularly on water availability, pollution and earth tremors, reported in literature from other parts of the world, where fracking is already in use. This literature also suggests an interaction with the scope for CCS itself, through possible damage of potential carbon storage sites.

*Higher energy efficiency*
The proportions of different power sources in this scenario are similar to those for the ambitious CCS pathway. Other impacts on ecosystem services are likely to depend on the sources of materials (e.g. for insulation or construction) used to achieve higher energy efficiency.

In terms of the uncertainties associated with ecosystem service impacts it is important to highlight that all four of the scenarios will have upstream consequences outside of the UK and downstream ones within it. The limited research on such impacts is therefore an issue for all four alternatives and highlights the need to further develop techniques and databases to link local consumption decisions with global consequences through identification and appraisal of supply systems (e.g. Wiedmann *et al.*, 2011; Yu *et al.*, 2014). Exploring ways to rank and mitigate UK impacts on natural capital globally is also highlighted in the recent recommendations of the Natural Capital Committee (2014), so this may well be an area in which there is important scope for a common focus of energy and environmental policies.

A second important aspect of uncertainty concerns cultural ecosystem services. Issues of public acceptability are of great importance for the transformation of the UK energy system (Parkhill *et al.*, 2013) and earlier analysis in this report indicated that variations in public attitudes are central to many conflicting assessments of impacts on cultural services. It is also very apparent that there is a growing issue of public acceptability with respect to the introduction of fracking in the UK (e.g. see RSPB, 2014). Nevertheless, it is important to emphasise that public acceptability is not a static phenomenon and could well change over time. Selman (2010, p.157) notes that:

*"Energy is likely to be a major driver of new landscapes as society seeks ways of weaning itself off fossil carbon fuels. ... by emphasizing the underlying narrative of ingenuity in rising to the challenge of sustainable development, we can learn to see beauty and attractiveness in emerging landscapes of carbon neutrality".*

This is not to suggest that changing societal attitudes is a simple or quick process, but it is important to acknowledge that such sources of uncertainty are not intractable and may evolve over time as the realities of a more unstable climate and future energy challenges become more evident.

Overall, it does not appear that any of the impacts or uncertainties regarding ecosystem services identified in this report are sufficient by themselves to obviously rule out any of the four CCC transition alternatives. More importantly, all four should also result in fewer negative impacts on ecosystem services and natural capital than the current reliance on fossil fuels such as oil or coal. The latter were not evaluated through a systematic review process in this study but, for instance, there is sufficient evidence of their greenhouse gas emission potential (e.g. IPCC, 2012, p.982) that the need for lower carbon means of electricity generation is in little doubt. Equally, while the energy supplies potentially available through fracking no doubt have attractions, reviewing the limited international experimental or observational research published to date indicates substantial agreement on significant negative impacts (Table 11) that is on a par with anything else identified in this study. Given the potential for fracking to also limit the scope for CCS and the importance of the latter across many transition pathways there are strong grounds for at least a cautious approach to the use of fracking in the UK.

# Conclusions

The aim of this research was to provide an overview of the uncertainties regarding prospective changes in power generation within the UK energy system and interactions with ecosystem services and natural capital. For each of the supply options evaluated (biomass, gas, nuclear and wind) separate impact matrices were developed using life cycle categories and ecosystem service indicators. Two different methods were then used to scores to the matrix cells, a systematic literature review approach for local impacts within the UK and expert judgement for global impacts. With the systematic reviews it was also possible to assess the degree of consensus among research papers regarding the impact assigned to individual cells.

*Methodological conclusions and implications*

This study had a very wide scope - examining the broadest array of ecosystem impacts across the whole life-cycle of five energy systems. The two methods provided alternative ways of assessing impacts and the matrix system provided a standardised recording framework to enable cross-comparison between energy systems. The fact that the local graphs and pie charts have larger areas showing as 'unknown', than the global ones, is largely due to differences in method.

The 'broad-brush' method encourages extrapolation from known facts whereas the local review permits only the inclusion of known facts but it is impossible to say which method produces the most correct/accurate results. A clearer understanding might be gained by having the local and global results on equal terms. That is, from applying the broad-brush method at the local scale and the systematic review at the global scale.

