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The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK

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ABSTRACT

This paper begins with an overview of the current supply and demand characteristics of primary energy for the provision of heat and power in the UK. This is followed by a brief review of a variety of solutions that are being proposed towards the establishment of a sustainable energy landscape, including clean coal, wind and solar energy. The discussion extends to the economics and performance of various renewable energy systems in comparison to fossil fuel equivalents. Placed in this context, the study then focuses specifically on the role of pumped heat, combined heat and power (CHP) schemes, and options for the recovery and conversion of waste heat into useful work, all of which have a potential to contribute towards the creation of a 'high-efficiency sustainable energy future'. It is concluded that although the problem is complex, the relative costs of competing technologies are not prohibitive, but comparable, leading to an inability to make a decisive choice and delaying progress. CHP and pumped heat are found to be similar in terms of overall efficiency, with the load factor (heat-to-power demand ratio) being of critical importance. Various waste heat conversion systems are also found to be similar in terms of the important indicator of power per unit cost.

1. Introduction

In this section the case is made for a high-efficiency sustainable energy future. The energy problem is considered from an economic, environmental, health and security perspective. An important realisation concerns the potential of various energy options to impact meaningfully on these diverse aspects. Some options, although quite capable of adequately addressing a number of them, fail to address others. These limitations must be borne in mind during strategic decision-making processes. This leads, in Section 2, to an overview of a wide range of technologies that are being considered as viable means for the provision of such an energy landscape in the United Kingdom.

1.1. Fossil fuels, combustion and energy

Mankind has been burning fossil fuels for light, heat and power for a very long time, and for good reason. On combustion, fossil fuels release substantial amounts of heat at high temperature and are thus associated with high energy and exergy densities. The latter in particular makes them ideal candidates for use in heat engines for the production of power, whether this is directly for motion (i.e. transportation) or conversion to electricity via generators, since the efficiency of any such engine will increase with the temperature of the available heat source. Fossil fuels are, and will remain, the most important energy carrier over the next few decades.

In the UK, oil, gas and coal accounted collectively for 90% of all the consumed primary fuel sources in 2009, including fossil, nuclear, wind, hydro- and imported electricity (see Fig. 1 [1]). Fossil fuels were also responsible for approximately 75% of the electricity generated in 2008 and 2009 [1]. Yet, along with high-grade (i.e. high temperature) heat, the combustion of fossil fuels also produces gases such as oxides of carbon (commonly, CO_x), nitrogen (NO_x) and sulphur (SO_x), as well as water vapour. Imperfect combustion also produces unburnt hydrocarbons (UHC) and particulate matter (PM) such as soot. Increasing attention over the past 15–20 years is being paid to these various emissions and their possible effects on human health and the Earth's climate [2].

1.2. Emissions, climate change and health effects

Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are considered to be the primary

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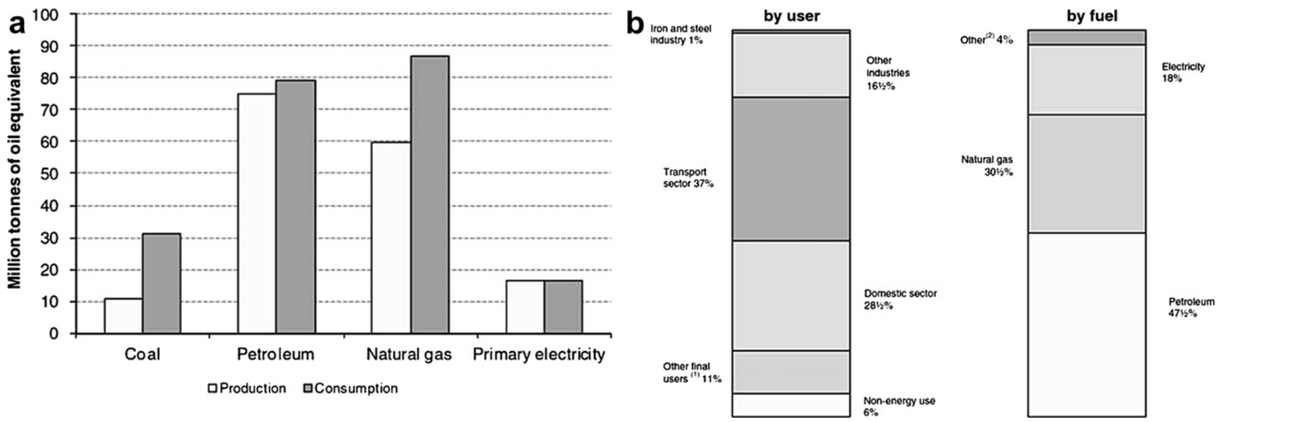

Fig. 1. (a) UK production and consumption of primary fuels in 2009. Includes non-energy use of petroleum and gas. Differences between consumption and production are made up by foreign trade, marine bunkers and stock changes. (b) UK energy consumption of breakdown in 2009. Taken from Ref. [1]. (1) Includes services and agricultural sectors. (2) Includes coal, manufactured fuels, biomass etc.

greenhouse gases (GHGs) in the Earth's atmosphere [2,3]. According to the Department of Energy and Climate Change [4], if one excludes H_2O vapour, CO_2 accounts for >99% of the weight and ~85% of the global warming potential of all GHGs. With this understanding in mind, it is possible to refer to GHG and CO_2 emissions (almost) interchangeably, though the significance of excluding H_2O is recognised and noted.

