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

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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

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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.

2. Methods and materials

2.1. Thermodynamic analysis

Thermodynamic methods provide an indication of the quantity (enthalpy) and quality (exergy) of an energy flow [12–14,16,17]. The latter helps to provide a measure of inefficiencies within a system resulting from exergy destruction, and consequently the maximum theoretical improvement potential. Identifying the energy service that a sub-sector or process provides allows the theoretical minimum *specific energy consumption* (SEC), the energy use per physical unit of output, to be calculated [18]. De Beer [18] viewed the definition of this energy service as being important. Thus, a broadly defined energy service, such as production of steel with certain properties (for example, its strength) permits a consideration of alternative materials, whereas specifying simply the making of steel allows options like scrap utilisation to be examined [18]. A narrowly defined energy service, such as making steel from iron ore, further limits the scope of improvements to those that produce virgin steel [18]. The definition of the energy service therefore requires careful consideration, too narrow a definition may limit the savings that can be made, whereas too broad a definition may not represent the realistic improvement potential.

The limitations of particular thermodynamic approaches clearly need to be recognised. Thus, exergy reflects the ability of undertake 'useful work', but does not represent well *heating processes* within an energy sector. Allen et al. [19] recently examined the end-use of electricity in the home, in the service sector, in industry, and the UK economy more generally in order to estimate how much is used for heat and power respectively. The share of electricity employed for heating applications in industry over the period 1970–2050 was found to rise to quite a high level: from 22 to 70% (see Fig. 1). These shares were insensitive to the precise nature of the forward projections (forecasts, transition pathways or scenarios [19]) adopted. The findings of this study represent a first indicative analysis of possible long-term trends in this heat/power share across the UK industry, although some of the necessary simplifying assumptions meant there were substantial uncertainties associated with the results. It can be argues that, where end-use *heat* demands are met by electricity, energy and exergy analysis should be performed in parallel in order to reflect the interrelated constraints imposed by the *First* and *Second Laws of Thermodynamics* [19]. An understanding of the actual end-uses for electricity will also enable policy makers to take account of the implications of a greater end-use of electricity in the future.

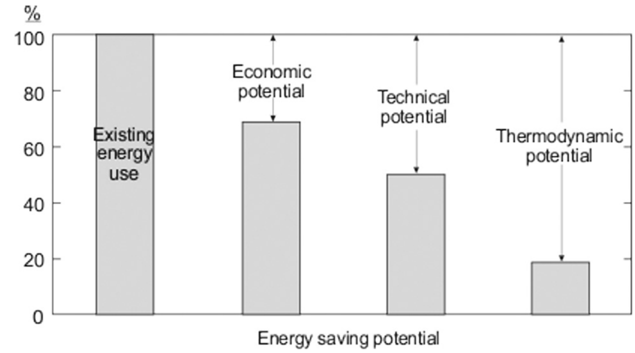

Fig. 2. The energy efficiency gap between theory and practice. *Source:* Hammond [14]; after Jaffe and Stavins [21].

The establishment of a minimum theoretical SEC serves as a comparison of where current technology performs and where the limit for improvement lies. Energy and exergy analysis [12–14,16,17] can indicate those areas where inefficiencies arise within the constraints of the existing system, as well as the improvements that may be possible. Indeed, Hammond and Stapleton [17] presented the maximum theoretical improvement, or energy saving, potential across the whole UK economy, as well as that for industry separately. There is obviously a distinction to be made between such an optimum and what can feasibly be achieved in practice. In the economics literature [16,20], this has widely been referred to as the 'energy efficiency gap' and the 'energy efficiency paradox' [17,21]. Economic and technical barriers (as well as the thermodynamic limits) that must be faced in securing energy-efficiency savings in practice [17,21]. These constraints are illustrated in Fig. 2 [14]. Roughly, this suggests that, although the thermodynamic (or exergetic) improvement potential might be around 80%, only about 50% of the energy currently used could be saved by technical means and, when economic barriers are taken into account, this reduces to perhaps 30% [14–16,20]. Thus, thermodynamic analysis can provide a valuable signpost to where technologies can have the greatest impact, although it is only one of several constraints. Chen et al. [22] recently