Important insights from this exercise concern the influence of how the parameters of systematic reviews are defined and the concentration of literature on particular elements of the overall life cycle. However, either approach is relatively quick compared to an in-depth literature review but due to gaps in knowledge (global) or search set-up issues and a judgemental scoring system (local), the data may be patchy/ fragmented and it is difficult to be certain all salient facts have been captured. The importance for some environmental impacts of considering modelling studies and review papers as well as observational or experimental research was also apparent. Additionally, there is the outstanding issue of the equal weighting of impacts across processes and the need to develop more effective weighting systems based on intensity and exposure of impacts.

There are alternative approaches that could be employed for this kind of analysis. For example a Rapid Evidence Review (http://www.civilservice.gov.uk/networks/gsr/resources-and-guidance/rapid-evidence-assessment/what-is) using a 'review of reviews' process could be investigated to ensure a more inclusive set of studies from which to draw conclusions. This could be particularly relevant given the importance of national and international reviews in the energy and climate change arena.

*Decision making methods /processes that could draw on this evidence base*

Multi-criteria analysis or multi-criteria mapping approaches could be used to weight the ecosystem service impacts in trade-off analysis (Davies *et al.* 2014; Stirling 2008; Stirling 2010). Bayesian Belief Networks could be used to value the effects of the ecosystem impacts for trade-off analysis based on monetary valuation. It is possible that benefit transfers could be used too, and potentially, it might be possible to utilise the valuation of impacts from other studies to help support decisions on alternative energy scenarios.

*Data gaps for future research to examine ecosystem service impacts*

Overall, greater uncertainties associated with upstream and downstream impacts were highlighted – i.e. those associated with infrastructure provision and siting. Conflicting evidence of impacts was particularly associated with cultural ecosystem services, much of which related to variations in public attitudes. Much of the upstream impact is associated with construction materials imported from outside of the UK. It is known that ecosystem impacts are site specific in many cases and this should be investigated more rigorously.

However, based on future scenarios and the lifetimes of different renewable energy systems the decommissioning stages will become just as important, especially if there are legal requirements to remove structures at the end of their lives.

Figure 9 highlights that impacts around the operation/fuel cycle are to some extent being studied. However, future fuel cycle impacts will depend on where feedstocks originate. If there is continued reliance on imports (nuclear feedstock and gas) there will be global fuel cycle (extraction/processing) impacts to consider. If the UK aims to become more energy self-sufficient by expanding renewables and particularly through fracking then there may be greater fuel cycle impacts occurring in the UK (e.g. land take, impact on water availability and quality, biodiversity impacts both on and offshore).

Separate reviews for CCS and fracking indicated the potential for interactions between the two, which needs further clarification in the UK setting, in addition to the substantially negative effects reported in observational or experimental studies of fracking.

Figure 11 highlights the little we know in any of the ecosystem service categories, so progress in any of these areas would be beneficial. However, given the concern on food security and drinking water, a focus on the provisioning services would be particularly useful.

*Policy considerations*

The implications for ecosystem service impacts for alternative power generation scenarios recently set out by the Committee on Climate Change and examined in this report are not sufficient to rule out any of the four alternatives and suggest that all of them would be an improvement on both the current energy generation mix and options which involved greater reliance on fracking.

At present, energy and environmental policies in the UK are often regarded as developing in parallel with relatively little interaction between the two. This, however, ignores much about how the real world functions and in an increasingly challenging future such artificial separation is unlikely to result in the best outcomes for the UK economy, society and environment. The interactions between energy supply options and ecosystem services examined in this working paper are therefore just one example of the wider 'whole systems' perspective at the core of UKERC Phase II that is needed to support the UK transition to more sustainable energy solutions.

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# Appendix 1: Energy Life Cycle Tables

Based on Figure 9.7 Generalised lifecycle stages for an energy technology (p. 730 in IPCC, 2012 *Renewable energy sources and climate change mitigation*).

