SPLiCE Phase 1
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

Output 1 from SPLiCE Phase 1
Significant evidence gaps on the environmental, social and economic impacts of energy system components.
Executive summary

Modern energy systems are extraordinarily complex including a high number of actors (e.g. government, private investors, utilities, banks, pensions funds, consumers, NGOs) driven by different objectives and operating across very different timescales. Future energy systems in a decarbonised world are likely to be at least as complex as the current energy system, as trade-offs between reduction in CO₂ emissions and other important characteristics of decarbonisation unfold and demand attention from the policy-making and academic community, as well as from a more inclusive set of stakeholders. The purpose of this report is to present the results of research aimed at identifying and prioritising evidence gaps from published literature on the impacts of the most salient energy system components of a future decarbonised system. We implemented a multistep mixed methodology to produce a prioritised list of research gaps in the literature which is both comprehensive and detailed bearing in mind the resources allocated to the project.

As a starting point we chose the DECC 2050 Pathways Calculator (https://www.gov.uk/2050-pathways-analysis) to select energy system components for inclusion in this study, as this would ensure broad coverage of the energy system and a taxonomy most stakeholders are familiar with. In order to ensure a comprehensive and inclusive selection mechanism we implemented a web-based survey with a wide coverage of interested stakeholders to select a limited number of energy system components for further analysis. An online, self-completion questionnaire was set up on Survey Monkey (https://www.surveymonkey.com) and kept open for about three weeks. Respondents were recruited through a number of established mailing lists (e.g. UKERC and the SDRN newsletters). Respondents to the survey were asked to score each energy system component through a number of criteria, chosen to enable analysis of the potential importance and significance of impacts of a given component in future decarbonised energy systems. These criteria included: Potential Contribution of Energy System Components; Criticality of Energy System Components; Persistence of Impacts; Local Social, Environmental or Economic impacts; Uncertainty of Impacts; and Uncertainty in Decision Making. As a consequence of this process we selected the following energy system components for further analysis.

<table>
<thead>
<tr>
<th>Carbon dioxide storage</th>
<th>Heat pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS power stations</td>
<td>Electric vehicles</td>
</tr>
<tr>
<td>Nuclear fission power stations</td>
<td>Offshore wind</td>
</tr>
<tr>
<td>Unconventional gas</td>
<td>Land dedicated to bioenergy</td>
</tr>
<tr>
<td>Energy storage</td>
<td>Power interconnectors and transmission / distribution</td>
</tr>
<tr>
<td>Carbon dioxide transmission network</td>
<td>Energy intensity of industry</td>
</tr>
<tr>
<td>Demand-side Response</td>
<td>Onshore wind</td>
</tr>
<tr>
<td>Aviation</td>
<td>Insulation and building fabric</td>
</tr>
</tbody>
</table>

Identification of impact categories from energy system components used in our study was based on previous work of the project team, and detailed feedback from the SPLiCE Management Board. The following impact areas were selected: marine environment; water; land; air; biodiversity; human health; social impacts; and economic impacts. In a number of instances sub-categories were agreed to make the task of identifying research gaps manageable within the allocated resources. In order to collect data on the environmental, social and economic impacts of energy system components, and related research gaps, we conducted a meta-review of review documents discussing impacts of the selected energy system components. In a number of instances however we relied on original studies rather than review studies as our search confined to reviews did not return any matches. The
literate search, according to the adopted protocol, was implemented in Web of Science (http://wok.mimas.ac.uk). We mitigated the risks of not searching for reviews published in the grey literature through expert interviews, and an ad-hoc Google Scholar search for those impacts not returning any match.

After assessing the quality of each review, we collected information related to the intensity of the impacts and to the level of confidence in the assessment of the impacts. Intensity of impacts is based on the assessment of the authors of the reports we reviewed and how they describe the impact. Confidence was considered to be a function of the agreement in the evidence discussed in the study and the type of evidence being discussed. After reviewing all the papers we produced an overall assessment of the intensity and confidence in the assessment for each impact category arising from each energy system component selected for further study through the web-survey.

For each energy system component we aimed at prioritising importance of impacts and related research gaps in literature by using the scores for intensity of impacts and confidence in the assessment. The aim was to place each impact in one of the cells of Table ES1 which combines intensity of impacts with confidence in the assessment. This procedure has the advantage of providing an automated and objective prioritisation of impacts and related research gaps for each energy system component, which is suggested by the colour coding in the table. For each energy system component, it would seem natural firstly to fill research gaps related to the impacts with ‘High’ intensity and ‘Low’ confidence, i.e. the red cell; secondly, to fill gaps related to the orange cells; thirdly gaps related to the yellow cells; and finally, to fill gaps related to the white cells. We validated our procedure and results by holding 10 interviews with selected experts.

Table ES1. Framework for prioritisation of impacts and related research gaps

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

After producing a prioritisation of research gaps for each energy system component, we prioritised research gaps in the literature across energy system components. Our methodology considered the following criteria:

- **Priority of the need.** This is taken from our assessment of impacts and research gaps through the literature review and expert interaction described above;
- **Likelihood of the need.** This is taken mainly from Ekins et al (2013) which presents a review of established UK energy system scenarios. When energy system components selected in this study were not discussed at length in Ekins et al (2013) we have used other more focused scenarios presented in the literature;
Urgency of the need. This is related to one of the criteria used in the web survey, namely “Potential Contribution of Energy System Components”;

Criticality of the need. This is also related to one of the criteria in the web survey, namely “Criticality of Energy System Components”.

Our methodology to prioritise research gaps in the literature across energy system components comprises the following steps.

- We ranked each combination of impact and energy system component based on their score under the Priority of the need criterion;
- As scores above are discrete, we used scores for the Likelihood of the need criterion, to prioritise any combination of energy system component and impact obtaining the same score under the Priority of the need criterion;
- Finally, as scores for both Priority and the Likelihood of the need criteria are discrete, we computed the average of the rank obtained from the Urgency and Criticality of the need criteria to prioritise any combination of energy system component and impact obtaining the same score under the criteria for Priority and Likelihood of the need.

As a consequence of the comprehensive and multistep methodology employed in our study, our final list of research gaps in the literature span a wide range of energy system components. Gaps related to Carbon Capture and Storage, Nuclear Power, Land for Bioenergy, Electric Vehicles and Demand-Side Response are very prominent in the list we produced. Research gaps in the literature related to unconventional gas have received a lower priority due to their more uncertain contribution to a future decarbonised energy system. Research gaps related to the Power Network, Aviation, Offshore Wind and Buildings and Insulation do not feature strongly in the top 20 list mainly because they received a somewhat lower score from the literature assessment and interaction with the experts. No gaps related to Electricity Storage and Heat pumps appear in the top 20 list due to receiving a comparatively low score from the literature review and interaction with experts.

As a result of the methodology discussed here, we have obtained a granular prioritisation of impacts and related research gaps identified through systematic assessment of published reviews and feedback from experts. It should, of course be noted that even where a gap is noted, this does not necessarily mean that there is no evidence or ongoing work in the area, rather that this study suggests that additional information is required. Our work could be refined based on further engagement with experts on specific gaps which have been identified in this fairly high level assessment. Another option would be to commission reviews of selected impacts of some energy system components for which we could not identify any published review. This preliminary reviewing step would also help to further focus research gap related to specific energy system components in a way which could not be delivered as part of the resources allocated to the current project.
Table of contents

1 Introduction and aims ............................................................................................................. 1

2 Methodology .......................................................................................................................... 1
   2.1 Identification and selection of energy system components ............................................. 2
   2.2 Identification of impact categories .................................................................................. 3
   2.3 Data Collection and Analysis .......................................................................................... 4
   2.4 Identification, evaluation and prioritisation of research gaps ......................................... 5

3 Results from web survey ........................................................................................................ 8

4 Prioritised areas ...................................................................................................................... 11
   4.1 Aviation ............................................................................................................................ 12
   4.2 Carbon capture and storage ............................................................................................ 13
   4.3 Demand Side response ..................................................................................................... 15
   4.4 Electric vehicles ............................................................................................................... 16
   4.5 Electricity storage ............................................................................................................ 17
   4.6 Energy intensity of industry ............................................................................................ 19
   4.7 Heat pumps ..................................................................................................................... 20
   4.8 Insulation and building fabric ........................................................................................ 21
   4.9 Land for bioenergy .......................................................................................................... 23
   4.10 Nuclear power ............................................................................................................... 25
   4.11 Offshore wind ............................................................................................................... 26
   4.12 Onshore wind ............................................................................................................... 27
   4.13 Power Networks ........................................................................................................... 28
   4.14 Unconventional gas ....................................................................................................... 30

5 Further prioritisation of research areas ................................................................................ 31
   5.1 Scores for the Priority of the Need criterion ................................................................. 32
   5.2 Scores for the Likelihood of the Need criterion .............................................................. 32
   5.3 Ranking based on the Urgency and Criticality of the Need criteria .............................. 34
   5.4 Prioritised Research Gaps .............................................................................................. 34

6 Limitation of our approach and learning for future assessments ........................................... 35

7 Conclusions ............................................................................................................................ 36

8 References .................................................................................................................................. 38

Appendices

Appendix 1: Complete list of energy system components
Appendix 2: Criteria used to select energy system components
Appendix 3: Literature search protocol
Appendix 4: Details on the methodology used to assessed published evidence
Appendix 5: Detailed findings from the literature
Appendix 6: Detailed results from the prioritisation procedure
Appendix 7: Exemplary research gaps for a prioritised selection of energy system components and impact areas
Appendix 8: Full ranking of energy system components and impact areas assessed in this study

Appendix 9: Web survey report
1 Introduction and aims

A major transformation is underway to decarbonise UK energy generation and use in order to cut greenhouse gas emissions by 80% by 2050. Numerous potential pathways for achieving the 2050 emissions target all demand significant new energy infrastructure in various forms, as well as substantial increases in energy efficiency across the economy.

SPLiCE seeks to provide substantive information about the wide-ranging potential environmental, social and economic impacts of decarbonising the UK energy system. Information needs to be presented in a way that enables informed choices to be made about different configurations of the energy system framed within a wider context. The intention of the programme is to identify what is known and not known about the impacts of different energy system components and then fill any key evidence gaps, either directly or by encouraging others to do so. The full SPLiCE Programme was planned to be delivered in two or three phases. The key research questions for the whole programme are:

- How can Government compare all the significant impacts of the energy decarbonisation options available, so that evidence-based choices can be made about the best mix of options to pursue?
- How can developers, planners and regulators access comprehensive and authoritative information about the impacts of energy infrastructure and other energy choices in order to make decisions about investment, deployment and impact mitigation?
- How can Government, industry and the research community present reliable, easy to understand information on impacts in order to improve public understanding and help engage the public and other interest groups to debate and build consensus around future energy options?

The purpose of this report is to present the results of research aimed at identifying and prioritising evidence gaps from published literature on the impacts of a number of energy system components. It should, of course be noted that even where a gap is noted, this does not necessarily mean that there is no evidence or ongoing work in the area, rather that this study suggests that additional information is required. The report is structured as follows. We start by presenting the methodology we followed in Section 2. As this procedure is necessarily complex we present our results across three subsequent sections. In section 3, we discuss the outcome of a web-based survey to select energy system components for further analysis. In section 4 we present the results from our literature analysis of published reviews and related prioritisation of impact areas for each energy system component selected as result of the outcomes of the web survey discussed in Section 3. In Section 5 we present a prioritisation of impact areas and related research gaps across the full spectrum of energy system components selected in Section 3. Section 6 discusses the limitation of our approaches. Finally, Section 7 draws conclusions from this study.

2 Methodology

Modern energy systems are extraordinarily complex, and involve a high number of actors (e.g. government, private investors, utilities, banks, pensions funds, consumers, NGOs) driven by different objectives and operating across very different timescales. Future energy systems in a decarbonised world are likely to be at least as complex as the current energy
system, as trade-offs between reductions in CO₂ emissions and other important
classifications of decarbonisation unfold and demand attention from the policy-making and
academic community, as well as from a broader set of stakeholders. Our methodology to
prioritise research gaps related to environmental, social and economic impacts of future
decarbonised energy systems is composed of a number of different steps, including:

1. Identification and selection of energy system components;
2. Identification of impact categories;
3. Data collection and analysis and
4. Identification, evaluation and prioritisation of research gaps

Identifying and prioritising research gaps related to a complex topic like the environmental,
social and economic impacts of energy systems is naturally challenging as different
disciplines give different importance to the impacts and to the methods of enquiry to address
them. Assessing and prioritising research gaps is logically a socially-constructed exercise
based on the perceptions of different stakeholders and on the current views of the research
community. This demands a methodology that includes feedback from stakeholders and
experts while being flexible enough to accommodate the particularities of specific energy
system components or disciplinary approaches. This has been achieved by placing feedback
from stakeholders at the core of step 1) above, and implementing an extensive interview
process as part of step 4).

2.1 Identification and selection of energy system components

We chose the DECC 2050 Pathways Calculator (https://www.gov.uk/2050-pathways-
analysis) as the starting point to select energy system components for inclusion in this study,
as this would ensure broad coverage of the energy system and a taxonomy most
stakeholders are familiar with. A number of items were added to the list of energy system
components contained in the DECC 2050 calculator, while others were merged into more
general categories in order to be both concise and comprehensive. The complete list of
energy system components for this study is presented in Appendix 1. In order to ensure a
comprehensive and inclusive selection mechanism we implemented a web-based survey
with a wide coverage of interested stakeholders to select a limited number of energy system
components for further analysis. An online, self-completion questionnaire was set up on
Survey Monkey (https://www.surveymonkey.com) and kept open for about three weeks.
Respondents were recruited through a number of established mailing lists (e.g. UKERC and
the SDRN newsletters). More information about circulation of the web-survey can be found in
the report presented in Appendix 7. Respondents to the survey were asked to score each
energy system component in Appendix 1 through a number of criteria, chosen to enable
analysis of the potential importance and significance of impacts of a given component in
future decarbonised energy systems. These criteria include:

- Potential Contribution of Energy System Components. This criterion looked at the
  significance of energy system components at the national scale within pathways of
  the UK energy system meeting the 2050 CO₂ targets (divided into importance to 2030
  and then to 2050);
- Criticality of Energy System Components. This criterion measures the extent to
  which an energy system component is critical for the UK energy system to achieve
  the 2050 targets, or plays an enabling role to critical technologies;
- Persistence of Impacts. This criterion measures the persistence of environmental,
  social and economic impacts of UK energy system components;
- Local Social, Environmental or Economic impacts. This criterion measures the
  extent to which impact can disproportionately affect a certain geographic area due to
  the size of a single installation or due to the impacts from the interaction of a number
  of smaller installations in the same area;
• Uncertainty of Impacts. This criterion measures knowledge on the nature and scale of potential social, environmental and economic impacts of energy system components;

• Uncertainty in Decision Making. This criterion relates to lack of established methods to address environmental, social or economic impacts from energy system components as part of existing local and national decision-making processes.

We asked respondents to score each energy system component against the above criteria with a ‘High’, ‘Medium’ or ‘Low’ rating, with the exception of “Criticality of Energy System Components” which was scored only ‘High’ or ‘Low’. For each criterion we produced a detailed definition of the scores. The definitions of criteria and the scoring system can be seen in Appendix 2. Bearing in mind the limited resources available for this task and the desire to identify a comprehensive and meaningful list of evidence gaps, we decided to select about 15 energy system components for the next stage of the analysis. The outcome from this process is described in section 3.

2.2 Identification of impact categories

It proved somewhat challenging to produce a detailed list of impacts which could be applied to the diverse list of energy system components selected by the web-survey respondents. Based on experience of the project team (Ricardo-AEA 2014a, Ricardo-AEA 2014b and Rowe et al 2008), and detailed feedback from the SPLiCE Management Board we decided to assess impacts on the marine environment, water, land, air, biodiversity and human health, as well as social and economic impacts. In a number of instances sub-categories were agreed to make the task of identifying research gaps manageable within the allocated resources (See Table 1, below). In order to prevent important gaps in the literature from being overlooked, we decided to add impact sub-categories for specific energy system components based on findings from the literature review. This option has been used a number of times during the data extraction phase described below (e.g. energy consumption in the case of Demand Side Responses).
Table 1. Impact categories and sub-categories used in the current study

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Impact sub-category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine Environment</td>
<td></td>
</tr>
<tr>
<td>Water: to include</td>
<td>Water quality</td>
</tr>
<tr>
<td></td>
<td>Waste to water</td>
</tr>
<tr>
<td></td>
<td>Water availability</td>
</tr>
<tr>
<td>Land</td>
<td>Land use, i.e. land change</td>
</tr>
<tr>
<td></td>
<td>Below ground</td>
</tr>
<tr>
<td></td>
<td>Waste to land</td>
</tr>
<tr>
<td></td>
<td>Above ground</td>
</tr>
<tr>
<td>Air</td>
<td>NO$_2$</td>
</tr>
<tr>
<td></td>
<td>SO$_2$</td>
</tr>
<tr>
<td></td>
<td>Particulate matter (PM)</td>
</tr>
<tr>
<td>Social Impacts</td>
<td>Public acceptability</td>
</tr>
<tr>
<td></td>
<td>Energy security</td>
</tr>
<tr>
<td></td>
<td>Visual intrusion</td>
</tr>
<tr>
<td></td>
<td>Differential incidence of impacts across</td>
</tr>
<tr>
<td></td>
<td>specific locations (rural vs urban), income</td>
</tr>
<tr>
<td></td>
<td>distribution and specific groups e.g. age</td>
</tr>
<tr>
<td></td>
<td>groups, gender, minority groups</td>
</tr>
<tr>
<td>Economic Impacts</td>
<td>Employment</td>
</tr>
<tr>
<td></td>
<td>Economic activity / revenues</td>
</tr>
<tr>
<td>Human Health</td>
<td></td>
</tr>
<tr>
<td>Biodiversity</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Data Collection and Analysis

Our procedure to collect and analyse data on the environmental, social and economic impacts of energy system components and related research gaps is complex, and includes the identification of relevant documents in the literature, data collection and assessment. Bearing in mind the number of impact categories and energy system components described above and the resources allocated to the project, we conducted a meta-review of review documents discussing impacts of the selected energy system components. In a number of instances however we relied on original studies rather than review studies, as our search confined to reviews did not return any matches. We identified relevant documents by implementing a systematic search strategy complemented by a less structured approach based on querying Google Scholar (http://scholar.google.co.uk), and soliciting feedback from a number of professional experts. Under the systematic search strategy we ran 425 searches (25 search terms obtained from the impact categories listed in Table 1 for each of the 17 energy system components$^1$). The literature search, according to the protocol in Appendix 3, was implemented in Web of Science (http://wok.mimas.ac.uk). We mitigated the risks of excluding reviews published in the grey literature in the systematic search through the use of a more inclusive Google Scholar search and by interviewing 10 experts, as discussed below.

---

$^1$ We ended up with 17 energy system component rather than the 16 described in Table 5 as we decided to split, for literature research purposes, electricity storage into electricity battery storage and compressed air energy storage.
For each document identified we assigned a Quality Assessment Score, which is based on the research question being asked, the search strategy implemented by the authors of the review, the weighting of the evidence discussed by the authors, and on the way results are summarised. Table 8 in Appendix 4 describes how reviews might look like for each of the scores related to the four criteria. After assessing the quality of each review, we collected information related to the intensity of the impacts and to the level of confidence in the assessment of the impacts for each energy system component in Table 5. Intensity of impacts is based on the assessment of the authors of the reports we reviewed and how they describe the impact (e.g. a “dominant” impact would be scored highly, whereas a “minor one would be scored low). Confidence was considered to be a function of the agreement in the evidence discussed in the study and the type of evidence being discussed. Details on how we scored confidence can be found in Appendix 4. After reviewing all the papers we produced an overall assessment of the intensity and confidence in the assessment for each impact category in the first column of Table 1, arising from each energy system component selected for further study through the web-survey. The scores on the quality of each review were used to negotiate overall intensity and confidence scores for each combination of impact and energy system component when the scores obtained from different reviews markedly differed.

2.4 Identification, evaluation and prioritisation of research gaps

Research gaps were identified by using evidence collated from published reviews, i.e. explicit calls for further research, identification of limitations in the analysis and discussion of impact features which were not adequately understood. For each energy system component we aimed at prioritising importance of impacts and related research gaps in literature by using the scores discussed above relating to the intensity of impacts and confidence in the assessment. The aim was to place each impact in one of the cells of Table 2, which combines these two elements. This procedure has the advantage of providing an automated and objective prioritisation of impacts and related research gaps for each energy system component, as illustrated by the colour coding in the table. For each energy system component, it would seem intuitive:

1) Firstly, to fill gaps related to impacts with ‘High’ intensity and ‘Low’ confidence – these elements are referred as “High Priority” in the text below;
2) Secondly, to fill gaps related to impacts with ‘Medium’ intensity and ‘Low’ confidence or ‘High’ intensity and ‘Medium’ confidence – these elements are referred as “Medium Priority” below;
3) Thirdly, gaps related to impacts with ‘Low’ Intensity and ‘Low’ confidence or ‘Medium’ intensity and ‘Medium’ confidence – these elements are referred as “Low Priority” below; and;
4) Finally, to fill gaps related to impacts with ‘High’ confidence or impacts with ‘Low’ intensity and ‘Medium’ confidence – these elements are referred as “Very Low Priority” below.
Table 2. Framework for prioritisation of impacts and related research gaps

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

As the procedure above is applicable only to impacts for which we were able to find evidence in the reviews, the judgement of the analyst was crucial to prioritise research gaps related to impacts for which we could not find any evidence. The analyst had to decide whether the lack of evidence was related to a very pressing research gap or an impact not being relevant for the energy system component under analysis. We mitigated risks related to this decision by carrying out interviews with experts in the fields discussed below. The expert interviewees included members of the academic, consultancy and industrial communities, and were selected on the basis of their specific expertise in relation to the energy system components. Their views are incorporated throughout this document, however as the ownership and responsibility for the conclusions of this report rests with its authors, the names and affiliations of the expert interviewees have not been provided, The authors of the report are extremely grateful to all of the expert interviewees for generously giving their time to contribute their views on this report. As an output of the literature review we produced a brief document for each of the energy system components considered in this study, illustrating the key findings from our work. Each document we produced contained three sections: 1) a relatively brief summary of the published impacts and associated research gaps related to the energy system component; 2) a discussion of the prioritisation list for the research gaps found in the literature for the energy system component discussed; and 3) when applicable, a version of Table 2, above (in which research gaps were prioritised). Edited versions of the section in the first element, incorporating feedback from interviewed experts, are presented in Section 4 of this report. Changes implemented as a consequence of feedback from interviews are clearly reported throughout this section. Edited versions of the remaining sections are presented in Appendix 5 and 6, respectively.

After producing a prioritisation of research gaps for each energy system component, one needs to prioritise research gaps across energy system components. This is a relatively
problematic task, as several criteria can be used to assess the relative importance of the gaps. In addition, it is difficult to identify stakeholders and experts with an overview of the research gaps across the whole energy system and who could therefore help to prioritise them. Our methodology considered the following criteria:

- **Priority of the need.** This is taken from our assessment of impacts and research gaps through the literature review and expert interaction described above;

- **Likelihood of the need.** The likelihood of the need to fill a research gap is related to the likelihood of the associated energy system component being a significant part of a decarbonised energy system. We have assessed this mainly through Ekins et al (2013), which presents a review of established UK energy system scenarios. When energy system components selected in this study were not discussed at length in Ekins et al (2013), we used other, more focused scenarios presented in the literature;

- **Urgency of the need.** This is related to a criterion used in the web survey, namely “Potential Contribution of Energy System Components”. As energy system components receiving a High score under this criterion are expected to play a significant role by 2030, there is more urgency to fill any associated research gap for energy system components with a Medium or Low score;

- **Criticality of the need.** This is also related to a criterion in the web survey, namely “Criticality of Energy System Components”. A High score implies that our respondents considered that a certain energy system component would be critical for the UK energy system to achieve the 2050 CO₂ targets, or will play an enabling role to other critical energy system components. As such, it is more important to fill any research gap related to components with a High score those with a Low score.

It is worth mentioning that among the criteria above, the priority of the need for further research is specific to any combination of energy system component and impact, and is scored accordingly. The other criteria, related to the likelihood, urgency, and Criticality of the needs are however specific only to energy system components (i.e. the score is constant across impacts related to the same energy system component). Our methodology to prioritise research gaps across energy system components comprises the following steps.

1) We ranked each combination of impact and energy system component based on their score under the Priority of the need criterion;

2) As scores above are discrete, we used scores for the Likelihood of the need criterion, to prioritise any combination of energy system component and impact obtaining the same score under the Priority of the need criterion;

3) Finally, as scores for both Priority and the Likelihood of the need criteria are discrete, we computed the average of the rank obtained from the Urgency and Criticality of the need criteria to prioritise any combination of energy system component and impact obtaining the same score under the criteria for Priority and Likelihood of the need.

As a consequence of this procedure we obtained a very granular prioritisation of research gaps related to the energy system components and impacts discussed in this study. It is worth mentioning that this very granular prioritisation should be taken as an indication of the importance of filling gaps rather than a strictly normative ordering of priorities. Our work and related prioritisation rests on a number of factors such as importance of impacts and degree of confidence discussed in the literature, energy system components tackled in scenario studies and the extent to which ranking of components obtained from the web-survey is representative of the views of the wider research, policy-making and stakeholder community. It is important to stress that any change in these factors might alter the scores that have been combined to obtain the final ranking, and ultimately the final ranking itself. On the positive side, however, the advantages of such a neatly formulated methodology are clear in the sense that our methodology is

- Objective given the inputs, i.e. final prioritisation is obtained through a process which is easy to understand, transparent and reproducible;
Inclusive, as feedback from stakeholders is thoroughly included in our work, i.e. through the expert feedback on our literature review leading to the scores for the Priority of the need criterion, and through the feedback collected from the web-based survey used to compute scores for the Urgency and Criticality of the need criteria;

Reflective of the current understanding in the literature, i.e. through our systematic review to produce scores for the Priority of the need criterion and through the use of established scenarios to produce scores for the Likelihood of the need.

The implementation of this procedure is discussed in Section 5.

3 Results from web survey

Data was collected from participants by means of an online, self-completion questionnaire on Survey Monkey (https://www.surveymonkey.com) and circulated for about three weeks through a number of established mailing lists. Out of 71 participants providing a usable response, we retained responses from 50 users. We decided to locate the threshold for inclusion in the dataset used in this study at 38 answers per stakeholder. This threshold was chosen as we noticed a clear discontinuity (from 38 to 72) in the number of answers provided by the respondents when ordered based on the number of responses provided, as discussed in Appendix 7. This left us with 9,074 data points from 50 stakeholders. Based on information provided respondents represented a diverse mix of stakeholders, with about a third coming from the academic sector and the remainder evenly split between NGOs, Government, Industry and other sectors. Only about a fifth of the respondents had direct experience of making business and policy decisions related to the environmental, social and economic impacts of energy system components. Confidence in the scores provided by the respondents were overwhelmingly self-rated as Medium. More importantly, we asked respondents to provide feedback on the relative importance of five of the criteria used to evaluate the environmental, social and economic impacts of UK energy system components in our study. The results are shown in Table 3. It is fair to conclude that respondents ordered the criteria used in the survey into three tiers of importance: potential contribution of energy system components was rated as the most important, followed by persistence of impacts and then local impacts, uncertainty of impacts and uncertainty in decision making all attributed a similar level of importance. We did not ask respondents to assign any weights to “Criticality of energy system components” as we planned to use this criterion to verify the overall ranking obtained from the survey. No marked difference could be observed with regard to the weights assigned to the criteria outlined above across stakeholders with and without decision-making experience related to the environmental, social and economic impacts of energy system components.

---

2 We also assess variation on weights assigned to the five criteria in Table 3 based on the background of the respondent. Interestingly, whilst government stakeholders assigned about 25% of the weights to the criterion “Potential Contribution of Energy System Component”, stakeholders from industry assigned an average of 40% of the weights to this criterion. The opposite split can be observed in the case of the criteria “Local Impacts”, “Uncertainty of Impacts” and “Uncertainty in Decision-Making”.
Table 3. Average weights assigned by respondent to five of the criteria used in the web survey

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Average weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential contribution of energy system components</td>
<td>33%</td>
</tr>
<tr>
<td>Persistence of social, environmental and economic impacts.</td>
<td>21%</td>
</tr>
<tr>
<td>Local social, environmental or economic impacts</td>
<td>16%</td>
</tr>
<tr>
<td>Uncertainty of impacts</td>
<td>17%</td>
</tr>
<tr>
<td>Uncertainty in decision making</td>
<td>13%</td>
</tr>
</tbody>
</table>

The following steps were implemented to compute the final ranking of energy system components:

1) Convert High, Medium and Low scores into numeric scores;
2) Compute an average score for each energy system component and scoring criterion across respondents;
3) Compute an overall score for each energy system component by weighting the average scores above with the weights in Table 3;
4) Compute overall ranking for each energy system component based on the overall score;
5) Verify compatibility with the Criticality criterion which has so far been left out from the computation.

Conversion of qualitative scores such as High, Medium and Low into numeric values for further manipulation implies some degree of arbitrariness. We decided to assign a score of 10 for High, 5 for Medium and 1 for Low, as these numbers are intuitively relatable. A sensitivity analysis performed on the data showed that the ranking of the energy system components is not materially influenced by the way in which qualitative scores are converted into numeric value, as discussed in Appendix 7.

The ranking of energy system components obtained from the procedure outlined above was assessed based on ranking under the criterion of “Criticality of energy system components”. The reason for choosing this criterion to verify our overall ranking relates to the aim of this exercise, i.e. to rank energy system components so that an assessment of research gaps with regard to their environmental, social and economic impacts can be implemented for a subset of energy system components. The ranking obtained under the criterion “Criticality of energy system components” is interesting, as energy system components obtaining a “High” score for this criterion were deemed to be critical to meeting UK 2050 targets or to play an enabling role to critical components. Other things being equal, it is more pressing to assess research gaps for energy system components which are deemed to be critical or as enabling critical components.
Table 4. Ranking of energy system component

<table>
<thead>
<tr>
<th></th>
<th>Overall Rank</th>
<th>Criticality Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide storage</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>CCS power stations</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Nuclear fission power stations</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Unconventional gas</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>Energy storage</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Carbon dioxide transmission network</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Demand-side responses</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>Aviation</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Land dedicated to bioenergy</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Power interconnectors and transmission / distribution</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Energy intensity of industry</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Domestic passenger transport</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Insulation and building fabric</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Gas power stations</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>Biomass power stations</td>
<td>20</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 4 shows the top 20 energy system components based on the overall ranking procedure discussed above, and their ranking in relation to the “Criticality of energy system components”. We have highlighted the top 15 ranked energy system components for each of the two approaches. Firstly, it is interesting to notice that the top 15 components tend to score equally well across the two rankings. However, key differences include:

1) **Unconventional gas, hydrogen storage and land dedicated to bioenergy** (ranked 4th, 8th and 13th, respectively, based on the overall rank) are not among the top 15 ‘critical’ components. Although the respondents of the survey do not acknowledge this, use of biomass in the power and industry sector is critical to deliver negative carbon dioxide emissions and allow other sectors to emit more carbon (Ekins et al 2013). Unconventional gas might not be seen as critical component in a decarbonised system, but it is probably the energy system component having attracted the highest level of recent attention from the public and the media (Jaspal and Nerlich 2014 and DECC 2014). For these reasons we retained unconventional gas and land dedicated to bioenergy for further assessment. Hydrogen storage, on the other hand, is an energy technology still requiring considerable basic research before becoming competitive (Argonne National Laboratory 2004). For this reason we believe it is not pressing to assess research gaps in relation to environmental, social and economic impacts of hydrogen storage, and as such it was not carried forward for further assessment.

2) **Domestic passenger transport, onshore wind and insulation and building fabric** are not among the top 15 energy system components based on our overall ranking, but are ranked as such in terms of ‘criticality’. Environmental, social and economic impacts of domestic passenger transport are likely to be related to used technologies,
arguably a combination of electric vehicles, internal combustion engines, hybrids and fuel cell vehicles. Confirming the results from energy system models, our respondents do not expect fuel cell vehicles to represent a significant part of the energy system anytime soon. The main impacts of hybrid vehicles are likely to be similar to those of electric vehicles. Bearing these considerations in mind, we did not include domestic passenger transport among the list of energy system components for further assessment as this already included electric vehicles, which are likely to cover the most important impacts arising from passenger transport. However, we did include onshore wind and insulation and building fabric among the energy system components for further assessment. This is because wind (both offshore and onshore) is consistently considered one of the four critical technologies for power supply in a decarbonised energy system (Ekins et al 2013), and because insulation is widely considered as an enabler of heat pumps – ranked 10th in our overall score (Fawcett 2011). Heat pumps are considered a very prominent avenue for decarbonisation of space and water heating, although concerns have been raised (Eyre and Baruah 2014). We feel that crucial aspects of the energy system would not be included in our subsequent analysis if these two components (onshore wind and insulation and building fabric) were left out of the subset for research gap assessment.

Table 5 illustrates the final list of energy system components retained for further assessment, and their associated sectors.

<table>
<thead>
<tr>
<th>Energy system component</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide storage</td>
<td>Storage</td>
</tr>
<tr>
<td>CCS power stations</td>
<td>Power sector</td>
</tr>
<tr>
<td>Nuclear fission power stations</td>
<td>Power sector</td>
</tr>
<tr>
<td>Unconventional gas</td>
<td>Energy sources</td>
</tr>
<tr>
<td>Energy storage</td>
<td>Storage</td>
</tr>
<tr>
<td>Carbon dioxide transmission network</td>
<td>Networks</td>
</tr>
<tr>
<td>Demand-side Response</td>
<td>Built environment and industry</td>
</tr>
<tr>
<td>Aviation</td>
<td>Transport sector</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>Built environment and industry</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>Transport sector</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>Power sector</td>
</tr>
<tr>
<td>Land dedicated to bioenergy</td>
<td>Energy sources</td>
</tr>
<tr>
<td>Power interconnectors and transmission / distribution</td>
<td>Networks</td>
</tr>
<tr>
<td>Energy intensity of industry</td>
<td>Built environment and industry</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>Power sector</td>
</tr>
<tr>
<td>Insulation and building fabric</td>
<td>Built environment and industry</td>
</tr>
</tbody>
</table>

4 Prioritised areas

This section summarises the results from our literature review and related prioritisation of impact areas identified in the literature for each energy system component, selected based on the results of the web survey discussed in the previous section. Three components that
relate to carbon capture and storage have been combined in section 4.2 below, thus giving 14 sub-sections to cover the 16 energy system components in Table 5. This section also draws on the outcomes of 10 interviews with experts. A fuller description of the findings from the literature for each energy system component can be found in Appendix 5.