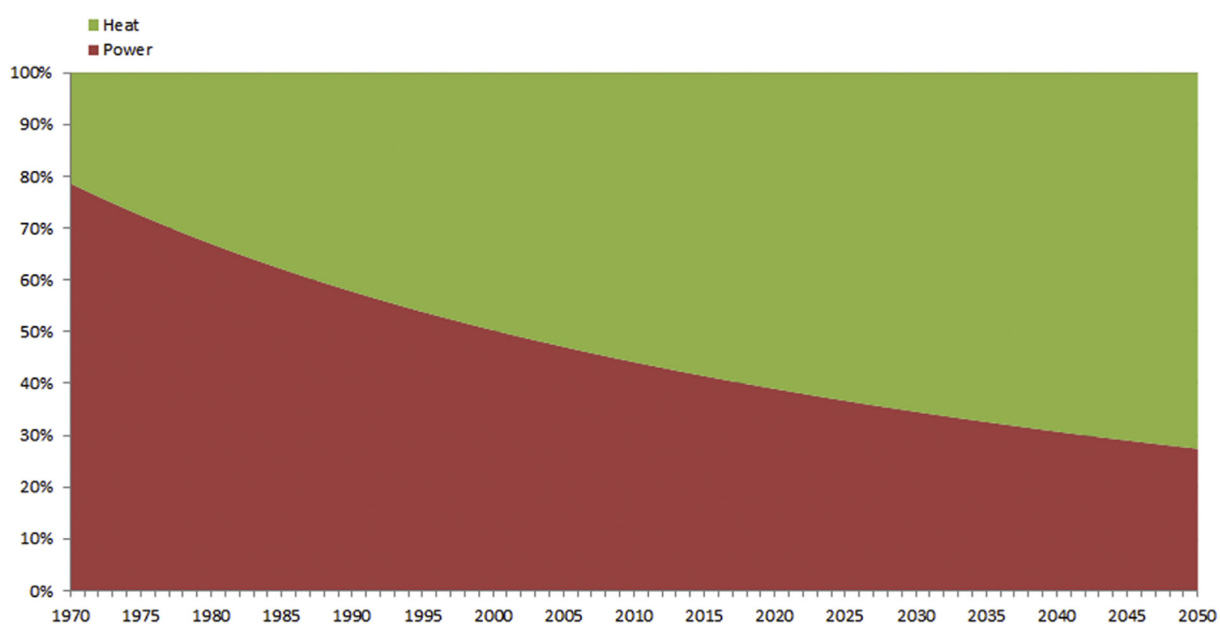

Fig. 1. The proportion (% share) of electricity end-use for heat and power applications within UK industry: 1970–2050. *Source:* based on data originally estimated in connection with the study by Allen et al. [19] for both historic trends and a 'low-carbon' projection.

undertook an examination of such constraints on the potential for converting surplus heat to electricity using *organic Rankine cycles* (ORCs). A spatially disaggregated database of surplus heat availability within UK industry [23] was used to estimate the thermodynamic, technical, and economic potentials. Around ~3.5 PJ/yr of electricity was found to be potentially economically available from UK industry, mainly in a relatively small number of sites in the steel, chemicals and cement sub-sectors. However, this result is sensitive to the input parameters, particularly on the price of electricity and the target payback period employed by companies [23]. Hidden costs, such as those giving rise to the possible disruption of production activities during installation, were found to be a key barrier to the take-up of ORC technology.

The above UK surplus heat database was also recently used in combination with information on the magnitude, temperature and location of the heat that is rejected by industrial sites in order to determine the potential for supplying district heating networks (DHNs) by Cooper et al. [24]. This assessment was based on a number of relevant criteria: the maximum allowable distance between the heat sources and demands, the minimum heat density of the demands which were considered feasible, the heat losses that might occur, and the seasonal profile of the heat demands. The potential gains from using absorption heat pumps, driven by high temperature heat to supply lower grade heat were found to be limited. High and low estimates of the heat rejected by the industrial sites were compared. Domestic and non-domestic heat demands were also examined, and the latter was found to have marginally greater potential [24]. Only half of the heat which is rejected by industry could be utilised by DHNs, when the most appropriate distance and heat demand density criteria were employed. The seasonality of the heat demands was found to have the largest impact on, for example, the need for supplementary heat sources.

