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Industrial energy, materials and products: UK decarbonisation challenges and opportunities

John Barrett[a], Tim Cooper[b], Geoffrey P. Hammond[c,*], Nick Pidgeon[d]

[a] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[b] School of Architecture, Design and the Built Environment, Nottingham Trent University, Nottingham NG1 4BU, UK
[c] Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK
[d] School of Psychology, Cardiff University, Cardiff, Wales CF10 3AT, UK

HIGHLIGHTS

- An interdisciplinary review is presented of industrial decarbonisation in the UK.
- Various socio-technical methods for analysing industrial energy use are explored.
- Materials content changes in manufacture products can lead to decarbonisation.
- The way that final consumers use products can also reduce energy demand.
- 2050 low carbon 'roadmaps' for some UK energy-intensive industries are presented.

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ABSTRACT

The *United Kingdom* (UK) has placed itself on a transition pathway towards a low carbon economy and society, through the imposition of a legally-binding target aimed at reducing its 'greenhouse gas' (GHG) emissions by 80% by 2050 against a 1990 baseline. Reducing industrial energy demand could make a substantial contribution towards this decarbonisation goal, while simultaneously improving productivity and creating employment opportunities. Both fossil fuel and process GHG emissions will need to be significantly reduced by 2050. Ultimately, all industrial energy use and emissions result from the demand for goods and services. Energy is required at each stage in the manufacture of a product from raw material extraction through to the final distribution and eventual disposal. The required energy and associated GHG emissions along UK supply chains emanate from many different countries, due to the growth of globalisation. A range of socio-technical methods for analysing decarbonisation have therefore been explored. Efficiency gains can be made in industry, including those associated with the use of heat and with improvements in processing. Changes in the materials needed to manufacture products (via material substitution, light-weighting and '*circular economy*' interventions) can also lead to emissions reductions. Likewise, altering the way the final consumer (industry, households or government) use products, including through product longevity and shifts from goods to services, can further reduce energy demand. The findings of an interdisciplinary study of industrial decarbonisation is therefore reported. This gave rise to the identification of the associated challenges, insights and opportunities, in part stemming from the development of a novel set of 2050 decarbonisation 'technology roadmaps' for energy-intensive industries in the UK. These determinations provide a valuable evidence base for industrialists, policy makers, and other stakeholders. The lessons learned are applicable across much of the wider industrialised world.

1. Introduction

1.1. Background

Energy systems pervade industrial societies and weave a complex web of interactions that affect the daily lives of their citizens [1]. Such societies face increasing pressures associated with the need for a rapid transition towards a low-carbon and secure energy future at moderate cost (that is one which is affordable or competitive). The British Government established a legally binding target of reducing the nation's

* Corresponding author.
E-mail address: G.P.Hammond@bath.ac.uk (G.P. Hammond).

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carbon dioxide (CO_2) emissions overall by 80% by 2050 in comparison to a 1990 baseline [2,3]. That will be a very difficult task to achieve. Thus, on the supply-side these challenges will require a portfolio of energy options to surmount them [1]: they may include *carbon capture and storage* (CCS) units coupled to fossil fuel power and industrial processing plants, and a switch to low or zero carbon energy sources {such as *combined heat and power* (CHP), nuclear power stations, and renewable energy technologies on a large and small scale}. But the demand for energy is the main driver of the whole energy system [1,4]. It gives rise to the total amount of energy used, as well as the location, type of fuel and characteristics of specific end-use technologies. Consequently, the need for reductions in energy demand, and associated 'greenhouse gas' (GHG) emissions, applies across the end-use spectrum from the built environment to industrial processes and products, from materials to design, and from markets and regulation to individual and organisational behaviour [1]. It is important to trace the whole life of products, services and supporting infrastructure, and their associated energy flows and pollutant emissions, as they pass through the economy. Heat is potentially wasted and energy is 'lost' at each stage of energy conversion, transmission, and distribution, particularly in connection with the process of electricity generation. Upstream energy inputs into the economy emanate from raw energy resources that are converted into useful energy in order to meet downstream, 'final' or 'end-use' demand.

Reducing the use of energy can be encouraged in various ways. Energy efficiency improvements result from using less energy for the same level of output or service, where the output can be measured in terms of either physical or economic units (i.e., tonnes {t} or pounds sterling {£}). But consumers can also be encouraged to reduce their energy use by changing their service demands [1]. One obvious way of doing that is via the adoption of a lower comfort temperature in the home or at the workplace, thereby requiring less energy to deliver it. Human behavioural changes can be assisted by devices such as 'smart' meters or appliances [5]. The latter technologies can play an important part in securing *demand-side response* (DSR) that better matches end-use electricity demand with supply [6]. Energy demands on the electricity network vary throughout the day with domestic peaks typically in the morning and evening. This profile may be smoothed, and the overall power requirement lowered, by shifting energy demands from household appliances (such as those for refrigerators, storage heaters, or washing machines) to other periods of the day. Flexible tasks in industry and the commercial sector can likewise be shifted to off-peak times [1].