### 4.1 Aviation

Our literature search identified 5 relevant reviews, which were assessed to determine the suggested priority list for future research. Several impact categories were not covered in great depth, as the reviews tended to focus on air, noise and to an extent economic impacts.

**The impact of aviation on the economy is suggested as a first priority area for future research.** The reviews we identified assessed impacts of aviation and airports on the economy only in relation to the depreciation of house prices. This seems a fairly established research area, for which a number of meta-analyses exist. We think it would be very important considering the current debate on airport expansion and future projections of passenger demand to have a better understanding of the wider impacts (both positive and negative) of aviation on local, regional and national economies. As no review could be identified addressing these impacts, there might be an opportunity to consolidate and assess existing evidence through a Rapid Evidence Assessment (REA) or expert scoping paper.

**The impact of aviation on air, human health and related social impacts are suggested as second priority areas for future research.** Local pollutants from airports are responsible for air quality and related human health impacts, as well as social impacts of aviation due to the fact that neighbourhoods near the airports are likely to be disproportionately affected by local pollution. It is fair to say that air quality, human health and social impacts of aviation are all driven by emissions of NO\textsubscript{x}, SO\textsubscript{2} and particulate materials (PM). Noise is also important. Despite existing research and high levels of air pollutants at several airports, the contribution of airport-related emissions to local air quality is hard to quantify. The presence of substantial levels of pollution from other sources, with many airports being located near to urban settlements, major highways and roads or industrial installations, makes quantification of airport emissions very hard to distinguish (Masiol and Harrison 2014). Several studies in the literature indicate that health impacts from aircraft PM emissions outweigh impacts from other aircraft pollutants. However, some references point to the lack of specific air pollution-derived health risks (Tesseraux 2004 and Masiol and Harrison 2014) while a series of local studies has highlighted the potential adverse effects on public health and the need for more information. Specifically, there is some debate as to whether health impacts of PM emitted by aircraft in flight can be treated (and modelled) as they are at ground level - although it is not clear if this assumption is supported by evidence. The relationship between aircraft noise, community annoyance and sleep disturbance is one of the best understood impacts but in the case of impacts on learning disruption, mental health and hormone changes there is no conclusive evidence to establish a strong causal relationship (Hume 2010, Mahashabde et al. 2011). The current lack of evidence on the contribution of airports to local air pollutants and generally accepted dose-response functions between pollutants and health impacts appears to present a significant research gap that should be addressed. Finally, as no review could be identified on the factors influencing public acceptability of airports, there might be an opportunity to consolidate and assess existing evidence through an REA or expert scoping paper.

**The impacts of biofuels used in aviation is suggested as a third priority area for future research.** Quite interestingly, we did not discover substantive evidence on the impacts of biofuels used in aviation. A Life Cycle Assessment (LCA) is likely to be beneficial to identify feedstocks with varying level of impacts. The EU Biofuel FlightPath Initiative was introduced in 2011, and aims to achieve two million tonnes of annual production of fuel derived from (sustainable) renewable sources by 2020. A number of recent reports conclude that there is sufficient sustainably produced biomass to meet the EU bioenergy targets by 2020 (e.g.
European Biofuels Technology Platform 2008, Kretschmer et al 2012, and Monforti et al 2013). For this reason we are led to conclude that evidence on the sustainability of the current target is robust enough, although further studies may be required in the future, especially if the target is reached or increased.

The impacts of aviation on the marine environment, water, land and biodiversity are suggested as fourth priority areas for future research. None of the reviews we identified discussed impacts of aviation on the marine environment, water, land and biodiversity. Impacts on the marine environment are likely to be minimal. Construction of airports is likely to induce land use changes and affect the economic development of neighbouring areas. There is an argument for indirect land use change impacts but we would expect them to be relatively small due to the lack of established evidence. Impacts of aviation on biodiversity are also likely to be small unless airports affect sites of nature conservation importance. Impact of aviation on water could be related to water acidification. As the importance of SOx and NOx emissions from aviation sources is considered to be secondary on a global scale we would consider impacts on water to be limited.

4.2 Carbon capture and storage

Our literature search identified 11 relevant reviews which were assessed to determine the priority list of research gaps, although coverage of the impact categories used in this study in these reviews varies depending on the phase (capture, transportation and storage) of Carbon Capture and Storage (CCS) under scrutiny. None of these reviews focuses explicitly on experience from the UK, although some evidence from UK-based studies is discussed.

The long-term safety of CO2 storage is suggested as a first priority area for future research. CO2 storage is affected by considerable uncertainty as to whether it will be secure over long time periods, as well as if and how the associated risk can be reliably assessed and managed (Watson et al 2012). In order to increase public confidence it is therefore important that additional research tackles this uncertainty. It seems essential to develop appropriate, credible and long term mechanisms to deal with risks and their associated liabilities, systematically assess the factors affecting the variability of estimates found in the literature, and develop automated low-cost monitoring, measurement and verification technologies (especially for deep underground storage facilities). As confidence on the long-term safety of storage undermines the whole purpose of CCS, the potential for long-term CO2 leakage seems a pressing area for future research.

Impacts of CO2 storage on the marine environment and biodiversity are suggested as second priority areas for future research, alongside the economic impacts of Enhanced Oil Recovery (EOR). Research on impacts of storing CO2 discussed in the review have largely focused on the impact on the marine environment of sub-seabed CO2 storage outside the UK, although some UK studies have been included. Seepage of CO2 from a sub-seabed storage reservoir through the overlying sediments has the potential to cause major chemical changes in the sediment pore water and at the sediment-water interface, leading to an alteration of dissolved metal concentrations and local biogeochemical cycles. Additional concerns are related to secondary geochemical effects and the potential propagation of water displacement (Carroll et al 2014). Changes in the marine environment have many direct and indirect impacts. Elevated CO2 concentrations can impact benthic microbes, more complicated marine organisms and finally influence marine flora and fauna at the community and ecosystem levels (Halsband and Kurihara 2013). Due to the variation in species' responses to elevated CO2, it remains very difficult to predict future changes in communities and ecosystem functions (Carroll et al 2014). The expert we interviewed stressed the importance of assessing impacts of CO2 on marine environment and biodiversity.

---

2 We believe that planning tools are in place if affected sites have international importance (AEF 2008). Effect on birds has found to be limited, including bird strikes which was reported in the region of 1 strike every 2,000 flights (AEF 2008).
in scenarios similar to those that would occur in a leakage from a CO\textsubscript{2} storage facility. In particular, it was mentioned that evidence from Plymouth Marine Laboratory (PML) simulation studies shows that even in the case of catastrophic failure, CO\textsubscript{2} would be dispersed very quickly if leaked from sub-seabed storage facilities. Bearing in mind the considerable disagreement in the literature it is important that a consensus on the impacts of CO\textsubscript{2} on the marine environment and biodiversity is reached and effectively communicated by the scientific community to a diverse set of stakeholders. This gap could be assessed by commissioning a review of evidence of CO\textsubscript{2} leakage in marine laboratories, controlled field experiments and natural volcanic vents. Ideally, most of the evidence surveyed would be from the UK or other locations where conditions are similar to those observed in the North Sea. Similarly, Enhanced Oil Recovery (EOR) related to CO\textsubscript{2} storage has a strong potential to positively affect the economics of depleted fields in the North Sea. Pershad et al (2012) estimated that the highest rates of EOR deployment in the UKCS would bring £2.7 billion in Gross Value Added (GVA) to the Scottish economy. Uncertainty is considerable and available data and models on sources and sinks are extremely limited. This gap could be further assessed by commissioning a review on the impact of EOR in the USA or an expert scoping paper refining this research gap.

**Impacts of CO\textsubscript{2} storage on society are suggested as third priority areas for future research.** Social impacts of CCS have been assessed in relation to its social acceptability, which is normally assessed for the capture, transport and storage system as a whole. Although only few people take an extreme stance on CCS, either positively or negatively (Seigo et al 2014), at the local level, the picture might look quite different. Although factors influencing the success of projects have been assessed in the literature, it would seem important to get a better understanding, particularly in relation to which factors influence opposition to and acceptance of specific projects and how they can be mitigated.

**Impacts of CO\textsubscript{2} separation on water, land and human health, and impacts of CO\textsubscript{2} storage on seismic activity are suggested as fourth priority areas for future research.** The CO\textsubscript{2} separation phase of CCS may impact water and land through the production of wastes. Cross-media effects are likely (although quantification is not possible due to lack of publicly available data), while increased removal efficiency in emission control technologies such as flue gas desulphurization (FGD) and pre-scrubbing may result in a shift from air emission to water or solid stream emissions (Koornneef et al 2012). Several kilotonnes per year of (hazardous) residues are produced by a commercial scale power plant. Although the reclaimer sludge can be treated in a number of ways, identification of the most appropriate treatment strategy is an open question. In addition, water consumption almost doubles as a result of the large additional cooling requirement of the CO\textsubscript{2} capture process. Health impacts of the separation phase of CCS have been found to be significant in the case of separation strategies using Monoethanolamine (MEA). The toxicity of MEA is well documented, produced by the formation of (carcinogenic) products from its reaction with atmospheric oxidants (e.g. NO\textsubscript{x}) under the influence of sunlight. Although this raises considerable concerns, it seems sensible to incorporate health impacts of CO\textsubscript{2} separation phase as a fourth-tier priority, unless it becomes clear that separation technologies using MEA have a strong competitive advantage on other technologies. There is a possibility that earthquakes could be caused by injection of CO\textsubscript{2} into geologic formations with potential for seismic activity being greatest in seismically vulnerable locations with pre-existing faulting. Current technology provides effective tools for investigating and preventing induced seismic activity (Sminchak et al 2009). The interviewed expert pointed out that CO\textsubscript{2} storage is likely to cause earth tremors but these are unlikely to be noticed as CO\textsubscript{2} is being stored in the North Sea, i.e. far from built-up areas. They also pointed out that there are thousands of these small tremors every year. For this reason we the priority of further research in this area is relatively low.

**Impacts of CO\textsubscript{2} separation on air quality and the economy, impacts of CO\textsubscript{2} storage on water and impacts of CO\textsubscript{2} transportation on human health are suggested as fifth priority areas for future research.** In terms of impacts on air quality emissions, SO\textsubscript{2}, NO\textsubscript{x}...
and PM emissions are expected to decrease or remain equal per unit of primary energy input compared to power plants without CO₂ capture. However, emissions will increase for those substances for which emissions per kWh of (input) primary energy do not decrease enough to compensate for the increase in primary energy required by CCS (Koornneef et al 2010). Estimates of impacts on PM are particularly uncertain, but as pointed out by the interviewed experts all CCS plants will have to comply with related European Directives. For this reason the priority of further research in this area is low. In terms of the transportation phase, existing reviews point to the fact that health impacts of CCS are at worst comparable to the impacts of transporting gas in transmission pipelines. The interviewed expert agreed with this. As the intensity of impact is thought to be low, the priority of further research in this area is also low. Leakage of CO₂ or brine from CO₂ geological storage aquifers constitutes a risk for overlying fresh groundwater resources, for example through the intrusion of contaminants such trace metals, metalloids, and some radionuclides (White et al 2012). Despite important knowledge gaps, the possible environmental impacts of geological storage of CO₂ in deep saline aquifers on shallow groundwater resources appears to be low (Lemieux 2011), especially in favourable geological environments, i.e. a tight caprock or the lack of aquifers in the formations immediately overlying the injection area (Lemieux 2011 and Lions et al 2014). Economic impacts of the separation phase of CCS include the capital component of the plant as well as the energy penalty related to lower efficiency of electricity production. Although these components will have to be reflected in the price of electricity from CCS plants, their impacts are likely to be small.

### 4.3 Demand Side response

Demand Side Responses (DSR) include all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing and level of instantaneous demand, or the amount of total electricity consumption. Our literature search identified 5 relevant reviews, which were assessed to determine the suggested priority list for future research. These surveys mainly focus on the economic impacts of DSR, and to a smaller extent, their social impacts.

**The impact of DSR on energy consumption is suggested as the first priority area for further research.** It is important to mention that the benefits from DSR in terms of reduced or shifted energy consumption can be assessed across a number of metrics, such as value of investments avoided, but also in terms of CO₂ and air quality pollutants. It is interesting to notice that a number of research gaps discussed in the literature relate to the overall impact of DSR on energy consumption rather than any particular, social, economic or environmental impact. Evidence on the way consumers implement DSR and their persistence seems to be fundamental to any assessment of such impacts. The expert interviewee noted that there is a potential trade-off between two types of ‘demand side response’ – absolute demand reduction, and load shifting. A reduced demand makes the impact of the consumer shifting their load smaller; in some cases technologies such as combi-boilers, which can increase efficiency, remove load shifting potential because they do not store energy.

**The economic and social impacts of DSR are suggested as the second priority area for further research.** Evidence suggests the economic impacts of DSR in the UK are sizeable, although there is considerable variation in the estimates even for relatively short- to medium-term benefits, as discussed in Bradley et al (2011). Unfortunately, it is difficult to compare the estimates in the literature as the values are presented in relation to different time frames, discounting factors and assumptions on extent of energy shifts. Although plentiful literature on economic impacts of demand side response exists, as pointed out by the expert we interviewed, there might be an opportunity to consolidate and assess existing evidence through an REA or expert scoping paper, as our literature search could not identify any reviews. Considering the possible size of net benefits of DSR, and variation it their estimation, it would seem important to increase certainty. The allocation of economic impacts
of DSR is not straightforward and is likely to depend on the response of different types of consumers to DSR initiatives. Some, but not all studies found that vulnerable and low-income consumers are less responsive than average to DSR signals, and therefore may benefit to a lesser extent from DSR measures (Frontier Economics and Sustainability First 2012, O’Connell et al 2014). Similarly, it has also been pointed out that while residential demand has a great potential for demand peak reduction and shifting, the greatest potential for responses creating welfare may lie with industrial and commercial demand. It might be simplistic to assume that benefits will be passed back to consumers in an equitable fashion and seems much more likely that some consumers, especially industrial, commercial and affluent households might benefit much more than others, if they are more able to respond to DSR measures. It would seem important to have a better understanding of how benefits arising from DSR are likely to be allocated by generators and utilities across different types of consumers (i.e. residential and non-residential) and across consumers of different sizes. It would also be helpful to better understand the implications of the social impacts of DSR on other policy targets, notably fuel poverty. The expert we interviewed considered the social impacts of DSR as an area with strong requirements for further research. More research is needed on customer engagement in demand side response, which implies the need for longitudinal studies. Customers experience a ‘learning curve’, which companies understand and work with by introducing concepts stage by stage, being aware of the ‘customer journey’. A longer-term analysis of customer engagement with DSR will be more enlightening than ‘snapshots’ or hypothetical willingness to pay questions. For this reason we increased the priority of further research in this area.

The air and human health impacts of DSR are suggested as third priority areas for further research. Although none of the reviews we identified discussed impacts of DSR on air and human health, it is fair to argue that these impacts ultimately depend not only on the impacts of DSR on the level and timing of power consumption but also on which plants are likely not to be used or built as a consequence of DSR. As DSR is likely to decrease the use of fossil fuel based marginal and peak plants, there is a strong argument for estimating the impact of DSR on air quality and related human health benefits.

The impacts of DSR on the marine environment, water, land and biodiversity are suggested as fourth priority areas for further research. None of the reviews we identified discussed impacts of DSR on the marine environment, water, land, air, human health and biodiversity. These impacts are likely to depend not only on which power generating technology is used by marginal and peak generators, but on the whole configuration of the power system. This is because technologies used in peak-time or by marginal generators are unlikely to have a sizeable direct impact on these aspects, unlike their likely direct impact on air and human health. Consequently, the impact of DSR is more difficult to assess, as it is more indirect, uncertain and ultimately dependent on the evolution of the whole power system. One should not underestimate these difficulties, although we believe that average impacts are likely to be small.

4.4 Electric vehicles

Our literature search identified 11 relevant reviews, which were assessed to determine the suggested priority list for future research. A number of impact categories were not covered in great depth, probably due to the fact that electric vehicles (EVs) are an emerging technology.

The impact of electric vehicles on air, human health and the economy are suggested as first priority areas for further research. There is some agreement that widespread EV deployment has a significant potential to positively affect air quality in urban areas as emissions shift from tailpipe to power plant. However, as air quality impacts are largely dependent on a combination of the scale of EV uptake, the future electricity mix (including the level of renewables integration) and vehicle performance, there is no consensus on the
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

The impact of electric vehicles on society is suggested as a second priority area for future research. It would be of interest to assess the allocation of potential costs and benefits from EVs across geographic areas (based on the potential location of UK-based facilities), on income brackets based on the skills required for the production of EVs, and on population groups (delineated, for example by age and gender). As none of these impacts were discussed at length in the papers we reviewed, there might be an opportunity to consolidate and assess existing evidence through a Quick Scoping Review, to verify the existence of the gap. As evidence is likely to be sparse we would expect that independent modelling would be required.

The impacts of electric vehicles on land and water are suggested as third priority areas for future research. Land use and water impacts mainly arise from mining activities and the manufacturing processes required for EV materials (Helmers & Marx, 2012). Expansion of biomass grown for electricity production may also bring environmental impacts, although it has been suggested that this would be a more effective use of biomass than liquid biofuel production (Richardson et al., 2013). The papers covering water-related issues agreed that EVs generate higher impacts on water use, aquatic ecotoxicity and eutrophication potential. However, overall there was little information on water-related impacts, and uncertainties about the intensity of potential impacts are high. It has even been suggested that water usage associated to EVs may be double that of conventional vehicles due to increased electricity requirements (Hawkins, Gausen & Hammer Strømman, 2012). As research gaps related to the impacts on water of electricity production and on land for bioenergy are covered elsewhere in the report we decided to assign land use and water impacts from EVs a third-level priority for research.

The impacts of electric vehicles on the marine environment and biodiversity are suggested as fourth priority areas for future research. None of the papers reviewed covered the impact of EVs on biodiversity or the marine environment. Impacts on the marine environment are likely to be limited at present and may be analysed if future LCAs become more thorough. Impacts on biodiversity are likely to be related to an expansion in the use of biomass for electricity generation, however these impacts will be captured in the assessment of other energy system components.

4.5 Electricity storage

Although there are many different technologies that can deliver electricity storage, our evidence base covers two key options: vehicle batteries and compressed air storage. It is worth mentioning that our expert interview suggested that emerging technologies, such as gravel batteries, liquid air or adiabatic compressed air might in the long run be significant and
transformative, and have quite different kinds of impacts. It was also suggested that it is important to differentiate between different applications for storage – grid storage has quite different technical requirements to car battery storage. Our search returned no reviews covering the environmental, social and economic impacts of electricity storage. The discussion below is based on five original studies we identified in the literature, of which four are about batteries, while one is about compressed air storage. These papers have been used to formulate the priority list below. Impacts of electricity storage in the papers we reviewed are largely formulated through the life cycle assessment (LCA) methodology. As discussed in the building and insulation section, results from LCA studies might be difficult to compare, and the outcome is strongly influenced by the system boundaries chosen. What emerges from our analysis is that the environmental impacts of electricity storage options mainly depend on the environmental profile of the electricity mix. Considering storage in isolation from the wider energy system, or the technology it is part of in the case of vehicle batteries, gives only limited insights into its key environmental, economic and social impacts. In the case of batteries, however, the impact of the cradle-to-gate battery inventory on an electric vehicles’ life cycle impact is in the order of a few percent, and could be further abated if battery active materials can be recycled (Gaines et al 2011). Authors point out that considerable information on production of battery materials is missing, but there seems to be strong agreement on this finding. However, in our expert interview the reliability of this consensus was questioned, due to the relatively small amount of evidence available.

Our first suggestion in relation to electricity storage is that the assessment of this energy system component is discussed alongside power networks or electric vehicles, depending on the specific nature of the electricity storage technology. Our expert interviewee agreed with this, and noted that the impacts of storage are highly contingent on what is going on in the whole system, and what needs it has of storage. In this context, our expert interview advised that understanding the different characteristics of different types of storage, within different system configurations, is important to understanding their potential impacts. In a number of instances, we could however identify opportunities for research that could be implemented in isolation.

**The social and economic impacts of batteries and compressed air energy storage systems are suggested as first priority areas for future research.** As we could not identify any review of social and economic impacts, we suggest that evidence is gathered on profitable applications of batteries and compressed air energy storage systems in the UK either through an REA or an expert scoping paper, which critically assesses the most relevant factors influencing quantitative forecasts. The latter seems a better alternative considering confidentiality of data in this field. We consider this area important, as commercial opportunities related to these technologies could be sizeable. Our expert interview noted that the market structures are not currently in place to reward the value that storage provides to the system and that societial safety concerns around large stores of energy would need to be addressed.

**The environmental impact of batteries is suggested as a second priority area for future research.** Considering that a critical review on current LCA studies has not been published, there might be an opportunity to consolidate and assess existing evidence through an REA or expert scoping paper. As discussed above, there is some agreement in the literature on the environmental impacts of batteries being low but bearing in mind the considerable global investment on battery technologies, and the suggestion from our expert interview, it seems prudent to gather evidence on this matter. An REA should be complemented with expert consultation, as the former would not be able to assess unpublished commercial information. Our expert interview suggested that a key research gap in LCAs is the way they assume batteries are being cycled, and whether this is realistic and appropriate to the application being explored. For example, battery cycling is very different in a car compared to grid applications, and between low and high voltage grid applications.
The long-term role of other less mature storage technologies and an assessment of the extent to which storage and DSR could be mutually supportive or exclusive are suggested as third priority areas for future research. Our expert interview also suggested that the two relatively mature technologies explored in this REA are unlikely to be the only, or even the most prominent storage technologies in the future. The interviewee favoured a more prospective approach, where the possible characteristics that a future system might require of storage are considered, the technologies that could meet these needs – including currently nascent ones – evaluated, and their impacts assessed. Focussing only on impacts of currently mature technologies may not be sufficiently future-proof in this area. Finally our expert interviewee also noted that storage is a means to an end, and that demand-side response (DSR) might deliver the same service with a very different impact. It was therefore suggested that a comparison of the extent to which storage and DSR could be mutually supportive or exclusive, and where the trade-offs lie between their different impacts, would be of use. For these reasons, the long-term role of other less mature storage technologies and an assessment of the extent to which storage and DSR could be mutually supportive or exclusive are suggested as two additional areas for future research.

4.6 Energy intensity of industry

Our search returned no reviews covering the environmental, social and economic impacts of Energy Intensity of Industry (EII). The discussion below is based on WSP, PB and DNV-GL (2015), and the expert interview. WSP, PB and DNV-GL (2015) is a collection of eight reports setting out potential pathways for the eight most heat-intensive industrial sectors to reduce greenhouse gas emissions and improve energy efficiency. These reports focus on technological deployment options (CCS, Biomass, Energy efficiency / heat recovery, Clustering, Electrification of heat and Decarbonisation of the grid). The reports contained some high-level commentary about how deployment of these options would affect energy usage and energy intensity. It is worth stressing that EII is a relative metric that does not itself have an impact on environment, economy and society. As impacts will be the result of specific deployment, our discussion here will be focused on the deployment options mentioned above. The interviewed expert pointed out that assessment of impacts from these options requires joined-up thinking from government and the academic community, across disciplinary and departmental boundaries. Future research would benefit from clear co-ordination and integration of all of the concerns of relevant departments, including DECC, BIS, Defra and DfT.

The role of biomass is suggested as a first priority area for future research. According to a number of energy scenarios, bioenergy could make a big contribution to decarbonising industry (Ekins et al 2013). The expert we interviewed pointed out that there are trade-offs and synergies with regard to the use of bioenergy, especially in in the chemical industry, which can use biomass either as a fuel or a feedstock. A life cycle comparison of the environmental impacts of using biomass in the chemical sector as a fuel or as a feedstock was identified as a useful area for further research. A more specific line of enquiry could be related to the production of bio-oil to be used in plastics, opening a potential avenue to sequester carbon. The interviewed expert also pointed out that sectors that are inherently linked to biomaterials, such as food and drink, focus their attention on issues related to supply chain coordination and safety rather than the carbon and environmental impacts. Hence, research on instruments helping these sectors to shift their attention would be particularly helpful. Bearing in mind expert advice, we propose the role of biomass as a first priority area for future research.

The role of waste is suggested as a second priority area for future research. The expert we interviewed pointed out that there are potential conflicts, as any strategy aimed at reducing waste might impact the feedstock available for the industrial users. BIS (2015) point out the strong potential to convert underutilised wastes into high value products used to produce energy, fuels and chemicals required to support modern economies. The UK has a
world-class science base in this area leading to a more sustainable and efficient approach to resource use and management through innovative processes and technologies. We understand that the Biotechnology and Biological Sciences Research Council (BBSRC), the Engineering and Physical Sciences Research Council (EPSRC) and a number of partners have commissioned an analysis of the economic impact of Industrial Biotechnology (IB) in the UK, including future economic projections to 2025. A comparison of the environmental impacts of using waste as feedstock, either through life cycle analysis or a review of existing studies, would be a helpful contribution to match the economic analysis currently being undertaken. Bearing in mind expert advice, we propose the role of waste as a second priority area for future research.

Collating evidence on the impacts of the energy efficiency and heating options most likely to be deployed in the heavy industry is suggested as a third priority area for future research. This would be framed within an effort to decarbonise the industrial sector out to 2050, as described in WSP, PB and DNV-GL (2015). The energy efficiency options across industrial sectors have been grouped into five categories: 1) Improving heat recovery and minimising losses; 2) Clustering (of sites to optimise resources); 3) Optimisation of current processes (e.g. material recycling, energy management, process and loss control, technology replacement, reconstruction or retrofitting for improved efficiency); 4) Process re-design for efficiency improvements (e.g. Batch reformulation, impulse drying); and 5) Material or product substitution (for lower fuel/carbon alternatives). The expert we interviewed pointed out that the cost of energy is important in energy intensive sectors although it might be less so in the food and drink sector. It must be mentioned that the environmental impacts of these options have not been explicitly mentioned in WSP, PB and DNV-GL (2015) as they were out of scope. For this reason it would be of benefit to further research these aspects. It would seem desirable to start by commissioning an REA or expert scoping paper to consolidate and assess existing evidence in the literature.

The role of CCS and Demand Side Response are suggested as a fourth priority area for future research. We had identified CCS as an interesting option for decarbonisation in the industrial sector. The interviewed expert confirmed that CCS will be significant for the iron and steel, cement, chemicals and refining sectors, although social acceptance of CCS was raised as a concern. Similarly, the interviewed expert pointed out that a number of energy intensive sectors have bid for demand response in the capacity mechanism and that more opportunities might be available. More research could be done about the role of energy intensive industries in the energy mix through demand side response. The interviewed expert pointed out that assessment of these options could occur in conjunction with demand side options, notably Demand Side Respons, so that the cumulative impact on the power sector could be assessed. For this reason, we have added DSR to CCS, as a fourth priority area for future research.

4.7 Heat pumps

Our search returned no reviews covering the environmental, social and economic impacts of heat pumps. The discussion below is based on 7 original studies, although only three of these studies presented data on the impacts relevant to this report. A number of impact categories were not covered in great depth, with most of the discussion in the articles focused on refrigerants used in heat pumps.

The evidence base on non-GHG environmental impacts seems fairly limited and has not produced any review studies. As with electricity storage, key environmental impacts are related to production of the electricity used by heat pumps. Direct and indirect emissions of GHG can be computed relatively easily. Impacts of refrigerants used in heat pumps in terms of CO₂ equivalent are likely to be significant but still a small proportion of total ‘avoided’ emissions associated with heat pump technologies. A number of studies have adopted an LCA methodology to assess non-CO₂ equivalent impacts of refrigerants, but there are
serious doubts that such an approach can yield robust results. A ‘leaked’ unit of refrigerant may have widely differing impacts due to the nature and location of the leak. As it is not currently possible to identify with accuracy the proportion of a leak entering specific ecosystems (e.g. marine environments), impact of leakage cannot be robustly quantified. Any modelling conducted with those data is likely to result in significantly overestimated impacts. Assessment of social and economic impacts of heat pumps is complicated by the fact that future scenarios assume very different deployment levels.

Impacts of heat pumps on society and the economy are suggested as a first priority area for future research. Gathering evidence on the social and economic impacts of heat pumps is important bearing in mind deployment scenarios recently published in the literature and the fact that no thorough discussion of these two areas was identified in our work. It seems urgent to deal with wide-ranging uncertainty in relation to the social and economic impacts of a technology considered key to decarbonising the residential sector. These two research gaps should be further refined through a Quick Scoping Review, but likely topics of interest may relate to factors influencing public acceptability and adoption of heat pumps, employment impacts and industry-wide schemes to ensure rapid uptake of skills required to install and service heat pumps.

Environmental (non-GHG) impacts are suggested as second priority area for future research. This would include the extent to which the leakage of refrigerant is likely to propagate based on site-specific and technology-specific properties. We consider this particularly important as data from LCA databases cannot be robustly used to model non-GHG impacts if it is not possible to characterise the specific way in which the leakage may penetrate specific environments, e.g. land, marine environment or water. If a robust procedure can be adequately produced it becomes interesting to assess whether it is possible to populate current LCA databases with missing information, to robustly model non-GHG impacts from heat pumps. Specific research areas could also include a priority listing of refrigerants, based on current use and expected future use in heat pumps.

4.8 Insulation and building fabric

Our literature search identified 9 relevant reviews, which were assessed to determine the suggested priority list for future research. All reviews employed the Life Cycle Analysis (LCA) framework. Coverage of these reviews in relation to the impact categories used in this study is however fairly limited, with most studies assessing energy consumption and related GHG emissions. Impact of insulation in the residential sector has received considerable attention in the literature, alongside the impact of other policy interventions to raise energy efficiency.

What emerges from our analysis is that application of LCA to buildings is complex due to the lack of established databases for impacts, wide variation between different data sources, site-specific factors, varied assumptions about building lifespan, the evolution of building functions over time and related uncertainties, and the importance of occupant behaviour. Case studies are difficult to compare because of building- and location-specific factors (Buyle et al 2013, Cabeza et al 2014 and Singh et al 2011). Khasreen et al (2009) states that no two case studies can be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used. Quantified generalisations in the literature can be found only in relation to energy used in buildings. Generalisation for other environmental impacts are much more qualitative in nature. Impacts are believed to correlate closely with primary energy demand of the buildings in their life cycle. The operational, ‘in use’ phase is said to be the most critical with regard to environmental loads arising from European buildings, due to high energy requirements for heating, ventilating, and air conditioning, along with domestic hot water and lighting (Buyle et al 2013; Ortiz et al 2009). Commercial buildings have been found to have more impact on the environment (per unit treated floor area) as compared to residential buildings (Sharma et al 2011).
The extent to which environmental impacts from LCA studies of buildings can be reliably generalised and compared is suggested as a first priority area for future research. This is important considering that all review studies adopt an LCA approach. This research priority could be addressed through a methodological note, a quick scoping review or a summary report from one or more experts in the field. It seems important to gather confidence on this matter before undertaking any further comparative analysis and generalisation. If the outcome from this exercise is positive, then one could explore the efforts necessary for methodological development, database development, decision support tools and software development and training, as advocated by Singh et al (2011). The expert interviewee also commented that the long lifetime of buildings is not usually reflected in a dynamic approach to LCA. Carbon intensity of the energy supply mix for example is usually considered as static, meaning that carbon savings would be calculated against the baseline of the current system. The interviewee further added that we need more empirical measurement of the performance of buildings so that cross-building comparison can be robustly implemented. When research questions overlap, empirical data should be collected to reflect this.

Social and water impacts of buildings are suggested as second priority areas for future research. Although the main focus is on energy reduction, both in policy and research, water consumption is an emerging issue and may play an important role in the future. Reducing the water consumption of households is gaining importance and will have to be examined more thoroughly in future research (Buyle et al 2013). Water consumption and related savings can be significant. Specific research gaps are related to the trade-offs between the consumption of water, energy and other materials, robust empirical data on the performance of water-saving measures and the extent to which water saving measures are profitable in the current regulatory setting. The number of studies on social impacts is comparatively small and warrants further investigation, especially in the case of green buildings (Zuo and Zhao 2012). Social impacts of buildings can potentially influence occupant behaviour and ultimately the environmental performance of buildings and the reliability of any conclusion in the literature using average values about occupant behaviour (Buyle et al 2013). The development of indoor environments, design choices and behaviour may have considerable impacts during the use phase of the building and the occupant’s experience (Singh et al 2011). The interviewee commented that there is some literature on owner perceptions of green buildings, for example for passivhauses in Sweden. The interviewee also commented that there is a tendency to ascribe any difference between theoretical performance of a building and actual performance to occupancy behaviour. Better empirical data simultaneously covering a number of indicators are needed to assess the importance of occupancy behaviour as a factor in this disparity.