Overall insights and lessons from such studies can be summarised, for example, as:-

- Thermodynamic analysis can make a significant contribution to the identification of the improvement potential available from various industrial processes and enabling technologies [16]. Thus, exergy analysis can yield an indication of the 'maximum' improvement potential available from different sources, perhaps an 80% improvement in end-use efficiency in some cases. However, it is important to recognise this cannot be achieved in practice, because of additional technical and economic barriers (see Fig. 2) which might limit the improvement potential to something closer to 30% [14–16].
- *Heat* has a variable thermodynamic quality depending on the ratio of the process temperature to the environmental temperature or datum [19]. Where end-use *heat* demands are met by electricity, energy and exergy analysis should therefore be performed in parallel in order to accurately reflect the interrelated constraints imposed by the *First* and *Second Laws*. The proportion of electricity required for industrial heating purposes was estimated to vary from 22 to 70% over the period 1970–2050 (see Fig. 1). That is a significant amount of end-use power consumption going forward, and is part of the reason that the UK Government and its energy and climate change advisory bodies [25–28] have recently taken a keen interest in the provision of *heat services* in Britain. An understanding of the actual end-uses for electricity will therefore enable policy makers to take account of the implications of a greater end-use of electricity in the future.
- It seems probable that non-domestic demands will form the majority of the heat demands which are initially met by industrial surplus heat supplied via DHNs [24]. They are likely to present initially more feasible space heating opportunities that make good use of heat rejected by industrial sites. However, domestic heat demands are greater overall, and so as district heating develops in the UK, they will represent the bulk of the heating requirements that might ultimately need to be supplied. But should the DHNs primarily be required to satisfy seasonally variable space heating loads, then industrial waste heat would need to be supplemented with other, more flexible, heat sources [24]. Obviously, the waste heat which is rejected by industry has many possible uses.

2.2. Carbon and related accounting

In addition to the energy use and emissions at a manufacturing site, a product will have upstream or 'embodied' energy and carbon resulting from material extraction, transport, and the early stages of production [12,13,29]. Sources of information on these embodied emissions were included in the *Inventory of Carbon and Energy* (ICE) (developed at the University of Bath by Hammond and Jones [12,13]), which examines energy and carbon emissions on a 'cradle-to-gate' basis using process environmental *life cycle assessment* (LCA) [29], and in UK input-output (IO) table models (of the type developed by the *Stockholm Environment Institute*, based originally at the University of York [30] and now at the University of Leeds). The effect of indirect emissions in the manufacture of a product (those not resulting directly from energy use or processes at the manufacturing site) can be considerable. In addition, a major or radical change in the manufacturing process could have significant effects in the embodied emissions of a product beyond the direct energy requirements and process emissions. This is important to consider as a technology that saves energy on site, but (indirectly) leads to greater upstream emissions, and would therefore not be a favourable choice. The IO approach of considering indirect emissions is similar to environmental LCA [16,20,29], but does not take into account environmental impacts other than energy use and GHG emissions, and also doesn't consider the use phase of a product which may also be important.

Life-cycle methodologies also link industrial energy demand to consumption. This has value in identifying all the opportunities that exist at different stages of the production process as well as considering changes in consumption patterns. This allows broader changes in consumption and efficiency to be aligned with the subsequent change in industrial energy [31]. There is also a growing appreciation of the uncertainty associated with these complex models, and of the need to understand detailed production structures of economies and trade flows [32]. It is clearly necessary to consider the relationship between energy, monetary flows and materials [33]. Fig. 3 below provides an example of the information generated from *Multi-Regional Input-Output* (MRIO) models in determining the flow of energy through industry and the economy as a whole [34]. This figure provides an analysis of energy flows {in the *European Union* (EU-27)}, but further studies have also considered other environmental pressures, such as water [35,36]. Increasingly, studies are undertaken to demonstrate the link of consumption at the city scale with global industrial energy demand [37,38].