## a) Biomass

| **Level 1** Lifecycle stage * | **Level 2** Process * | **Level 3** Process – detail (further elaboration of level 2 headings for each specific energy type) | **Subject** ES impact zone – land, water, air etc.. | **Local and/or Global Impact?** (to feed into **Local systematic** review or **Global 'broad-brush'** matrix) | |
|---|---|---|---|---|---|
| | | | | **Local** (UK) | **Global** |
| **Upstream** (i.e. (1) construction of CHP power stations in the UK (2) construction of biomass processing facilities in the UK) | Resource extraction | Concrete – quarrying sand and gravel [sea-bed] + transport [by sea] | Land /marine [PML to cover] | Y (5) | X ***(9) |
| | | Concrete – quarrying limestone + transport | Land /air | Y (4) | X ***(9) |
| | | Steel – mining of iron ore, coal, flux materials (e.g. limestone) and alloys (e.g. manganese) + transport [by land / sea] | Land /air /water use? marine [PML to cover] | X (3) | Y (3) [1] |
| | Material manufacturing | Concrete – cement production + transport | Land /air /water use | Y (4) | X ***(9) |
| | | Concrete – concrete production + transport | Land /air /water use | Y | X |
| | | Steel – steel production (70% new steel/blast furnace + 30% recycled steel/electric arc furnace) + transport [by land / sea] | Land /air /water use? marine [PML to cover] | Y (3) (10) | Y (3) [2] |

| | | | | | |
|---|---|---|---|---|---|
| | Component manufacturing | Concrete – component production + transport | Land /air /water use? | Y | Y (Assume some import of concrete components) [3] |
| | | Steel – component production (e.g. girders, reinforcing rods, cables, nuts & bolts etc) + transport [by land / sea] | Land/air/water use? marine [PML to cover] | Y (10) | Y (bound to be component imports) [3] |
| | Construction – (1) CHP power stations (2) biomass processing facilities | Concrete + transport | Land /air | Y | X |
| | | Steel + transport [by land / sea] | Land /air marine [PML to cover] | Y | X |
| | | Construction processes | Land use / landscape /visual impact | Y | X |
| Fuel Cycle (i.e. fuel production and processing in the UK) | Resource production | Source of *Misc.*/SRC planting material | Land /soil /species | Y | **Y (6)** (SRC from Sweden) [B1] |
| | | Ground prep & planting | Land /soil /species | Y | X |
| | | Growth cycle treatments/ management | Land /soil /species /water use / $CO_2$ | Y | X |
| | | Harvesting + transport | Land /soil /species | Y | X |
| | Processing | Processing *Misc.*/SRC to chips/pellets for direct combustion + transport | Land /energy | Y | X |
| | | Processing *Misc.*/SRC to secondary fuel (liquid/gas) Although Miscanthus (and possibly SRC) can be converted to ethanol/biogas this is | Land /energy /air | X | X |

| | | | | | |
|---|---|---|---|---|---|
| | | hampered by high lignin content. (8). No evidence found of biogas from this feedstock being used in UK CHP. | | | |
| | Delivery to site | Road haulage to power station | Land/ CO2 | Y | X |
| | | Import of wood chips/pellets (transport by ship/road) NB It is impossible to know the source-type of imported wood fuel products (e.g. wood waste, SRF etc) and end use may be co-firing rather than CHP. | Land / air / water/ marine [PML to cover shipping?] | X | **X** Assumption: (in the absence of further info). CHP will draw primarily on locally produced biomass. (7) |
| **Operation** (i.e. CHP generation in the UK) | Combustion (generation of heat/power) | Combustion of *Misc.*/SRC chips/pellets to generate heat & power [via **moving grates** and **fluidised bed** direct combustion technologies **and steam turbine** or **Organic Rankie Cycle (ORC) turbines** for thermal energy. **Heat accumulators** accommodate variance in heat demand (2)] | Air/ /pollutants /CO2 | Y | X |
| | | Combustion of *Misc.*/SRC derived secondary fuels e.g. syngas [integrated within CHP process] | Air /(pollutants – tars, particulates, alkali metals, nitrogen, | Y | X |

| | | | | | |
|---|---|---|---|---|---|
| | | | sulphur and chlorine) / CO2 | | |
| | Maintenanc e | Maintenance of plant & machinery + performance monitoring (efficiency and environmental standards) | Land /water /air | Y | X |
| | Operations | On-site storage | Land | Y | X |
| | | Noise (ambient/exhaust) | Land | Y | X |
| | | Liquid effluent management [boiler blowdown/turbine washing/pipe flushing and drain effluent containing suspended solids and chemicals. Requiring consent for discharge to public sewage system or containment and removal from site (2)] | Land /water | Y | X |
| | | Management of other pollutants (e.g. oils/lubricants and other chemicals used to service machinery) | Land /water | Y | X |
| | | Ash disposal from solid biomass fuels | Land | Y | X |
| Downstream (i.e. decommissioning of CHP power stations in the UK and reversion of land to previous use). | Dismantling | Steel / concrete – CHP power plant & biomass processing facilities | Land | Y | X (doubt that anything is exported from UK) |
| | Decommissi oning | Steel / concrete – CHP power plant & biomass processing facilities | Land | Y | X (doubt that anything is exported from UK) |