Economic impacts of buildings, and the social and health impacts of insulation, are suggested as third priority areas for future research. The interviewee pointed out that during periods of rapid technological change, training of the labour force in the building industry will be very important in influencing the adoption of such technologies and practices. It was also questioned whether integration of supply chains, rather than a contracting / sub-contracting approach may help adoption of new building practices. Considering expert advice, we added economic impact of buildings as third priority area for future research. In the case of insulation, different practices have been found to have a small but significant impact on health (among a wider range of energy efficiency measures) – a position consistent with previous reviews (Maidment et al 2014). Higher impacts were found in studies investigating impact on specific medical conditions, in studies employing medical tests or using information from third parties rather than self-reported, in studies using control groups, and in studies published after 1989. In terms of impacts across different social categories, Maidment et al (2014) discovered significant impacts of insulation on children, people in poor health and for vulnerable groups as a whole. Greater effects of energy efficiency interventions on health were found in studies focusing on participants with low incomes. Maidment et al (2014) supports the continued use of household energy efficiency.
improvement to tackle fuel poverty and reduce health inequalities. Among the research gaps, long-term mental health impacts, and the broad cumulative social and human health impacts of insulation, receive most prominence. This includes the impact of using objective measures of health in empirical studies, as opposed to self-reported measures. Despite the reportedly small impacts of insulation on health, there is a case for further research due to considerable deployment of insulation in decarbonisation scenarios published in the literature. It is therefore important to establish clear evidence on long-term cumulative impacts for a policy designed to tackle fuel poverty, reduce health inequalities and deliver CO₂ savings. As pointed out by the expert we interviewed, there are also health concerns with highly insulated buildings, if not carefully designed, leading to over-heating in the summer. It was also mentioned that a considerable amount of research has focused on insulation. Considering expert advice we consider further research in this area to be a third-level priority.

4.9 Land for bioenergy

Our literature search identified 16 relevant reviews, which were assessed to determine the suggested priority list for future research. It is fair to say that current literature focuses on environmental impact. Social and economic issues have received very little focus; no article discussed at length impacts on human health or the marine environment. It is important to note that studies focus on impact factors in isolation, with integrated approaches are notably lacking. The expert interviewee agreed that studies that looked at multiple impacts in a joined up way would be desirable because they would provide a more systematic idea of the trade-offs between the various impacts. As customary in the literature, direct impacts refer to those caused by converting land which was not previously used for crop production to the production of bioenergy (Land Use Change – LUC). Indirect impacts are caused when agricultural land is converted to bioenergy production, forcing intensification of farming or land use change elsewhere to satisfy demand for the displaced crop, e.g. by converting a forest into agricultural land, sometimes in response to market dynamics, such as increased food prices. Indirect land use change (ILUC) may imply a substantial amount of CO₂ emissions being released into the atmosphere.

The indirect land impacts of bioenergy, and all impacts outside of the UK, are suggested as first priority areas for future research. This is an area where application of an integrated approach would be highly beneficial, in terms of use of integrated (economic/agronomic) modelling for studying environmental (ILUC, GHG, biodiversity, water management), economic and social impacts. This is especially true of impacts of large scale 2nd generation bioenergy demand in USA/EU and related production in the global south, as well as in the USA and EU. Of particular interest is the sustainability of marginal "underutilised agricultural lands" in the USA/EU. Additionally, research on the impacts of indirect and direct LUC for bioenergy has hitherto focused on "climate regulation", through biogeochemical processes (carbon sequestration, conversion, storage, GHG reduction). Very little research has gone into the impact of direct and indirect LUC on biophysical processes on land, which in turn affect water regulating services, perturbations of which can affect climate and water systems. According to the expert we interviewed, profound uncertainties remained around various impacts (both direct and indirect), including environmental, social and economic, of significantly increased production outside of the UK (especially in the global south). As the impacts of these could be significant, the interviewee suggested that these global impacts, to which UK demand for bioenergy could be a contributing factor, were among the highest priority research gaps.

The UK-based direct land impacts of bioenergy, as well as the impacts on biodiversity and water in the UK are suggested as second priority areas for future research. Direct LUC can significantly affect nitrogen, carbon and water in the soil (through compaction, for example) (Thomas et al 2013). Most 2nd generation crops cause LUC by displacing agricultural crops, except where marginal lands are used (Rushton et al 2014). Soil Organic Carbon (SOC) changes depends on the crop type and management, and former land use.
There is consensus that conversion of arable to miscanthus / short rotation coppice (SRC) increases SOC, but the conversion of grassland is not so beneficial (van der Hilst et al 2012, Rowe et al 2009). SRC has a positive effect on nitrogen leaching (Thomas et al 2013) but there is less certainty in relation to miscanthus (Rowe et al 2009). Impact on soil condition and fertility depends on the previous use of the land, the 2nd generation crop being planted, and production methods (Spiertz et al 2009). The interviewed expert pointed out that impacts of bioenergy on land are very dependent on the specific bioenergy crop. In addition, there is considerable uncertainty on the impact on soil of removing root matters from previously cultivated crops. For these reasons, research gaps related to this area are placed as at a second-level priority for research.

Direct land use change is thought to be the key driver for adverse biodiversity impacts, leading to habitat loss and changes to species richness and abundance, often paired with biological homogenisation (Rushton et al 2014 and Immerzeel et al 2014). The biodiversity impact of large-scale bioenergy production, the intensification of production, and the use of marginal land should be further studied. Water impacts can be significant and vary considerably with pre-existing land use, crop type and management. Due to the multitude of factors influencing final impacts, generalisation is difficult. There is also potentially a serious risk in terms of availability of hydrological resources, especially in areas with limited supply and where resources are not carefully managed (Rowe et al 2009). The impact on water quality heavily depends on crop type and management. In comparison to arable crops, however, conversion to bioenergy implies benefits in terms of lower usage of fertiliser and pesticide. Areas for further research include the potential application of bioenergy cultivation for public services, such as phytoremediation and flood risk management. The expert we interviewed confirmed that impacts on water are very dependent on the specific bioenergy crops and what the baseline for comparison is (i.e. what you are comparing the bioenergy crop to). They also pointed out that there is considerable uncertainty regarding impacts of widespread biocrop production across an entire catchment. For this reason, research gaps related to this area are also placed as at a second-level priority for research.

**The impacts of using land for bioenergy production on the economy and society are suggested as a third priority area for future research.** The economic and social impacts of land used for bioenergy are normally framed within the ‘fuel vs food’ debate and related conflicts with availability of land and water for food production. Until now price increases linked to bioenergy production have been limited for most crops, as the agricultural sector has responded by increasing production, although it is not clear whether a considerable increase in the production of bioenergy could continue to be accommodated in such a manner. In addition to competition with food, increased use of biomass has an effect on specific sectors, e.g. forest based industries such as pulp and paper. The perception that an expansion of bioenergy use will produce serious competition with food is not accepted by many experts (Popp et al 2014). However, the expert interviewee directly questioned this, as this statement might hold at the present time, with relatively low oil and gas prices. Higher fuel prices as well as other demand drivers could start to see considerable interaction between biomass and other agricultural products. Surprisingly, none of the reviews we assessed discussed the impact of land for bioenergy on rural communities. For this reason there might be an opportunity to consolidate and assess existing evidence through an REA or expert scoping paper. In general, economic aspects of bioenergy, including impacts on food security and food prices, are under researched - with impacts on trade one of the least studied topics (Ridley et al 2012).

**The impacts of land for bioenergy on the marine environment, air and human health are suggested as fourth priority areas for future research.** These impacts are given lowest priority, as they have not been discussed in the literature identified. Air quality impacts have been discussed before, although they were reported to be low (Forestry Commission and Biomass Energy Research Centre 2010). Impacts on human health are also likely to be low, as they are largely correlated with air quality impacts. Finally, impacts of land for
bioenergy on the marine environment might be related to the discharge of fertilisers. As such issues have not been discussed in the literature, we would expect them to be minor.

4.10 Nuclear power

Our literature search identified 12 relevant papers, which were assessed to determine the priority list of research gaps. The human health impacts of nuclear power, which are discussed in 7 of the review papers, have attracted the highest level of attention in the literature. One of the main concerns associated with nuclear power, the release of radionuclides into the environment and the related impacts, could be categorised in a number of different ways in this study but in order to avoid duplication, these impacts have been categorised mainly as impacts on land. The as-yet unresolved issue of how to dispose of nuclear waste has also been categorised as an impact on land. It is worth noting that some of the impacts associated with nuclear power generation span several of the categories used in this study, and ideally would belong to a different category entirely (e.g. the release of radionuclides into the environment). It is also recognised that, although gaps are identified in the literature through our process, this is an area where there is a considerable amount of ongoing work.

The impact of nuclear power on human health and land are suggested as a first priority area for future research. Although a relatively high proportion of the reviews discussed the impacts of nuclear power generation on human health, they emphasise that there are still considerable uncertainties related to the transfers of radionuclides, including the impact of low doses to large populations over long periods of time, and how to appraise the risks associated with low-probability, high consequence disasters (Baxter 1991, Brender et al 2011, Dockerty et al 2014, Mobbs et al 2011, Smith et al 2013, Stamford and Azapagic 2012, CEPN 1995). One interviewee however highlighted that it is not clear that a scientifically proven ‘safe’ and publically accepted disposal option will ever emerge. Interviewees stressed that the impacts of radiation on human health are still not well known, due to the major complexities of the interactions, down to the cellular level. Interactions may have inter-generational effects through genomic instability and the bystander effect. There remains uncertainty around the possibility of increased radiation susceptibility of vulnerable sub-populations, and synergistic effects, e.g. what happens if an organism is subject to both a radiation and a chemical impact. In terms of impacts on land, those related to the release of radionuclides into the environment and those associated with mining and processing of nuclear fuel have been identified as causes for concern but they are not well understood (Dockerty et al 2014, MacKenzie 2000). There is also the as-yet unresolved problem of how to dispose of nuclear waste safely and in a publically acceptable and economically sustainable way (Holm et al 2002, MacKenzie 2000, Salvatores and Palmiotti 2011). One expert interviewee commented that terrestrial ecotoxicity is under-represented in the literature (for example, re-suspension of radionuclides in the Chernobyl area from fires), and that there is also uncertainty around impacts relating to mining and associated. Another expert interviewee thought that toxic impacts on land from uranium mining were substantial, and that there were also social and cultural issues as some mining takes place on land that is of high cultural and spiritual value to indigenous peoples. There is also an ethical question relating to the scope of Strategic Environmental Assessment (SEAs), which, under EU rules are only required to assess impacts within the EU. This means that mining impacts are typically excluded from nuclear SEAs.

The impact of nuclear power on society, the economy and water are suggested as second priority areas for future research. Social impacts such as a lack of public acceptability (MacKenzie 2000), and economic impacts such as the costs of radioactive waste storage, of decommissioning, and of damages associated with major accidents (Ragaišis et al 2014) were discussed in the reviews identified but not comprehensively evaluated. Research gaps in the area of social impacts highlighted in the expert interviews include the full footprint of nuclear disposal infrastructure (including the transport lines and a
receiving facility to house all buried nuclear waste), options for agreeing on the siting of nuclear waste disposal facilities (including volunteerism and local democracy), nuclear plants’ vulnerability to terrorist attack, and the impact of nuclear plants on roads and other infrastructure in rural communities. An expert interviewee pointed out that the potential impact on displaced populations following a nuclear accident is under-researched. Another key research gap arising from the interviews is related to the management of profound scientific uncertainties when undertaking regulation and public engagement. Nuclear power involves questions of low probability but high impact risk. Under conditions of fundamental scientific uncertainty, policy decisions are very high-stakes. Under such uncertainty, what is sometimes portrayed as objective, evidence-based policy making actually has significant subjective elements, and is not necessarily purely ‘scientific’. With regard to the economic impacts, the interviewees agreed that there are significant gaps in research related to internalisation of nuclear liability costs, related to both waste disposal and accidents, and on probabilistic risk assessments (PRAs) in the context of beyond design-base cascading accidents. The interviewees pointed out that failure to internalise liabilities implies that taxpayers are ultimately responsible for these costs and that nuclear receive a hidden subsidy. Impacts of nuclear power on water, such as the water consumption used in the mining and processing of nuclear fuel, were identified but not assessed in depth in the reviews we examined. According to the analysis in this study the impacts of nuclear power on these categories was less intense but also with low confidence levels, suggesting a need for future research in order to fill research gaps. The expert interviewee commented that issues of radiation on ecology and eco-toxicology, especially regarding water, are under-represented in the literature. There are significant issues around storm surge, flooding, tidal ingress and nuclear islanding. Under some climate change scenarios, storm surges and flooding may happen over a relatively short time horizon. Given that the UK’s nuclear plants are all located by the sea there may be a particular vulnerability here.

The impact of nuclear on the marine environment and biodiversity are suggested as the third priority areas for future research. Only one review (Dockerty et al 2014) considers the impacts of nuclear power generation on the marine environment and (marine) biodiversity. These impacts were considered of medium intensity with a medium/low confidence. Given the coastal siting of many of the UK’s nuclear capacity, and the related issues highlight above long-term marine vulnerability may be present.

The impact of nuclear power on air quality is suggested as a fourth priority area for future research. No review was identified addressing the impacts of nuclear power on air quality. Radionuclides from nuclear power generation are emitted into the air, but their impacts are discussed under the category of health.

### 4.11 Offshore wind

Our literature search identified 7 relevant reviews, which were assessed to determine the suggested priority list for future research. Identified papers focused on the impacts on the marine environment and biodiversity as well as economic and social impacts. However, comments made in the expert interviews suggested that the strength of the evidence base was limited by methodological problems (as discussed below), and that while the possible environmental impacts suggested in the literature were in most cases plausible, judgements about the magnitude and even in some cases the direction of the impact, remain somewhat speculative.

The impact of offshore wind farms (OWFs) on biodiversity is suggested as a first priority area for future research. Evidence in the review shows that there are both positive and negative impacts of OWFs on biodiversity, but evaluation is complicated by the need to have sufficient baseline and trend data, as well as suitable control areas. For birds, the operational phase of wind farms presents the biggest risk from collisions with pylons, or pylons acting as barriers to avoid (Bailey et al 2014, Mangi 2013). However, this remains a
contentious issue, and a number of factors remain unclear (Inger et al 2009). For example, bird vulnerability and mortality are related to a combination of site-specific, species-specific and seasonal factors (Bailey et al 2014, Premalatha et al 2014). The impact of anthropogenic underwater noise and vibrations on marine life is also a growing concern, with an increasing body of evidence demonstrating its adverse effect on species such as marine mammals with very sensitive hearing (Dockerty et al 2014, Inger et al 2009, Mangi 2013, Mann and Teilmann 2013). Disturbance is most severe during construction when audio receptors of sensitive species can be damaged by loud noises (Dockerty et al 2014). Noise during the operational phase is likely to be less intrusive, although it might mask communication and orientation signals among fish (Inger et al 2009, Mann and Teilmann 2013, Premalatha et al 2014). The impacts of OWFs on seabirds and noise-sensitive marine mammals, and on the consequences that impacts on individuals at specific sites may have on the population of affected species and the ecosystem services provided, are areas requiring further research. Habitat loss due to offshore wind farms is unlikely to be significant based on evidence published in the literature, with artificial reefs created by OWFs often producing an increase in both the density and biomass of fish. However, according to feedback from the expert interview, there remains considerable uncertainty regarding the overall effects of artificial reefs. We think it would be helpful to have a better understanding of how species composition are affected by OWFs and whether an increase in biomass in the presence of artificial reefs is a result of concentrating biomass from surrounding areas or an overall net increase.

Social and economic impacts are suggested as second priority areas for future research. The reviews we identified assessed impacts of OFWs on the economy and society only in relation to public acceptability, fisheries and recreational value of the shoreline. Public acceptability and recreational values of the shoreline seem fairly recognised research areas; in which established methodologies such as contingent valuation and choice experiments are employed. Impacts of OWFs on fisheries are concern fish stocks and the wider marine environment, with the additional complication that the presence of OWFs affects the level of fishing effort and its distribution across fishing grounds. We think it would be helpful to have a better understanding of the drivers of public acceptability, recreational value of the shoreline and of the fishermen’s behaviour in presence of OWFs - as well as the relationship between positive impacts of OWFs on the population of commercial fish and their negative impacts.

Impacts on water, land, air quality and human health are suggested as third priority areas for future research. None of the reviews we identified discussed impacts of OWFs on water, land, air and human health. It is worth mentioning that none of these impacts are likely to arise as part of the ordinary operation of OWFs. Impacts on air quality can arise during the construction phase of the farm, such as through combustion of fossil fuels from offshore construction vessels, but such impacts are almost certainly minimal. Consequently, one can also exclude significant impacts on human health arising from the construction phase of OWFs. There is an argument for impacts on water, land, air quality and human health arising from the construction of wind turbines but we would expect these impacts to also be minimal, due to lack of established evidence based on Life Cycle Analysis studies.

4.12 Onshore wind

Our literature search identified 8 reviews, which were assessed to determine the priority list of research gaps. Terrestrial wind energy is a mature renewable technology, historically viewed as a benign, clean and ‘green’ energy source. However, there has been increasing resistance to onshore wind, questioning the economics, environmental impacts and capacity to deliver (intermittency). Impacts can be high, but tend to be very local in their effects; assessment of cumulative impacts is recognised as important.

The impact of onshore wind on biodiversity is suggested as first priority area for future research. Biodiversity studies are often observational with little or no experimental
control. The intensity of impacts can be locally high and can put endangered species at risk (Mateo-Tomas et al. 2010), but equally, there are many cases (often underreported) where there is little or no effect; the wider translation to different landscapes and situations is largely not understood. Bird and bat strikes clearly happen and when they impact keystone species it is highly emotive, but for a specific location questions need to be asked about the counterfactuals. Better understanding and methods to measure and value the consequences for biodiversity should lead more informed planning decisions and reduce the uncertainty and potential for dispute. Techniques for real-time monitoring (using radar and Thermal Animal Detection Systems (TADS)) are being employed to tailor wind farm operational management to flight behaviour. Research is needed for both techniques to establish operational guidelines in different conditions and under different circumstances. Other research gaps suggested in the literature are often specifically related to birds and include ranging behaviour and habitat preference and population impacts.

The social impacts of onshore wind are suggested as a second priority area for future research. Public acceptability is often key to planning approval. Issues that need research include the stability and dynamics of development within designated areas (Clark and Roddy, 2012), factors influencing local opposition to development of wind farms (NIMBYism) (Devine-Wright, 2005) and general public acceptability of wind energy (Batel, et al., 2013). Considering the concentration of onshore wind farms in specific areas, local community effects (both positive and negative) can be very large and should be researched. There is already interest in community and specific stakeholder attitudes, including how many turbines are appropriate for different locations (Jones et al, 2011), the spatial extent of the impact on communities (Jones & Eiser, 2010), the importance of remoteness (Hanley & Nevin, 1999) and wider landscape issues (Wolsink, 2007).

The impacts of onshore wind on land and human health are suggested as a third priority area for future research. The impact of isolated turbines and how they differ from wind farms needs further work, particularly in relation to non-linear impacts of different scales of activity in different parts and forms of landscapes (although, similar issues around the impact of micro turbines in urban areas have not been raised). One of the fundamental assumptions when making cumulative assessments of impacts is that they are additive, where in many cases they clearly are not (Scottish Natural Heritage, 2012). Other assumptions must be made explicit and tested. Issues surrounding land and human health need to be examined to provide evidence of their impact intensity. For human health, the release of toxic emissions during manufacture and management of waste following decommissioning were identified but need to be investigated in detail. For land, the potential for indirect land use change (ILUC) appears low, but has not been authoritatively discounted and the consumption of resources during manufacture and the impact of waste following decommissioning (especially plastics) have been identified as needing further investigation.

The impacts of onshore wind on water, air quality and the economy are suggested as fourth priority areas for future research. In general, water is not considered to be significantly impacted by the operation of terrestrial wind farms (Averson & Hertwich 2012) although where turbines are erected on peat bogs there may be impacts on hydrology that could destabilise the ecosystem (Tosh et al. 2014). Impacts on air quality, which are only reported during the manufacture and decommissioning phases (Dockerty et al., 2014), are comparable with normal manufacturing processes (Averson & Hertwich, 2012). Economic impact (revenue, jobs, etc.) varies at different scales; from local to national. Local community effects can be very large, but in the UK the impact appears relatively small (Biggar Economics, 2012). The latter are considered under social impacts.

4.13 Power Networks

Our search returned no reviews covering the environmental, social and economic impacts of power networks - including electricity interconnections (IC) and transmission and distribution (T&D). The discussion below is based on Ricardo-AEA (2014) and a summary document
from the UN, both referring to the impacts we focus on in our study. Generally speaking, the environmental impacts of T&D and IC infrastructure are relatively small, and occur mostly during the construction phase, with offshore/marine structures having even less impact than onshore. The operational impacts throughout the lifetime of the asset are quite limited due to a small footprint.

The impact of power networks on the economy is suggested as the first priority area for future research. It is clear that power networks enable the diffusion of electricity generation technologies and the proper functioning of the market, i.e. allowing cross-border power flows which are fundamental in order to facilitate market price convergence and arguably stability across European markets. Although these two categories of impacts have not been explicitly mentioned in either of the two papers reviewed in this study, it is the author’s opinion that their impact is likely to be particularly strong on factors such as electricity prices, security of supply through interconnection, and deployment of electricity generating sources. The expert we interviewed agreed that economic impacts were important but commented that there is a considerable strand of literature already published on this. Considering that a critical review on these impacts has not been published, there might be an opportunity to consolidate and assess existing evidence through an REA or expert scoping paper.

The impact of power networks on human health is suggested as a second priority area for future research. This is particularly related to exposure to electromagnetic fields, as there is little consensus in the literature as to their actual impacts on human health (UN 2006). As this impact may considerably affect the general public’s perception of power networks, addressing this gap might also produce benefits with regard to the social impacts of power networks.

The impacts of power networks on land and water are suggested as third priority areas for future research. Land-related impacts have received considerable interest, motivated by direct Land Use Change (LUC) of the construction phase. All forms of network construction have low indirect LUC impacts although soil condition and quality may be affected by erosion, contamination and sealing, which have a medium impact (UN 2006). The construction phase has a higher risk of pollution due to soil erosion, machine contamination, and possible herbicide use (UN 2006). The expert interviewee commented that issues are more to do with substations than transmission and distribution lines. In substations, there is the risk of leakages of the fluids used as insulators. However, newer assets have replaced oil-based insulators with gaseous products. For this reason the research priority in this area is relatively low. The construction and operation of networks has limited impact on availability and quality of water (Ricardo-AEA 2014).

The impacts of power networks on society, air quality, the marine environment and biodiversity are suggested as fourth priority areas for future research. Air quality impacts are considered low priority, as these are mainly related to the construction phase of the network asset, with very small impacts from the operational lifetime of the asset. Social impacts, which have been traditionally restricted to public acceptability, are considered to be low. The main biodiversity impacts of networks occur onshore, when land is converted for infrastructure construction. Biodiversity impacts include disturbance, fragmentation and loss of connectivity (Ricardo-AEA 2014). However, due to a relatively small infrastructural footprint, these impacts are not significant. Finally, impacts on the marine environment have not been explicitly considered in the reviews we assessed. We believe that these impacts are not likely to be significantly different from those related to cables laid to bring power generated by offshore wind turbines to the terrestrial system. Considering expert advice, the priority for further research in these areas is low, to enable research on water to be given precedence. The interviewee also raised a research gap related to social understanding of what kind of service they should expect from the electricity system, how they can interact with it, and how this might change. As this is particularly relevant to Demand Side Response we propose this issue is taken forward as part of cumulative impacts.
4.14 Unconventional gas

The literature search returned 11 relevant reviews on the environmental, social and economic impacts of unconventional gas. These reviews tend to focus on specific issues such as impacts on hydrology and atmospheric emissions and in relatively few locations, predominantly in the USA. In places the impacts were high, but acted across a range of scales from local to regional. Specific social, environmental and economic impacts were detailed in the reviews, but these were sometimes more hypothetical than actual, especially when related to the environment or human health. The reviews described the environmental pressures created by unconventional gas extraction (i.e. the chemicals released and their potential toxicity), but as the technology is relatively new, there is little evidence of the full range of impacts, especially possible long-term impacts.

The impact of unconventional gas on air is suggested as the first priority area for future research. The interviewed expert pointed out that fugitive emissions (e.g. accidental venting of methane to the atmosphere) are very important, as we have no robust estimate of total emissions. There is evidence that the oil and gas industry as a whole produces a considerable amount of fugitive emissions. According to the expert, better calculation of potential and actual emissions is required. Emissions will be predominantly methane; their impact as GHG must be assessed. We also need a better understanding of the mechanisms of release and their pathways, for example how gas leaks out of a hole in a casing. In the USA the need for a monitoring network was seen as essential. Concerns were raised over air quality legislation (in the USA), and the feeling expressed that better definition of regulations is needed; this should be fed by evidence from research. Other gaps identified in the reviews focussed on atmospheric impacts were suggestions that could be read as the need for an integrated assessment. They included a proposal to develop location-specific case studies, make broader population health impact assessments, and have a comprehensive classification of emissions. The latter compliments other calls for full life cycle assessments. Considering expert advice, we assign this area as a primary focus for further research.

The impact of unconventional gas on water and seismic activity are suggested as the second priority areas for future research. One area consistently identified as essential was the need for representative monitoring and the establishment of dynamic baselines to compare impacts. New exploitation of unconventional gas is often in areas where traditional extraction has already taken place, and the geological formations may already be releasing methane and other hydrocarbons; it is important to know the background prior to extraction. BGS has a baseline dataset for the UK. Support to maintain this dataset through a programme of monitoring and improved access with estimates of confidence is needed to maximise its value in use as evidence. It was also highlighted that the chemicals used and processes undertaken need better documentation and understanding. It is not simply knowledge of the character of additives but their fate and pathways in the field. Chemicals are injected under pressure, in conditions of varying pH and in mixtures with other chemicals; by-products may be persistent and toxic. A better understanding of the wider interactions between chemicals with different stakeholders (operators, residents, etc.) would provide more confidence on the probability and risks associated with exposure. The impact of compromised water quality and availability will create pressures that need improved understanding; they are likely to be reflected in economic, technological, social and political fields. These interactions will appear across the whole life cycle and, when multiple extraction sites are considered, need to be examined as cumulative impacts. Finally, from a water perspective, there is a common call for more in-depth research into how the near-surface groundwater system varies from location to location and changes under different stresses. Until there is better understanding of how different formations, geology, and locations respond to specific interventions we will not be able to effectively account for the entire fluid volume. New research into the use of isotopes to map groundwater systems would be extremely valuable. Bearing in mind the importance of fugitive emission we have decreased the priority of water accordingly. In the case of land, the expert we interviewed
considered a better understanding of the relationship between fracking and seismicity very important. He felt that we need improved knowledge of residual rock stress and earthquakes, so we can better manage the stresses through fracking to minimise impacts. These areas would link to how varying the pressure of the frack affects seismicity. In more general terms, there is (very limited) research looking at the impact on land use and there are a number of threads requiring investigation, including indirect land use change, multifunctional land use and a number of topics that overlap with other themes (impact on land value associated with changed use, visual impacts and their social valuation). However, according to the interviewed expert, research on seismicity is more pressing than other land-related research areas. For this reason we increased the priority of further research in this area.

The impacts of unconventional gas on human health, society and the economy are suggested as third priority areas for future research. For human health, systematic tracking of exposure is necessary to inform risk mitigation. Other apparently ancillary stressors (e.g. noise, light, traffic and rapid change) all need to be understood and taken into account. We found that the assessment of population scale impacts is not well understood. As with a number other impacts, baseline health statistics and monitoring are required. None of the papers reviewed covered in any depth the social and economic impacts of unconventional gas. As these have the potential to be considerable, for example through boomtown growth during exploitation to its subsequent collapse once extraction terminates (Adgate et al 2014) or through the net wider impacts of UK-based extraction of unconventional gas on the economy, we think that these gaps should addressed. A possibility would be to commission a review on social and economic impacts of unconventional gas in the USA and how they could apply to an UK context, or an expert scoping paper refining this research gap. Bearing in mind expert advice, we decreased the priority of further research in these three areas as filling those gaps was judged to be less urgent than those related to land and water.

The impacts of unconventional gas on the marine environment and biodiversity are suggested as fourth priority areas for future research. Hydraulic fracturing under the ocean was not covered by any of the reviews. However, studies in the Gulf of Mexico where traditional tight gas extraction, using similar techniques, can provide information on the effectiveness of capping and the expected rate of failure of concrete casing allowing gas leaks. The interviewed expert pointed out that the UK has considerable experience with exploration in the North Sea. No review was identified addressing the impacts of unconventional gas on biodiversity, which leads us to consider that impacts are likely to small unless biodiversity-rich areas are affected. However, these areas are likely to be covered by current planning system and related legislation.

5 Further prioritisation of research areas

This section reports the results of the methodology to prioritise the research gaps across energy system components described in Section 2. Before presenting these results, we will:

- present the scores for the Priority of Need criterion – obtained through the prioritisation discussed in Section 4;
- explain how we obtained the scores for the Likelihood of the Need criterion presented in Table 6;
- present the ranking which we obtained from the Criticality and Urgency of the Need criteria obtained from the web survey discussed in Section 3.
5.1 Scores for the Priority of the Need criterion

The scores we obtained for the Priority of the Need Criterion are shown in Appendix 6. As they have mainly been obtained through the procedure discussed in Section 2 and are reflective of the discussion in Section 4, they will not be discussed further. It is important to mention, however, that when we could not gather enough evidence from the literature in relation to a certain impact of an energy system component, we produced a score based on the relative prioritisation discussed in Section 4. For example, if the research gaps related to the impacts of a given energy system component were considered to be more pressing than gaps related to impacts judged to have “High priority”, we concluded that the score for the former must be larger than ‘High’. We indicated these components by introducing, in the table in Appendix 6, a bigger than (">") or a smaller than (“<”) sign together with the score used as relative benchmark. Long-term safety of CCS provides an example of the application of this procedure. When scores could not be assigned across impacts for a specific energy system component we produced scores in Appendix 6 through benchmarking across energy system components or by further interaction with experts. These cases are indicated by a star (*) in the table.

5.2 Scores for the Likelihood of the Need criterion

It is important to explain how we obtained the score for the Likelihood of the Need criterion presented in Table 6, which as mentioned in Section 3, is based on Ekins et al (2013). An absolute consistent result emerging from all the model runs discussed in Ekins et al (2013) is that the UK electricity system needs to reduce CO2 emissions by at least 80% by 2030 if the UK is to meet its GHG emission reduction target for 2050 cost effectively. As this implies considerable changes in the location of the generating capacity and related network requirements we assigned in Table 6 a “Very Likely” score to the research gaps in the Power Network, as they are very likely to require filling, regardless of the particular technologies being deployed to deliver low-carbon electricity.

In fact, Ekins et al (2013) reports that there is continuing uncertainty in relation to which low-carbon technology will become dominant in a future decarbonised energy system. On the positive side however, there are only four main options: nuclear power, large-scale renewables, fossil fuel power stations with CCS and smaller scale, more decentralised renewables. As quite small changes in assumptions can produce quite large changes in the outcomes with regard to the deployment levels of these four technology groups, Ekins et al (2013) concluded that it seems wise to deploy all of them until a clear best choice or optimal mix emerge. This implies that it is important to continue to address research gaps for these energy system components while such uncertainty persists. For this reason we assigned in Table 6 a “Very Likely” score to the energy system components in our study related to the four groups mentioned above, namely Nuclear power, CCS, Land for Bioenergy and Offshore Wind. It is worth mentioning that Onshore Wind would also be part of the core electricity options for decarbonised 2050 energy system discussed in Ekins et al (2013). However, considering the new government’s pledge to end onshore wind subsidies (Guardian 2015) and the changes in the planning system for projects larger than 50MW contained in the Queen’s speech (BBC 2015), the contribution of Onshore Wind to a future decarbonised system is at best unclear. For these reasons we have assigned in Table 6 a “Somewhat Likely” score to Onshore Wind, as the salience of related research gaps in the future is far from certain.

The role of International Aviation is not discussed at length in Ekins et al (2013), as the models used in the reviewed scenarios focus on national emissions. The importance of emissions from International Aviation in a decarbonised energy system is however clear from the scenarios reviewed in CCC (2012). The “likely scenario” from previous CCC analysis (CCC 2009) postulated about 45 MtCO2 emissions from aviation in 2050. Baseline scenarios from DIT (2011) are just short of 50 MtCO2 in 2050, while the high abatement case is lower
than 20 MtCO$_2$. Considerable demand growth for aviation is assumed in these studies, e.g. 150% increase from 2005 to 2050 in the baseline case of CCC (2009) and a 105% increase in the baseline case of DfT (2011). All these factors led us to assign in Table 6 a “Very Likely” score to aviation, as research gaps related to this energy system component are very likely to require filling.

Another conclusion in Ekins et al (2013) is related to the importance of energy efficiency and conservation in a decarbonised energy system. The lower the amount of energy required to satisfy a desired level of energy services, the easier it will be to deliver the necessary low carbon supply. With regard to the energy system components discussed in this study, Energy Intensity of Industry, Insulation and Building Fabric, and Demand Side Reponses seem those most related to energy efficiency and conservation. Bearing in mind the fact that energy efficiency and conservation measures can however be delivered by a number of other energy system components, we assigned a “Likely” score in Table 6 to Energy Intensity of Industry, Insulation and Building Fabric and Demand Side Reponses. In fact, based on our reasoning, research gaps are likely to require filling only if energy efficiency and conservation mainly take place in these three sectors.

A “ Likely” score has also been assigned to Electric Vehicles, Heat Pumps and Electricity Storage. All the model runs in Ekins et al (2013) show some electrification of heat and transport, using a largely decarbonised power system, but the degree of electrification differs markedly across the runs. Electric vehicles (including battery vehicles and plug-in hybrids) do not make a major contribution to transport in all scenarios, sometimes replaced by biofuels and hydrogen fuel cell vehicles, especially in the later UKERC model runs, where an updated version of the model MARKAL was deployed. Electricity makes a major contribution by 2050 to heating in all scenarios discussed in Ekins et al (2013), either directly or through heat pumps. However, questions have been recently raised about the large-scale deployment of heat pumps (Eyre and Baruah 2014). A lower number of heat pumps in the residential sector was also recently assumed by the Committee on Climate Change (CCC 2013) as part of the recent review of the Fourth Carbon Budget. One can notice that uncertainty in relation to electricity vehicles and heat pumps is higher than uncertainty related to the four groups of low-carbon electricity generation technologies discussed above. For this reason we have assigned only a “ Likely” score to Electricity Vehicles and Heat Pumps in Table 6. The same score has been assigned to Electricity Storage as this energy system component comprises mainly batteries used for Electricity Vehicles.

