Energy Policy 52 (2013) 103–116

Contents lists available at SciVerse ScienceDirect

Energy Policy

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

The energy and environmental implications of UK more electric transition pathways: A whole systems perspective

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HIGHLIGHT

- 'Whole systems' energy/environmental appraisal of 3 UK transition pathways.
- The impact of upstream emissions and environmental burdens are emphasised.
- They arise from the expenditure of energy resources upstream of a power station.
- The policy implications of the pathways and their upstream emissions are described.
- They suggest that CCS is found to deliver only ~70% reduction in carbon emissions.

ARTICLE INFO

Article history:
Received 27 October 2011
Accepted 30 August 2012
Available online 11 November 2012

Keywords:
Transition pathways
United kingdom
Whole systems appraisal

ABSTRACT

Electricity generation contributes a large proportion of the total greenhouse gas emissions in the United Kingdom (UK), due to the predominant use of fossil fuel (coal and natural gas) inputs. Indeed, the various power sector technologies [fossil fuel plants with and without carbon capture and storage (CCS), nuclear power stations, and renewable energy technologies (available on a large and small {or domestic} scale)] all involve differing environmental impacts and other risks. Three transition pathways for a more electric future out to 2050 have therefore been evaluated in terms of their life-cycle energy and environmental performance within a broader sustainability framework. An integrated approach is used here to assess the impact of such pathways, employing both energy analysis and environmental life-cycle assessment (LCA), applied on a 'whole systems' basis: from 'cradle-to-gate'. The present study highlights the significance of 'upstream emissions', in contrast to power plant operational or 'stack' emissions, and their (technological and policy) implications. Upstream environmental burdens arise from the need to expend energy resources in order to deliver, for example, fuel to a power station. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakage that occurs in coal mining activities – a major cotribution – and from natural gas pipelines. The impact of upstream emissions on the carbon performance of various low carbon electricity generators [such as large-scale combined heat and power (CHP) plant and CCS] and the pathways distinguish the present findings from those of other UK analysts. It suggests that CCS is likely to deliver only a 70% reduction in carbon emissions on a whole system basis, in contrast to the normal presumption of a 90% reduction. Similar results applied to other power generators.

1. Introduction

1.1. Background

Electricity generation contributes approximately 30% of United Kingdom (UK) carbon dioxide (CO_2) emissions (POST, 2007), the principal 'greenhouse gas' (GHG) having an atmospheric residence time of about 100 years (Hammond, 2000). This is predominantly due to the use of fossil fuel (coal and natural gas) combustion for this purpose. Indeed, all the main power sector technologies [fossil fuel plants with and without carbon capture and storage (CCS), nuclear power stations, and renewable energy technologies (available on a large and small {or domestic} scale)] involve differing environmental impacts and other risks (El-Fadel et al., 2010; Hammond and Waldron, 2008). But changes in atmospheric concentrations of GHGs affect the energy balance of the global climate system. Human activities have led to quite

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http://dx.doi.org/10.1016/j.enpol.2012.08.071

dramatic increases since 1950 in the 'basket' of GHGs incorporated in the Kyoto Protocol; concentrations rising from 330 ppm to about 430 ppm presently (IPCC, 2007). Prior to the first industrial revolution the atmospheric concentration of 'Kyoto gases' was only some 270 ppm. The cause of the observed rise in global average near-surface temperatures over the second half of the 20th Century has been a matter of dispute and controversy. But the most recent scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) states with 'very high confidence' that humans are having a significant impact on the global warming (IPCC, 2007). They argue that GHG emissions from human activities trap long-wave thermal radiation from the Earth's surface in the atmosphere (not strictly 'greenhouse' phenomena), and that these are the main cause of rises in climatic temperatures. In order to mitigate anthropogenic climate change, the *Royal Commission on Environmental Pollution* in the UK (RCEP, 2000) recommended at the turn of the Millennium a 60% cut in UK CO_2 emissions by 2050. The British Government subsequently set a tougher, legally binding target of reducing the nation's CO_2 emissions overall by 80% by 2050 in comparison to a 1990 baseline (DTI, 2007).