| | | | | | |
|---|---|---|---|---|---|
| | | Reversion of infrastructure land to previous/new use | Land | Y | X |
| | | Reversion of crop production land to agriculture | Land /soil /water use/ species | Y | ~~X~~ Y – see above re import from Sweden |
| | Disposal and recycling | Concrete (approx. 30% of UK aggregates come from recycled sources – transported/crushed – uses water) (12) | Land /air /water | Y | X (doubt that anything is exported from UK) |
| | | Steel (highly recyclable – approx. 30% of UK steel comes from recycled sources) (13) | Land /air /water | Y | X (doubt that anything is exported from UK) |

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## b) Gas

| Level 1 Lifecycle stage * | Level 2 Process * | Level 3 Process – detail (further elaboration of level 2 headings for each specific energy type) | Subject ES impact zone – land, water, air etc.. | Local and/or Global Impact? (to feed into Local systematic review or Global 'broad-brush' matrix) | |
|---|---|---|---|---|---|
| | | | | Local (UK) | Global |
| Upstream (i.e. (1) construction of power stations in the UK (2) construction of natural gas processing plant in the UK and elsewhere (3) construction of extraction wells) | Resource extraction | Concrete – quarrying sand and gravel [sea-bed] + transport [by sea] | Land /marine [PML to cover] | Y (5) | X ***(9) |
| | | Concrete – quarrying limestone + transport | Land /air | Y (4) | X ***(9) |
| | | Steel – mining of iron ore, coal, flux materials (e.g. limestone) and alloys (e.g. manganese) + transport [by land / sea] | Land /air /water use? marine [PML to cover] | X (3) | Y (3) [1] |
| | | | | | |
| | Material manufacturing | Concrete – cement production + transport | Land /air /water use | Y (4) | X ***(9) |
| | | Concrete – concrete production + transport | Land /air /water use | Y | X |
| | Component manufacturing | Steel – steel production (70% new steel/blast furnace + 30% recycled steel/electric arc furnace) + transport [by land / sea] | Land /air /water use? marine [PML to cover] | Y (3) (10) | Y (3) [2] |

| | | | | | |
|---|---|---|---|---|---|
| | | Concrete – component production + transport | Land /air /water use? | Y | Y (Assume some import of concrete components ) [3] |
| | Construction (1) – power stations | Steel – component production (e.g. girders, reinforcing rods, cables, nuts & bolts etc) + transport [by land / sea] | Land/air/water use? marine [PML to cover] | Y (10) | Y (bound to be component imports) [3] |
| | | Concrete + transport | Land /air | Y | X |
| | | Steel + transport | Land /air | Y | X |
| | Construction (2) – natural gas processing plant | Construction processes | Land use / landscape /visual impact | Y | X |
| | | Concrete + transport | Land /air | Y | Y [4] |
| | | Steel + transport [by sea] | Land /air marine [PML to cover] | Y | Y [4] |
| | Construction (3) – extraction wells (well site investigation ; preparation of well pad; well drilling; hydraulic fracturing; well completion) | Construction processes | Land use / landscape /visual impact | Y | Y [1] |
| | | Concrete + transport [by sea] | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [6] |
| | | Steel + transport [by sea] | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [6] |
| | Construction (4) – transmission pipelines | Construction processes | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [6] |
| | | Concrete + transport [by sea] | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [7] |

| | | | | | |
|---|---|---|---|---|---|
| | | Steel + transport [by sea] | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [7] |
| Fuel Cycle (i.e. fuel production and processing) | Resource production | Construction processes | Land /air /marine [PML to cover] | Y? [North Sea?] | Y [7] |
| | | Natural gas extraction from conventional sources | Land (subsidence) /air /marine [PML to cover] | Y[no on-shore conventional natural gas extraction in the UK but relevant for offshore] | Y? [onshore sources – to be identified] [8] |
| | Processing | Pumping of marine-extracted gas to on-shore processing facility via pipeline (gathering lines) (2) **NB: In future processing may also be done at the gas field (FLNG – Floating Liquefied Natural Gas) negating the need for an onshore LNG processing plant. (Under development by Shell – due for completion 2017) (8)** | Land /air /marine [PML to cover] | Y? [North Sea to UK?] | Y [9] |
| | | Processing to remove impurities (e.g. carbon dioxide, nitrogen, helium and hydrogen sulphide, also ethane, propane, butane and pentane) (2, 8) **[NB: Is processing always done locally to** | Land /air | Y | Y [10] |