A related issue is that of "carbon leakage" [39]. By focusing only on UK energy use and GHG emissions, a national decrease may be seen that in reality corresponds to increased levels of imports [31]. No net fall in emissions may result, if the boundary of the analysis is drawn beyond the UK borders [40]. This carbon leakage may involve an overall rise in emissions, compared to the manufacture of the same products in the UK, due to increased transport requirements when importing from other nations, and because the manufacturing processes being undertaken elsewhere may be less efficient than those, for example, in the UK.

There is an increasing evidence base documenting the effect of embodied emissions on future energy policy in the UK [41,42], carbon targets [43] and employment [44]. These contributions have created scenarios to consider changing industrial energy demand in the future and the underlying drivers.

Overall insights and lessons from such studies can be summarised, for example, as:-

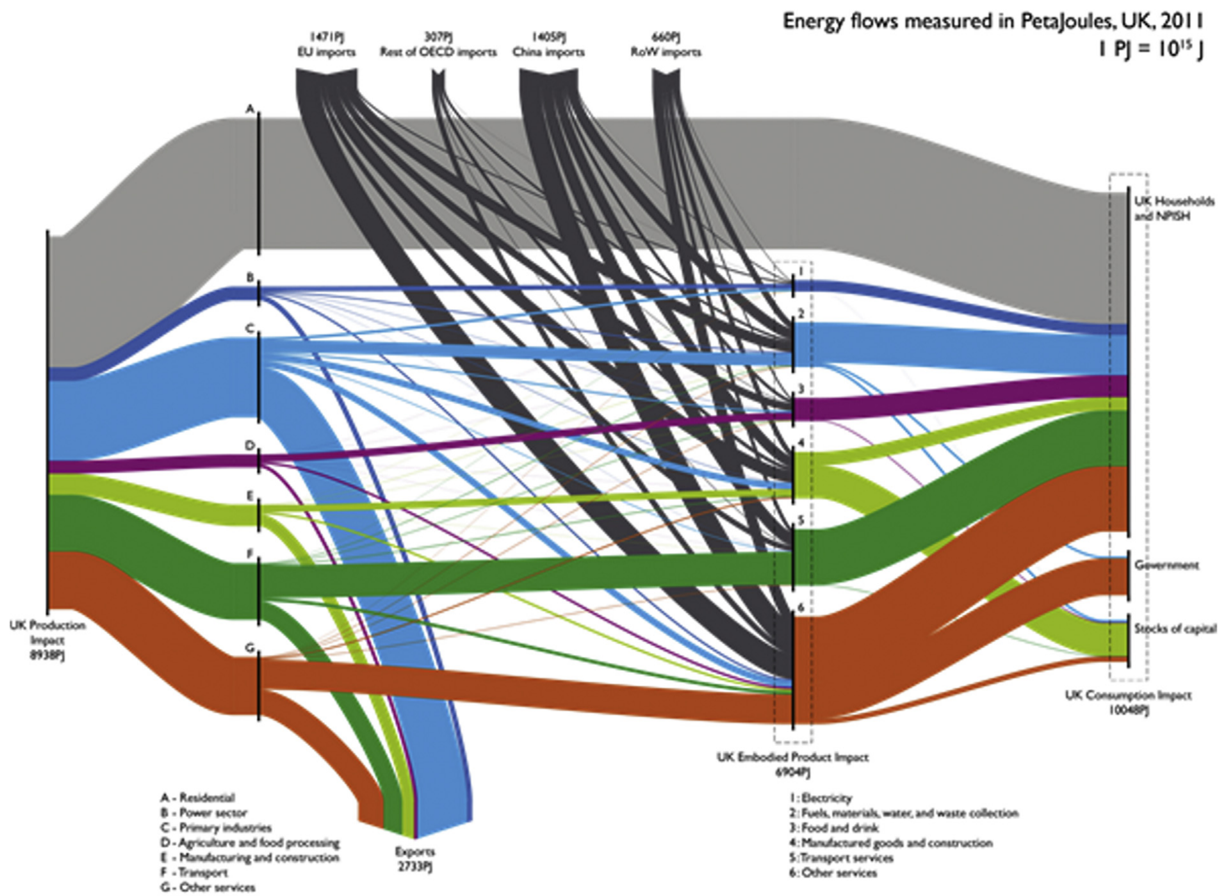

Fig. 3. EU-27 industrial energy flows. *Source:* Scott et al. [34].