Based on the scenarios reviewed in Ekins et al (2013), consumption of gas in the power sector markedly decreases, with its role confined to providing back-up capacity for inflexible low-carbon generating capacity. With regard to the provision of residential heating, it is clear that heat will be no longer provided on a large scale by individual gas boilers (Ekins et al 2013). In fact, none of the reference scenarios reviewed in the study included a significant use of gas to produce heat in the residential sector by 2050. It is also important to notice that a significant role of gas in a future decarbonised energy system, which is far from certain, does not necessarily imply a role for Unconventional Gas as worldwide supply of conventional gas is abundant while the development of LNG promises liquid international markets. Based on this reasoning, we have assigned a “Somewhat Likely” score in Table 6 to Unconventional Gas. However, this score might need revision if development of unconventional gas is pursued to boost economic growth or energy security.

### Table 6: Scores in relation to the Likelihood of the need to fill related research gaps

<table>
<thead>
<tr>
<th>Energy System Component</th>
<th>Likelihood of the Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation</td>
<td>Very likely</td>
</tr>
<tr>
<td>Carbon Capture and Sequestration (CCS)</td>
<td>Very likely</td>
</tr>
<tr>
<td>Demand Side Responses (DSR)</td>
<td>Likely</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>Likely</td>
</tr>
<tr>
<td>Electricity storage</td>
<td>Likely</td>
</tr>
</tbody>
</table>
SPLICE Phase 1
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

### 5.3 Ranking based on the Urgency and Criticality of the Need criteria

Finally, energy system components have been ranked based on the ranking for the Urgency and Criticality of the Need criteria through the scores obtained from the web survey discussed in Section 3. Our composite ranking, shown in Table 7, gives equal importance to the ranking obtained from the two criteria. Weighting schemes could have been used although we preferred to give equal importance to the two criteria as it was not clear to us that one should be preferred on the other.

**Table 7** Rankings of energy system components according to the Urgency and Criticality criteria and the composed ranking

<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>URGENCY</th>
<th>CRITICALITY</th>
<th>COMPOSED RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation</td>
<td>14</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Carbon Capture and Sequestration (CCS)</td>
<td>18</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Demand Side Responses (DSR)</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Electricity storage</td>
<td>8</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Energy intensity of industry</td>
<td>13</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>11</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Insulation and building fabric</td>
<td>2</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Land for bioenergy</td>
<td>25</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Nuclear plants</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>7</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>15</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Power Networks</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Unconventional gas</td>
<td>24</td>
<td>31</td>
<td>14</td>
</tr>
</tbody>
</table>

### 5.4 Prioritised Research Gaps

This section briefly discusses the prioritisation list of impact areas and exemplary research gaps in published literature obtained from the method discussed in Section 2 and the results discussed above. For the sake of conciseness we present only the prioritisation of the first 31 groupings of impact areas in Appendix 7. For each area we present up to two exemplary research gaps. Prioritisation of all areas for which we could find evidence in the literature is presented in Appendix 8. For an exhaustive discussion of identified research gaps for each area, interested readers are referred to the related material in Section 4 and Appendix 5.
Appendix 7 we also point out whether the research gap should be filled through commissioning new research or by commissioning a preliminary quick scoping review or expert paper (the latter option identified by the wording “Review” in column 3) of Table 14. The latter choice is motivated by the fact that by looking at existing reviews it is possible that certain gaps were identified only because no existing reviews have been published. It is fair to say that these cases would likely have been flagged up in the interviews we held with experts, but as a safety measure it would seem prudent in those instances to embark on a quick scoping review before commissioning new research. This preliminary reviewing step would also deliver the additional benefit of being able to further focus the research gap in a way that could not be delivered as part of the resources allocated to the current project.

Impact areas and research gaps in existing literature reviews presented in Appendix 7 span a wide range of energy system components. It is naturally difficult to draw any strong generalisation from this very diverse list, although this diversity testifies to the breadth and appropriateness of the methodology employed in this study. Gaps related to Carbon Capture and Storage, Nuclear Power, Land for Bioenergy, Electric Vehicles and Demand-Side Response are very prominent due to the priority score they received in the literature review and interaction with experts, and the high perceived likelihood of this gap needing filling. Taken together these four energy system components account for about 50% of the top 20 priority groups. Research gaps related to unconventional gas have also received a high priority score although their more uncertain contribution to a future decarbonised energy system implies a comparatively lower ranking than the four energy system components mentioned above. Research gaps from the Power Network, Aviation, Offshore Wind and Buildings and Insulation sectors do not feature strongly in the top 20 list, mainly because they received a somewhat lower score from the literature assessment and from interaction with the experts. In the case of Onshore Wind this lack of prominence is mainly due to its more uncertain contribution to a future decarbonised energy system, especially related to recent policy announcements. No gaps related to Electricity Storage and Heat pumps appear in the top 20 list due to a comparatively low score from the literature review and interaction with experts. As Electricity Storage is mainly related to batteries, the overlap with electric vehicles implies that research gaps related to electric batteries might however be taken forward as part of the electricity vehicle component. Finally, it is worth mentioning that two sets of gaps related to Energy Intensity of Industry can be found in the 20 most pressing sets of priorities identified in this study. However, from the discussion in Section 4 above this assessment is somewhat uncertain due to the paucity of review information we could identify in the literature.

6 Limitation of our approach and learning for future assessments

This report presents a comprehensive methodology, given allocated resources and time, to prioritise research gaps in published literature on the environmental, social and economic impacts of energy system components in a decarbonised future. In this section we briefly discuss lessons learned from carrying out this assessment.

A comprehensive, in-depth and exhaustive analysis of research gaps in published literature would need considerably more resources and allocated time than those we had available. It was also sometimes problematic to locate specialist expertise within the team related to some of the impacts of energy system components. Consequently, some of the evidence was assessed by analysts with a background not necessarily related to the topic being discussed in the reviews. Future studies might consider allocating some resources to bring in
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

specialist knowledge when required. Expert interviewees were used to increase the reliability of the analysis, but because only one interview was conducted per energy system component (at most) there is the possibility that some information might have been overlooked, especially in topics which were very broad in scope. Future studies might consider engaging with a secondary expert in order to validate the feedback obtained from primary experts, although it is not clear how disagreement between experts would then be negotiated.

The analysis was designed around review studies. However, we found that in some areas there were few if any review studies - e.g. heat pumps - so there was a mismatch in some cases between the data available and our analysis framework. In these cases, single studies were used as data points, which clearly provides a considerably less comprehensive evidence base than using review studies. We used the interviews with the experts to verify whether the expert was aware of any reviews that had not been identified by us. Future studies might want to verify the existence of reviews not identified by the research team before the interviews with experts take place, and with as many experts as possible.

We noticed that different choices were adopted by different authors regarding the boundaries of energy system components and impacts. In some cases, e.g. impacts of buildings, researchers have focused on specific methodologies, e.g. Life Cycle Analysis (LCA), while in other cases a more diverse set of methodologies have been employed. In the former case results from the studies and therefore our work might be influenced by assumptions in the methodology and limitations of the data. As an example, results from LCA used to assess impacts of the building stock can raise many questions, such as the data sources used and the boundaries chosen, which may strongly influence the results.

Given the very limited amount of time available, and the number of reviewed documents, our work should be framed as a cautious attempt at drawing conclusions and making recommendations for filling research gaps in published literature. Future studies would benefit from considering other methods to elicit research gaps, such as the use of expert panels. This option might lead to incomparable outputs from different expert outlooks, and lobbying for ‘pet projects’ but overall it would seem desirable to explore the use of mixed approaches based on systematic reviews of published evidence integrated with expert panels. Our mixed approach was based on interviews with representative experts but future studies could reach a more comprehensive and inclusive outcome by engaging with panels of experts for each energy system component, rather than a single representative expert. Research teams who might want to implement this option should however be mindful of the cost implications that this much more comprehensive engagement process could imply.

7 Conclusions

This report presents the results from a research project implementing a multi-step mixed approach methodology to identify and prioritise research gaps in the literature related to the environmental, social and economic impacts of energy system components. It should be noted, that even where a gap is identified, some evidence may already be known or research may be underway – the method suggests where more evidence would be beneficial. Our approach was based on a systematic assessment of published review studies for a selected number of energy system components in a decarbonised future energy system. Our methodology engaged experts and stakeholders throughout the process. We used feedback from experts through a web-based survey to narrow down the number of energy system components for further study. Expert feedback was also used to validate the findings from our assessment of the literature and define a ranking of impacts for each energy system component selected in the web-based survey. We finally used scores obtained from the
literature review as well as information obtained from the web-based survey and scenarios published in the literature to produce a granular ranking of research gaps in the literature on the impact of decarbonised energy systems.

As a consequence of the comprehensive and multistep methodology employed in our study, our final list of research gaps in the literature span a wide range of energy system components. Gaps related to Carbon Capture and Storage, Nuclear Power, Land for Bioenergy, Electric Vehicles and Demand-Side Response are very prominent in the list we produced. Research gaps in the literature related to unconventional gas have received a lower priority due to their more uncertain contribution to a future decarbonised energy system. Research gaps related to the Power Network, Aviation, Offshore Wind and Buildings and Insulation do not feature strongly in the top 20, mainly because they received a somewhat lower score from the literature assessment and interaction with the experts. No gaps related to Electricity Storage and Heat pumps appear in the top 20 due to a comparatively low score from the literature review and interaction with experts.

As a result of the methodology discussed here, we have obtained a granular prioritisation of impacts and related research gaps identified through systematic assessment of published reviews and feedback from experts. Our work could be refined based on further engagement with experts on specific gaps that have been identified in this fairly high level assessment. Another option would be to commission reviews of selected impacts of some energy system components for which we could not identify any published review. This preliminary step would also help to further focus research gaps related to a specific energy system component in a way that could not be delivered as part of the resources allocated to the current project.
8 References


Cabeza et al (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector A review


Committee on Climate Change (CCC) (2009), Meeting the UK Aviation Target – options for reducing emissions to 2050, London: CCC


Committee on Climate Change (CCC) (2013) Fourth Carbon Budget Review - technical report - sectoral analysis of the cost-effective path to the 2050 target


Dockerty et al (2014) Interactions between the energy system, ecosystem services and natural capital, London: UKERC


Field RA, Soltis, J and Murphy S (2104) Air quality concerns of unconventional oil and natural gas production Environmental Science: Process & Impacts 16, 954-969


SPLICE Phase 1

Significant evidence gaps on the environmental, social and economic impacts of energy system components.

Fox AD, Desholm M, Kahlert J, Christensen TK and Krag Petersen IB (2006) Information needs to support environmental impact assessments of the effects of European offshore wind farms on birds. *Ibis* 148 (S1) 129-144


Significant evidence gaps on the environmental, social and economic impacts of energy system components.


Kahrlas GA, Blotevogel J, Stewart PS and Birch T (2015) Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation and toxicity *Environmental Science and Technology* 49 16-32


Kretschmer et al; (2012) Mobilising Cereal Straw in the EU to feed advanced Biofuel production, Brussels: Institute for European Environmental policy


Maidment et al (2014) The impact of household energy efficiency measures on health A meta-analysis


Masiol and Harrison (2014) Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution A review, Atmospheric Environment, 95, pp. 409-455


Moore CW, Zielinska B, Pétron G and Jackson RB (2014) Air impacts of increased natural gas acquisition, processing and use: a critical review Environmental Science and Technology 48 8349-8359


Notter et al (2010) Contribution of Li-ion batteries to the environmental impact of electric vehicles, Environmental Science and Technology, 44, pp.6550-6556


Ortíz et al (2009) Sustainability in the construction industry A review of recent developments based on LCA


Significant evidence gaps on the environmental, social and economic impacts of energy system components.


Scottish Natural Heritage (2012) Assessing the cumulative impact of onshore wind energy development Scottish Natural Heritage, Edinburgh pp 41


Singh et al (2011) Review of Life-Cycle Assessment Applications in Building Construction


Tosh, D.G., Montgomery, W.I. & Reid, N. (2014). A review of the impacts of wind energy developments on biodiversity. Report prepared by the Natural Heritage Research Partnership (NHRP) between Quercus, Queen’s University Belfast and the Northern Ireland Environment Agency (NIEA) for the Research and Development Series No. 14/02

UK CCS Research Centre (2012) Research and Pathways to Impact Delivery (RAPID)

UN, "Multi Dimensional Issues in International Electric Power Grid Interconnections", 2006


Significant evidence gaps on the environmental, social and economic impacts of energy system components.


WSP, Parsons Brinckerhoff, DNV-GL, "Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 ", March 2015


Zuo and Zhao (2012) Green building research–current status and future agenda A review
Appendices

Appendix 1: Complete list of energy system components
Appendix 2: Criteria used to select energy system components
Appendix 3: Literature search protocol
Appendix 4: Details on the Methodology used to assessed Published Evidence
Appendix 5: Detailed findings from the literature
Appendix 6: Detailed results from the prioritisation procedure
Appendix 7: Exemplary Research Gaps for a Prioritised selection of Energy System Components and Impact Areas
Appendix 8: Full Ranking of Energy System Components and Impact Areas Assessed in this Study
Appendix 9: Web survey report
Appendix 1 - Complete list of energy system components

Table A1.1. List of energy system components used in the survey and related sector.

<table>
<thead>
<tr>
<th>Energy system component</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas power stations</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Coal power stations</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Biomass power stations</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Power Sector</td>
</tr>
<tr>
<td>CCS power stations</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Wave power</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Tidal Stream</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Tidal Range</td>
<td>Power Sector</td>
</tr>
<tr>
<td>PV</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Geothermal power</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Hydroelectric power</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Energy-from-waste plants</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Land dedicated to bioenergy</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Unconventional gas</td>
<td>Power Sector</td>
</tr>
<tr>
<td>Gas Transmission and Distribution Grid</td>
<td>Networks</td>
</tr>
<tr>
<td>Power Interconnectors and Transmission/Distribution Network</td>
<td>Networks</td>
</tr>
<tr>
<td>Hydrogen Transmission and Distribution Grid</td>
<td>Networks</td>
</tr>
<tr>
<td>District Heating</td>
<td>Networks</td>
</tr>
<tr>
<td>CO₂ Transmission Network</td>
<td>Networks</td>
</tr>
<tr>
<td>Average Internal Temperature of Buildings</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Insulation and building fabric</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Heating and Cooling Demand</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Lighting, Cooking and Demand from Appliances</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Energy intensity of industry</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Biomass Boilers</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Gas Boilers</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Biogas (including anaerobic digestion of bio waste)</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Biomass for industrial heating</td>
<td>Built Environment and Industry</td>
</tr>
<tr>
<td>Electricity Storage</td>
<td>Storage</td>
</tr>
<tr>
<td>H₂ Storage</td>
<td>Storage</td>
</tr>
<tr>
<td>CO₂ Storage</td>
<td>Storage</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Transport</td>
</tr>
</tbody>
</table>
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

<table>
<thead>
<tr>
<th>Energy system component</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Vehicles</td>
<td>Transport</td>
</tr>
<tr>
<td>Hybrid vehicles</td>
<td>Transport</td>
</tr>
<tr>
<td>Plug-in Vehicles</td>
<td>Transport</td>
</tr>
<tr>
<td>Liquid Biofuels</td>
<td>Transport</td>
</tr>
<tr>
<td>Domestic freight</td>
<td>Transport</td>
</tr>
<tr>
<td>Aviation</td>
<td>Transport</td>
</tr>
<tr>
<td>Shipping</td>
<td>Transport</td>
</tr>
<tr>
<td>Domestic Passenger Transport Demand</td>
<td>Transport</td>
</tr>
</tbody>
</table>
**Appendix 2 - Criteria used to select energy system components**

**Potential Contribution of Energy System Components** looks at the significance of energy system components at the national scale within the pathway of the UK energy system meeting the 2050 CO\(_2\) targets. This criterion can be measured in GW, GWh, number of deployed units or any other measure suited to the energy system component under consideration.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH</strong></td>
<td>The energy system component is a significant(^4) part of the UK energy system <strong>by 2030</strong></td>
</tr>
<tr>
<td><strong>MEDIUM</strong></td>
<td>The energy system component is a significant part of the UK energy system <strong>after 2030</strong></td>
</tr>
<tr>
<td><strong>LOW</strong></td>
<td>The energy system component is not a significant part of the UK energy system regardless of the time scale</td>
</tr>
<tr>
<td><strong>N/A</strong></td>
<td>Potential Contribution is not a relevant indicator for the UK energy system component under consideration</td>
</tr>
<tr>
<td><strong>Don’t know</strong></td>
<td>I would prefer not to provide a response based on the current state of my knowledge</td>
</tr>
</tbody>
</table>

**Criticality of Energy System Components** measures the extent to which an energy system component is **critical** for the UK energy system to achieve the 2050 targets or plays an **enabling** role to critical technologies.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH</strong></td>
<td>The energy system component is <strong>critical</strong> to meet UK 2050 targets or <strong>plays</strong> an <strong>enabling</strong> role to critical components</td>
</tr>
<tr>
<td><strong>LOW</strong></td>
<td>The energy system component is <strong>not critical</strong> to meet UK 2050 targets and does <strong>not</strong> play an <strong>enabling</strong> role for other critical components</td>
</tr>
<tr>
<td><strong>N/A</strong></td>
<td>Criticality is not a relevant indicator for the UK energy system component under consideration</td>
</tr>
<tr>
<td><strong>Don’t know</strong></td>
<td>I would prefer not to provide a response based on the current state of my knowledge</td>
</tr>
</tbody>
</table>

\(^4\) Measures of significance depend on the type of energy system component. As a rule of thumb you may consider as significant:
- factors influencing or providing more than 5% of energy demand
- energy supply or storage options with capacity in the region of 5% of total capacity
- energy-using equipment deployed at scale above 1,000,000 units
- network components deployed at a scale above 500 kilometers.
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

**Persistence of Impacts** measures the extent to which environmental, social and economic impacts of UK energy system components are permanent or reversible.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>Environmental, social or economic impacts of an energy system component are permanent and irreversible</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>Environmental, social or economic impacts of an energy system component are semi-permanent or difficult to reverse</td>
</tr>
<tr>
<td>LOW</td>
<td>Environmental, social or economic impacts of an energy system component are temporary or reversible</td>
</tr>
<tr>
<td>N/A</td>
<td>Persistence of impacts is not a relevant indicator for the energy system component under consideration</td>
</tr>
<tr>
<td>Don't know</td>
<td>I would prefer not to provide a response based on the current state of my knowledge</td>
</tr>
</tbody>
</table>

Local social, environmental or economic impacts from energy system components can arise due to the size of a single installation or due to the impacts from the interaction of smaller installations in the same area.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>An energy system component that implies large installations or many small installations that interact with other in the area to produce a step change in the cumulative impacts locally</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>An energy system component that implies medium installation or many small scale installations that interact with other in the area to produce cumulative impacts increasing in a linear manner.</td>
</tr>
<tr>
<td>LOW</td>
<td>An energy system component that implies small installations which do not interact with other energy system components to produce cumulative impact</td>
</tr>
<tr>
<td>N/A</td>
<td>Local Impacts is not a relevant indicator for the energy system component under consideration</td>
</tr>
<tr>
<td>Don't know</td>
<td>I would prefer not to provide a response based on the current state of my knowledge</td>
</tr>
</tbody>
</table>

---

5 As a rule of thumb you may consider power stations above 50 MW, major network and storage facilities.
6 As a rule of thumb you may consider power stations smaller than 20 MW, consumer technologies in the homes and in the transport sector.
7 As a rule of thumb you may consider power stations above between 20 MW and 50 MW, regional networks and storage facilities.
**Uncertainty of Impacts** is related to the knowledge on the nature and scale of the potential social, environmental and economic impacts arising from energy system components.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>Knowledge of the nature and scale of impacts of an energy system component is <strong>sparse</strong> and evidence shows considerable <strong>variability</strong>.</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>Knowledge of the nature and scale of impacts of an energy system component is <strong>maturing</strong> both in terms of quantity and consistency in the evidence.</td>
</tr>
<tr>
<td>LOW</td>
<td>Knowledge of the nature and scale of impacts of an energy system component is <strong>well established</strong> and show considerable <strong>consistency</strong> in the evidence.</td>
</tr>
<tr>
<td>N/A</td>
<td>Uncertainty of Impacts is not a relevant indicator for the energy system component under consideration.</td>
</tr>
<tr>
<td>Don't know</td>
<td>I would prefer not to provide a response based on the current state of my knowledge.</td>
</tr>
</tbody>
</table>

**Uncertainty in Decision Making** is related to lack of established methods to address environmental, social or economic impacts from energy system components as part of existing local and national decision-making processes.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>Methods in local and UK-wide decision-making are <strong>emerging</strong> to address impacts from an energy system component.</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>Methods in local and national decision-making are fairly <strong>advanced</strong> to address impacts from an energy system component, although there is no consensus in their implementation.</td>
</tr>
<tr>
<td>LOW</td>
<td>There are <strong>established</strong> methods for local and UK-wide decision-making to address impacts from an energy system component.</td>
</tr>
<tr>
<td>N/A</td>
<td>Uncertainty in Decision Making is not a relevant indicator for the energy system component under consideration.</td>
</tr>
<tr>
<td>Don't know</td>
<td>I would prefer not to provide a response based on the current state of my knowledge.</td>
</tr>
</tbody>
</table>
Appendix 3 - Literature search protocol

The type of evidence review we employed is a Quick Scoping Review using systematic techniques. The review follows the stages listed in Harden and Thomas (2005). This document describes the first four steps of that process. Stage five, related to the scoring system is described in Section 3 of the report while stages six, seven and eight are excluded due to being outside the scope of the review.

**Stage 1:** the review aims to map out the published evidence base for various environmental, social, and economic impacts for the different energy system components. It will identify and categorise the level of evidence and agreement on the impacts based on the IPCC’s AR5 method for assigning confidence.

**Stage 2:** the following systematic techniques are used: a formal search strategy, a list of inclusion criteria, a standardised process for data/information extraction, and a scoring system for assessing study quality.

**Stage 3:** the review uses the following search strategy:

1. Number of search terms: 425 (25 search terms representing the impacts for each of the 17 energy system components)
2. Document types: review papers only
3. Search terms:
   - **Marine environment:**
     - “marine AND impacts AND [insert energy system component]”
   - **Water:**
     - “water AND quality AND impacts AND [insert energy system component]”
     - “wastewater AND impacts AND [insert energy system component]”
     - “water AND availability AND impacts AND [insert energy system component]”
   - **Land:**
     - “land AND impacts AND [insert energy system component]”
     - “land AND use AND impacts AND [insert energy system component]”
     - “soil AND impacts AND [insert energy system component]”
     - “waste AND land AND [insert energy system component]”
     - “land AND visual AND intrusion AND impacts AND [insert energy system component]”
   - **Air:**
     - “air AND NOx AND impacts AND [insert energy system component]”
     - “air AND SO2 AND impacts AND [insert energy system component]”
     - “air AND PM AND impacts AND [insert energy system component]”
   - **Social impacts:**
     - “social AND impacts AND public AND acceptability AND [insert energy system component]”
     - “social AND impacts AND rural AND [insert energy system component]”
     - “social AND impacts AND urban AND [insert energy system component]”
     - “social AND impacts AND income AND [insert energy system component]”
     - “social AND impacts AND gender AND [insert energy system component]”
     - “social AND impacts AND age AND [insert energy system component]”
     - “social AND impacts AND minorities AND [insert energy system component]”
     - “social AND impacts AND energy AND security AND [insert energy system component]”
   - **Economic impacts:**
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

- “economic AND impacts AND employment AND [insert energy system component]”
- “economic AND impacts AND revenues AND [insert energy system component]”
  - Human health:
    - “health AND impacts AND [insert energy system component]”
  - Biodiversity impacts:
    - “biodiversity AND impacts AND [insert energy system component]”
  - Waste impacts:
    - “waste AND impacts AND disposal AND [insert energy system component]”

- Databases: Web of Science (academic database)
- Process: titles and abstracts are read in order to determine relevance

**Stage 4:** the evidence review uses the following inclusion criteria:

- Studies included in Web of Science
- Studies produced from the search terms listed above
- Studies written in English
- Review studies (i.e. not primary studies)
Appendix 4 – Details on the Methodology used to assessed Published Evidence

In this section we describe at length the methodology we used to score evidence from the studies we reviewed. The criteria used to obtain scores for the Quality Assessment of the reviews are shown in Table 8. The table also describes how reviews might look like for each of the scores related to the four criteria. For example, a review with a clearly formulated question will score 3 under the “Research question” criterion while a review with only qualitative consideration of the strength and quality of the data will score 2 with regard to the “weighting” criterion.

Table 8. Used framework for assessing identified studies

<table>
<thead>
<tr>
<th>Score</th>
<th>Research question</th>
<th>Search strategy</th>
<th>Weighting</th>
<th>Summary of results</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Clearly formulated question</td>
<td>Explicit, systematic search strategy</td>
<td>Systematic scoring of ‘data pedigree’ and confidence</td>
<td>Quantitative meta-analysis, caveats and assumptions detailed</td>
</tr>
<tr>
<td>2</td>
<td>Research question broadly identified</td>
<td>Limited search strategy</td>
<td>Qualitative consideration of strength and quality of data</td>
<td>Qualitative analysis, caveats and assumptions detailed</td>
</tr>
<tr>
<td>1</td>
<td>Research question not identified</td>
<td>Selected evidence only</td>
<td>Limited consideration of strength and quality of data</td>
<td>Limited analysis, difficult to trace evidence</td>
</tr>
</tbody>
</table>

After assessing the quality of each review, we collected information related to the intensity of the impacts and to the level of confidence in the assessment of the impacts. Evidence for both items was scored as ‘High’, ‘Medium’ and ‘Low’, based on the judgment of the authors of the document and the description of impacts. The approaches used to rank ‘impacts’ was adapted from Warren (2015). For example, an impact described as “dominant” or “central” in the review would be scored as “High” while an impact described as “minor” would be scored as Low.
Table 9. Scale for assessing the intensity of impacts.

<table>
<thead>
<tr>
<th>High Impact</th>
<th>The following words are used in relation the impact to highlight it has high importance: “critical”, “crucial”, “very important”, “large”, “main”, “primary” or equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Impact</td>
<td>The following words are used in relation the impact to highlight it has medium importance: “has some importance”, “average”, “quite important” or equivalent</td>
</tr>
<tr>
<td>Low Impact</td>
<td>The following words are used in relation the impact to highlight it has low importance: “not important”, “limited”, “no impact”, “small” or equivalent</td>
</tr>
</tbody>
</table>

For each impact covered by any of the identified studies we also produced a score related to the confidence of the assessment in the published study under analysis. Confidence was considered to be a function of the agreement in the evidence discussed in the study and the type of evidence being discussed. The former was scored ‘High’, ‘Medium’ and ‘Low’ as shown in Table 10, which applies to both qualitative and quantitative evidence.

Table 10. Scale for assessing agreement in the discussed evidence.

<table>
<thead>
<tr>
<th>SCORE</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Quantitative: distribution function of impacts with narrow min-max ranges or low variance</td>
</tr>
<tr>
<td></td>
<td>Qualitative: use of the following phrases: “undisputed”, “strong agreement”, “robust evidence”, “strong consensus”, or equivalent</td>
</tr>
<tr>
<td>Medium</td>
<td>Quantitative: distribution function of impacts with wide min-max ranges or high variance</td>
</tr>
<tr>
<td></td>
<td>Qualitative: use of the following phrases: “some agreement”, “some consensus”, “average” “reasonable evidence”, “medium agreement”, or equivalent</td>
</tr>
<tr>
<td>Low</td>
<td>Quantitative: low number of studies, variance in the results, primarily qualitative assessments</td>
</tr>
<tr>
<td></td>
<td>Qualitative: use of the following phrases: “exploratory”, “emerging evidence”, “disagreement”, “different views”, “differing perspectives”, “low agreement”, or equivalent</td>
</tr>
</tbody>
</table>

The type of evidence discussed in the studies was scored according to the ‘Robust’, ‘Medium’ and ‘Limited’ framework shown in Table 11. The table also describes how evidence in the review might look like for each of the three scores.

Table 11. Scale for assessment of discussed evidence

<table>
<thead>
<tr>
<th>SCORE</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust</td>
<td>Controlled experiments and large sample of direct measurements, historical/field data with high sample of direct measurements</td>
</tr>
<tr>
<td>Medium</td>
<td>Historical/field data with small sample sizes of direct measurements, robust model results</td>
</tr>
<tr>
<td>Limited</td>
<td>Some modelled data, indirect measurements, qualitative judgments</td>
</tr>
</tbody>
</table>

After impacts were scored in relation to agreement and type of evidence, the resulting score for the confidence in the assessment discussed in each of the identified studies was obtained
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

from the scoring system in Table 12. For example, an impact which according to a specific review was judged to show “high” agreement based on “limited” evidence would score “medium” in terms of confidence.

Table 12. Framework for assessing confidence of discussed evidence

<table>
<thead>
<tr>
<th>Agreement</th>
<th>Medium</th>
<th>High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[High agreement Limited evidence]</td>
<td>[High agreement Medium evidence]</td>
<td>[High agreement Robust evidence]</td>
</tr>
<tr>
<td>Medium</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td></td>
<td>[Medium agreement Limited evidence]</td>
<td>[Medium agreement Medium evidence]</td>
<td>[Medium agreement Robust evidence]</td>
</tr>
<tr>
<td>Low</td>
<td>LOW</td>
<td>LOW</td>
<td>MEDIUM</td>
</tr>
<tr>
<td></td>
<td>[Low agreement Limited evidence]</td>
<td>[Low agreement Medium evidence]</td>
<td>[Low agreement Robust evidence]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limited</th>
<th>Medium</th>
<th>Robust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evidence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5 – Detailed findings from the literature

Appendix 5.1 Aviation

Our literature search identified 5 relevant reviews, which were assessed to determine the suggested priority list for future research. Coverage of these reviews in relation to the impact categories used in this study is however somewhat limited, with most studies focusing on air quality and related human health risk. Economic impacts have been assessed only in relation to the house price depreciation brought about by noise. The boundaries of what constitutes ‘aviation’ varies from study to study, although it is generally recognised that modern airports contribute pollution not only from aircraft engines, but also from airport buildings, ancillary services, particulates from tyres/runways, etc. The airport system does not generally include the ground-based transport systems that bring people and goods to the airport, although one may argue that the latter is a built in function of the former.

Marine Environment
No review was identified addressing the impacts of Aviation on the Marine Environment.

Water
No review was identified addressing the impacts of Aviation on Water.

Land
No review was identified addressing the impacts of Aviation on Land.

Air Quality

High levels of a number of local air quality pollutants are a matter of concern at several airports, where target values are often exceeded, e.g. NO\textsubscript{2} concentrations breach the UK annual mean air quality objective (40 mg m\textsuperscript{3}) around Heathrow in London (Masiol and Harrison 2014). However, as most airports are located in the vicinity of large cities, the contribution of airport-related emissions to such breaches is hard to quantify. The presence of substantial levels of pollution from other sources, with many airports being located near to urban settlements, major highways and roads or industrial installations makes the signal of the airport emissions and, in particular, of aircraft emissions very hard to distinguish (Masiol and Harrison 2014).

NO\textsubscript{X}: although various studies have attempted to estimate the contribution of airport operations to ambient NO\textsubscript{X} levels, the results are often conflicting with some results indicating that concentrations of NO\textsubscript{X} close to the airport are dominated by road traffic sources while others report that most nitrogen oxides were released from aircraft (Masiol and Harrison 2014). SO\textsubscript{2}: the importance of SO\textsubscript{2} emissions at local scale, i.e. near the airports, has been highlighted in the literature e.g. at both Los Angeles and Hong Kong airports. However, on a global scale the aviation source is considered to be secondary with respect to other major sources of SO\textsubscript{2} (Masiol and Harrison 2014). PM: impacts of airport operation on PM are even more uncertain due to lack of data. Tesseraux (2004) concludes that emissions from airports have an impact on the air quality of the adjacent communities, but that impact does not result in levels higher than those in a typical urban environment.

Currently available information on the impact of airport emissions upon local air quality is inadequate (Masiol and Harrison 2014). Research gaps pointed out by the review we assessed include:

1. Careful quantification of direct emissions from aircraft for a large variety of engines, emission inventories;
2. Standardisation of measurement procedures of engine exhaust at ground level for PM;
3. Chemical and physical characterisation of PM including chemical and physical modifications affecting PM in the atmosphere;
4. Significance of airport operations for emission reduction and management;
5. Assessment of Airport Emission over a full range of scales;
6. Current data on aircraft-generated PM are still wholly inadequate and many open questions wait to be addressed;
7. Impact of Auxiliary power units, vehicular traffic and ground service equipment on air quality near to airports.

**Social Impacts**

No review was identified addressing the social impacts of Aviation. However, as impacts of aviation on air, health and economics discussed here are local by definition, one can get a first impression on the intensity and confidence of the social impacts from aviation related to local communities by looking at the air quality, health and economics impacts.

**Economic Impacts**

The only economic impacts of aviation covered by the reviews we identified were related to noise depreciation. Economic impacts of airport noise seems a fairly established research areas, with studies normally using hedonic pricing methodologies, i.e. measuring the impact of noise on property values in the areas around the airports. A number of meta-analyses exist in the literature. Typical Noise Depreciation Indices (NDI) values range between 0% and 2.3% with median estimates being between 0.6% and 0.7%. NDI Indices tend to be similar across countries and stable over time. Values for UK South East airports are unusually high, i.e. 5 times as high as other airports located in countries with similar average personal income (He et al 2014). No research gaps were pointed out by the reviews we assessed.