Hence, considerable interest is being shown in CO_2 in particular and a variety of 'decarbonised' strategies that would promote the reduction of CO_2 emissions over the next few decades are being considered. A hypothetical road map for the worldwide curbing of CO_2 emissions with estimated contributions from various practices and technologies has been published by the International Energy Agency (IEA) [5] and can be seen in Fig. 2(a). Note here: (i) the equal expectations from carbon capture and storage (CCS) and renewable technologies, which have been identified as having a similar potential towards this goal of between 17 and 19%; and (ii) the 43% combined potential assigned to energy efficiency in various forms, which has been associated with a 2.5-fold higher potential.

The UK Government has made a legally binding international commitment directly with respect to total GHG (and hence CO_2) emissions, currently (2009 figures) at 570 Mt CO_2 of which 470 Mt are associated with CO_2 [4]. In 1997 it adopted the Kyoto protocol that stipulates a reduction in total GHG emissions by 12.5% below 1990 levels (780 Mt CO_2 [4,6]) by 2008–2012. Subsequently, in the Climate Change Act of 2008 it pledged to cut emissions by 80% relative to 1990 levels by 2050 and by at least 34% by 2020, though GHG/CO_2 emissions had already dropped by 20%/11% between 1990 and 2008 [4], in line with the Kyoto targets. To this end it has been imposing progressive caps on GHG emissions through 5-year 'Carbon budgets', the first of which covers the period from 2008 to 2012 and stipulates a reduction of 22% below 1990 levels.

The historical evolutions of the emissions of CO_2 and of the total GHG emissions weighted by global warming potential since 1980 are shown in Fig. 2(b). Also shown here are the Kyoto and first carbon budget targets. Both targets have been broadly met, however, the economic downturn caused by the financial crisis has acted as a catalyst in this direction. In particular note the sudden drop in emissions after the contraction of 2008 and the slight rebound in 2010.

Nevertheless, the IEA observes that "Current energy and CO_2 trends run directly counter to the repeated warnings sent by the United Nations Intergovernmental Panel on Climate Change (IPCC), which concludes that reductions of at least 50% in global CO_2 emissions compared to 2000 levels will need to be achieved by 2050 to limit the long term global average temperature rise to between 2.0 °C and 2.4 °C" [5]. It proceeds to note that "Recent studies suggest that climate change is occurring even faster than previously expected and that even the '50% by 2050' goal may be inadequate to prevent dangerous climate change". Clearly there is an element of uncertainty with regards to the effect of the human-based release of CO_2 into the atmosphere on the Earth's climate, the science of which is highly complex and not well understood. The conventional approach of the majority of the scientific and policy communities has been a precautionary one.

In addition, beyond the possible contribution of the release of combustion products to the greenhouse effect, NO_x and SO_x emissions have been associated with other detrimental aspects of climate change, such as acid rain, while air pollution from PM, aerosols and even O_3 have been linked to adverse effects on human

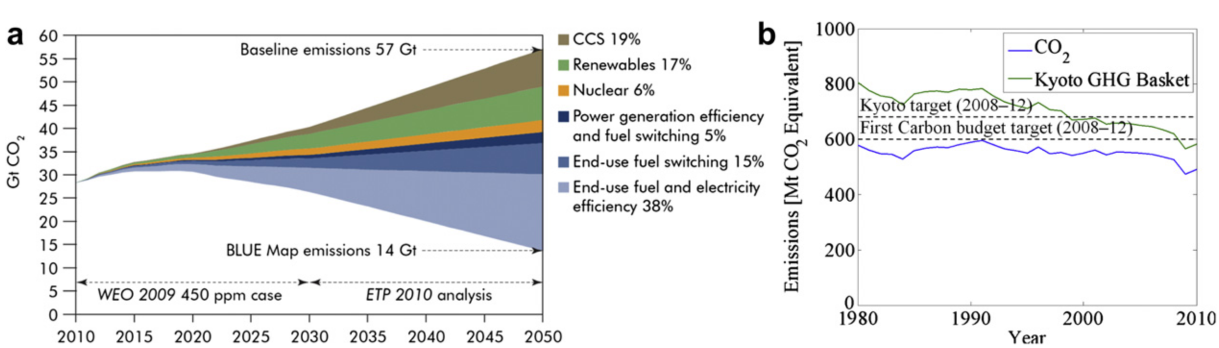

Fig. 2. (a) Envisaged contributions of various strategies towards a global reduction of CO_2 emissions; taken from Ref. [5]. (b) UK GHG and CO_2 emission history from 1980 to 2010, with progress towards the Kyoto budget for total GHG emissions and the UK Government first carbon budget (2008–2012).