- Life-cycle methodologies are proving to be valuable tools in understanding the complexity of global supply chains. For industrial energy, this provides information on different opportunities for efficiency gains and energy savings from the production of raw materials through to final consumption.
- Different methodologies have various strengths and weaknesses with process LCA giving detailed product information, whilst input-output approaches provide a more complete picture of energy demand, albeit at a less granular level. However, studies that identify the uncertainty and data issues of both approaches have made considerable advances.
- The reliance of the UK on imports of materials has had a significant effect on the industrial energy demand in the country. As the UK economy is increasingly based on services, industrial energy has declined and material imports mean that there has been an outsourcing of industrial production (and, effectively, GHG emissions).
- Thus, increased demand for products to satisfy UK consumption is being meet by manufacturing and processing overseas.

2.3. Decomposition analysis

A decomposition analysis separates the effect of different factors contributing to changes in energy demand or energy-related GHG emissions over time. Examining the underlying reasons for falls in energy use and emissions over time via this technique provides a better understanding of how earlier gains were realised, and whether a similar approach will yield further improvement in the future [45]. With suitable data, such analysis can be applied to either the whole industrial sector or to a particular sub-sector. Hammond and Norman [45], for example, used decomposition analysis to examine changes in energy-related carbon emissions across UK industry between 1990 and 2007. The effects of changes in output, structure, energy intensity, fuel mix, and the emissions factor of electricity respectively on GHG emissions were examined for 21 industrial sub-sectors, based on the 2-digit UK *Standard Industrial Classification* (SIC) level. Technical improvements were found to enhance energy efficiency, and thereby decrease the energy intensity (i.e., energy use per unit of output). Such gains had the greatest influence on UK industrial energy-related GHG emissions over the period 1990–2007 [45], although other factors also made important contributions.

Griffin et al. [46] utilised the so-called *Log Mean Divisia Index* (LMDI) methodology for decomposition analysis [46,47] as part of an evaluation of the opportunities for the reduction of GHG emissions in the UK *Cement* sector. Energy use in UK cement kilns dropped by approximately 65% between 1973 and 2010 [46]. The different effects contributing to this change in energy demand were analysed [46]: falls in clinker output; switching between dry, semi-dry, semi-wet and wet kiln technologies (a structural effect); and SEC improvements resulting from different kiln technologies. The findings from this decomposition analysis are depicted in Fig. 4, where it can be observed that over all time periods the effect of improvements in SEC of the different kiln types represent the smallest component in reducing energy demand. Indeed, over the most recent time period (2000–2010) the effect of SEC improvements has been substantially smaller than in any previous period.

A similar decomposition analysis of final energy demand in the UK *Food & Drink* sub-sector over the period 2001–2007 was undertaken by Norman [48], and reported by Griffin et al. [15]. The LMDI methodology was again used, and the industry was disaggregated into eleven sub-sectors or product groups (the maximum disaggregation allowed by the UK data available). It suggested an increase in energy demand was caused by rising monetary production value, with a rather smaller