**Human Health**

The impact of aviation on human health is a reflection of its contribution to local air quality and therefore the findings reflect the uncertainty of its impact on air quality discussed above. Some of the references point at the lack of specific air pollution-derived health risk (Tesseraux 2004 and Masiol and Harrison 2014) while on the other hand, a series of local studies have highlighted the potential adverse effects on public health and the need for more extensive information. "US airports: emissions were estimated to cause about 195 early deaths rising to 350 in 2018 while the annual figure for the UK was 110. Interestingly, up to 65% of the health impacts of UK airports could be mitigated by replacing current fuel with low fuel sulphur content (FSC), by electrifying Ground Service Equipment (GSE), avoiding use of Auxiliary Power Units (APUs) and use of a single engine during the taxi (Masiol and Harrison 2014)."

**NOx**: A concentration–response relationship cannot be clearly defined based on current health data but health impacts have been estimated to be small compared to PM impacts (Mahashabde et al 2011).

**PM**: Several studies in the literature indicate that health impacts from aircraft PM emissions outweigh impacts from other aircraft pollutant species. Aviation-related risk of premature mortality is estimated to be around 200 yearly deaths in the USA. As a measure of uncertainty, the 90% confidence interval had a range of 130 to 340.

**Noise**: The relationship between aircraft noise, community annoyance and sleep disturbance is one of the best understood impacts with well-defined exposure–response functions in the literature (Mahashabde et al 2011). Aircraft noise has been linked to learning disruption in students but there are currently no exposure–response functions to quantify this impact. Physiological impacts such as hypertension are better understood as compared to mental...
health effects and hormone changes, which currently lack conclusive evidence to establish a strong causal relationship with aircraft noise (Hume 2010, Mahashabde et al 2011).

Research gaps pointed out by the reviews we assessed include:

1. Quantification of impact of aircraft emission on surface air quality and human health, especially within and in the surroundings of major airports;
2. Generally accepted dose-response function for noise-hypertension;
3. Impact of aircraft noise on learning, mental health and hormone change
4. Development of clearer metrics which better reflect the resident’s experience of noise, reflecting the complex interaction of psychological and sociological issues

Biodiversity
No review was identified addressing the impacts of Aviation on Biodiversity.
Appendix 5.2 Carbon Capture and Sequestration

CCS includes three steps; initial capture of the CO₂ (mainly from power plants but possibly from energy intensive industrial processes), transportation and finally storage. In the case of power plants, capture systems for the removal of CO₂ include post-combustion, pre-combustion and oxyfuel combustion, although this document focuses only on post-combustion capture. It is worth noting, however, that UK-based research is being implemented for all three separation techniques (UK CCS Research Centre 2012) CO₂ can be transported from the point of extraction to the point of storage through pipeline or ship. Carrying CO₂ in pipelines is not a new concept, as there exists an extensive pipeline infrastructure as part of CO₂ enhanced oil recovery (CO₂ EOR) operations (Gale and Davison 2004). CO₂ can be stored in underground geological formations, such as depleted oil and gas fields, deep aquifers, salt caverns, unminable coal seams and deep-sea sediments, or by injecting liquefied CO₂ into the water column at great depths (Koornneef et al 2012).

Important considerations for choosing suitable storage solutions are injective, capacity and containment potential. Coverage of the impact categories used in this study in the reviews we identified varies depending on the phase of CCS under scrutiny. Studies reviewing the capture phase focus on impacts on water, land and air, whilst those reviewing the transportation phase focus on health and safety impacts, and studies reviewing the storage phase focus on the marine environment, water, and biodiversity. The current focus of this document in relation to the impacts of CO₂ storage on marine environment (and related biodiversity) is justified by the fact that UK storage is located offshore, as confirmed by the interviewed expert.

As a number of impacts discussed below are related to CO₂ leakage from reservoirs, it is worth pointing out that CO₂ leakage could occur through existing or induced faults and fractures, along a spill point or a well, as well as being caused by caprock failure, permeability increase and wellhead failure (Koornneef et al 2012). The interviewed expert pointed out that there have been examples of catastrophic valve failures in pilot injections but they have been remediated. Active management of risks can considerably reduce failure rates. Developing quantified understanding of well seal degradation is considered an area with an intermediate level of understanding by UK CCS (2012). The same applies to developing best practice guidelines for well construction, completion, remediation and risk assessment to feed into safety regulations. According to Koornneef et al (2012), the estimation of failure rates for ‘non-engineered’ parts of the storage system relies heavily on expert judgment, which is mainly based on experience in the oil and gas industry, natural analogue studies and modelling. Expert judgment provides a perspective on the order of magnitude of the probability of failure, but cannot be compared with the considerably more certain rates used in Quantitative Risk Assessments (QRAs) for engineered systems. In addition, failure rates are highly site specific as they depend on site-specific geological characteristics (Koornneef et al 2012). The interviewed expert pointed out that QRAs are however not the most appropriate technique. A more suited approach, such as the Bow Tie approach, implies identification of the whole set of risks, the defining fault, feature or event, and required remediation strategies. The Features, Events and Processes (FEP) approach was also mentioned. The expert pointed out that DNV provides guidelines and quality-controlled procedures for managing risk. UK CCS (2012) comments that very little work has been undertaken on UK-specific CO₂ storage, except for high level storage assessments. As geological, geophysical and petrophysical principles are generic, it may be possible to undertake work in other locations, which is of direct use to the UK. UK CCS (2012) reports that the storage aspects are perceived as poorly quantified, and of high irreducible uncertainty. It is important to mention that safe storage is one of the key CCS uncertainties discussed in a recent UKERC project. According to Watson et al (2012), there is “uncertainty as to whether geological storage of CO₂ will be secure over long time periods, as well as if and how the associated risk can be reliably assessed and managed”. UK CCS (2012) confirms that the issue of future liability for stored CO₂ and for the definition of permanent storage/acceptable leakage rates is crucial.
In terms of CO₂ leakage, **research gaps** pointed out by the reviews we assessed include:

- Developing appropriate, credible and long term mechanisms to deal with risks and their associated liabilities. This is considered essential by Watson et al (2012);
- Improving understanding of seal systems including CO₂-rock interactions, dynamic pressure and cap rock integrity. This should include strategies for the scale-up of small-scale measurements to significantly large seal systems;
- Reducing uncertainty related to likely leakage rates from geological storage over long time periods and methods to assess and reduce them;
- Understanding likely magnitude and duration of CO₂ exposure for local-scale leakage scenarios in order to assess impacts;
- Creating procedures to ensure that state of the art knowledge is included in the risk management of geological storage projects;
- Developing automated monitoring, measurement and verification (MMV) technologies to address any gaps for offshore deep underground storage systems;
- Developing a database of leakage, seepage, detection and use to develop best practices for risk and environmental impacts assessments. Specific areas could be related to leakage characterisation and quantitative methods to include likelihood and impacts of leakages and comprehensive risk management schemes for maximum impact scenarios;
- Developing ‘smart’ analytical processes that can detect a leakage signal from background noise;
- Multiple secondary seals to promote retention and dispersion of any leaked CO₂. This has large gaps of basic data on several areas such as subsurface temperature, rock physics, critical stress, chemical reactivity, 3D regional geometry, effective permeability and coupling to reservoir;
- Improved modelling of CO₂ within reservoir and future-time migration physically, and in pressure, especially for regional aquifers.

**Marine Environment**

Impacts of CCS on the marine environment are related to the impact of CO₂ sub-seabed storage. Research in this field builds on research focused on ocean acidification with key differences between ocean acidification and CO₂ geological storage being the magnitude, rate of change and duration of CO₂ exposure (Carroll et al 2014). The interviewed expert pointed out that a number of natural analogues, e.g. CO₂ venting from volcanic sources are available to assess the impacts of CO₂. Carroll et al (2014) discuss the recent surge of interest in utilising volcanic CO₂ vents as natural laboratories, although impact studies based on them must consider several potential limitations related to industrial leakage scenarios. Seepage of CO₂ from a sub-seabed storage reservoir through the overlying sediments has the potential to cause major chemical changes in the sediment pore water and at the sediment-water interface. Seawater acidification is likely to alter dissolved metal concentrations and local biogeochemical cycles leading to increases in nitrate uptake and ammonium efflux, and decreases in phosphate uptake in incubated sediment cores (Carroll et al 2014). The interviewed expert reported that preliminary studies by QICS and PML point at a limited impact of CO₂ release on the marine environment in the UK. An emerging concern associated with CO₂ leakage from storage reservoirs, according to Carroll et al (2014), is the secondary geochemoical effects of acidification on near-surface sediments. The significant formation of water displacement in the reservoir and its potential propagation to surface sediments also poses a concern. Groundwater sourced from deep basins is often saline to hypersaline, and anoxic. Given its higher density than seawater, the expelled brine may accumulate in pools at the seafloor, which creates hostile conditions for native fauna (Carroll et al 2014). UK CCS (2012) confirms that limited evidence is available on the potential environmental impacts of CO₂ storage, particularly in the marine environment. Collation of baseline and time series biogeochemical data describing proposed CCS sites are required (UK CCS 2012). The same applies to data on carbonate system variation from natural process and CCS leakage scenarios. Effective monitoring of changes in carbonate
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

system parameters (pH, pCO₂ and DIC) produced by leakage from proposed CCS sites are needed. A robust baseline for natural carbonate parameter variability needs to be established so that carbonate parameter change can be detected and compared with normal variability (UK CCS 2012). According to the interviewed expert all of the gaps below, mainly taken from Carroll et al (2014), have been filled.

Research gaps pointed out by the reviews we assessed include:

- Secondary geochemical effects of acidification (e.g. metals, toxicants and altered geochemical cycles) in both in near-surface sediments and in the deep subsurface;
- Thermodynamic and kinetic data at relevant temperatures and pressures needed as input for coupled reactive transport models and models for predicting specific mineral precipitation;
- The extent to which shallow subsurface and seabed information is used to characterise potential CO₂ storage sites or establish baseline information for future monitoring purposes;
- The extent to which information from natural analogues, e.g. leakage from volcanic CO₂ vents, can be used in environmental impact assessment studies due to lack of baseline environmental data;
- Improved evidence base on the potential environmental impact of CO₂ storage projects, particularly in the offshore domain and including impacts of brine migration from sub-seabed geological formations to the marine biosphere as well as CO₂ migration/leakage;
- Determination of spatial, temporal and biogeochemical characteristics of different CCS leakage scenarios;

Water

Water can be affected both in the separation and storage phase of CCS. In the former, water consumption increases due to the energy penalty and the additional water demand by CO₂ capture systems with reported increases varying between 32% and 96% for a 1 GWe CCS plant (Koornneef et al 2012). In case of post-combustion technology, water consumption almost doubles as a result of the additional cooling requirement of the CO₂ capture process. In the separation phase, cross-media effects are likely although quantification is not possible due to lack of publicly available data. Liquid waste stream for amine based post-combustion capture processes may come from the reclaimer section. Increased removal efficiency in emission control technologies such as flue gas desulphurisation (FGD) and pre-scrubbing may result in a shift from air emissions to water or solid stream emissions, which may in turn affect emissions to water bodies (Koornneef et al 2012). The interviewed expert pointed out that any CCS plants would have to control their discharge to water in accordance with existing Environmental Agency rules and regulations. It is also worth pointing out that this document considers only current amine capture. Technological progress is likely to deliver more efficient capture technologies and with smaller impacts.

Leakage of CO₂ or brine from CO₂ geological storage aquifers constitutes a risk for overlying fresh groundwater resources, for example through the potential alteration of groundwater quality by the intrusion of contaminants such trace metals, metalloids, and some radionuclides (White et al 2012). Leakage can directly modify the chemical properties of fresh water and, as a result, the effect of biogeochemical processes controlling trace element availability (Lions et al 2014). Impacts of geological storage of CO₂ in deep saline aquifers on groundwater resources include the near-field (due to the upward vertical migration of free-phase CO₂ to surficial aquifers) and the far-field impact (caused by large-scale displacement of formation waters by the injected CO₂). To date, studies have shown that trace elements can be significantly mobilised without necessarily exceeding quality thresholds. In a few cases where aquifers are naturally rich in trace elements, CO₂ is able to increase concentrations up to or exceeding threshold values (Lions et al 2014 and White et al 2012). Despite important knowledge gaps, the possible environmental impact of geological storage...
of CO₂ in deep saline aquifers on shallow groundwater resources appears to be low (Lemieux 2011). The interviewed expert confirmed that it is very hard for CO₂ in deep saline acquirers to reach the surface. Scoping calculations with simple, yet realistic, models suggest that environmental impacts can be low in favourable geological environments, i.e. a tight caprock or the lack of aquifers in the formations immediately overlying the injection area (Lemieux 2011 and Lions et al 2014).

**Research gaps** pointed out by the reviews we assessed include:

- Factors influencing the variation in water demanded in the CO₂ separation phases of CCS;
- Site-specific factors influencing the likelihood of exceeding threshold values in terms of water quality when CO₂ is stored in aquifers.

**Land**

Potential impacts on land are observed during the separation phase. Degradation products and other impurities are separated from the solvent in the reclamer. Several kilotonnes per year of residues from the reclamer, which are hazardous waste, are produced by a commercial scale power plant. The reclamer sludge can be treated in a wastewater treatment installation (WWT) but this implies that a fraction of the sludge is emitted to the surface water and the other fraction (WWT sludge) needs to be disposed of. Co-firing is an option but re-introducing the sludge into the boiler will redistribute the elements of the sludge over other waste streams (Koornneef et al 2012), although the interviewed expert is sceptical that part of the reclamed elements would go into water. Assessment of environmental options for solvents is identified in UK CCS (2012) as a topic characterised by an intermediate level of knowledge, as part of the knowledge area related to solvent degradation, reclaiming and waste disposal. **Research gaps** pointed out by the reviews we assessed include

- Identification of the most appropriate treatment of the reclamer sludge;
- Assessment of environmental options for treatment of spent solvent and effect on the environment and humans.

**Air Quality**

Impacts on air quality are discussed in the literature only in relation to the separation phase of CCS. Depending on the solvent that is used, impurities need to be removed from the flue gas to limit operational problems, for example through FGD for SO₂, DeNOₓ installations for NOₓ, electrostatic precipitators and fabric filters for PM (Koornneef et al 2012). SO₂, NOₓ and PM emissions are expected to decrease or remain equal per unit of primary energy input compared to power plants without CO₂ capture but emissions per kWh output will increase for those substances which do not decrease enough to compensate for increase in primary energy input required by CCS (Koornneef et al 2010). In coal-fired power plants, SO₂ emissions are reduced significantly compared to a power plant without capture, as the former would be equipped with improved FGD facilities (Koornneef et al 2010). Any reduction of NOₓ emissions per MJ primary energy is expected to be at best small (i.e. 3%), implying that emissions are likely to increase proportionally with primary energy use (Koornneef et al 2010). In the case of PM, estimates of the impact are particularly uncertain, with the high variance of estimates representing the assumptions used in literature, i.e. ranging from a deep reduction in PM due to the application of post-combustion CO₂ capture to no impacts on PM emissions. Results from an amine based post-combustion capture demonstration project however indicate a decrease in emission of particulate matter of 64-80% per MJ primary energy (Koornneef et al 2010). An increase in emission per MJ primary energy has never been assumed. The interviewed expert pointed out that all plants would be subjected

---

*Minimum expected additional reduction per primary MJ is approximately 40%, with the average it is 85%. In plants using amine as solvent, concentrations of SO₂ in the inlet gas are required to decrease as these compounds may react with the solvent. In plants using chilled ammonia, most of the acid gases can be removed from the flue gas when a proper design of the scrubbing process is applied but no explicit quantitative estimates are available (Koornneef et al 2010).*
Social Impacts

Social impacts of CCS have been researched in relation to its acceptability, which is normally assessed for the capture, transporting and storing system as a whole. UK CCS (2012) note that not much work has so far engaged with the public acceptability implications of differences technological choices at the capture, transport or storage stages. Seigo et al (2014) report that only few people take an extreme stance on CCS, either positively or negatively. Perceptions of risks and benefits are one of the main factors influencing the acceptance of CCS, alongside trust in stakeholders. Seigo et al (2014) conclude that CCS is reluctantly accepted but a number of studies report a strong need to see the technology in context, i.e. knowledge of other alternatives, and embedded in a comprehensive strategy addressing the problem of climate change. Concerns have been raised as the technology is perceived as an end-of-pipe solution that does not reduce the production of CO₂ from fossil fuels, and might displace future investment in renewable technologies (Seigo et al 2014). UK CCS (2012) reports that some empirical work hints at the public negatively surrounding CCS due to its fossil fuel connotations. It also points out there is a small but burgeoning body of empirical work suggesting that the general public does not always see CO₂ as a problem. Although at the societal level, perceived risks should not be a major barrier to CCS implementation. However at the local level, the picture might look different. The local context has been found to play a large role in terms of acceptance of specific projects, especially with regard to the history and social structure of a community (Seigo et al 2014). The interviewed expert also mentioned the importance of the industrial heritage of a community in influencing acceptance. Factors influencing the success of projects include their ability to adjust to the local social context, a communication strategy being integral part of the project from the beginning, alignment of important stakeholders; trust in the developer; quality of public engagement activities, and the public and stakeholders' perceptions of the need for the facility. As pointed out by the interviewed expert, communication with the local community is very important - especially in relation to the expected benefits from the project. Actual and perceived fairness is another variable that plays an important role in acceptance. Recent studies emphasise the role of procedural fairness, while distributive fairness has almost entirely been neglected. Because CO₂ storage sites are confined to some areas while storing emissions from all around the country and possibly beyond, this type of fairness might influence acceptance. The interviewed expert pointed out that there are benefits accruing to the local community such as employment, which have not been discussed thoroughly. According to the expert, academic literature seems to have focused more on the negative social impacts of CCS. Research gaps pointed out by the reviews we assessed include:

- Key factors for acceptance of a specific project, and how these factors might differ from those that are crucial for acceptance of CCS at the societal level;
- Public acceptability implications of different technological choices at the capture, transport or storage stages on public acceptability;
- Importance of history of the community, in terms of previous fossil fuel industry activities and empowerment, in influencing local acceptance of a project, and how knowledge about the local context can be used to foster support or opposition to a project;
- Importance of different type of fairness, e.g. procedural and distributive, in shaping local acceptance of a project;
- Management of public expectations in the engagement and deployment process; best-practice on how public expectations of all aspects of CCS can be managed so as to avoid disappointment, frustration and potential hostility at later dates;
Economic Impacts

Economic impacts of CCS occur in both the separation and storage phase. In the former, impacts are related to the capital component of separating CO₂ as well as the energy penalty from reduced efficiency of electricity production from CCS plants. Although these components will have to be reflected in the price of electricity from CCS plants, their impacts are likely to be small. The energy penalty of CO₂ capture, for example, is reported to vary between 8% and 13% (Koornneef et al 2012). On the positive side, storing CO₂ in depleted oilfields delivers benefits in the form of improved production rates and total productive lifetime of the field through enhanced oil recovery (EOR). As the economic benefits offset the cost, EOR is expected to be the earliest method of CO₂ storage, although in the long term deep saline aquifers are likely to be preferred due to their large capacity (White et al 2012). In the UK Continental Shelf (UKCS) nineteen oilfields may be technically suited for CO₂-EOR, with a combined potential incremental recovery of 2.5 billion barrels of oil, associated with storage in the region ca. 0.8 Gt CO₂. The highest rates of EOR deployment in the UKCS would bring £2.7 billion in Gross Value Added (GVA) to the Scottish economy relative to a scenario where the oilfields are decommissioned (Pershad et al 2012). Uncertainty is however considerable, i.e. at least +/- 50%. The interviewed expert pointed that that EOR extends the life of the oilfields and produce oil with a smaller life cycle carbon compared to oil extracted elsewhere and having to be imported to the UK. Available data and models on sources and sinks are extremely limited. None of the reviews we identified explicitly addressed economic impacts of CCS and related research gaps.

Human Health

In the capture phase of CCS, human health impacts are related to the emission of local air pollutants (SO₂, NOₓ and PM) described above. As impacts of air pollutants on health are not a research area exclusive to CCS, they are not discussed here. More specific to CCS is the health impact of Monoethanolamine (MEA), one of the chemical absorption technologies that can be used in the capture stage. Annual emitted quantities range between 40 and 160 tonnes for a plant capturing 1 Mt per annum, but is possibly lower for capture facilities implementing mitigation measures. The toxicity of MEA is well documented. The interviewed expert pointed out that a Norwegian project – Mongstad – is assessing variability of produced quantities of MEA. Another potential concern is the formation of (carcinogenic) products from the reaction of amines and atmospheric oxidants (e.g. NOₓ) under the influence of sunlight. Data on exact emissions of reaction products from additives used in the capture phase or emissions of the additives themselves are not publically available as this information is commercially sensitive. In addition, solvent additives (e.g. corrosion inhibitors) may result in trace emissions of heavy metals (Koornneef et al 2012).

The effects on human health of exposure to certain concentrations of CO₂ are well documented, as CO₂ is not only an asphyxiant but also toxic at high concentrations (Koornneef et al 2010). CO₂ can accumulate to potentially dangerous concentrations in low-lying areas and in dips in the ground or river valley floors. CO₂ is a colourless and odourless gas, although one could add mercaptans so that leaks are readily detected. On the positive side, CO₂ is not flammable or explosive. Potential risks for CO₂ release during the transmission phase are related to transmission pipeline failure, as CO₂ is likely to be transmitted by a pipeline network to onshore and near-shore CO₂ storage locations. Several quantitative risk assessments (QRAs) for CO₂ pipelines have already been performed, but direct comparison of risk assessments is made difficult by the variance in the methodologies and input parameters. Opposing views and controversies around the risks of CO₂ transport are found in the literature. On one hand, it is stated that risks of CO₂ transport are known and that CO₂ pipelines do not pose a higher risk than transporting hydrocarbons or other dangerous substances. On the other hand, some authors suggest that there is no significant
experience with designing CO₂ pipelines, as existing pipes in the USA are mainly sited in areas of low to medium population density (Gale and Davison 2004 and Koornneef et al 2010).

A QRA based on a literature review concluded that the most conservative distance of the $1 \times 10^{-6}$ risk contour to a CO₂ pipeline is 204 m, which is in the same order of magnitude as the currently regulated distances for high-pressure natural gas pipelines (Koornneef et al 2010). When assessing historical data, CO₂ pipelines do not seem to be less prone to incidents than natural gas pipelines (Gale and Davison 2004) but arguably CO₂ pipes are safer than natural gas pipelines (a view shared by the interviewed expert) and hazardous liquid pipelines because of the lack of fatalities or injuries, and cost of resultant damage when incidents have occurred. This has led Gale and Davison (2004) and Koornneef et al (2010) to conclude that CO₂ networks do not represent a significant risk in terms of potential release. It is worth noting, however, that according to UK CCS (2012) the current level of understanding related to fracture control and corrosion models for CO₂ and CO₂ mixtures is rated as limited. The same applies to some areas related to dispersion of CO₂ clouds from pipeline realises and failure probability modelling. The interviewed expert pointed out that National Grid might have better and more recent evidence on this matter.

**Research gaps** pointed out by the reviews we assessed include:

- A more precise estimate of MEA emissions as current estimates vary by a factor of four. As pointed out by the interviewed expert, a Norwegian project – Mongstad – is exploring this topic;
- Impacts of chronic exposure effects and other toxicity end-points of MEA, including its carcinogenicity;
- Data on exact emissions of reaction products from additives used in the capture phase or emissions as this information is not publically available;
- Develop techniques and technologies for leak mitigation and remediation with the aim of feeding them into design standards for pipelines network and monitoring systems
- Fracture controls (both brittle and ductile) for both parent and weld materials
- Aging and corrosion models for CO₂ pipeline;
- Better understanding of crack formation, propagation mechanisms, crater formation and high pressure leaks;
- Develop and validate models for dense flow in pipelines, depressurisation, leakage and dispersion of dense-phase CO₂ and impurities in a wide range of scenarios
- Develop understanding if potential impact of acute and chronic exposure of the more vulnerable and sensitive populations to CO₂, as current knowledge is based on tests with healthy subjects;
- Validation of lower acceptable CO₂ concentrations from more recent studies compared to higher and relatively old concentrations found in the literature.

**Biodiversity**

Biodiversity can be impacted by the construction of CCS infrastructure as well as the leakage of CO₂ in the environment, with research apparently focusing in both cases on CO₂ seabed storage. CCS infrastructure development may have immediate negative impacts on seabed benthic communities and associated ecological processes due to habitat disturbance. The magnitude of such impacts depends on the seabed substrate and extent and type of infrastructure, with the possibility that disturbed communities could actually recover and even benefit from the disturbance in terms of overall diversity and heterogeneity (Carroll et al 2014). As pointed out by the interviewed expert, impacts from constructing a CO₂ pipeline are not likely to differ from constructing any other type of pipelines, for example those transporting gas from offshore fields.

Research on impacts of CO₂ on biodiversity focuses on leakages from sub-seabed storage sites, which is a research body related to research on biogeochemical impacts. The interviewed expert was sceptical of biodiversity impacts from sub-seabed CO₂ leakages,
reflecting their perception of low impacts on the marine environment. Koornneef et al (2012) points out that impacts of CO₂ escaping the reservoir are complicated by the fact that it is very difficult to assess the location where the CO₂ may enter the biosphere (Koornneef et al 2012). Elevated CO₂ concentrations are reported to impact benthic microbes, more complicated marine organisms and finally influence marine flora and fauna at the community and ecosystem levels. CO₂ leakage may cause selective enhancement of CO₂ tolerant microorganisms which can gain a fitness advantage over less resistant competitors (Halsband and Kurihara 2013). Some recent research has begun to elucidate the range of effects although they are providing contrasting evidence on the degree of adaptation to elevated CO₂ levels⁹. In the case of more complicated marine organisms, the effects of CO₂ are expected to produce negative but responses show variation at the inter- and intra-specific level (Carroll et al 2014). High variability of responses is a considerable challenge for impact assessments related to CCS but a number of trends based on limited evidence are emerging. Deep-sea biota, marine invertebrates with low metabolic rates, external fertilisation and developmental stages are thought to be particularly sensitive to CO₂ perturbations¹⁰. It is important to stress, as pointed out by the interviewed expert, that deep sea biota will not be influenced by UK storage as projects will be located on the shallow shelf at 50-100m deep. Potential avoidance strategies of species to localised high CO₂ concentration arising from a leakage have not been thoroughly studied, but it seems that exposure around CCS release points are inevitable for organisms too small to swim against currents or across hydrographical boundaries (Halsband and Kurihara 2013). Understanding of the tolerance of marine organisms to CO₂ perturbations is limited, although it is crucial in the context of CCS.

Many of the organism-level responses to elevated CO₂ have the potential to cascade to the community level and may interdependently or interactively affect an entire ecosystem, especially when functionally important species are affected. Due to the variation in species’ responses to elevated CO₂, it is difficult to predict future changes in communities and ecosystem functions. Exposure to high CO₂ concentrations may directly change the structure of a given community, especially in environments which are relatively stable or those with acute exposure to high levels of CO₂ from which communities are unable to recover (Carroll et al 2014). Impact assessments of potential leakage on ecosystem functions require information on community, phyla, and functional group responses. UK CCS (2012) reports that understanding the tolerance of marine ecosystems to long-term, low-level CO₂ dosing is a knowledge area with limited level of understanding. Evidence on volcanic CO₂ vents, which are likely to mirror impacts from CO₂ storage, generally indicates decreased diversity, biomass, and trophic complexity of marine communities at the seafloor (Carroll et al 2014). However, as volcanic events are normally associated with specific events such as seismic activity or magmatic fluid injection, this may result in confounding community and ecosystem effects.

Research gaps pointed out by the reviews we assessed include:

- Mechanisms behind any observed intra- and inter-species variation in responses of marine flora and fauna to CO₂ leakage in sub-seabed geological storage, including impacts on different reproductive strategies, behavioural responses related to mating behaviour, escape from predators and feeding behaviour;
- Integrated understanding of both biological and physical processes to more accurately quantify ecosystem impacts of sub-seabed CO₂;
- Effect of long-term exposure on ecosystems, including dose-effect relationships for ecosystems or target species taking into account the level, duration and location of exposure to the CO₂;

---

⁹ Some deep marine or subseafloor microbes and meiofauna (e.g. nematodes) may, to varying degrees, be able to adapt to elevated CO₂ levels but some studies have demonstrated the opposite effect.

¹⁰ Since deep-sea organisms are adapted to stable environmental conditions, they may be vulnerable to high CO₂ but on the other hand deep sea organisms have possibly adapted to high CO₂ over evolutionary time scales, as pCO₂ in the deep-sea is naturally higher than at the surface (Halsband and Kurihara 2013).
- Understanding and quantification of ecosystem recovery rates after remediation of a leakage;
- Effects of multiple stressors related to the potential leakage of CO$_2$ and provision of baseline physical and biological data which can be used to assess varying magnitude, duration and frequency of CO$_2$ exposure;
- Measuring responses of marine organisms to transient exposure to severe low pH conditions. Understanding responses to transient low pH conditions is a requirement to fully quantify the environmental consequences of catastrophic CCS leakage events
- Impacts on marine food webs, such as potential shifts in food web structure, and organisms higher up the food chain - including commercial species. This has clear socioeconomic implication due to the market value of the commercial fish.

**Seismic Activity**

There is a possibility that earthquakes could be caused by injection of CO$_2$ into geologic formations (White et al 2012). Potential for seismic activity is greatest in seismically vulnerable locations with pre-existing faulting. While seismic implications must be considered for injection facilities, induced seismic activity may be prevented through proper siting, installation, operation, and monitoring. Current technology provides effective tools for investigating and preventing induced seismic activity, although more research is recommended for developing site selection criteria and operational constraints for CO$_2$ storage sites near zones of seismic concerns (Sminchak et al 2009). The relationship between earthquake activity and the timing of injection, the amount and rate of fluid injected, and other factors are still uncertain and are current research topics. The interviewed expert pointed out that CO$_2$ storage is likely to cause earth tremors but these are unlikely to be noticed as CO$_2$ is being stored in the North Sea, i.e. far from built-up areas. They also pointed out that there are thousands of these small tremors naturally occurring every year.
Appendix 5.3 Demand Side Responses (DSR)

Demand Side Response (DSR) includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing and level of instantaneous demand, or amount of total electricity consumption (Albadi and EL-Saadany 2008). A mixed picture emerges when assessing the extent to which environmental, social and economic impacts of Demand Side Response have been researched so far. We identified 5 reviews, but these surveys have mainly focussed on the economic impacts of DSR, and to an extent its impact on social metrics by assessing how costs and benefits are allocated across a number of stakeholders.

Benefits from DSR have been classified in a number of ways. For example, O’Connell et al (2013) distinguishes between operating, planning and economic benefits. Consequently, DSR influences the ordinary operation of the power network, including provision of reserve generation, peak curtailment and balancing of supply and demand, as well as system expansion (i.e. the need to invest in network reinforcements, capacity reserves and peaking units) (Conchado and Linares 2012). It is important to mention that these benefits can be assessed across a number of metrics, such as value of investments avoided, but also, when marginal and peak plants are fossil-fuel based (as they normally are), in terms of CO₂ and air quality pollutants. Considering the novelty of DSR it should not be surprising that some research gaps discussed in the literature relate to the overall impact of DSR on energy consumption rather than any particular, social, economic or environmental impact. Research gaps pointed out by the review include:

1. Evidence on the way consumers shift their electricity use in response to incentives, including which appliances consumers are willing to use in a flexible way;
2. Persistence of DSR impact on energy consumption over time, especially if it is not automated or directly controlled;
3. Impact of non-economic and economic signals on energy consumption, alone or as part of intervention package;
4. Difference in consumer responses to price signals according to the strength of the price signal;

Marine Environment
No review was identified addressing the impacts of Demand Side Responses on the Marine Environment.

Water
No review was identified addressing the impacts of Demand Side Responses on Water.

Land
No review was identified addressing the impacts of Demand Side Responses on Land.

Air Quality
No review was identified addressing the impacts of Demand Side Responses on Air Quality.

Social Impacts
It is important to mention that some of the net benefits discussed below for the economic impacts of Demand Side Responses (DSR) are not net social impacts, as they do not take into consideration costs imposed on other parties in order to obtain certain benefits. As an example, a reduction in energy consumption implies foregone revenues for generators, and as such it creates a welfare transfer from generator and utilities to consumers rather than an increase in total (social) welfare. Bradley et al (2011) argues that welfare transfers from generator and consumers, however, are beneficial to society and highly desirable as they help households reduce and control escalating energy bills as well as contributing to reducing fuel poverty. If the whole or a part of the electricity price reductions are passed to consumers, as one would expect in a competitive market, it is easy to see how social impacts of DSR can be considerable. The allocation of this impact is not straightforward and...
may run against desired outcomes and ultimately depends on the response of different types of consumers to DSR initiatives.

Some, but not all studies found that vulnerable and low-income consumers are less responsive than average to DSR signals, and therefore may benefit to a lesser extent from DSR measures (Frontier Economics and sustainability First 2012, O’Connell et al 2014). Similarly, it has also been pointed out that while residential loads have a great potential for demand peak reduction and shifting, the greatest potential for net welfare gains may lie with industrial and commercial loads. It might be simplistic to assume that benefits will be passed back to consumers in an equitable fashion. It seems much more likely that some consumers, especially industrial, commercial and affluent households might benefit much more than others, if they are more able to respond to DSR measures.

Research gaps pointed out by the reviews we assessed include:

- Responses of vulnerable and low-income consumers to DSR initiatives;
- The extent to which DSR is likely to contribute to reduction of fuel poverty;
- The allocation of DSR benefits by generators and utilities between residential and non-residential consumers and across consumers of different sizes.

Economic Impacts

Economic impacts of Demand Side Responses (DSR) in the UK have been thoroughly reviewed by Bradley et al (2011). Benefits included in this review are related to energy reduction, peak demand shift and other benefits resulting from smart metering. All of these benefits are related to the configuration of the power system in the near-term. In more exploratory terms, Bradley et al (2011) also include benefits related to balancing wind generation and those related to change in the electric system management philosophy in conjunction with use of various technologies such as electric vehicles (EVs), heat pumps (HPs) and smart appliances.