| | | | | | |
|---|---|---|---|---|---|
| | | extraction, or in 'destination' country or both??] | | | |
| | | Transfer to/from storage (depleted oil/gas reserves/aquifers/salt caverns) (2) | Land /air /marine? [PML to cover] | Y? | Y? [11] |
| | Delivery to site | Conversion to/from liquefied natural gas (LNG) for shipping/transport (or storage in tanks) | Land / air /marine? [PML to cover] | Y [regasification plant at terminal] | Y [12] |
| | | Gas transmission (via overland mainline transmission pipeline) (2) | Land /water/marine [PML to cover] | Y | Y [interconnector pipeline etc] [13] |
| Operation (i.e. combined-cycle gas turbine power generation in the UK) [NB: combined cycle gas produces lower CO2 emissions than conventional | Combustion | Ship/truck transport of liquid gas (LNG) | Land /air /marine [PML to cover] | Y [ receiving ports and onward transport ] | Y [LNG transport by ship e.g. from Qatar] [14] |
| | | Air intake and purification via filtering (ammonia, chlorine, hydrocarbons, sulphur, nitrates; particulates & airborne debris (e.g. seeds etc). (7) | Land (filter disposal?) /water /air | Y | X |

| | | | | | |
|---|---|---|---|---|---|
| thermal power plants & minimal particulates]. | | | | | |
| | | Gas Turbine cycle: (mixing air and gas; ignition, electricity generation) (7) | Land /water /air | Y | X |
| | | Heat Recovery Steam Generation: generation of steam from gas turbine exhaust: steam used to generate electricity via Steam Turbine (7) | Land /water /air | Y | X |
| | Maintenance | Discharge of hot gases to atmosphere (7) (plus very small amount of particulates) | Land /water /air (CO2) | Y | X |
| | Operations | Maintenance of plant & machinery + performance monitoring (efficiency and environmental standards) | Land /water /air | Y | X |
| | | Atmospheric Emissions Management (via catalytic converters for carbon monoxide; catalytic converter plus injection of aqueous ammonia for nitrous oxides) (7) | Land /water /air | Y | X |
| | | Noise (ambient/exhaust) 'Integrated Pollution Prevention and Control (IPPC) Permit | Air /local population | Y | X |

| | | | | | |
|---|---|---|---|---|---|
| | | limits the noise impact allowed by the station. However, any noise produced by the plant's turbines should be almost imperceptible at the site boundary' http://www.carringtonpower.co.uk/faqs. | | | |
| | | Liquid effluent management [boiler blowdown/turbine washing/pipe flushing and drain effluent containing suspended solids and chemicals. Requiring consent for discharge to public sewage system or containment and removal from site (2)] [From biomass table – assume this also applies for GAS??] | Land /water | Y | X |
| | | Management of other pollutants (e.g. oils/lubricants and other chemicals used to service machinery) | Land /water | Y | X |
| Downstream (i.e. (1) de-commissioning of power stations in the UK (2) of natural gas processing plant in the UK and | Dismantling | Steel / concrete (1) power stations replaced by combined-cycle gas / (2) natural gas processing plants | Land /air /water / marine [PML to cover] | Y | Y [15] |
| | | Steel / concrete (3) extraction wells / (4) transmission pipelines | Land /air /water / marine [PML to cover] | Y | Y [16] |

| | | | | | |
|---|---|---|---|---|---|
| elsewhere (3) of extraction wells (4) of transmission pipelines and reversion of land to previous use). | Decommissioning | Steel / concrete (1) power stations replaced by combined-cycle gas / (2) natural gas processing plants | Land /air /water / marine [PML to cover] | Y | Y [15] |
| | | Steel / concrete (3) extraction wells / (4) transmission pipelines | Land /air /water / marine [PML to cover] | Y | Y [16] |
| | | Reversion of land to previous use (infrastructure) | Land /water | Y | Y [17] |
| | Disposal and recycling | Concrete (approx. 30% of UK aggregates come from recycled sources – transported/crushed – uses water) (12) | Land /air /water / marine [PML to cover] | Y | Y [18] |
| | | Steel (approx. 30% of UK steel comes from recycled sources) (13) | Land /air /water / marine [PML to cover] | Y | Y [19] |