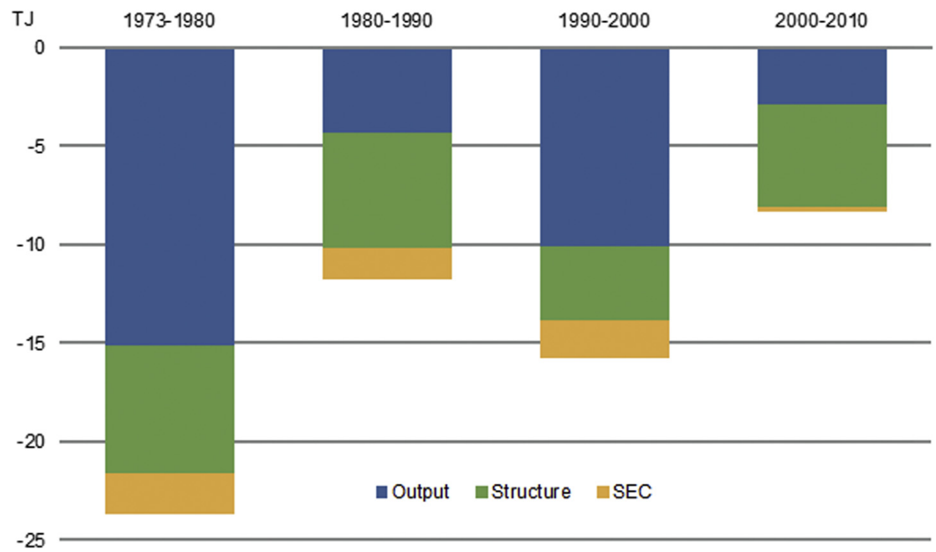

Fig. 4. Decomposition of UK cement kiln energy use 1973–2010: variations caused by changes in structure, output, and SEC. *Source:* adapted from Griffin et al. [15].

increase resulting from shifts in the structure of *Food & Drink* (both of these effects have been relatively stagnant post-2005). The dominant effect on energy demand reduction was a fall in energy intensity. Hence, the UK *Food & Drink* sub-sector is both growing and steadily reducing its energy intensity. Output volume was fairly static, but there has been a move towards added value products. This structural effect would indicate that such higher value added products are more energy-intensive. This is consistent with a shift towards a greater amount of processing at manufacturing sites, rather than within the home [15].

Key challenges, insights and opportunities identified in these industrial decomposition analysis studies include:-

- A general slowing of industrial energy intensity improvements has been observed in both the UK [15,45], and more widely in other developed nations [49,50]. Reduction in energy demand caused by energy intensity improvements in the 1980s were observed to have been significantly influenced by public industrial energy *research, development and demonstration* (RD&D) programmes [51], especially within the *energy-intensive* (EI) sub-sectors. As a result of these trends, there is expected to be relatively larger energy improvement potential in *non-energy-intensive* (NEI) sub-sectors of industry, particularly in 'small and medium sized enterprises' (SMEs) [47]. This does not mean that the improvement potential in EI sub-sectors has 'run its course', but that larger interventions and major changes to the current system may be required to obtain significant improvements, rather than relying on relatively small, continual changes [15,45].
- Decomposition analysis of the *Cement* sub-sector [15,46] suggests that a limit to the efficiency of cement kilns may be being approached (see Fig. 4). However, now that there are no wet kilns left in the UK, further potential for reducing energy demand in this way is limited. Over the whole period studied (i.e., 1973–2010) there had been a falling demand for clinker, and this significantly restricted the scope for energy demand reductions in the *Cement* sub-sector.
- Similarly, decomposition analysis of the *Food & Drink* sub-sector [15] indicates that structural effects resulting from higher value added products led to a greater sectoral energy-intensity. This is consistent with a shift towards a greater amount of processing at the manufacturing site, rather than within the home (as has been observed elsewhere in the EU [52]).

3. Emissions reduction from materials production

3.1. The context

The GHG emissions from the UK industrial sector can be split by sub-sector [1,15,23,45], including emissions from energy use (including those indirectly emitted from electricity use) and process emissions. Sub-sectors with significant process emissions are steel, chemicals, cement, aluminium, glass, ceramics and lime. Information on energy use [28], emission conversion factors [53] and process emissions [54] need to be combined in order to determine the total emissions. A number of sub-sectors were found to dominate GHG emissions from the industrial sector in the UK [15], and this suggested *Pareto-like* priorities for bottom-up studies [1,15,46–48,55,56]: steel (25%), chemicals (19%), cement (8%), food & drink (7%), paper (6%), plastics (6%) and so on. Thus, just six sub-sectors account for 71% of UK emissions. The post-2008 economic recession in Britain (and globally elsewhere) has resulted in the closure of some large plants, and this should be considered when assessing the data. In regard to large energy users, particularly aluminium smelters and steel mills, a number of plants have been shut-down or earmarked for closure. The long-term future of these industrial sub-sectors, and how much capacity other plants may change in response, is currently uncertain [15]. The closure of major industrial facilities must be set against the background of a general economic slowdown with significant closures also seen in the cement and paper sub-sectors.