Net benefits arising from DSR are significant; in the region of £200 million per year when benefits resulting from smart metering are considered, according to the estimates by DECC and Ofgem (2011a, b) discussed in Bradley et al (2011). Variation in estimates for these relatively short-term benefits is however considerable, with an estimate produced by Ofgem (2010) being substantially higher than those reported in DECC and Ofgem (2011a, b). Regrettably, it is difficult to compare the estimates across these three studies as the values are presented in relation to different time frames, discounting factors and assumptions on extent of energy shifts. Bradley et al (2011) comments that the estimates from DECC and Ofgem (2011a, b) are however believed to be very conservative. An even higher level of uncertainty is related to the more long-term benefits of DSR. Bradley et al (2011) reports that benefits related to change in the management philosophy of the power system can vary between £25 million and £500 million annually, while an additional €80-130 per KW of DSM would be achieved due to increased ability to balance wind generation. Although no figures are presented, welfare gains from operating and planning benefits of DSR are described as substantial in O’Connell et al (2014), therefore confirming, to an extent, the discussion in Bradley et al (2011).

Research gaps pointed out by the reviews we assessed include:

- An assessment of the factors influencing the variability of the estimates of the economic impacts of DSR published in the literature;
- The extent to which energy savings from DSR are assumed to be persistent by the estimates of the economic impacts of DSR.

Human Health

No review was identified addressing the impacts of Demand Side Responses on Human Health.
Biodiversity

No review was identified addressing the impacts of Demand Side Responses on Biodiversity.
Appendix 5.4 Electricity Vehicles

Our literature search identified 11 relevant reviews, which were assessed to determine the suggested priority list for future research. A number of impact categories were not covered in great depth, probably because EVs are an emerging technology. The current level of confidence of each impact category was also assessed. This information can then be used to prioritise areas of future research. A summary of the findings for each impact category assessed is presented below.

Marine Environment

The literature reviewed did not cover the potential impact of EVs on the marine environment.

Water

Research into the impacts of EVs on water is very limited. The majority of information is derived from life cycle assessments (LCAs), which assess factors such as freshwater ecotoxicity, eutrophication potential and acidification potential. Researchers acknowledge that there are significant uncertainties when quantifying the effects on water systems, although it is agreed that EV production processes and increased electricity demand are responsible for the majority of impacts (Hawkins, Singh, Majeau-Bettez, and Strømman, 2012; Hawkins, Gausen, and Strømman, 2012; Nordelöf et al. 2014). Impacts on water are linked to other impact categories, such as air quality, where emission of pollutants may subsequently cause acidification of aquatic environments.

Research gaps pointed out by the reviews we assessed include:

- A number of papers highlighted the need for more publicly available data in order to conduct more thorough and effective life cycle assessments for EVs.
- The specific EV production processes responsible for impacts to water are unclear, besides stating that impacts originate from the vehicle supply chain. Production of lithium-ion batteries was suggested as a cause (Nordelöf et al., 2014), however it is not clear whether utilising different battery technologies could mitigate these effects.

Land

Land use impacts, which are mainly related to the mining and manufacturing processes required for EV materials, are considered only by a selection of papers we assessed. LCAs include impacts such as terrestrial ecotoxicity potential and acidification potential, while effects such as metal depletion were highlighted by other reviews (Hawkins et al 2012, Majeau-Bettez, and Strømman, 2012; Nordelöf et al., 2014). EVs may also lead to greater adoption of renewable energy systems, which again may have an impact on land use. One review acknowledged that although land use effects may occur, biomass grown for electricity generation is more effective than for biofuel production, in terms of greenhouse gas reduction and kilometres driven per hectare of biomass produced (Richardson et al., 2013).

Research gaps pointed out by the reviews we assessed include:

- LCAs on a greater range of EVs to analyse the latest technologies. These LCAs could include land in the impact assessment if good quality data was available;
- Given the limited land availability for biomass production, further work could be carried out to determine whether electricity generation or biofuels production is a more efficient use of biomass.

Air Quality

Increased adoption of EVs has a significant potential to influence emissions. This topic was therefore discussed in the majority of papers reviewed, with many focussing on greenhouse gas emissions. Researchers agree that any benefits are largely dependent on the future
electricity mix and therefore it is currently difficult to reach a consensus on the extent of emissions reductions (Bradley and Frank, 2009; Dowds et al., 2009, Habib et al., 2015).

With increased deployment of EVs, air quality improvements are expected in urban areas as emissions are shifted to power plants. NO\textsubscript{x}, SO\textsubscript{2} and PM were discussed less thoroughly, with several papers acknowledging that this is dependent on the level of renewables integration into the grid (Richardson, 2013, Yilmaz and Krein, 2013).

**Research gaps** pointed out by the reviews we assessed include:

- Most studies focus on electric cars, while other vehicle types (such as electric buses) are not explored in detail.
- Studies on emissions are often based on current technologies and therefore do not consider the rapid advances being made in EV technologies. The effect over different vehicle lifetimes would also be of relevance.
- Future energy mixes could be modelled in greater detail to determine feasible emissions reductions. Most studies calculate projections based on the current electricity mix, coal or natural gas. This would allow for greater clarity on the emissions benefits in relation to air quality, NO\textsubscript{x}, SO\textsubscript{x}, PM and other pollutants, and the effect of displacing emissions from tailpipe to power plant.
- Findings from LCA studies greatly vary depending on whether EV production processes are taken into account. The need for greater understanding of the impacts of EV production is a common theme throughout the papers reviewed, however researchers suggest that this may be difficult to quantify due to the complexity of processes.

**Social Impacts**

Substantial knowledge gaps seem to exist in this category. Several papers agree that a greater uptake of electric vehicles will shift emissions from urban areas to power plants, however the wider consequences of this have not been analysed. Many papers also suggested that grid security could be improved via vehicle-to-grid (V2G) technology if the correct infrastructure can be implemented. A major discussion point was also the effect of renewables integration and the required infrastructure to enable this. Two papers mentioned the reduction of noise pollution associated with greater EV deployment (Hacker et al., 2009, Helmers et al., 2012), while the reviews revealed that fears surrounding the safety and security of public EV charging stations are common (Hacker et al., 2009).

**Research gaps** pointed out by the reviews we assessed include:

- Reduction of noise pollution associated with greater EV deployment is expected in urban areas, however the safety implications associated with this have not been fully addressed. For example, what are the potential impacts on pedestrians with visual impairments who may rely on their hearing to detect approaching vehicles?
- Wider social issues such as public acceptability, differential impacts across space (rural vs. urban), income brackets and population groups (age, gender, ethnic minorities), were not covered in the literature reviewed.
- The impact of shifting emissions from urban areas to power plants has not been thoroughly analysed.

**Economic Impacts**

Economic impacts covered in the literature are mainly related to the electricity grid, however any benefits are dependent on the uptake of EVs, requirement for updated grid infrastructure (due to renewables integration) and the charging strategies that consumers utilise (Dowds et al., 2009).

**Research gaps** pointed out by the reviews we assessed include:
Investigation into the potential employment opportunities and economic impacts as EV technology continues to advance.

Current research on V2G is inconclusive (and the value of the possible revenue stream for EV owners).

The impact of smart-charging strategies on the electricity grid (Richardson, 2013).

**Human Health**

The potential impacts of EVs on human health are difficult to quantify, although according to recently published LCAs appear to be higher compared to conventional cars (Hawkins, Singh, Majeau-Bettez, & Strømman, 2012). As the review papers contained very little information on this topic it is difficult to pinpoint specific research gaps, however more detailed information on the effects of the displacement of emissions from urban areas to power plants would be informative.

**Biodiversity**

The papers reviewed did not cover the potential impact of EVs on biodiversity.
Appendix 5.5 Electricity Storage

There are many different technologies that can deliver electricity storage (see below). Our evidence base covers two of these technologies: vehicle batteries and compressed air storage. Four battery papers, and one paper on compressed air storage are reviewed here. None of these papers is a review study, as none were identified during the literature search.

Electricity storage is a complex energy system component as a number of technologies can be used to store electricity. US DoE (2013) lists the following options: Liquid Air Storage, Pumped Heat Storage, Pumped Hydro Energy Storage, Batteries, Compressed Air Energy Storage and Flywheels, Superconducting Magnet Energy Storage and Power Supercapacitors. Among batteries one can differentiate between Flow Batteries, Sodium Sulphur, Lead-Acid, Lithium-ion, Sodium Nickle Chloride, Nickel-cadmium (Ni-Cd) and Nickel-metal hydride (Ni-MH) batteries. Unfortunately, most of these technologies are somewhat immature and still not ready to enter the market place. ARUP (2012) reports that Liquid Air Storage has not been demonstrated in the MW scale, Pumped Heat Storage is not commercially mature, while Flywheels, Superconducting Magnet Energy Storage and Power Supercapacitors are both very expensive and in some cases have limited grid scale applications. Pumped Hydro Energy Storage, on the other hand, show very limited potential for new UK sites. For these reasons we focused the literature search on batteries and compressed air storage.

Batteries

All references dealing with batteries, i.e. Gaines et al (2011), Majeau-Bettez et al (2011), McManus (2012) and Notter et al (2010) implement Life Cycle Analysis or Life Cycle Inventory of a number of battery specifications. Metrics used to compare the environmental performance vary in the studies. Gaines et al (2011) for example use energy and Greenhouse Gas emissions only; other studies use a more comprehensive assessment as shown in Table 13. Impacts used in LCA are somewhat aggregate and do not neatly fit in the impact taxonomy we have adopted in our study. Use of possibly scarce natural resources, for example, seemed to be one of the key concerns addressed in the papers although it was not used in our framework. In addition, these papers presented a limited range of battery types, which made it difficult to establish a baseline against which one could form a judgement to assess the intensity of impacts.
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming Potential</td>
<td>v</td>
<td>v</td>
<td>v</td>
<td>V</td>
</tr>
<tr>
<td>Fossil depletion</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human toxicity</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal depletion</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photochemical Oxidant Formation</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulate matter formation</td>
<td>v</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural Land Occupation</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Land Occupation</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Land transformation</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Depletion</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abiotic Depletion Potential</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable cumulated energy demand</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco indicator 99 H/A</td>
<td>v</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Energy Cycle</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
</tbody>
</table>

Table 13 Metrics of environmental impacts of batteries used by the papers assessed in our study

Although we cannot discuss the specific impacts of batteries against the framework adopted in this study, we notice that environmental burdens of mobility are dominated by the operation phase for both a gasoline-fuelled ICEV and a European BEV. The share of the total environmental impact by the battery (measured in Ecoindicator 99 points) is 15% (Notter et al 2010). As long as the electricity is not produced by renewable hydropower, impact of batteries used in electric cars is relatively small. The findings in Notter et al (2010) validate the conclusions from MacLean and Lave (2003) and Samaras and Meisterling (2008), which conclude the environmental impact of the operation dominates in the transport sector. The LCA results of BEVs mainly depends on the environmental profile of the electricity mix, as the vehicle tailpipe emissions are shifted to the power generation units. The small environmental impacts of the battery on the overall assessment of transport service can be explained by the very small quantities of lithium used, namely only 0.007 kg per kg Li-ion battery. The finding in Notter et al (2010) is also supported by the discussion in Gaines et al (2011). Although considerable information on production of battery materials is missing, the impact of the cradle-to-gate battery inventory on an electric vehicles’ is on the order of a few percent and could be further abated if battery active materials can be recycled (Gaines et al 2011).

Compressed air energy storage

In Compressed Air Energy Storage (CAES) systems, air is compressed in a cavern when power prices are low, and then used to run a natural gas-fired turbine to generate power when prices are high, with the aim of profiting from the price difference. This type of system can independently compress air or generate electricity or both. As the prices of electricity and
natural gas fluctuate, which directly impacts potential revenues, one needs to optimise operation strategies and maximise profit. Investment decisions require economic analyses to assess profitability of proposed facilities in certain power market conditions. Unfortunately, the only reference we identified, Yucekaya (2013), discusses the economic performance of compressed air energy storage systems rather than their environmental, social and economic impacts. Considering the description of the system, it is likely that the main environmental impacts of the technology are associated with electricity generation by fossil fuel combustion. Bouman et al (2013) confirms this intuition.
Appendix 5.6 Energy intensity of Industry (EII)

It is important to note that Energy Intensity of Industry (EII) is a relative measure of energy usage per unit of output. EII will either increase or decrease going forward, as a result of technological changes and related measures, referred to as deployment options. These changes may include implementation of energy efficiency technologies (including CHP), material or product substitution (for lower fuel/carbon alternatives), fuel switching, and CCS implementation. Impacts on EII will depend on how total energy usage changes relative to sectorial output.

In this section we review the Decarbonisation & Energy Efficiency Roadmaps to 2050 for the 8 most energy intensive sectors in the UK. We highlight the deployment options in each sector and effect on energy usage. Based on the “current trends” scenario of low continuous growth for the industry, the author has made inferences as to the possible impact of EII. Note this is highly sensitive to the pathways, scenarios, and deployment options explored.

The impacts of CCS and fuel switching technologies have already been covered under different energy system components in the SPLiCE study, or else have deliberately excluded from the study. Indirect impacts of deployment options (CCS, fuel switching and electrification of heat) have impacts on the power generation sources - wind, gas and nuclear – which are components of the SPLiCE study. Please refer to the other components for an assessment of impacts.

The focus of this document is on the remaining deployment options, which are mainly energy efficiency options. Only the options most likely to be deployed are considered here. Within the context of the pathways constructed for analysis in the Roadmaps, “likely” options are those deployed in pathways of low and intermediate level of decarbonisation ambition (up to 50% emission reduction per sector in 2050, relative to 2012). It is worth mentioning that the impacts considered in the SPLiCE study have not been explicitly mentioned in these roadmaps.

Reviews of Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

This set of reviews have been commissioned by DECC and BIS, and were produced in March 2015 for the following sectors, by WSP, Parsons Brinckerhoff, DNV-GL:

- Chemicals
- Iron and Steel
- Oil Refineries
- Food and Drink
- Pulp and Paper
- Cement
- Glass
- Ceramic

The reviews below analyse pathways to sector specific decarbonisation by 2050. Pathways assume a “current trends” economic scenario with low, continuous growth of the industry in the UK.

Chemicals

Energy Intensity of Industry

The Business as Usual pathway for the Chemicals Industry includes deployment of options such as fuel switching (biomass), energy efficiency measures and CCS (process) results in overall reduction in energy and fuel used, resulting in only a limited 30% CO₂ emission reductions from 2012 in 2050 in the UK. The authors infer a low energy intensity in this pathway.

More ambitious pathways (40-60% CO₂ reductions and maximal technical reduction) further include deployment of options such as biomass feedstock, and will increase (substantially)
energy used and result in a large expected overall increase in energy use and costs. Author infers increased energy intensity in these pathways [p71].

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

Energy Efficiency Deployment Options

The main EE options deployed in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Improved insulation
- Improved waste heat recovery
- Improved process control
- More efficient equipment
- Improved steam system efficiency

In the 40-60% reduction pathway, these options were further deployed:

- Catalytic cracking
- Integrated gas turbines with cracking furnace
- Clustering (of sites to optimise resource use)
- Bioprocessing

Iron and Steel

Energy Intensity of Industry

The BAU and 20-40% CO₂ emissions reduction pathway (relative to 2012 by 2050) for the Iron and Steel Industry includes deployment of options such as stove flue gas recycling, steam or power upgrades and reduced yield losses, retrofit solution and installation of advanced technologies, results in potential reduction in energy and fuel used. Author infers decreased energy intensity in these pathways.

More ambitious pathways (40-60% CO₂ reductions and max technical reduction) further include deployment of options such as CCS, and will increase energy used. Author infers increased energy intensity in these pathways. [P.83]

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

Energy Efficiency Deployment Options

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Stove flue gas recycling at integrated Blast Furnace(s) – Basic Oxygen Furnace sites
- (Generic) Reducing yield losses or avoiding off-spec products
- Other options which contribute appreciable savings to the pathway include: improved automation and process control, heat recovery and re-use, near-net-shape casting, pulverised coal injection, and coke dry quenching

In the 20-40% reduction pathway, these options were further deployed:

- Retrofit solutions (without carbon capture):
- Advanced technologies and rebuild (without carbon capture):
- Clustering (of sites to optimise resources)

Oil Refineries

Energy Intensity of Industry

The BAU and 40-60% CO₂ emissions reduction pathway (relative to 2012 by 2050) for the Oil Refining industry includes deployment of options that increase overall energy efficiency, and
results in potential reduction in energy and fuel used. Author infers decreased energy intensity in these pathways.

More ambitious pathways (Max technical reduction) further includes deployment of options such as CCS, and will increase energy used. Author infers increased energy intensity in this pathway. [p.67]

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

**Energy Efficiency Deployment Options**

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Waste heat and energy recovery
- Replacement of the following, for improved efficiency:
  - Motors, pumps, compressors and fans
  - Oil storage heating
  - Process heaters and furnaces
- Advanced control and improved monitoring
- Lighting

In the 40-60% reduction pathway, these options were further deployed:

- Steam: utilities optimization

**Food and Drink**

**Energy Intensity of Industry**

The BAU and 60-80% CO₂ emissions reduction pathway (relative to 2012 by 2050) for the Food and Drink Industry includes deployment of options such as process design, fuel switch (biomass), and improvements in steam production and distribution and the electrification of heat, results in a reduction in energy and fuel used. Author infers a decreased energy intensity in these pathways.

More ambitious pathway (max technical reduction) further includes a significant transfer of energy use from natural gas to electricity, and will increase energy used. Author infers increased energy intensity in these pathways. [p.85]

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

**Energy Efficiency Deployment Options**

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Process design (improving layout and process flows)
- Improved steam production, distribution and end-use with state of the art systems
- Reduced packaging

**Pulp and Paper**

**Energy Intensity of Industry**

In Pulp and Paper industry, deployments of the options described below per pathway result in either a saving in energy used, or a saving in energy costs (very sensitive to price forecasts). Author infers decreased energy intensity in these pathways. [p.74].

- The BAU and 40-60% CO₂ emissions reduction pathway (relative to 2012 by 2050) includes deployment of options that increase overall energy efficiency and also increased use of biomass.
- Max technical 1 - significant transfer of energy use from natural gas to electricity coupled with deployment of advanced technology and clustering.
Max Technical 2 - increased use of biomass plus advanced efficiency measures.

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

Energy Efficiency Deployment Options

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Improved process control
- Extended nip press - non-tissue
- (Waste) heat recovery and heat integration
- Energy management
- Focus on maintenance
- SAT steam system

In the 40-60% reduction pathway, these options were further deployed:

- Heat recovery on hoods future
- Impulse drying (a paper machine option)

Cement

Energy Intensity of Industry

The BAU and 20-40% CO₂ emissions reduction pathway (relative to 2012 by 2050) for the cement industry includes deployment of options such as using alternative cements and cementitious substitution, and fuel switching to biomass, results in potential reduction in energy and fuel used. Author infers a decreased energy intensity in these pathways.

The more ambitious pathway (Max technical reduction) further includes deployment of options such as CCS, and will increase energy used. Author infers increased energy intensity in this pathway. [P. 71].

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

Energy Efficiency Deployment Options

The main EE options in the BAU and 20-40% reduction pathways are [taken from Section 4.4 of Roadmaps]:

- Electrical efficiency improvements
- Alternative cements
- Cementitious substitution
- Use of alternative raw materials (calcined)

Glass

Energy Intensity of Industry

The BAU for the Glass Industry includes deployment of options that increase overall energy efficiency and reduce overall fuel use. Author infers decreased energy intensity in these pathways.

In the 20-40%, 40-60% and 60-80% CO₂ emissions reduction pathways (relative to 2012 by 2050), deployment of electrification of heat may increase fuel costs, however, this will be offset by energy efficiency measures.

More ambitious pathways (max technical reduction) further includes deployment of options such as electrification of most processes, and CCS, and will result in a very large overall increase energy used. Author infers increased energy intensity in this pathway. [p.79]

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.
Energy Efficiency Deployment Options

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Increased use of recycled glass
- Conventional improvements to furnace construction
- Waste heat recovery
- Improved process control
- Oxy-fuel combustion (increasing thermal efficiency through increased oxygen in furnace)
- Batch palletisation

In the 40-60% reduction pathway, these options were further deployed:

- Conventional improvements to furnace construction
- Batch reformulation
- Improved process control

Ceramic Energy Intensity of Industry

The BAU pathway for the Ceramics Industry includes deployment of options that increase overall energy efficiency and reduce overall fuel use. Author infers decreased energy intensity in these pathways.

The 40-60% CO₂ emissions reduction pathway (relative to 2012 by 2050) energy efficiency measures are offset by electrification of heat, with an undetermined impact on energy usage.

More ambitious pathways (max technical reduction) further include the extension of the electrification for other processes beyond heating, and will significantly increase energy used. Author infers increased energy intensity in these pathways. [p.72]

Note that actual EII will vary with industrial growth and output, and energy usage as determined by the deployment of these options.

Energy Efficiency Deployment Options

The main EE options in the BAU pathway are [taken from Section 4.4 of Roadmaps]:

- Adoption of available lowest carbon process: in all four subsectors (heavy clay, refractories, technical ceramics, and white wares).
- Reduction of radiant and convective heat losses and leakage
- Improving heat use by regenerative processes
- Improving combustion efficiency
- Low mass refractory for kiln cars
- Improved process control in all subsectors
- Reduced air/product mass ratio in the heavy clay kilns

In the 40-60% reduction pathway, adoption of lowest carbon process (kiln replacements using BAT) was also deployed.
Appendix 5.7 Heat Pumps

Our search returned no reviews covering the environmental, social and economic impacts of heat pumps. The discussion below is based on 7 original studies. On closer inspection, only three of these studies presented data on the relevant impacts. This section is mainly based on Eunomia and CACRR (2014) and Greening and Azapagic (2012). Heat pumps take low temperature heat from the environment and turn it into higher temperature heat by using electrical energy. Their main environmental impact arises from the electricity used in operation (something generally true for space conditioning technologies (IEA 2002)). Many studies on heat pumps focus therefore on operational carbon emissions in comparison with other heating systems, and do not consider other environmental impacts. These comparisons will change with the assumed efficiency of the heat pump system, the carbon intensity of the electricity used and the comparison technology. Studies about heat pumps are often concerned with future rates of uptake, and scenarios for this vary considerably (e.g. DECC 2013, Delta-EE 2012).

The majority of all life cycle assessments carried out on systems for space conditioning or generation of electricity by combustion confirm that most of the environmental impact stems from the operation phase (IEA 2002). For this reason, environmental evaluations need to take into account indirect impacts related to the generation of electricity used by heat pumps. The fact that the great majority of GHG emissions from heat pumps are related to the indirect emissions associated with the generation of electricity is fairly uncontroversial in the literature. Deployment of heat pumps from a CO₂-equivalent perspective seems a worthwhile endeavour. When compared against gas condensing boilers, heat pumps delivered up to 36% of Mt CO₂ equivalent savings on a lifecycle basis, i.e. taking into account emissions from refrigerants and indirect emissions (Greening and Azapagic 2012). The projected increased roll-out of heat pumps was found to be beneficial in reducing CO₂ equivalent impacts through the displacement of more carbon intense technologies despite the associated rise in emissions due to refrigerant losses (Eunomia and CACRR 2014).

Impacts of refrigerants

Refrigerants are a fundamental element of a heat pump installation as they carry the energy from the heat source to the heat emitters. Refrigerants can leak both during normal operation and at the end-of-life, and thereby have an environmental impact. There is concern both about their global warming potential and local impact in the receiving environment. These impacts depend on the type of refrigerant used (and the degree and location of leakage). The most common fluids currently used in heat pumps are Hydrofluorocarbons (HFCs), which typically have a global warming potential of over 1000 times that of CO₂. GHG emissions associated with refrigerant use might become increasingly important if large-scale deployment of heat pumps comes to fruition and if substantial leakage of refrigerants take place. It is worth noting that a number of alternatives are available for refrigerants. In fact, the nowadays prevalent HFC-based refrigerants came to the fore after growing awareness of ozone depletion lead to a phase-out of the once dominant Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) refrigerants due to their large impact on the ozone layer. This has led to the increasing use of Hydrofluorocarbons (HFCs) and blends, particularly R134a, R407C and the R410A. As the Global Warming Potential (GWP) of HFCs is now a significant environmental concern, it is highly likely that HFCs will be controlled in the future and substituted with further synthetic refrigerants, particular Hydrofluoroolefins (HFOs) (Eunomia and CACRR 2014). Similarly, a number of naturally occurring substances such as ammonia, hydrocarbons and carbon dioxide (CO₂) are still utilised as refrigerants and could become the dominant choice in the future (Eunomia and CACRR 2014).

There is currently relatively little quantitative analysis available on refrigerant leakage rates over the lifetime of a heat pump. As a result of a data collection exercise based on 'log book' records from existing installations across the UK, Eunomia and CACRR (2014) concluded that annual leakage rates from operation of heat pumps were of the order of 3.5%, but substantial uncertainty remains as log books were generally of poor quality. It is worth noting
that findings are considerably higher than the annual 2% leakage rate assumed in Forsén (2005) but lower than the 6% assumed in Greening and Azapagic (2012). In terms of leakage at end-of-life Forsén (2005) and Greening and Azapagic (2012) adopt very similar assumptions, at 20% and 15% respectively.

The most well established method to compute GHG emissions from refrigeration and heat pump applications is called TEWI (Total Equivalent Warming Impact) which integrates direct and indirect GHG emissions over the whole lifetime into a single number expressed in terms of CO$_2$ equivalency. TEWI incorporates direct emissions due to leakage of refrigerants, indirect emissions related to electricity generation and direct emissions at demolition. TEWI calculation based on national electricity emission factors confirms that 98.5% of GHG emissions for heat pumps installed in the UK consist of indirect emissions related to electricity generation (Forsén 2005). Similarly, Eunomia and CACRR (2014) conclude that whilst refrigerant leakage produced significant CO$_2$ equivalent emissions, this was nonetheless a small proportion of the total reduced emissions associated with heat pump technologies.

Assessments of performance of heat pumps in relation to non-CO$_2$-equivalent impacts are however much more uncertain. Unfortunately, impacts of refrigerants beyond CO$_2$ equivalent are difficult to quantify and related research is very limited (Eunomia and CACRR 2014). Whilst for atmospheric impacts, such as CO$_2$ equivalent and Ozone layer Depletion Potential (ODP) there is relative certainty of dose-response effect, for non-atmospheric releases the impact of a leaked kg of refrigerant may have widely differing impacts due to the nature and location of the leak. It is not possible to identify with accuracy the proportion of a leak that would enter specific ecosystems (e.g. marine environments) and therefore the impact of leakage of a ‘generic’ kg of refrigerant cannot be robustly quantified.

Eunomia and CACRR (2014) argue that it is not possible to utilise LCA data on the environmental impacts of refrigerants to analyse the impact of a leakage in a robust manner and that any modelling conducted with those figures could result in significantly raised impacts. Only one database among the four assessed by Eunomia and CACRR (2014), EcoInvent, contained relevant data on two of the refrigerants, namely CO$_2$ and R134a. No data were contained in any dataset on any of the other refrigerant options. Although it is not possible to model the impact of non-CO$_2$ equivalent impacts with any accuracy, it is possible to identify the impacts that are of greatest concern by using LCA studies but unfortunately findings show considerable variation. When assessing life cycle environmental impacts of applications in the UK, heat pumps in the residential sector were judged as not being a sustainable alternative to condensing gas boilers as most of the non-CO$_2$-equivalent impacts caused by of refrigerant (R134a) leakage usually computed in life cycle analyses was several-fold higher than for boilers (Greening and Azapagic 2012). In particular,

- Marine water Aquatic Eco-Toxicity Potential (MAETP) increased up to 23 times compared to the condensing boiler;
- Terrestrial Eco-Toxicity Potential (TETP) increased up to 13 times compared to the condensing boiler;
- Ozone layer Depletion Potential (ODP) and Fresh Water Aquatic Eco-Toxicity Potential (FAETP) increased up to 7 times compared to the condensing boiler;
- Human Toxicity Potential (HTP) increased up to 5 times compared to the condensing boiler.

On the other hand, when performing a similar exercise Eunomia and CACRR (2014) concluded that the R134a refrigerant has large impacts only for MAETP and ODP. All other non-CO$_2$ equivalent impacts, including FAETP, HTP and TETP are negligible. It is important to reiterate that eco-toxicity impacts are highly diverse and it is therefore not possible to provide a single value for toxicity that is representative of all locations. Refrigerant leakage in vapour form, for example, is likely not to have a significant impact on marine (or indeed other) ecosystems as it is emitted directly into the atmosphere. Leakages occurring in liquid form are likely to remain in and around the point of leakage unless it is able to drain into a
drainage system. Eunomia and CACRR (2014) conclude that the true toxicity impact of leaked R134a is highly uncertain and unlikely to be as significant as the values computed in LCA studies.
Appendix 5.8 Insulation and building fabric

Our literature search identified 9 relevant reviews, published in a number of academic journals but all assessing studies based on the Life Cycle Analysis (LCA) framework. Coverage of these reviews in relation to the impact categories used in this study is however fairly limited, with most studies assessing energy consumption and related GHG emissions. The focus of research on the operational phase of buildings can partly be justified by the observation that 80-90% of a building’s life-cycle impacts come in this operational phase. Improving building energy performance is fairly uncontroversially considered to be both possible and desirable. The impact of insulation in the residential sector has received considerable attention in the literature, alongside the impact of other policy interventions to raise energy efficiency. A number of systematic reviews have been published including at least two meta-analyses.

Published reviews provide very few conclusions on the impacts of building fabric, with most reviews consisting of a sequence of paragraphs, one for each of the reviewed articles detailing the location of the building, its use, a brief description of the building and some methodological considerations. Results are normally described in general terms - referring to the environmental impacts of the building as a whole. Reported LCA studies are very specific, with generally very few alternatives being assessed in the same paper. Studies assessing subsystems of a building are as equally detailed and specific as the studies assessing whole buildings. LCA studies of buildings form a very scattered literature spread over several national and international publications (Cabeza et al 2014 and Singh et al 2011). The case studies are difficult to compare because of their site-specific impacts, e.g. related to climate, solar access, rain flows, and neighbourhood security (Buyle et al 2013, Cabeza et al 2014 and Singh et al 2011). In addition, buildings are more difficult to evaluate compared to relatively standardised industrial products as they are large in scale, complex in materials and temporally dynamic due to the long lifespan of buildings, limited life of building components and the evolution of functions over time related to maintenance, retrofitting and changing user requirements (Buyle et al 2013, Cabeza et al 2014, Khasreen et al 2009, Zuo and Zhao 2012). The long use phase of buildings results in considerable uncertainties in LCA findings, and requires many more assumptions, which consequently influences the credibility of the results (Ortiz et al 2009, Zuo and Zhao 2012). The end of life phase possesses further uncertainties related to renovation, remodelling, demolition and land filling of various building elements (Singh et al 2011).

Other limitations are related to the fact that LCAs of full buildings vary from building to building since each has its own function and different engineering characteristics (Ortiz et al 2009). Furthermore, engineering is not the only issue, as seemingly near-identical buildings can vary by up to a factor of 5 in energy consumption. The uses, occupant behaviour and management of buildings are key variables, not just the material fabric and technology installed. The production processes of buildings are not very standardised, which causes a clear lack of data inventory for LCA studies (Khasreen et al 2009). In addition, limited quantitative information exists about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition. The data that does exist suggests that there is a high degree of variability in all of the impacts associated with the various life-cycle phases of a building. LCA also involves making certain key assumptions, such as the length of time a building will continue to be in use into the future. LCA methods are still evolving and face significant challenges before becoming standard industry practice. Major efforts are necessary in methodological development, database development, decision support tools, and software development and training (Singh et al 2011). The nature of the building industry makes it difficult to have an international dataset available for all users. Ideally, one would have an internationally accepted framework, protocol, and conversion tools based on different factors, to enable the comparison between LCA studies. The currently available datasets are typically not transparent, and most of them are based on local and simple materials but not components or composites. There is a need to produce accurate local datasets with the possibility to
convert their results to an internationally comparable form. Khasreen et al (2009) state that no two case studies can be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used.

In terms of coverage, LCA of buildings generally include the embodied energy of materials and building component combinations, the transport of materials and building components to the site, the use of the building (implied energy use), maintenance, replacement and demolition, as well as the transport of waste to the treatment site. The waste of materials and water consumption is sometimes included. The transport of equipment to site, the construction phase at the site of the building, and construction waste is generally not included (Khasreen et al 2009).

**Energy Consumption of Building Fabric**
Quantified generalisations in the literature can be found only in relation to energy use in buildings. Operating energy takes the major share (80–90%) of life cycle energy use of buildings followed by embodied energy (10–20%), whereas demolition and other process energy has negligible or little share (Ramesh et al 2010). One review of 73 case studies from around the world (mainly in developed countries with temperate climates, but also including some developing countries and tropical climates) concludes that normalised life cycle energy use of conventional residential buildings falls in the range of 150–400 kWh/m² per year (primary energy) and that of the office buildings in the range of 250–550 kWh/m² per year (primary energy) (Ramesh et al 2010).

**Environmental Impacts of Building Fabric**
Ramesh et al (2010) concludes that the impacts on the environment correlate closely with primary energy demand of the buildings in their life cycle. The operation phase is said to be the most critical with regard to environmental loads arising from European buildings, as high environmental loads are emitted into the atmosphere due to the high-energy requirement for heating, ventilating, and air conditioning, domestic hot water and lighting (Buyle et al 2013; Ortiz et al 2009). Commercial buildings have been found to have more impact on the environment (per unit treated floor area) as compared to residential buildings (Sharma et al 2011). Another frequent conclusion is the minor importance of the transportation of materials during construction (Buyle et al 2013). Although the main focus is on energy reduction, both in policy and research, water consumption is an emerging issue and may play an important role in the future. Reducing the water consumption of households is gaining importance and will have to be examined more thoroughly in future research (Buyle et al 2013).

