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Life cycle sustainability assessment of UK electricity scenarios to 2070

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ABSTRACT

Decarbonising the UK electricity mix is vital to achieving the national target of 80% reduction of greenhouse gas (GHG) emissions by 2050, relative to a 1990 baseline. Much work so far has focused only on costs and GHG emissions ignoring other sustainability issues. This paper goes beyond to assess the life cycle sustainability of different electricity scenarios for the UK, extending to 2070. The scenarios include the main technologies relevant to the UK: nuclear, gas, coal with and without carbon capture and storage (CCS), wind, solar photovoltaics and biomass. Three levels of decarbonisation are considered and the implications are assessed for techno-economic, environmental and social impacts on a life cycle basis. The results show that decarbonisation is likely to increase electricity costs despite anticipated future cost reductions for immature technologies. Conversely, sensitivity to volatile fuel prices decreases by two-thirds in all the scenarios with low-carbon technologies. To meet the GHG emission targets, coal CCS can only play a limited role, contributing 10% to the electricity mix at most; the use of CCS also increases other sustainability impacts compared to today, including worker injuries, large accident fatalities, depletion of fossil fuels and long-term waste storage. This calls into question the case for investing in coal CCS. A very low-carbon mix with nuclear and renewables provides the best overall environmental performance, but some impacts increase, such as terrestrial eco-toxicity. Such a mix also worsens some social issues such as health impacts from radiation and radioactive waste storage requirements. UK-based employment may more than double by 2070 if a renewables-intensive mix is chosen. However, the same mix also increases depletion of elements nearly seven-fold relative to the present, emphasising the need for end-of-life recycling. Very low-carbon mixes also introduce considerable uncertainty due to low dispatchability and grid instability. With equal weighting assumed for each sustainability impact, the scenario with an equal share of nuclear and renewables is ranked best.

Introduction

Achieving the UK's legally-binding target of reducing greenhouse gas (GHG) emissions by 80% by 2050 on 1990 levels (see Fig. 1) will require a complete decarbonisation of the UK electricity mix (UKERC, 2009). This is due to at least three reasons. First, electricity is by far the highest contributor to UK GHG emissions, being responsible for 79% of emissions from the energy sector and 28% of the total national emissions in 2012 (DECC, 2013). Secondly, the share of electricity is expected to grow significantly in the future owing to the anticipated electrification of other sectors, including transport (UKERC, 2009). It is also widely regarded that decarbonisation of electricity is going to be relatively easier than of other sectors as low-carbon technologies are either already available or will be deployable in the near-to-medium future. Whilst in other countries with differently structured economies, different sectors such as agriculture or transport can make greater contributions to national emissions, many nations face a similar challenge to that of the UK owing to the increasing significance of electricity as an energy source.

The decarbonisation of electricity is a very ambitious target, given the current electricity mix in the UK which is dominated by fossil fuels, contributing more than 87% to the total (see Fig. 2). Much work has been carried out so far in an attempt to find out how this might be achieved, often using scenario analysis. Examples include work by the Tyndall Centre (2005), UK Energy Research Centre (Ekins et al., 2013) and UK government Department of Energy and Climate Change (DECC, 2011a).

However, thus far the focus has been on direct GHG emissions from power plants and the costs of transforming the electricity system to meet the GHG emission targets. Indirect emissions from the whole life cycle of power generation have only been considered in this context by the Committee on Climate Change (2013) and the Transition Pathways consortium (Hammond et al., 2013; Hammond and O'Grady, 2013), with the latter also considering some environmental issues other than climate change. This leaves many other sustainability issues overlooked or sparsely addressed, including a broad range of life cycle environmental and social aspects. Therefore, if decarbonisation is seen as an opportunity to provide more sustainable energy, these other issues should be considered across the whole life cycle of power options (rather than just emissions from power plants) to prevent ‘leakage’ of impacts from one life cycle stage to another.

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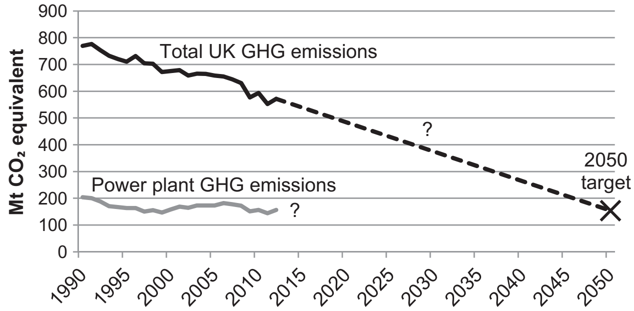

Fig. 1. UK greenhouse gas emissions and the 2050 legally-binding target (DECC, 2012).

Previous papers have discussed how different electricity technologies can be assessed on a range of sustainability issues on a life cycle basis and how some present-day options compare under UK conditions (Stamford and Azapagic, 2011; Stamford and Azapagic, 2012). With regard to future electricity scenarios, the European NEEDS project carried out life cycle sustainability assessment for several countries in Europe considering different environmental, economic and social aspects (Schenler et al., 2008). However, no equivalent analysis exists for the UK.