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## c) Nuclear

| Level 1 Lifecycle stage * | Level 2 Process * | Level 3 Process – detail (further elaboration of level 2 headings for each specific energy type) | Subject ES impact zone – land, water, air etc.. | Local and/or Global Impact? (to feed into Local systematic review or Global 'broad-brush' matrix) | |
|---|---|---|---|---|---|
| | | | | Local (UK) | Global |
| Upstream | Resource extraction | Concrete – quarrying sand and gravel [sea-bed] + transport [by sea] | Land /marine [PML to cover] | Y (3) | N(4) |
| (i.e. construction of nuclear power stations in the UK (1), generator turbines, cooling towers, control rooms, fuel rods (2) | | Concrete – quarrying limestone + transport | Land /air | Y (5) | N(4) |
| | | Steel – mining of iron ore + transport [by sea] | Land /air /water use? marine [PML to cover] | N (6, 7) | Y |
| | | Steel – mining of iron ore + transport [by sea] | Land /air /water use? marine [PML to cover] | N (6, 7) | Y [note b – applies to whole row] |
| | | Graphite – mining + transport | Land /air / water / marine [PML to cover] | N | Y(8) |
| | | Steel – mining of iron ore + transport [by sea] | Land /air /water use? marine [PML to cover] | N (6, 7) | Y [note b – applies to whole |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | row] |
| | Material manufacturing | Concrete – cement production + transport | Land /air /water use | Y | N**(4) |
| | | Concrete – concrete production + transport | Land /air /water use | Y | N |
| | | Steel – production from iron ore + transport [by sea] | Land /air /water use? marine [PML to cover] | Y (7) | Y (7) |
| | Component manufacturing | Concrete + transport | Land /air /water marine [PML to cover] | Y | Y (9) |
| | | Steel + transport [by sea] | Land/air/water marine [PML to cover] | Y | Y (10) |
| | Construction (1) – nuclear power stations, intake and discharge tunnels | Concrete + transport [by sea] | Land / air / landscape / visual impact marine [PML to cover] | Y | N |
| | | Steel + transport [by sea] | Land / air marine [PML to cover] | Y | N |
| | | Excavation of site | Land / air marine [PML to cover] | Y | N |
| Fuel Cycle (i.e. fuel production and processing) | Resource extraction | Uranium mining – open cast mining, underground mining, in-situ leaching | Land / air / water / marine [PML to cover] | N | Y (11) |
| | Processing | Uranium milling – leaching with sulphuric acid, leaching with alkaline agents, energy for drying + transport [by | Land /air / water / marine [PML to cover] | N | Y (12) |

| | | | | | |
|---|---|---|---|---|---|
| | | sea] | | | |
| | | Uranium enrichment and conversion + transport | Land /air / water | Y (13) | N (14) |
| Operation (i.e. generation of electricity in gas cooled reactors (1) | Combustion | Enriched uranium dioxide clad with stainless steel generates heat contained in reactor core + energy | Land/air | Y | N |
| | Maintenance | Maintenance of plant & machinery + energy | Land / air / water | Y | N |
| | Operation | Water intake for heat exchanger (intake of cold water and discharge of warm water) | Air / marine [PML to cover] | Y | N |
| | | Discharges of wastes | Land / air / water / marine [PML to cover] | Y | N |
| | | Carbon dioxide intake to act as coolant (15, 16) | Air | Y | N |
| | | Steam production to drive turbines | Air | Y | N |
| | | Management of other pollutants (e.g. gases (1) and radionuclides) | Land / air /marine [PML to cover] | Y | N |
| | | Spent fuel storage and reprocessing | Land / air / water | Y | ~~Y~~ N the UK does not allow export of nuclear waste – |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | hence this cannot be global |
| Downstream (i.e. de-commissioning of power stations in the UK, final disposal of spent fuel) (17, 18, 19) | Dismantling | Removal of nuclear facility from site | Land /air /water | Y | N |
| | Decommissioning | Decontamination of structures and components | Land /air /water / marine [PML to cover] | Y | N |
| | | Remediation of contaminated ground and water | Land / water / marine [PML to cover] | Y | N |
| | | Reclamation of the uranium site | Land / air / water | N | Y |
| | Disposal and recycling | Disposal of steel and other waste | Land /air /water / marine [PML to cover] | Y | Y |
| | | Interim storage of fuel (20) | Land / water | Y | N |
| | | Final disposal of spent fuel | Land / air / water / marine [PML to cover] | Y | N (21) |