**Social and Economic Impacts of Building Fabric**
The number of studies on social and economic impacts is comparatively small. The social performance, for example, of green buildings warrants further investigation (Zuo and Zhao 2012). Social impacts of buildings can potentially influence user behaviour, therefore ultimately influencing the environmental performance of the building. The development of indoor environments, design choices and related user behaviour may have a completely new set of potential impacts during the use phase of the building (Singh et al 2011). Since inhabitant behaviour is difficult to predict, it is also an issue of concern when considering the reliability of any conclusion on environmental impacts (Buyle et al 2013).

**Impacts of Insulation**
A number of energy efficiency measures, including various insulation types (e.g., loft, cavity, internal, and external solid wall insulation), have been found to have a small but significant positive impacts on health (Maidment et al 2014) which is consistent with previous reviews (Liddell and Morris 2010, PHIS 2006; Thomson et al. 2009 and Thomson et al. 2013). No significant differences in terms of positive health impacts were found when comparing the health effects of installing insulation only to installing insulation alongside a wider package of efficiency measures (Maidment et al 2014). Higher positive health impacts were found in studies investigating specific medical conditions, in studies employing medical tests or using
information from third parties rather than self-assessment, in studies using control groups and in studies published after 1989. In terms of social impacts, Maidment et al (2014) discovered significant positive impacts for children, people in poor health, and for vulnerable groups as a whole. However, there was no significant difference between the size of the effect on vulnerable groups as a whole and that for the general population. Greater effects of energy efficiency interventions on health were found in studies focusing on participants with low incomes. It is worth stressing that among the extensive evidence discussed in Maidment et al (2014), no negative health impacts from household energy efficiency interventions were found in relation to any of the intervention and population subgroups analysed. This supports the continued use of household energy efficiency improvement to tackle fuel poverty and reduce health inequalities. Research gaps identified in the literature related to: impact of statistical methodology on results; lack of assessment of long-term cumulative impacts; impact of use of objective measures of health; gap between self-reported and objectively assessed; quantitative studies on the impact on mental health; impact of customer satisfaction, guidance, and "customer care".
Appendix 5.9 Land for Bioenergy

The environmental impacts of land dedicated to the production of bioenergy seems to be a well-researched topic based on the reviews identified in the literature. Our search strategy returned 16 unique references, most of them spanning a number of impacts we focus on in our study. Notably absent in the environmental literature however, few studies present an integrated and joined up assessment of impacts, acknowledging the complex inter-dependence of water, air, land, biodiversity and climate systems. In addition, very few papers referred to economic and social impacts, and only tangentially.

Marine Environment

No review was identified addressing the environmental, social and economic impacts of land dedicated to the production of bioenergy on the marine environment.

Water

Land-use change brought about by the cultivation of bioenergy products can cause higher water consumption, especially during the summer, although the impact depends on numerous components including crop type and local conditions (Rushton et al 2014, Gabrielle et al 2014, Dockerty et al 2014). Evapotranspiration rates vary significantly with land use and crop species (Dockerty et al 2014). Due to the multitude of factors influencing final impacts, generalisation is difficult. There is a serious risk for detrimental effects on availability of hydrological resources, if not carefully managed (Rowe et al 2009).

The impact on water quality depends on crop type and management. In comparison to arable crops, however, conversion to cultivation of bioenergy implies benefits in terms of lower usage of fertiliser and pesticide usage as well as pollutant interception (Rushton et al 2014, Dockerty et al 2014). However, in some cases higher use of pesticide have been reported (Chavez et al 2011). Hardy crops on marginal land compare favourably to large-scale energy crops, in terms of fertiliser usage (Evans et al 2011). Lower levels of fertiliser and pesticide have been generally reported also for Short Rotation Coppice (SRC) and other second generation crops (Rushton et al 2014). Improved water quality is also reported in case of application of SRC for phytoremediation, i.e. removal of nitrates and other nutrients from waste water (waste water “polishing”) (Rowe et al 2009). Perennial crops (Miscanthus, Switchgrass, willow SRC) tend to have lower levels of nitrate leaching into groundwater (Gabrielle et al 2014). Land use change from arable to perennial, multiyear rotations lignocellulosic crops (such as SRC), can have positive effects on water quality, especially phosphorous and nitrate leaching (Chavez et al 2011).

Research gaps pointed out by the review we assessed include:

- Models for landscape, catchment and regional impacts of SRC;
- Interactions between the use of water for bioenergy with other abstractions e.g. public water supply;
- Flood risk management benefits;
- Impact of energy crops as buffers along waterways preventing nutrient runoff from agricultural land;
- Nitrogen from organic waste;
- Phosphorus leaching impacts from sludge usage.

Land

Land Use Change (LUC) occurs with land conversion, crop changes, intensification of farming, and demand conversion (food to fuel). Four types of LUC have been identified: (1) Clearing of primary / native flora / fauna in developing nations with abundant land (2) Conversion of cattle pasture (notably in Brazil) (3) Conversion of existing cropland primarily in EU/USA, triggering ILUC (indirect land use change) and LUC through imports described in 1 & 2 (4) Conversion of marginal agricultural land, which could minimise LUC impacts (Miyake et al 2012).
The impact of LUC depends on pre-existing usage (Rushton et al 2014). LUC can have a considerably negative impact on lifecycle emissions of advanced biofuels (Popp et al 2014) and significantly affect nitrogen, carbon and water (e.g. through compaction) in the soil (Thomas et al 2013). Most 2nd generation crops cause LUC displacing agricultural crops, except where marginal lands are used (Rushton et al 2014). Land displacement can affect agriculture and forestry production (Fritsche et al 2010). ILUC is caused by the displacement of agricultural or forestry production to other land and the intensification of farming. Intensity of impact depends on numerous factors (e.g. farming system) (Rushton et al 2014).

Certain crops improve carbon stocks (Rushton et al 2014). Soil Organic Carbon (SOC) changes depends on the crop type and management, and former land use. Conversion from forest/grassland and annual lignocellulosic crops to arable cropping systems decreases SOC stocks. A shift from arable to SRC/perennial grasses may increase SOC (Gabrielle et al 2014). There is consensus that conversion of arable to miscanthus/SRC increases SOC but conversion of grassland is not so beneficial (van der Hilst et al 2012, Rowe et al 2009). SRC has a positive effect on nitrogen leaching (Thomas et al 2013) but there is less certainty in relation to miscanthus (Rowe et al 2009).

Impact on soil condition depends on the previous use of the land. When arable land is converted to miscanthus, erosion risk is significantly reduced, but risk increases when pastures are converted (Van der Hilst et al 2012). Soil fertility may be impacted by production methods (Spiertz et al 2009). A positive impact on soil quality has been reported (Dockerty et al 2014). In terms of erosion, conversion from arable crops to 2nd generation biomass is expected to reduce erosion risks (Rowe et al 2009). Finally, in terms of phytoremediation, SRC can be applied to improve soil contamination (especially cadmium removal) (Rowe et al 2009) and in some cases to rehabilitate marginal land (Evans et al 2011).

Finally, it has been noted that research on the impacts of LUC for bioenergy has hitherto focused on "climate regulation" through biogeochemical processes (carbon sequestration, conversion, storage, GHG reduction) while very little research has gone into the impact of LUC on biophysical processes of land, which in turn affect the climate through water regulating services, perturbations of which can affect climate and water systems.

**Research gaps** pointed out by the review we assessed include:

- Methodologies for considering uncertainty in ILUC assessments
- Methodologies to increase transparency of LUC modelling efforts;
- Soil carbon impacts, at high resolution;
- Lifetime-end land use reversion;
- Large-scale production (and use) impacts of biofuels, in particular on LUC/ILUC, GHG, biodiversity, resource management;
- Coupling economic and agronomical models to study direct and indirect LUC;
- Projections for EU LUC, as demand for cropland decreases;
- Availability and potential and sustainability of marginal "underutilised agricultural lands" in USA/EU;
- Miscanthus effect on nitrogen leaching;
- Impact of LUC on biophysical processes which affect climate via the water/carbon/energy nexus. Research can address the impact at four relevant scales: leaf, field, regional and global scale
- Complexities and interlinkages between land use change and the water, nutrient and carbon cycles.

**Air Quality**

None of the reviews we assessed reported impacts of land for bioenergy in terms of air quality. On the other hand, considerable attention has been devoted to the GHG implications, both in terms of carbon and N\textsubscript{2}O. These are not reviewed here as they are considered out of scope.
Social Impacts
Social impacts of land for bioenergy are mainly related to informal land use and communities where property rights and governance are weak. In Latin America, inequity in land rights and weak governance can cause exploitation of fragile land (Spiertz et al 2009) or land take issues (Dockerty et al 2014). Social issues can be caused by use of marginal land, especially when this takes place in the presence of informal land use rights (Rushton et al 2014). Large-scale bioenergy projects may be dominated by large international companies, leading to negative socioeconomic impacts - especially on land tenure issues (Gabrielle et al 2014). A number of papers discuss social sustainability concerns due to the effect of ILUC and biofuel imports on land use in the "global south" (Miyake et al 2012). In terms of public acceptability, ILUC may cause loss of native flora/fauna, which is considered a key barrier to public acceptance (Evans et al 2011)). SRC and miscanthus is likely to have significant visual impacts in contrast to traditional crops, which has generated of mix of positive and negative impacts (Rowe et al 2009). It is fair to conclude that the complexity of assessing social implications is high, and methodologies are still in their development stages. These two factors contribute to create a gap in the literature (Gabrielle et al 2014)

Research gaps pointed out by the review we assessed include:
- Social effects of biofuel exports in the Global South;
- Methodologies to assess the social implications;
- Factors influencing the public acceptability of bioenergy

Economic Impacts
Economic impacts of land used for bioenergy are normally framed within the ‘fuel vs food’ debate (Dockerty et al 2014). Bioenergy production could conflict with availability of land and water for food production, although this potential impact may be limited by use of marginal land for 2nd generation bioenergy production (Popp et al 2014)). Bioenergy may compete with the food sector, either directly if food commodities are used as the energy source, or indirectly if bioenergy crops are cultivated on soil that would otherwise be used for food production. Food prices and food security could be impacted if demand for crops or for land is significant. Although this has been a concern of the biofuel sector, until now the price increases have been limited for most crops, and the agricultural sector has responded by increasing production. Besides competition with food, increased use of biomass has an effect on specific sectors, e.g. forest based industries such as pulp and paper. Overall, many experts (Popp et al 2014) do not accept the perception that expansion of bioenergy use will produce serious competition with food). Surprisingly, none of the reviews we assessed discussed the impact of land for bioenergy on rural communities. In general, economic aspects of biofuels are under researched, with impacts on trade one of the least studied topics (Ridley et al 2012). Impact on food security and food prices are also under studied (Ridley et al 2012), although it was reported that the consensus is that expansion of bioenergy use will not set serious competition with food (Popp et al (2014)). No research gaps were identified in the reviews we assessed.

Human Health
None of the reviews we assessed discussed the impact of land for bioenergy on human health. Human health was found to be one of the least studied topics in biofuel literature (Ridley et al 2012).

Biodiversity
The biodiversity impact of biofuel crops depends on the crop species and the former land use. The impact on biodiversity depends on the cropping systems, with large-scale monocultures generally causing a loss of biodiversity (Spiertz et al 2009). There is some consensus on the fact that the reduction in biodiversity caused by perennial crops is likely to be lower than that for 1st generation production (Gabrielle et al 2014, Immerzeel et al 2014, Fletcher et al 2011). LUC is the key driver for biodiversity change, leading to habitat loss and
changes to species richness and abundance, often paired with biological homogenisation (Rushton et al 2014 and Immerzeel et al 2014). Invasion of non-native species, particularly with miscanthus and energy grasses is also important (Rushton et al 2014). LUC is sometimes thought to have considerable negative impacts on biodiversity (Popp et al 2014) but in other instances conclusions are mixed. Conversion from native/non-crop habitats generally leads to a decrease in vertebrate diversity and abundance while conversion of arable to biofuel crops can positively impact biodiversity (Fletcher et al 2011, Rowe et al 2009). SRC is generally expected to have positive impact in comparison to arable lands with regard to flora, avian, and invertebrate diversity (Rowe et al 2009). Bioenergy expansion may also lead to indirect impacts on biodiversity, which are harder to quantify (Immerzeel et al 2014).

**Research gaps** pointed out by the review we assessed include:

- Impacts of cropping systems on biodiversity;
- Impacts of energy grasses on biodiversity;
- Effects of perennial crops on biodiversity relative to previous land use and landscape structure, especially miscanthus;
- Potential for non-native crops to become invasive, when producing 2nd generation biofuels (miscanthus, jatropha);
- Effects of SRC on soil invertebrates, mammals, amphibians and reptiles;
- Impacts of land-sparing vs land sharing on a large scale;
- Integration of multiple spatial scales to avoid field scale bias;
- Insights into changes in species distribution;
- Assessments of changes in species extinction risk;
- The effects of mitigating measures on biodiversity;
- The effects of intensification of production systems on (agro)biodiversity;
- Assessment and definition of the potential of marginal and degraded land;
- Impacts of genetic engineering of 2nd generation crops for pesticide/herbicide resistance
- Impacts of the interplay of social, economic, ecological factors on biodiversity;
- Investigation of conservation opportunities of 2nd generation biofuels (e.g. converting from annual to perennial crops);
- Impacts of production on land which is not in agricultural production.
Appendix 5.10 Nuclear Power

The human health impacts of nuclear power generation have attracted considerable attention in the literature, as they are discussed in 7 of the review papers we identified. However, there are still many uncertainties associated with the human health impacts of nuclear power.

Marine Environment

Only one review out of 12 considered the impacts of nuclear power on the marine environment. Dockerty et al (2014) found both local and global impacts on the marine environment. Locally there are negative impacts such as decreased marine biodiversity and increase in harmful algal blooms. Globally there are additional negative impacts associated with mining and shipping.

Water

Only 2 reviews addressed the impacts of nuclear power on water. According to these reviews (Dockerty et al 2014, McMahon and Price 2011), local impacts relate to water consumption for mining and processing nuclear fuel, and global impacts relate to water transport pollution, discharge of waste waters and antifouling chemicals from ships.

More generally, energy and water are strongly dependent on each other and "addressing the interdependence of water and energy requires increased integrated resource planning, collocation of water and energy facilities, and systems thinking at multiple scales" (McMahon and Price 2011, p.185).

Land

Locally, nuclear power generation and in particular accidents have caused terrestrial ecotoxicity and the release of radionuclides into the environment, the effects of which are not well understood (Dockerty et al 2014, MacKenzie 2000). Globally, there are impacts on the land associated with mining and processing of nuclear fuel (Dockerty et al 2014). Additionally, and most problematically, there is the need to find a scientifically sound and publically acceptable disposal procedure for nuclear waste (Holm et al 2002, MacKenzie 2000, Salvatores and Palmiotti 2011). This problem has not yet been solved and poses as-yet unanswered risks and intergenerational questions (Stamford and Azapagic 2012).

Research gaps include a call for "guidance that could be globally accepted" and the need to "synthesise human and environmental radiological protection into a coherent framework" (Holm et al 2002, p.245).

Air Quality

No review was identified addressing the impacts of nuclear power on air quality. Radionuclides from nuclear power generation are emitted into the air but the impacts are discussed under the category of health, as there is considerable consensus that the largest impact from emissions of radionuclides into the air is on health.

Social Impacts

The greatest social impact of nuclear power is the lack of public acceptability, particularly following nuclear accidents. MacKenzie (2000) suggests that every effort should be made to avoid further major accidents and that the international dimension of the problem "highlighted the requirement for maintenance of uniform and rigorously high standards of safety in all countries using nuclear power", particularly as many nuclear accidents result from human error (MacKenzie 2000, pp.325-326).

Economic Impacts

Only 2 out of 12 review papers addressed the economic impacts of nuclear power generation. They found that economic impacts such as costs of radioactive waste storage, of decommissioning, and of damages associated with major accidents have not been evaluated comprehensively (Ragaišis et al 2014). Additionally, any evaluation would depend
on which possible impacts are included and which are excluded, and on which discount rate is applied (CEPN 1995).

Human Health
There is considerable agreement that there are definite health impacts associated with nuclear power, such as carcinogenesis, but there are still many uncertainties, such as the biological distributions and biochemical transfers of radionuclides, the impact of low doses to large populations over long periods of time, and how to appraise the risks associated with low-probability, high-consequence disasters (Baxter 1991, Brender et al 2011, Dockerty et al 2014, Mobbs et al 2011, Smith et al 2013, Stamford and Azapagic 2012, CEPN 1995). Additionally, there has been a lack of preparedness to deal with nuclear accidents, e.g. Chernobyl, and therefore there is a need for an adequate monitoring system with which to deal with any future fallout episode (Baxter 1991, p.33).

Biodiversity
Only Dockerty et al (2014) considers the impacts of nuclear power generation on biodiversity. They argue that there are negative impacts associated with decreased biodiversity in particular marine organisms.
Appendix 5.11 Offshore Wind

Our literature search identified 7 relevant reviews on the environmental, social and economic impacts of Offshore Wind Farms (OWFs). Identified papers focused on the impacts on biodiversity as well as economic and social impacts.

**Marine Environment**
No review was identified addressing the impacts of Offshore Wind on the marine environment. Impacts on habitat provision have been incorporated as part of impacts on biodiversity.

**Water**
No review was identified addressing the impacts of Offshore Wind on Water.

**Land**
No review was identified addressing the impacts of Offshore Wind on Land.

**Air Quality**
No review was identified addressing the impacts of Offshore Wind on Air Quality.

**Social Impacts**
Public acceptability has received considerable attention among the social impacts of OWFs. Willingness to pay (WTP) has generally been used to measure the extent to which OWFs visually impair the landscape and affect recreational choices; in technical terms the extent to which they are a visual externality or disamenity. OWFs being perceived as visual externalities or disamenities and related public acceptability are influenced by a number of variables, including:

- **Age**: the younger the respondents, the weaker the perception of OWFs being a visual disamenity;
- **Income**: the higher the income, the higher the WTP to reduce OWFs’ visual disamenity;
- **Education**: the higher the level of education, the lower the WTP for siting OWFs further offshore;
- **Existing pattern of beach use**: Preferences for reducing visual disamenities from OWFs are found to be stronger among beach users;
- **Knowledge and familiarity with OWFs**: This can influence public acceptability both positively and negatively although there is no consensus at this stage;
- **Distance from the coast**: OWFs located at larger distances from the shore are preferred to wind farms located nearer to the coast;
- **Proximity to the site**: Preferences for reducing the visual disamenities are found to be stronger among people living close to the area chosen for development.

It can be concluded that the general public hold significant preferences for reducing the visual disamenities from offshore wind farms, although considerable variation has been observed. However, several authors report that considerable shares of the respondents do not hold significant preferences for reducing the visual impacts from offshore wind farms at all. Existing research indicate a diminishing marginal demand for disamenity reductions. The demand for moving an offshore wind farm an additional km further away from the coast is higher for wind farms at near shore location when compared to locations further offshore.

**Research gaps** pointed out by the review we assessed include:

- Impact of familiarity with OWFs on perceptions of OWFs visually damaging the landscape;
- Existence of a generational difference in relation to the perception of OWFs visually damaging the landscape;
SPLICE Phase 1

Significant evidence gaps on the environmental, social and economic impacts of energy system components.

- Spatial- and experienced-based drivers in public acceptability of OWFs and the perception of OWFs visually damaging the landscape;
- Cumulative impacts of OWFs on public acceptability;

Economic Impacts
Economic impacts of OWFs assessed in the literature are mainly related to fisheries and the recreational value of the shoreline. The establishment of OWFs reduces the amount of fishing grounds by preventing access to areas containing and surrounding OWFs. Larger installations with multiple devices tend to be enclosed within enforced exclusion zones for both safety and protection of the installations and may act as Marine Protected Areas (MPA) to most fisheries (Inger et al. 2009). These closed areas and related loss of fishing ground is a prime concern to the fishing sector, which can be mitigated by involving fishermen as key stakeholders from the earliest consultation stages (Inger et al. 2009). OWFs have also potential impacts through displacement of fishing effort into the remaining open fishing areas. A trade-off may exist between the negative impacts of OWFs on open areas (through increased fishing effort and therefore lower fish stocks) and the recovery of stocks in closed areas (Inger et al. 2009, Mangi 2013). In some other cases, however, no significant changes in fish species have been observed after the establishment of OWFs measured by catches of commercial fish in areas adjacent to OWFs. Catches decreased during initial construction, but recovered some time afterward (Mangi 2013). In terms of recreational activities, it has been found that OWFs less than 5 km from the coast have a negative impact on the propensity to spend leisure time at the specific beach/city, while OWFs located at larger distance have a mixed impact on recreational behaviour (Ladenburg and Lutzeyer 2012). One can conclude that in areas with fewer recreational activities, the optimal location of offshore wind farms may be closer to the coast than in areas where a higher demand and supply of recreational activities is observed. It is important to stress that distance from the coast has an important impact on the cost of OWFs. Near or medium-range distances seem to be the optimal location from a visual disamenity point of view. Investment costs such as foundation, installation and grid costs of offshore wind farms increase linearly as distance from the shore increases and exponentially as water depths increase (EEA 2009). As further distances from the shore are often associated with increased water depths, costs can increase substantially. Although OWFs further off the coast are associated with a lower level of visual disamenity and impacts on birds, it is important to notice that this is far from being costless. If those concerns are addressed by increasing costs there are trade-offs associated with taking these concerns into account (Ladenburg and Lutzeyer 2012).

Research gaps pointed out by the review we assessed include:
- Factors affecting the negative impacts of OWFs on catches in fishing grounds remaining open;
- Drivers of the positive impacts of OWFs on the fish population related to the closed areas acting like marine-protected areas;
- Factors affecting the existence of a trade-off between negative and positive impacts of OWFs on catches of commercial fish;
- Holistic assessment of the factors affecting the optimal distance of OWFs from the shore;
- Factors influencing the extent to which OWFs impact recreational activities on the shore and the sea

Human Health
No review was identified addressing the impacts of Offshore Wind Farms on Human Health.

Biodiversity
Evaluation of impacts on biodiversity is complicated by the need to have sufficient baseline data and trends within the area of potential effects (Bailey et al. 2014) as well as suitable control areas. This is particularly challenging for the marine environment due to the general
paucity of data, relative to land-based habitats, the distance travelled by sound under water and the high mobility of many marine species, with the last two factors significantly extending the area of potential effect beyond the immediate vicinity of the proposed development (Bailey et al 2014). It is well established that there are positive as well as negative impacts of OWFs on biodiversity (Bailey et al 2014, Inger et al 2009 and Premalatha et al 2014). Potential "win-wins" should be evaluated alongside options for minimising environmental impact (Inger et al 2009).

Habitat Provision
Among the impact of OWFs on the marine environment, habitat provision has received considerable attention. Habitat loss due to offshore wind farms is unlikely to be significant (Inger et al 2009). In fact, there is considerable consensus that the presence of artificial reefs created by OWFs facilitates new habitat, and have consistently been demonstrated to increase both the density and biomass of fish (Inger et al 2009, Mangi 2013 and Premalatha et al 2014). Artificial reefs may however promote the establishment and spread of non-native species. In fact, species composition of artificial reefs may not be the same as natural reefs, and their presence may also influence the biodiversity of surrounding areas. It remains unclear whether the artificial reefs facilitate an increase in the absolute levels of the population or whether the effects are simply a result of concentrating biomass from surrounding areas (Inger et al 2009). Electromagnetic fields (EMFs) are another impact of OWFs on the marine environment, specifically caused by the intensive network of electrical cables to transfer power between devices, to transformers and to the mainland. The resulting electromagnetic fields (EMFs) have the potential to affect magneto-sensitive species such as bony fish, marine mammals and sea turtles, as well as animals using geomagnetic cues during migration (Inger et al 2009; Premalatha et al 2014).

Birds
For birds, the operational phase of wind farms presents the biggest risk due to collisions with pylons, or pylons acting as barriers to avoid (Bailey et al 2014, Mangi 2013). The potential impacts of collisions with wind farms on birds are still a contentious issue, and a number of factors remain unclear. Importantly, OWFs carrying navigation lights have the potential to attract seabirds (Inger et al 2009). It is also becoming evident that OWFs may not have such a detrimental effect on avian populations as earlier studies suggested (Inger et al 2009). Bird mortality caused by OWFs is relatively low, although some have been associated with the deaths of many birds (Dockerty et al 2014, Mangi 2013), but as the scale of wind energy expands, there is the potential for significant impacts (Premalatha et al 2014). OWFs have been found to have a negative impact on local bird population (Inger et al 2009, Premalatha et al 2014), which may be attributed to avoidance rather than the direct effect of collisions (Inger et al 2009). Vulnerability and mortality have been identified as being related to a combination of site-specific, species-specific and seasonal factors11 (Bailey et al 2014, Premalatha et al 2014). Collision risk models rely heavily on expert-based estimates and there is even less information on avoidance responses to large OWFs by birds, although some studies documented a substantial response by migrating birds, which reduced the collision risk (Bailey et al 2014). Initial findings demonstrate that non-lethal effects of wind farms, such as disturbance or reduction in habitat quality have minimal impacts (Inger et al 2009). Wind farms constructed further offshore could reduce the collision risk significantly but less is known about the distribution and habitat use of seabirds in those areas (Bailey et al 2014).

Noise
The impact of anthropogenic underwater noise and vibrations on marine life is a growing concern, with an increasing body of evidence demonstrating its adverse effect over a range of taxa, particularly acoustically sensitive species such as marine mammals which have very

---

11 A large number of factors can heighten collision risk of birds at OWFs, including characteristics of turbines and geometry of arrays formed by the turbines, weather conditions, topography, bird species, and numbers of birds using the site. Species-specific risks are a function of flight altitude, flight manoeuvrability, percentage of time spent in flying, nocturnal behaviour, and habitat specialisation (Premalatha et al 2014).
sensitive hearing (Dockerty et al 2014, Inger et al 2009, Mangi 2013, Mann and Teilmann 2013). Disturbance is most severe during construction when audio receptors of sensitive species can be damaged by loud noises involved in the construction (Dockerty et al 2014). Noise during the operational phase is likely to be less intrusive (Inger et al 2009, Mann and Teilmann 2013, Premalatha et al 2014) although it might mask communication and orientation signals among fish (Premalatha et al 2014). Wind turbines produce infrasound that are below the audible range of humans but are potent enough to cause houses and other nearby structures to vibrate. It is likely that vibrations caused by OWF may mislead some of the marine species and may mask vibration-related cues (Premalatha et al 2014).

**Research gaps** pointed out by the review we assessed include:

- Noise exposure criteria for behavioural responses of marine mammals to construction noise;
- Chronic long-term cumulative effects of noise;
- Effects of noise on species other than fish and mammals (e.g. turtles);
- Assessment as to whether effects on individuals, at specific sites, are strong enough to have consequences for the population and produce population level effects;
- Consequences of behavioural responses of affected species on vital rates;
- Behavioural mechanisms and cues used by birds to detect and avoid wind farms;
- Collision risks to mobile marine animals, especially underwater collision risk related to free-moving components such as chains;
- Interactions between ecosystem services and organisms in the ecosystem, and impacts of OWFs on the ecological functions provided by ecosystems;
- Multi and inter-disciplinary biodiversity orientated research ranging from engineering to policy;
- Empirical data on flight heights for different seabird species which can be used in collision risk models, as currently they heavily rely on expert-based estimates;
- Cumulative impacts both across time and arising from the introduction of increasing number of OWFs on wider marine ecosystems rather than focusing on the effects of individual installations;
- Impacts of OWFs moving further offshore on collision risk of birds, as less is known about the distribution and habitat use of seabirds further offshore;
- Interactions between individual species, e.g., birds, fish, and mammals, affected by specific OWF processes such as noise, and other organisms in the ecosystem;
- Implications of disturbance and reduction in habitat quality;
- Behavioural responses to electromagnetic fields effects;
- Impacts of artificial reefs on the composition of species the ecosystem;
- Impacts of artificial reefs on concentration of affected population versus overall positive impact on biomass;
- Establishment of data collection over large spatial areas and long temporal scales critical for supporting decision-making.
Appendix 5.12 Onshore wind

Terrestrial wind energy is a mature renewable technology. Historically it has been viewed as a benign, clean, ‘green’ energy source and, as the UK has better wind resource opportunities than many European states, the Government expects it to grow to help meet its renewable energy obligations. However, there has been increasing resistance to onshore wind development, questioning the economics, environmental impacts and capacity to deliver (intermittency). Considerable research has been carried out on these issues and 8 documents were identified to provide reviews. Impacts can be high, but tend to be very local in their effects; assessment of cumulative impacts is recognised as important.

Marine Environment

No review was identified addressing the impacts of onshore wind on the marine environment. Offshore wind (reported separately) would be expected to have a far more significant interaction.

Water

In general, water is not considered to be impacted by the operation of terrestrial wind farms, although Saidur et al (2011) consider the impact to be large and positive if wind replaces high resource demand of traditional power generation. Where turbines are erected on peat bogs there may be impacts on hydrology that could destabilise the ecosystem (Tosh et al 2014). Impacts on water are included in life cycle assessments (Averson and Hertwich, 2012) but are not considered a major impact route; where they occur they may be predominantly overseas in manufacture (Dockerty et al 2014).

Land

Wind farms do not exclude other land uses or necessarily change the form of use that the land previously had. However, they may alter the former land management intensity and may impact surrounding habitats (especially woodland and blanket bog). Dockerty et al (2014) examined the role of land in supplying ecosystem services, and the greatest effects were on cultural services with spiritual and aesthetic services showing moderately negative impacts. However, visual intrusion is dependent on specific location and individual perspective, it is commonly stated that the effect can be mitigated through careful planning. Cumulative impacts of multiple developments and in context of other land management need further investigation (Scottish Natural Heritage, 2012).

Air Quality

Impacts on air quality and atmospheric emissions are only reported during the manufacture and decommissioning phases (Dockerty et al 2014). Where these are taken into account they are comparable with normal manufacturing processes (Averson and Hertwich, 2012). A form of economic discounting to assess the costs and benefits of the whole life cycle is needed so comparisons with other alternative sources can be made.

Social Impacts

In the papers reviewed there was very limited reference to social impacts, although public acceptability and planning is a major barrier to deployment in the UK. The reviews covered predominantly wind farm development in rural settings with no mention of micro generation in urban areas. As mentioned above under Land, impacts on cultural services show mixed responses, but are predominantly negative (Dockerty et al 2014). Impacts can be high but are very localised as in the case of the single turbine at Ore Brae on Orkney; here depopulation and ageing are being counteracted by a Community Development Trust that operates the turbine under Community Ownership (Biggar Economics, 2012).
Economic Impacts
Only one of the papers (Biggar Economics, 2012) talks about economic impacts (revenue, jobs, etc.) at different scales (from local to national). Local community effects can be very large, but in terms of UK the impact appears relatively small.

Human Health
Once operational, the impacts are noise/vibration and stress from change (Leung and Yang, 2012), although other issues including potential accidents (e.g. from supporting activities and 'blade throw; were not mentioned). These are all low intensity. From full life cycle analyses other impacts have been identified (Averson and Hertwich 2012), but these relate to toxicity and emissions during manufacture and decommissioning; in terms of impacts these seem low, but more research is required.

Biodiversity
This is considered the major topic of risk. Traditionally, bird strikes were highlighted as the key impact with the focus on specific species (usually soaring raptors); there are different methods of assessing the number of strikes and their influence on populations (e.g. Drewitt and Langston, 2006). More recently in the USA and Europe work has been carried out on bats where impacts on woodland species are detectable, but there is little research on other orders or taxa, communities or habitats (Tosh et al, 2014). Four impact pathways that are consistently described are (Drewitt and Langston, 2006):

1. Collision
Direct mortality from birds hitting not only blades, but also parts of the structure and supporting guys. Recorded numbers are low, but not usually effectively counted (i.e. a simple body count not corrected for removal by scavengers) and key species suffer inordinately.

2. Displacement
Displacement occurs to different extents all through the life cycle of a turbine and wind farm; it infers relocation of activities to new or different locations. There have been very few studies due to lack of before-after and control-impact (BACI) assessments. Although effects have been demonstrated, their impact is not clear (Drewitt and Langston, 2006).  

3. Barrier effect
Barrier effects are similar to displacement, but relates to migration and local flight paths. The effect depends on species, type of movement, flight height, closeness to flight path, layout, conditions at time of passage, etc. As with Displacement, the effects have been demonstrated but are largely inconclusive. In both cases cumulative impacts of multiple developments need to be considered (Scottish Natural Heritage, 2012)

4. Habitat change
Habitat change due to the small footprint per turbine base is expected to be as low as 2% (Fox et al 2006). However, changes due to modified management can create considerable impacts. For example, the creation of new habitat for pocket gophers in California increased the prey availability, attracted raptors and raised the collision risk (Thelander et al 2003).
Appendix 5.13 Power Networks

Our search returned no reviews covering the environmental, social and economic impacts of power networks - including electricity interconnections (IC), transmission and distribution (T&D). The discussion below is based on Ricardo-AEA (2014) and a summary document from the UN, both referring to the impacts we focus on in our study.

Marine Environment
No review was identified addressed the impact of electricity IC, T&D on the marine environment.

Water
Construction and operation of IC and T&D networks, both on and offshore, has limited impact on quality and medium impact on availability of water (Ricardo-AEA, 2014). These includes low impacts on point source and diffuse pollution, groundwater and marine pollution. Medium impacts on surface water flows and availability, and groundwater abstraction and recharge are expected. There is a higher risk of pollution during the construction phase, due to soil erosion, machine contamination, and possible herbicide use (UN, 2006).

Research gap identified:
- Poor understanding of the impact of network construction and operation on ground water contamination, point source pollution and flood risk.