There is obviously a need to stimulate improvements in resource use efficiency generally, and to encourage energy demand reduction from the 'bottom-up'; induced by way of a portfolio of measures to counter market deficiencies – economic instruments, environmental regulation, and land use planning procedures. Scenarios such as the 'dematerialisation' or 'Factor Four' project advocated by Ernst von Weizsacker and Amory and Hunter Lovins [7] suggest that economic welfare in the industrial world might be doubled while resource use is halved; thus the *Factor 4*. This would involve a structural shift from energy-intensive manufacturing to energy-frugal services [8]. Britain has moved some way in this direction, with about a 40% improvement in primary energy intensity since 1965 [9]. Increases in resource use efficiency at the *Factor 4* level would have an enormous knock-on benefit of reducing pollutant emissions that have an impact, actual or potential, on environmental quality. von Weizsacker et al. [10] subsequently advocated *Factor 5* increases, or an 80% improvement in resource productivity, and the UK Fore*sight* Programme even contemplated *Factor 10* over the long-term [9]. Improvements in resource efficiency of this type have been advocated in the UK by Allwood and Cullen [11]; albeit with a focus on material use. In reality, such a strategy requires a major change ('paradigm shift') to an energy system that is focused on maximising the full fuel/energy cycle efficiency, and minimising the embodied energy and GHG emissions in materials and products [12,13] by way of reuse and recycling. In order to make such an approach a practicable engineering option, it would be necessary to use systems analysis methods to optimise the energy cascade. Thus, thermodynamic analysis will be an important technique for identifying process improvement potential [9,14].

1.2. The issues considered

The industrial sector in the UK accounts for some 21% of total delivered energy and 29% of CO_2 emissions [15]. It is very diverse in terms of manufacturing processes, ranging from highly energy-intensive steel production and petrochemicals processing to low-energy electronics fabrication [16]. The former typically employs large quantities of (often high-temperature) process energy, whereas the latter tends to be dominated by energy uses associated with space heating. Around 350 separate combinations of sub-sectors, devices and technologies can be identified [16]; each combination offers quite different prospects for energy efficiency improvements and carbon reductions, which are strongly dependent on the specific technological applications. Some element of sectoral aggregation is therefore inevitable in order to yield policy-relevant insights. In addition, this large variation across industry does not facilitate a cross-cutting, 'one size fits all' approach to the adaptation of new technologies in order to reduce energy demand but, rather, requires tailored solutions for separate industries [16]. Thus, it is widely recognised that data on industrial energy use and the potential for GHG emissions reduction is arguably weakest in respect to any of the UK end-use demand sectors (i.e., in contrast to households, commerce, or transport). There is clearly a great need for research aimed at providing better information in support of UK industrial strategy for policy makers, including the potential impact of fuel switching (particularly to potentially low-carbon energy carriers, notably electricity), as well as the identification of difficult sectors/processes and areas where investment could be targeted most effectively.

Reducing industrial energy demand could make a substantial contribution towards the UK Government's goal of significant (80%) decarbonisation by 2050 [2,3], while simultaneously improving productivity and creating employment opportunities. Both fossil fuel and process GHG emissions will need to be significantly reduced out to 2050. Ultimately, all industrial energy use and emissions result from the demand for goods and services. Energy is required at each stage in the manufacture of a product from raw material extraction through to the final distribution and eventual disposal. The required energy and associated GHG emissions at different points along these UK supply chains emanate from many different countries, due to the growth of globalisation. A range of socio-technical methods for analysing decarbonisation have been explored by the interdisciplinary members of the UK *Engineering and Physical Sciences Research Council* (EPSRC) funded *Centre for Industrial Energy, Materials and Products* (CIE-MAP): see < http://ciemap.leeds.ac.uk/ > . Efficiency gains that can be made in industry, including those associated with the use of heat and with improvements in processing. Changes in the materials needed to manufacture products (such as material substitution, light-weighting and '*circular economy*' interventions) can also lead to emissions reductions. Likewise, altering the way the final consumer (industry, households or government) use products can reduce energy demand via product longevity and shifts from goods to services. Thus, the challenges, insights and opportunities associated with industrial decarbonisation over the transition towards a low-carbon future for the UK are described with the purpose of providing a valuable evidence base for industrialists, policy makers, and other stakeholders. The interdisciplinary lessons learned are applicable across much of the wider industrialised world.