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## d) Wind

| **Level 1** Lifecycle stage * | **Level 2** Process * | **Level 3** Process – detail (further elaboration of level 2 headings for each specific energy type) | **Subject** ES impact zone – land, water, air etc.. | **Local and/or Global Impact?** (to feed into **Local systematic** review or **Global 'broad-brush'** matrix) | |
|---|---|---|---|---|---|
| | | | | **Local (UK)** | **Global** |
| **Upstream (i.e. construction of wind turbines)** | **Resource extraction** | Concrete – quarrying sand and gravel [sea-bed] + transport [by sea] | Land /marine [PML to cover] | Y (3) | N ***(4) |
| | | Concrete – quarrying limestone + transport | Land /air | Y (2) | N ***(4) |
| | | Steel – mining of iron ore, coal, flux materials (e.g. limestone) and alloys (e.g. manganese) + transport [by land / sea] | Land /air /water/ marine [PML to cover] | N (1) | Y (1) [1] |
| | | Steel – mining of iron ore, coal, flux materials (e.g. limestone) and alloys (e.g. manganese) + **transport** [by land / sea] | Land /air /water/ marine [PML to cover] | N (1) | Y (1) |

| | | | | | |
|---|---|---|---|---|---|
| | | Aluminium-mining from bauxite | Land/air/water | N | Y (6) |
| | | Aluminium-**transport** [by sea] | land/air/water /marine | N | Y (6) [note b – applies to whole row] |
| | Material manufacturing | Concrete - cement production + transport | Land /air /water | Y (2) | N ***(4) |
| | | Concrete - concrete production + transport | Land /air /water | Y | N |
| | | Steel - steel production (70% new steel/blast furnace + 30% recycled steel/electric arc furnace) + transport [by land / sea] | Land /air/ marine [PML to cover] | Y (1) (5) | Y (1) [2] |
| | | Aluminium – Aluminium production + transport | Land/air/water | Y | Y |
| | Component manufacturing | Concrete - component production + transport | Land /air | Y | Y (Assume some import of concrete components) [3] |
| | | Steel – component production (e.g. girders, reinforcing rods, cables, nuts & bolts etc) + transport [by land / sea] | Land/air/water / marine [PML to cover] | Y (5) | Y (bound to be component imports) [3] |
| | | Aluminium-component | Land/air | Y | Y |

| | | | | | |
|---|---|---|---|---|---|
| | | production + transport | | | |
| | Construction | Tower | land | Y | N |
| | | Nacelle | air | Y ~~N~~ | N |
| | | Hub | land/air | Y ~~N~~ | N |
| | | Blades | air | Y | N |
| | | Foundations | Land/air | Y | N |
| | | Grid Connection cables | Land/air | Y ~~N~~ | N |
| | | On-site erection and assembling | land/air | Y ~~N~~ | N |
| | | Transport of turbine component | land/air | Y | N |
| **Fuel Cycle** (i.e. fuel production & processing) | | | | N/a | N/a |
| **Operation** | **Operation** | Generation of electricity | land/marine | Y | N |
| | **Maintenance** | Maintenance of turbines, including | | | |
| | | Oil Changes | land/air/water /marine | Y | ~~Y~~ N – local |
| | | Lubrication | air | Y | N |
| | | Transport | land/air/water | Y | ~~Y~~ N – local |
| **Downstream** (i.e. decommissioning of wind turbines in the UK and reversion of land to previous use). | **Dismantling** | Dismantling turbines | land/air/water use/marine | Y | N |
| | | transporting turbine to disposal sites | land/air/water use/marine | Y | Y |
| | **Decommissioning** | | | | |
| | **Disposal and recycling** | Recycling some components | land/air/water use/marine | Y | N |
| | | Depositing inert components in landfills | land/air/water use/marine | Y | N |

| | | | | | |
|---|---|---|---|---|---|
| | | Recovering other material such as lubricant oil | land/air/water use/marine | Y | N |