The history of electricity generation since the time of Edison has been based around the concept of employing large, centralised power stations (see, for example, Alderson et al., 2012; Buchanan, 1994; Hammond, 2000; Hughes, 1983). Thus, the bulk of electricity in Britain is still generated by large thermal power plants that are connected to a high-voltage transmission network, and is then distributed to end-users via regional low-voltage distribution networks (Hammond and Waldron, 2008; POST, 2007). A simplified model of energy flows in the UK is illustrated in Fig. 1 (Hammond, 2000). It should be noted that heat is wasted and energy is 'lost' at each stage of energy conversion and distribution, particularly in the process of electricity generation. The schematic energy flow diagram shown in Fig. 1 hides many feedback loops in which primary energy sources (including fossil fuels, uranium ore, and hydro-electric sites) and secondary derivatives (such as combustion and nuclear-generated electricity) themselves provide upstream energy inputs into the 'Energy Transformation System'. The latter is that part of the economy where a raw energy resource is converted to useful energy which can meet downstream 'final' or 'end-use' demand (Slesser, 1978). 'Renewable' energy sources are taken to mean those that are ultimately solar-derived: mainly solar energy itself, biomass resources, and wind power. This centralised model has delivered economies of scale and reliability (Allen et al., 2008a), but there are significant drawbacks. It suffers, for example, from overall energy system losses of about 65% in terms of primary energy input (Allen et al., 2008b; DECC, 2010; Hammond, 2000; Hammond and Stapleton, 2001). These losses predominantly result from heat wasted during electricity production (58%), but there are smaller losses rising in transmission and distribution – approximately 1.5% and 5% respectively (Allen et al., 2008b; POST, 2007). The use of micro-generation and other decentralised or distributed power technologies has the potential to reduce such losses. It has recently been predicted that micro-generation could provide 30–40% of the country's electricity needs by 2050 (Allen et al., 2008a).

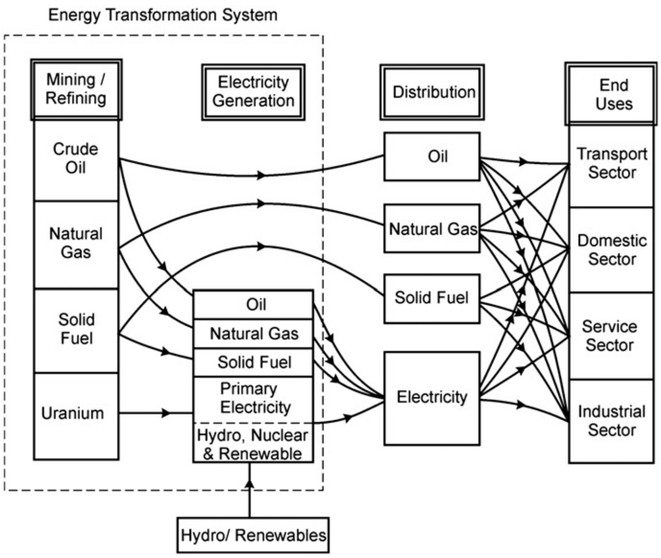

Fig. 1. A simplified representation of the UK energy system.
Source: Hammond (2000).

1.2. The issues considered

Three transition pathways for a more electric future out to 2050 (Foxon et al., 2010) have been evaluated here in terms of their life-cycle energy and environmental performance within a broader sustainability framework (Hammond and Jones, 2011b). An integrated approach is used (see, for example, Allen et al., 2008a) to assess the impact of such pathways, employing both energy analysis and environmental life-cycle assessment (LCA), applied on a 'whole systems' basis. Energy analysis required estimates of the energy outputs of the power generators during use, and the energy requirements for their construction and operation. In contrast, the LCA yielded estimates of pollutants or wastes released into the environment as a consequence of the power network (in terms of 17 separate impact indicators, together with a tentative 'single score', aggregate LCA metric). Carbon footprints have become the 'currency' of debate in a climate-constrained world. They represent the amount of carbon [or carbon dioxide equivalent (CO_{2e})] emissions associated with a given activity or community, and are generally presented in terms of units of mass or weight [kilograms per functional unit (e.g., $kgCO_{2e}/kWh$)]. Embodied energy and carbon appropriate to the various power generators specified in the current work have been determined using proprietary LCA software tools and databases, together with the '*Inventory on Carbon and Energy*' (ICE) [developed at the University of Bath (Hammond and Jones, 2008, 2011a)]. 'Embodied energy' is here defined as the total primary energy consumed from direct and indirect processes associated with power production and within the boundary of 'cradle to gate' (Hammond and Jones, 2011a). This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the power plant is constructed for operational use. Similarly, 'embodied carbon' is the sum of fuel-related carbon emissions (i.e., embodied energy which is combusted, but not the feedstock energy which is retained within materials) and process-related carbon emissions (Hammond and Jones, 2011a). The present study highlights the significance of 'upstream emissions' and their (technological and policy) implications. Upstream environmental burdens arise from the need to expend energy resources in order to deliver, for example, fuel to a power station. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakage that occurs in coal mining activities – a major contribution – and from natural gas pipelines. Thus,

'whole system' GHG emissions = upstream GHG emissions
+ operational GHG emissions

where the 'operational' or 'stack' emissions are those directly associated with the combustion of fossil fuels within power