Therefore, this paper applies a life cycle approach to assess the sustainability of future electricity scenarios for the UK. Five scenarios up to 2070 are considered with a range of technological options suitable for the UK. The novelty of this work is at least three-fold: firstly, it applies a full life cycle approach to scenario analysis of electricity generation in the UK which has not been done previously; secondly, it considers the most comprehensive range of sustainability issues to date; and thirdly, it goes beyond the usual time horizon of 2050 to consider the implications of the electricity system transformation up to 2070. The longer time frame is chosen to reflect better the longevity of modern power plants, particularly nuclear reactors which have lifespans of 60 years. Additionally, this allows the electricity mix to change radically whilst allowing for reasonable build rates for individual technologies.

The following section outlines the methodology and data used in this study, including a description of the scenarios themselves. The results are presented and discussed in the Results and discussion section and the conclusions are drawn in the Conclusions section. Further details on the assumptions and results can be found in Supplementary information. The life cycle models for the scenarios are available within the Scenario Sustainability Assessment Tool (SSAT) v2.1 developed as part of this work. SSAT, which can be downloaded from www.springsustainability.org/?page=tools, is an interactive tool which also allows users to define their own scenarios and examine the related sustainability implications.

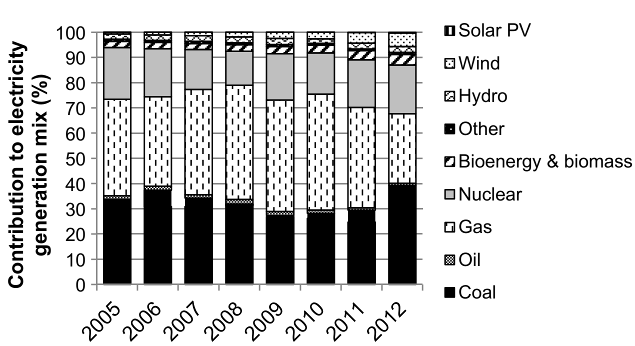

Fig. 2. Electricity generation mix in the UK from 2005 to 2012 (DECC, 2013).

Methodology

Life cycle sustainability assessment

A life cycle approach has been applied to assess the sustainability of future electricity systems using techno-economic, environmental and social sustainability indicators developed by Stamford and Azapagic (2011) following extensive engagement with stakeholders from industry, government, academia and non-governmental organisations. In total, there are 36 indicators which are summarised in Table 1. Each indicator assesses a particular sustainability issue on a life cycle basis, from 'cradle to grave'. As shown in Fig. 3, the life cycle includes the construction and decommissioning of power plants, extraction and processing of fuels (if relevant), generation of electricity and waste management. The following electricity generation options are considered, each being relevant to UK conditions and expected to play a major role in the future electricity mix (DECC, 2011a):

- coal (subcritical pulverised) with and without carbon capture and storage (CCS);
- natural gas (combined cycle gas turbine, CCGT);
- nuclear (pressurised water reactor, PWR);
- solar photovoltaics (PV);
- wind (offshore); and
- biomass (wood and *Miscanthus* pellets).

Further details on the technologies can be found in the Technology data sources and assumptions section, following the description of the scenarios.

Future scenarios

Three main scenarios are considered, each with either one or two sub-scenarios depicting possible futures for electricity in the UK to 2070; their characteristics are summarised in Table 2. All the scenarios are driven by the need to reduce GHG emissions, as this is one of the main energy policy drivers in the UK (DECC, 2011a,c). The three main scenarios explore three different GHG reduction levels for electricity – 65%, 80% and 100% – by 2050 relative to 1990. The 100% reduction from electricity is what is required to achieve the national target of 80% reduction of GHG emissions. The other two targets are chosen to examine the implications of falling short of this target with the 80% scenario matching the national GHG emission reduction target and 65% being less ambitious still. Note the following:

- The year 2050 is the target year for UK policy hence the reduction targets in the scenarios relate to this year; however, the scenarios extend to 2070 to consider implications beyond the target year.
- UK GHG emission reduction target refers to the direct emissions of GHG rather than the life cycle emissions. Therefore, the reduction targets considered in the scenarios also refer to the direct emissions; however, the implications of reaching these targets are estimated on a life cycle basis.
- The decarbonisation targets in the scenarios refer only to CO_2, as opposed to the basket of GHGs included in the national targets; however, direct emissions of non-CO_2 GHGs from power plants typically cause around 1% of the direct global warming impact, so this simplification should have negligible effect.

The narratives for scenarios 65% and 100% are based on those developed by the Tyndall Centre (Azapagic et al., 2011) but have been developed further to focus on electricity (as opposed to the original scenarios which considered the whole UK energy system). The third scenario (80%) has been developed as part of this research. The scenarios are summarised in Table 2 and described in more detail below, together with the sub-scenarios. They are also differentiated in terms of their emission pathways in Fig. 4. The year 2009 is considered as a reference year in this research as the most complete data sets were available for