Land
Main impacts include LUC during onshore T&D and IC construction phase, due to conversion of forest or pasture land (Ricardo-AEA 2014, UN 2006). Marine IC has a low impact, generally. Further, all forms of network construction have low indirect LUC impacts. Soil condition and quality may be affected by erosion, contamination and sealing, which have medium impact (UN 2006). Visual intrusion is also a consideration, but low impact (UN 2006).

Research gap identified:
- Poor understanding of impact of network construction and operation on soil erosion and indirect LUC

Air Quality
Possible release of NO\textsubscript{x} and SO\textsubscript{x} and PM during the construction of networks, but with a relatively low impact (Ricardo-AEA, 2014). Indirect effects of networks on power generation may be more important, via displacement of network stations with which may be more or less polluting (UN 2006).

No research gaps were identified.

Social Impacts
The main concern is public acceptability due to visual pollution of network infrastructure. However, the intensity of this impact is low (Ricardo-AEA 2014).

No research gaps were identified.

Economic Impacts
No mention of economic impacts of power networks and interconnection, including smart grids, since reviews concentrated on environmental impacts.

No research gaps were identified. However, in the Author’s opinion, economic and market issues are the most significant impact of these networks (relative to environmental impacts), and include impacts on electricity prices and the security of energy supply.
Human Health
The main health concern is the effect of exposure to electromagnetic fields (UN 2006). There is little consensus in the literature as to the actual impact of these.

**Research gap** identified:
- The lack of a compelling model of the physiological mechanisms by which EMFs might produce health effects.

Biodiversity
Main biodiversity impacts of networks occur onshore, when land is converted for infrastructure construction on land with natural and semi-natural vegetation. Biodiversity impacts include disturbance, fragmentation and connectivity (Ricardo-AEA 2014). Due to a relatively small infrastructural footprint however, these impacts are not significant.

**Research gap** identified:
- Release of chemicals during construction and operation of networks, with effects on biodiversity through acidification, eutrophication and toxic pollution.
Appendix 5.14 Unconventional Gas

Unconventional gas is not currently exploited widely around the world, although a number of countries are actively investigating its extraction. Consequently, the reviews available tend to focus on specific issues and in relatively few locations, almost exclusively in the USA. Eleven reviews were identified and selected, focused predominantly on impacts on hydrology and atmospheric emissions. In places the impacts were large, but operated across a range of scales from local to regional. Specific social, environmental and economic impacts were described in detail in the reviews, but these were sometimes accompanied by descriptions of pressures with inferred impacts, rather than observations, especially in their interaction with the environment or human health. The reviews described the environmental pressures created by unconventional gas extraction (i.e. the chemicals released and their potential toxicity), but as the technology is relatively new, there is little evidence of the full range of possible effects. The interviewed expert pointed out that there are potential impacts not mentioned in the reviews such as the long-term impact on geology of the effects of fracking fluids and gas extraction.

Marine Environment

Hydraulic fracturing under the ocean was not covered by any of the reviews. However, Jackson et al (2013) cite studies in the Gulf of Mexico where traditional tight gas and oil extraction, using similar techniques, can provide information on the effectiveness of capping and the expected rate of failure of concrete casing allowing gas leaks. The interviewed expert pointed out that the UK has considerable experience with exploration in the North Sea.

Water

Water plays a fundamental role in hydraulic fracturing; it is needed in high volumes, is mixed with a variety of chemicals, injected into the well as frack fluid and comes out as flowback, carrying chemicals, their breakdown products and petrochemical compounds. The progression of water through a fracking cycle can be shown to have 5 compartments (acquisition, chemical mixing, well injection, flowback & produced water and wastewater treatment). From the reviews used in the assessment, water is the most important receptor of impacts. Only one of the reviews does not describe impacts on the water system whilst in over half (6) impacts on water was their main topic. The reviews cover a range of spatial scales up to regional (Vidic et al 2013) and national levels (Vengosh et al 2014). Four main areas of risk can be highlighted from the reviews (see for example Vengosh et al 2014):

1. Contamination of shallow aquifers with fugitive hydrocarbon gases

The reviews reported risks to groundwater in the USA where they have generated more debate and opposition than any other topic (Rahm and Riha, 2014). Impacts are generated through the interactions between injected water and gases within the geological formations, i.e. during the well injection and flowback processes. The aquifer system and its constituent processes are poorly understood and the consequences of hydraulic fracturing are perceived as potentially catastrophic by the public (Rahm and Riha, 2014). Methane in drinking water is not a toxic health hazard, but is potentially explosive if trapped gas is combined with oxygen (air) and a spark. In the USA there is no authoritative baseline data describing the distribution of contamination without hydraulic fracturing, nor is there a consistent national system for monitoring the impacts of hydraulic fracturing. The interviewed expert pointed out that for the UK, there is a well-established baseline describing methane in groundwater created and managed by the British Geological Survey (BGS). In the Marcellus region in northeast USA (the largest shale gas basin currently exploited) methane is naturally present in groundwater, sometimes at high levels. There is no conclusive evidence that hydraulic fracturing is the sole or dominant cause of contamination of shallow aquifers with hydrocarbon gas, with contradictory studies showing only some or no relationship between water quality and distance from wells (see Rahm and Riha, 2014), but it is widely agreed

http://www2.epa.gov/hfstudy/hydraulic-fracturing-water-cycle
that, in combination with other developments (e.g. urban expansion), aquifers will become increasingly stressed (Fontenot et al., 2013).

2. Contamination of surface water and the disposal of wastewater

Information predominantly from the USA has identified a selection from 81 chemicals that are known to be routinely added during hydraulic fracturing (for gelling, foaming, lubricating, crosslinking, breaking, pH adjusting, acting as biocide, inhibiting corrosion, stabilising clay and controlling iron) (Stringfellow et al., 2014). These chemicals return to the surface, sometimes in modified or degraded forms, along with contaminants that occur naturally in the drilled strata. In the USA artificial additives are recorded in a register and databases (e.g. Globally Harmonised System of Classification and Labelling of Chemicals and Frack Focus (http://fracfocus.org/)) that present chemical and physical characteristics. However, there is no standard approach. In some US states the individual companies or sites do not have to inform the regulatory authority which chemicals are being used whilst, as pointed out by the interviewed expert, in others there is a legal requirement for full disclosure. Some companies voluntarily offer information to databases but others may see the combinations to be commercially confidential. In general the chemicals appear to non-toxic, with only two classified as Category 2 oral toxins (Stringfellow et al 2014), but 37% of the chemicals have no toxicity information. New chemicals are being developed for use (e.g. biocides). Biocides are needed for bacterial control, as they are required to function for the duration of the process. Most are non-oxidising and divided into lytic and electrophilic biocides. They are eye and skin irritants to mammals but acutely toxic to aquatic life (Kahrilas at al 2015).

3. Accumulation of toxic and radioactive elements in soil or sediments

The build-up of toxic material (metals, salts and organics) over time will accumulate in soil, stream and pond sediments. The materials have to be considered as additions to those that are already present in the environment (i.e. background concentrations such as the naturally occurring radionuclides (NORM)) and form an important issue. In the US, one brine-treatment discharge site exceeded the radioactive discharge limits for licensed waste disposal facilities (Warner et al., 2013). To understand the legacy and long-term environmental and health impacts will require more studies across broader geographic areas. Focus is needed on the mechanisms of release of accumulated material and their interaction with the environment (Vengosh et al 2014).

4. Over-extraction of water

In the USA shale related water use is small compared to agricultural irrigation and cooling in electricity generation (Rahm and Riha, 2014). However, the condition of the flowback and produced water means it has to be isolated and is usually disposed of by re-injection into geological formations above and below the shale. As a consequence the water tables and aquifers of regions with hydraulic fracting are stressed. Water recycling is attempted, but often only at low levels (~5%).

Land

The impact of hydraulic fracturing on land and its use was not covered directly by any of the reviews. Dockerty et al (2014) draw a comparison with carbon capture and storage.

Air Quality

The impact of unconventional natural gas on air quality has been examined at local, regional and national levels ((Moore et al 2014)). Releases can occur through all phases of exploitation (pre-production, production, storage & distribution, use and well decommissioning). Emissions are classified as greenhouse gases (GHG), ozone precursors, hazardous air pollutants (HAPS) and particulates (Field et al 2014). Recent studies have suggested that methane emissions are underestimated by about 50% (Moore et al 2014); the uncertainties and consequences for climate change need further study. For air quality, BTEX (benzene, toluene, ethyl benzene and xylenes) are the most common in preproduction and production although other VOCs (volatile organic compounds) are also released. Their impacts on human health are well documented for individuals, but not at
population levels (Field et al 2014); they contribute to neurological conditions and respiratory ailments, but their potential to induce cancer (especially benzene) is recognised but has not been demonstrated as linked to hydraulic fracturing. Although other atmospheric pollutants are generated (NOx, particulates, black carbon, mercury, etc.) these are deemed to be less than the equivalent emissions from coal fired power generation. Silica, used as a proppant, has been recorded to be present at high levels close to sites in initial phases; this causes lung damage (Moore et al 2014).

**Social Impacts**
No review was focussed solely on how unconventional gas creates social impacts. Comparison with studies of boomtown growth and collapse has been made for other drivers (e.g. gas) with overlap in health and economics (Adgate et al 2014).

**Economic Impacts**
No review was identified solely addressing the impacts of unconventional gas on economics. A number of metrics have been identified ranging from house prices to valuing ecosystem services, but their impact is considered mainly through health (Adgate et al 2014).

**Human Health**
Health impacts are considered through hazards, their magnitude and pathways to exposure. Occupational risks (accidents and exposures), locational exposures and population impacts are all recognised, although the latter is not well understood.

**Biodiversity**
No review was identified addressing the impacts of unconventional gas on biodiversity.
## Appendix 6 - Detailed results from the prioritisation procedure

**Figure A6.1** Assessment of Aviation based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
<th>Air, Human Health &amp; Social</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure A6.2 Assessment of impacts of Carbon Capture and Storage based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>CONFIDENCE</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTENSITY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Marine Environment, Biodiversity &amp; Economic Storage</td>
<td></td>
<td>Social Impacts</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>Water – Separation Land - Storage</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Land &amp; Health – Separation</td>
<td>Water – Storage Air &amp; Economic – Separation Health – Transport</td>
<td></td>
</tr>
</tbody>
</table>
**Figure A6.3** Assessment of Demand Side Responses based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td><strong>Economics</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Social</strong></td>
</tr>
<tr>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Figure A6.4 Assessment of impacts of Electric Vehicles based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Air, Human Health &amp; Economic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Social</td>
<td></td>
<td>Water &amp; Land</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure A6.5** Assessment of Electricity Storage (Batteries and Compressed Air Energy Storage – CAES) based on evidence discussed in identified studies

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low, Medium, High</td>
</tr>
<tr>
<td>Medium</td>
<td>Economic &amp; social</td>
</tr>
<tr>
<td>Low</td>
<td>Environmental impact (batteries)</td>
</tr>
</tbody>
</table>
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

**Figure A6.6 Assessment of impacts of Insulation and Buildings** based on evidence discussed in identified studies

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td>Social &amp; water – buildings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Health &amp; social – insulation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure A6.7** Assessment of impacts of Land for Bioenergy based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Low Indirect Land</td>
</tr>
<tr>
<td></td>
<td>Medium Social &amp; Economic</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
</tbody>
</table>
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

Figure A6.8 Assessment of impacts of Nuclear Power based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

- **Human Health Land**
- **Water Social Economic**
- **Marine Environment and Biodiversity**
Figure A6.9 Assessment of impacts of Offshore Wind based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Biodiversity</td>
</tr>
<tr>
<td>Medium</td>
<td>Social</td>
</tr>
<tr>
<td>High</td>
<td>Economic</td>
</tr>
</tbody>
</table>

Confidence levels: Low, Medium, High.
Figure A6.10 Assessment of impacts of Onshore Wind based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
<td>Social</td>
</tr>
<tr>
<td>Low</td>
<td>Land</td>
</tr>
</tbody>
</table>
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

**Figure A6.11** Assessment of impacts of Power networks based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>Human Health</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td>Biodiversity</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Land &amp; Water</td>
<td>Air</td>
<td>Social</td>
</tr>
</tbody>
</table>
Figure A6.12 Assessment of impacts of Unconventional Gas based on evidence discussed in identified reviews

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>CONFIDENCE</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Social</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Human Health</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Economic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>Marine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biodiversity</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 7 - Exemplary Research Gaps for a Prioritised selection of Energy System Components and Impact Areas

Table 14 Ranking of energy system components according to the Urgency and Criticality criteria and the composed ranking

<table>
<thead>
<tr>
<th>RANKING</th>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CCS - Storage</td>
<td>Long-term Safety</td>
<td>Systematic assessment of factors affecting the variability of estimates found in the literature</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Developing appropriate, credible and long term mechanisms to deal with risks and their associated liabilities</td>
</tr>
<tr>
<td>2</td>
<td>DSR</td>
<td>Energy Consumption</td>
<td>Evidence on the way consumers implement DSR including identifying shifted loads and intensity of price responses</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Persistence of energy reductions from DSR for different types of DSR measures</td>
</tr>
<tr>
<td>3</td>
<td>Nuclear Power</td>
<td>Human Health</td>
<td>Uncertainty related to biological distributions and biochemical transfers of radionuclides, including impact of low doses to large populations over long periods of time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Uncertainties related to risk appraisal and management of low-probability, high consequence events</td>
</tr>
<tr>
<td>3</td>
<td>Nuclear Power</td>
<td>Land</td>
<td>Impacts arising from release of radionuclides into the environment and those associated with mining and processing of nuclear fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Safe disposal of nuclear waste and in a publically acceptable and economically sustainable way</td>
</tr>
<tr>
<td>4</td>
<td>CCS - Storage</td>
<td>Marine environment and biodiversity</td>
<td>Robust assessment of impacts of CO₂ leakages in sub-seabed storage, focused on UK-based experience. Topics may include: impacts on chemistry in the sediment water, dissolved metal concentrations and local biogeochemical cycles; secondary geochemical effects; factors affecting the variability in species responses; impacts of organism-level responses on the community and ecosystem response</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Uncertainty of economic impacts of Enhanced Oil Recovery (EOR) in depleted fields in the North Sea</td>
</tr>
<tr>
<td>4</td>
<td>CCS - Storage</td>
<td>Economic</td>
<td>Systematic assessment of factors influencing the quantification of benefits of EOR in the UK</td>
</tr>
</tbody>
</table>
Significant evidence gaps on the environmental, social and economic impacts of energy system components.

<table>
<thead>
<tr>
<th>RANKING</th>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Land for Bioenergy</td>
<td>Land (Indirect)</td>
<td>Integrated modelling for studying environmental (GHG, biodiversity, water management), economic and social impacts of indirect land use change. Applies to direct and indirect, environmental, social and economic. For example, impacts of large scale 2nd generation bioenergy demand in USA/EU and in the Global South. Integrated approaches would be substantially beneficial.</td>
</tr>
<tr>
<td>5</td>
<td>Land for Bioenergy</td>
<td>non-UK impacts</td>
<td>Implications of the social impacts (allocation of net benefits across different types of customers) of DSR on other policy targets, e.g. fuel poverty – through RAE or expert paper. Long term (longitudinal) analysis customer engagement in DSR, including ‘learning curve’ experienced by customers. Estimates of net benefits at system level of DSR measures, including critical assessment of factors influencing the variability of the estimates – through RAE or expert scoping paper.</td>
</tr>
<tr>
<td>6</td>
<td>DSR</td>
<td>Social Review</td>
<td>Air impacts depending on EV uptake, future electricity mixes and vehicle performance and development from both car passengers and other vehicles, e.g. buses and road freight. Human health impacts related to air quality improvements. Impacts of adoption of EVs in terms of value (and related employment) of UK industry in a global market - through REA or expert scoping paper.</td>
</tr>
<tr>
<td>7</td>
<td>Electric Vehicles</td>
<td>Air</td>
<td>Life cycle comparison of the environmental impacts of using biomass in the chemical sector as a fuel or as a feedstock. Assessment of impacts and development of guidelines for use of real-time monitoring to tailor wind farm operational management to bird flight behaviour. Displacement and barrier effect of onshore wind on animal activities, including migration and local flight paths. Analysis of factors inflecting the intensity of impacts such as species, type of movement, flight height, closeness to flight path, layout of the farm and conditions at time of passage.</td>
</tr>
<tr>
<td>8</td>
<td>Energy Intensity of Industry (EII)</td>
<td>Biomass</td>
<td>Extent (likelihood of occurrence and quantity) of accidental venting of methane to the atmosphere, including strategies to manage this matter. Mechanisms of fugitive emissions release and their pathways, for example how gas leaks out of a hole in a casing.</td>
</tr>
<tr>
<td>9</td>
<td>Onshore Wind</td>
<td>Biodiversity</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Unconventional Gas</td>
<td>Air (Fugitive Emissions)</td>
<td></td>
</tr>
</tbody>
</table>
### Significant evidence gaps on the environmental, social and economic impacts of energy system components.

#### Exemplary Research Gap Based on Analysis of Published Literature Reviews

<table>
<thead>
<tr>
<th>RANKING</th>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>REVIEW</th>
<th>EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Power Network</td>
<td>Economic</td>
<td>Review</td>
<td>Impact of power networks on diffusion of renewable electricity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Review</td>
<td>Impact of cross-border connections on the economy e.g. electricity price and system stability</td>
</tr>
<tr>
<td>12</td>
<td>Aviation</td>
<td>Economic</td>
<td>Review</td>
<td>Impacts of aviation on local, regional and national economies</td>
</tr>
<tr>
<td>13</td>
<td>Land for Bioenergy</td>
<td>Land (Direct)</td>
<td>Review</td>
<td>Methodologies to increase transparency of Land Use Change modelling efforts, including lifetime-end land use reversion and large scale production (and use) impacts</td>
</tr>
<tr>
<td></td>
<td>Land for Bioenergy</td>
<td>Biodiversity</td>
<td></td>
<td>Addressing complexities and interlinkages between land use change, and water, nutrient and carbon cycle</td>
</tr>
<tr>
<td></td>
<td>Land for Bioenergy</td>
<td>Water</td>
<td></td>
<td>Site-specific and species-specific factors influencing impacts on biodiversity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Impact of large scale bioenergy production, intensification of production, and use of marginal land</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Management requirements in areas with limited supply to avoid risk of water availability</td>
</tr>
<tr>
<td></td>
<td>Land for Bioenergy</td>
<td>Environmental Impacts</td>
<td>Review</td>
<td>Relative importance of factors affecting water quality including crop type and management and usage of fertiliser and pesticide</td>
</tr>
<tr>
<td>14</td>
<td>Buildings</td>
<td>Environmental Impacts</td>
<td></td>
<td>Extent to which environmental impacts from LCA studies of buildings can be reliably generalised and compared - through a REA or expert scoping paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More empirical data on building performance so that comparison can be robustly implemented</td>
</tr>
<tr>
<td>15</td>
<td>Energy Intensity of Industry (EII)</td>
<td>Waste</td>
<td></td>
<td>Assessment of potential conflicts between strategies aimed at reducing waste and security of supply to plants using it as feedstock</td>
</tr>
<tr>
<td></td>
<td>Unconventional Gas</td>
<td>Water</td>
<td></td>
<td>Comparison of the environmental impacts of using wastes as feedstock either through life cycle analysis or a review of existing studies</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Structure and dynamics of near-surface groundwater system, including how different formations, geology and locations respond to specific interventions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Properties of chemical additives and related by-products, as well as their fate and pathways in the field. This includes better understanding of the relationship between chemicals and different stakeholders (operators, residents, etc.)</td>
</tr>
<tr>
<td>16</td>
<td>Unconventional Gas</td>
<td>Land (Seismic Activity)</td>
<td></td>
<td>Better understanding of existing stress in rock before fracking and impact on likelihood and size of seismicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Impact of fracking operation parameters (especially frack pressure) on seismicity</td>
</tr>
</tbody>
</table>

Ref: Ricardo-AEA/ED59332/OP1/Issue Number V1.1
<table>
<thead>
<tr>
<th>RANKING</th>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Power network</td>
<td>Human Health</td>
<td>Review</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exposure to electromagnetic fields – through REA or expert scoping paper</td>
</tr>
<tr>
<td>18</td>
<td>Offshore Wind</td>
<td>Biodiversity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impacts on seabirds and noise-sensitive marine mammals including consequences that site-specific, species-specific and seasonal factors may have on the population of affected species and services provided by the ecosystems</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Uncertainty related to the total effects of artificial reefs, including impact on fish density and biomass</td>
</tr>
<tr>
<td>19</td>
<td>Nuclear Power</td>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Robust estimates of costs of radioactive waste storage and decommissioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Social</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Factors affecting public acceptability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water consumption for mining and processing nuclear fuel</td>
</tr>
<tr>
<td>20</td>
<td>CCS - Storage</td>
<td>Social</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Factors influencing the success of specific projects and how they can be mitigated</td>
</tr>
<tr>
<td>21</td>
<td>Aviation</td>
<td>Air</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Robust quantification of impacts of airports to local air pollutants, in particular Particulate Matters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Assessment as to whether PM emitted by aircraft in flight can be treated and modelled differently from those emitted at ground level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Human Health</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Generally accepted dose-response functions between pollutants and health impacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Social</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Any potential relationship between aircraft noise and learning disruptions, mental health and hormone changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Factors affecting public acceptability of airports – through REA or expert scoping paper</td>
</tr>
<tr>
<td>22</td>
<td>Land for bioenergy</td>
<td>Economic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impacts of increased use of biomass on specific sectors, e.g. forest based industries such as pulp and paper.</td>
</tr>
</tbody>
</table>
**RANKING** | **ENERGY SYSTEM COMPONENT** | **IMPACT AREA** | **EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS**
---|---|---|---
1 | Pulping and paper | Social | Impact of land for bioenergy on rural communities, e.g. on employment, demographics and welfare
23 | DSR | Air | Air and related human-health impact of DSR as a function of marginal generating technology, level of power demand, ability to shift consumption and sector in which DSR takes place
24 | Electricity Storage | Economic | Factors affecting profitable applications of batteries and compressed air energy storage systems in the UK
24 | Electricity Storage | Social | Factors influencing societal safety concerns around large stores of energy
25 | Electric Vehicles | Social | Allocation of potential benefits from EVs across geographic areas, income brackets, and population groups based on age and gender - through QSR and subsequent modelling
26 | Heat Pumps | Social | Factors influencing public acceptability and adoption of heat pumps - through a REA or expert scoping paper
26 | Heat Pumps | Economic | Employment impacts and industry-wide schemes to ensure rapid uptake of skills required to install and service heat pumps - through a REA or expert scoping paper
27 | Onshore Wind | Social | Factors influencing local opposition to development of wind farms (NIMBYism) and general public acceptability of wind energy
28 | Unconventional Gas | Human Health | Systematic tracking of exposure in conjunction with ancillary stressors (e.g. noise, light, traffic and rapid change) especially at the population scale
28 | Unconventional Gas | Social | Social and economic impacts of unconventional gas in the USA e.g. boomtown growth,
### Exemplary Research Gap Based on Analysis of Published Literature Reviews

<table>
<thead>
<tr>
<th>RANKING</th>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>EXEMPLARY RESEARCH GAP BASED ON ANALYSIS OF PUBLISHED LITERATURE REVIEWS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas</td>
<td></td>
<td>Migration patterns and pressure on public services, and how they could apply to an UK context</td>
</tr>
<tr>
<td></td>
<td>Unconventional Gas</td>
<td>Economy</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Nuclear Power</td>
<td>Marine Environment</td>
<td>Sensitivity of impacts of nuclear plants as a function of changes in storm surge, flooding, tidal ingress and nuclear islanding expected in response to change in the climate</td>
</tr>
<tr>
<td></td>
<td>Nuclear Power</td>
<td>Biodiversity</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Aviation</td>
<td>Land (Impact of Biofuels)</td>
<td>A Life Cycle Assessment (LCA) to identify feedstocks with lowest level of impacts in case deployment targets (e.g. EU Biofuel FlightPath Initiative) are reached or increased</td>
</tr>
<tr>
<td>31</td>
<td>Energy Intensity of Industry (EII)</td>
<td>Environmental impacts of energy efficiency heating options</td>
<td>Review Environmental impacts of options identified in WSP, PB and DNV-GL (2015) as these impacts were out of scope</td>
</tr>
</tbody>
</table>
Appendix 8 - Full Ranking of Energy System Components and Impact Areas Assessed in this Study

<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>PRIORITY SCORE</th>
<th>LIKELIHOOD</th>
<th>COMPOSED SCORE(^\text{13})</th>
<th>FINAL RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS - Storage</td>
<td>Long-term Safety</td>
<td>&gt; High</td>
<td>Very Likely</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>DSR</td>
<td>Energy Consumption</td>
<td>&gt; High</td>
<td>Likely</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>Human Health</td>
<td>High</td>
<td>Very Likely</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>Land</td>
<td>High</td>
<td>Very Likely</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>CCS - Storage</td>
<td>Marine environment and biodiversity</td>
<td>High</td>
<td>Very Likely</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>CCS - Storage</td>
<td>Economic</td>
<td>High</td>
<td>Very Likely</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Land for Bioenergy</td>
<td>Land (Indirect)</td>
<td>High</td>
<td>Very Likely</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Land for Bioenergy</td>
<td>non-UK impacts (esp. in the Global South)</td>
<td>High</td>
<td>Very Likely</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>DSR</td>
<td>Social</td>
<td>High</td>
<td>Likely</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>DSR</td>
<td>Economic</td>
<td>High</td>
<td>Likely</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Air</td>
<td>High</td>
<td>Likely</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Human Health</td>
<td>High</td>
<td>Likely</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Economic</td>
<td>High</td>
<td>Likely</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Energy Intensity of Industry (EII)</td>
<td>Biomass</td>
<td>High (*)</td>
<td>Likely</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Biodiversity</td>
<td>High</td>
<td>3 Somewhat Likely</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>Air (Fugitive Emissions)</td>
<td>High</td>
<td>Somewhat Likely</td>
<td>14</td>
<td>10</td>
</tr>
</tbody>
</table>

\(^\text{13}\) The composed score is obtained by computing the average of the rank obtained from the Urgency and Criticality of the Need criteria, as discussed in Section 2.
### ENERGY SYSTEM COMPONENT

<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>PRIORITY SCORE</th>
<th>LIKELIHOOD</th>
<th>COMPOSED SCORE</th>
<th>FINAL RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Network</td>
<td>Economic</td>
<td>&gt; Medium</td>
<td>Very Likely</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Aviation</td>
<td>Economic</td>
<td>&gt; Medium</td>
<td>Very Likely</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Land for Bioenergy</td>
<td>Land (Direct)</td>
<td>High/Medium</td>
<td>Very Likely</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Land for Bioenergy</td>
<td>Biodiversity</td>
<td>High/Medium</td>
<td>Very Likely</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Land for Bioenergy</td>
<td>Water</td>
<td>High/Medium</td>
<td>Very Likely</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Buildings</td>
<td>Environmental Impacts</td>
<td>&gt; Medium</td>
<td>Likely</td>
<td>2</td>
<td>14</td>
</tr>
</tbody>
</table>
| Energy Intensity of Industry (EII) | Waste | < High | Likely | 11 | 15 | Unlikely
| Unconventional Gas      | Water                   | High / Medium  | Somewhat Likely  | 14             | 16            |
| Unconventional Gas      | Land (Seismic Activity) | High / Medium  | Somewhat Likely  | 14             | 16            |
| Power network           | Human Health            | Medium         | Very Likely      | 1              | 17            |
| Offshore Wind           | Biodiversity            | Medium         | Very Likely      | 4              | 18            |
| Nuclear Power           | Economic                | Medium         | Very Likely      | 6              | 19            |
| Nuclear Power           | Social                  | Medium         | Very Likely      | 6              | 19            |
| Nuclear Power           | Water                   | Medium         | Very Likely      | 6              | 19            |
| CCS - Storage           | Social                  | Medium         | Very Likely      | 8              | 20            |
| Aviation                | Air                     | Medium         | Very Likely      | 12             | 21            |
| Aviation                | Human Health            | Medium         | Very Likely      | 12             | 21            |
| Aviation                | Social                  | Medium         | Very Likely      | 12             | 21            |
| Land for bioenergy      | Economic                | Medium         | Very Likely      | 13             | 22            |
| Land for bioenergy      | Social                  | Medium         | Very Likely      | 13             | 22            |
| Buildings               | Social                  | Medium         | Likely           | 2              | 23            |
| Buildings               | Water                   | Medium         | Likely           | 2              | 23            |
| DSR                     | Air                     | Medium (*)     | Likely           | 2              | 23            |
| DSR                     | Human Health            | Medium (*)     | Likely           | 2              | 23            |
| Electricity Storage     | Economic                | Medium         | Likely           | 5              | 24            |
**Significant evidence gaps on the environmental, social and economic impacts of energy system components.**

<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT AREA</th>
<th>PRIORITY SCORE</th>
<th>LIKELIHOOD</th>
<th>COMPOSED SCORE&lt;sup&gt;13&lt;/sup&gt;</th>
<th>FINAL RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Storage</td>
<td>Social</td>
<td>Medium</td>
<td>Likely</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Social</td>
<td>Medium</td>
<td>Likely</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>Heat Pumps</td>
<td>Social</td>
<td>Medium (*)</td>
<td>Likely</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>Heat Pumps</td>
<td>Economic</td>
<td>Medium (*)</td>
<td>Likely</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Social</td>
<td>Medium</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>27</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>Human Health</td>
<td>Medium</td>
<td>Somewhat Likely</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>Social</td>
<td>Medium</td>
<td>Somewhat Likely</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>Economy</td>
<td>Medium</td>
<td>Somewhat Likely</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>Marine Environment</td>
<td>Medium / Low</td>
<td>Very Likely</td>
<td>6</td>
<td>29</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>Biodiversity</td>
<td>Medium / Low</td>
<td>Very Likely</td>
<td>6</td>
<td>29</td>
</tr>
<tr>
<td>Aviation</td>
<td>Land (Impact of Biofuels)</td>
<td>&lt; Medium</td>
<td>Very Likely</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>Energy Intensity of Industry (EII)</td>
<td>Energy efficiency impact and heating options</td>
<td>&lt; Medium</td>
<td>Likely</td>
<td>11</td>
<td>31</td>
</tr>
</tbody>
</table>

Ref: Ricardo-AEA/ED59332/OP1/Issue Number V1.1
## Energy System Component Impact

<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT</th>
<th>PRIORITY SCORE</th>
<th>LIKELIHOOD</th>
<th>COMPOSED RANKING¹⁴</th>
<th>FINAL RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Networks</td>
<td>Land</td>
<td>Low</td>
<td>Very Likely</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Power Networks</td>
<td>Water</td>
<td>Low</td>
<td>Very Likely</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Offshore</td>
<td>Social</td>
<td>Low</td>
<td>Very Likely</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>Offshore</td>
<td>Economic</td>
<td>Low</td>
<td>Very Likely</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>CCS - Storage</td>
<td>Land (Seismic Activity)</td>
<td>Low</td>
<td>Very Likely</td>
<td>8</td>
<td>34</td>
</tr>
<tr>
<td>CCS - Separation</td>
<td>Water</td>
<td>Low</td>
<td>Very Likely</td>
<td>8</td>
<td>34</td>
</tr>
<tr>
<td>CCS - Separation</td>
<td>Land</td>
<td>Low</td>
<td>Very Likely</td>
<td>8</td>
<td>34</td>
</tr>
<tr>
<td>CCS - Separation</td>
<td>Health</td>
<td>Low</td>
<td>Very Likely</td>
<td>8</td>
<td>34</td>
</tr>
<tr>
<td>Buildings</td>
<td>Economic</td>
<td>Low</td>
<td>Likely</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Buildings - Insulation</td>
<td>Social</td>
<td>Low</td>
<td>Likely</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Buildings - Insulation</td>
<td>Human Health</td>
<td>Low</td>
<td>Likely</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Electricity Storage</td>
<td>Environmental impacts</td>
<td>Low</td>
<td>Likely</td>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Land</td>
<td>Low</td>
<td>Likely</td>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>Electric Vehicles</td>
<td>Water</td>
<td>Low</td>
<td>Likely</td>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>Heat Pumps</td>
<td>Environmental impacts</td>
<td>Low (*)</td>
<td>Likely</td>
<td>8</td>
<td>38</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Land</td>
<td>Low</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>39</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Human Health</td>
<td>Low</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>39</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>Marine Environment</td>
<td>Low</td>
<td>Somewhat Likely</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Power Network</td>
<td>Air</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>Power Network</td>
<td>Social</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>Power Network</td>
<td>Biodiversity</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>CCS - Separation</td>
<td>Economic</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>CCS - Separation</td>
<td>Air</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>8</td>
<td>42</td>
</tr>
</tbody>
</table>

¹⁴ The composed score is obtained by computing the average of the rank obtained from the Urgency and Criticality of the Need criteria, as discussed in Section 2.
<table>
<thead>
<tr>
<th>ENERGY SYSTEM COMPONENT</th>
<th>IMPACT</th>
<th>PRIORITY SCORE</th>
<th>LIKELIHOOD</th>
<th>COMPOSED RANKING</th>
<th>FINAL RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS - Storage</td>
<td>Water</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>CCS - Transportation</td>
<td>Health</td>
<td>Very Low</td>
<td>Very Likely</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>Electricity Storage</td>
<td>Less mature storage technologies</td>
<td>&lt; Low</td>
<td>Likely</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>Electricity Storage</td>
<td>Conflicts and synergies with DSR</td>
<td>&lt; Low</td>
<td>Likely</td>
<td>5</td>
<td>43</td>
</tr>
<tr>
<td>Energy Intensity of Industry (EII)</td>
<td>CCS and DSR in Industry</td>
<td>&lt; Low</td>
<td>Likely</td>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Water</td>
<td>Very Low</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Air</td>
<td>Very Low</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>Economic</td>
<td>Very Low</td>
<td>Somewhat Likely</td>
<td>10</td>
<td>45</td>
</tr>
</tbody>
</table>
Appendix 9 – Web survey report

See file “SPLiCE M1.2 Web survey report V1.0”