3.2. Cement

Cement was one of a number of industrial sub-sectors that have been examined via detailed, bottom-up research [15,46]. The UK cement sector was responsible for around 7 Mt CO_2 emissions in 2010. These emissions were due to direct fuel use, the chemical reactions that occur as part of the production process, and electricity use (leading to indirect emissions) [46]. The approach taken of defining the energy use and emissions in relation to physical output, and then of assessing the technologies that could be applied to this baseline, was replicated across the other sub-sectors [1,15]. Historical trends showed that the sub-sector made considerable reductions in its GHG emissions (see again Fig. 4). Thus, it was noted that the UK cement sector made reductions in its emissions per unit of cement over the past two decades [46], due to clinker substitution, fuel switching and efficiency improvements respectively. This has largely been driven by energy costs and policy. Making substantial reductions in specific emissions out to 2050, as is required by emissions reduction targets, will require measures that go beyond this, e.g., the adoption of CCS technologies [15] and the adoption of alternative cement formulations [15,46,48]. Both of these options are open to considerable uncertainty, and will likely require greater support from both industry and government policy to be realised in practice. Reductions in output from the sector have led to falls in GHG emissions historically, and continuing this trend, through the more efficient use of cement, also holds potential. The sector faces a considerable challenge in contributing to carbon reductions over the longer-term; a similar situation exists in many energy-intensive industries.

The lessons learned from the technical evaluation of the *cement* subsector [1,15,46–48] were:-

- Conventional kiln fuels of high carbon content (i.e., coal and petcoke) may be substituted by alternative fossil fuels (such as oil or natural gas) or biogenic fuels (from wastes, including biomass material) thereby resulting in lower emissions. The substitution of the present coal input with oil or natural gas would lead to emission reductions of some 7 and 12% respectively [15]. Biofuels are some 20–25% less carbon intensive in terms of direct emissions when compared to coal.
- The production of clinker is the most energy and carbon intensive stage of *cement* manufacture. Replacing a higher proportion of clinker with other materials could thus reduce the energy used and carbon emitted in the course of cement production. The bulk of factory-made cements in the UK are supplied with high clinker content with further clinker substitution occurring downstream at the concrete mixing plant [15,48]. Such clinker and cement substitutes tend to require less transportation and the concrete producer can optimise the final product; thus reducing waste, energy use and additional handling [15,48].
- Post-combustion CCS is an 'end-of-pipe' technology and could be retrofitted to existing cement plants involving replacement of the exhaust stack, but with all other components unchanged [15,46,48]. Chemical (amine) absorption is seen as the most promising of these methods. However, they exhibit poor economies of scale (relative to power generation plants), and require a large amount of additional energy for solvent regeneration during the process that separates the CO_2 for transport.
- There has recently been considerable interest in the development of novel low energy, low CO_2 cements as an alternative to *ordinary Portland cement* (OPC). The range of options have been well characterised, assessed, and their potential implications studied by the UK Portland cement industry [15]. Further attractive options are being developed by other commercial firms, but detailed product or process information has not yet been published for these [46,48].

3.3. Chemicals

The UK *chemicals* sub-sector gives rise to the highest industrial energy consumption [48,55]; mainly due to low temperature heat processes (30%), electrical motors (19%), drying/separation processes (16%), and high temperature heat processes (11%) [47]. Chemicals represents a complex collection of products covering a wide range of feedstocks, processes and products [48]: advanced materials, cleaning fluids, composites, dyes, paints, pharmaceuticals, plastics, and surfactants [55]. It sits on the boundary between EI and NEI industrial sectors. Physical outputs are moved around on an international scale within or between major companies that are truly multi-national [55]. The industry is also highly focused on private R&D and protective of information, which means that data availability is particularly poor. This high technology sector takes full advantage to modern developments in electronics and *information and communications technology* (ICT), such as for the automatic control of chemical process plants and automation in the use of analytical instruments [55]. The scale of operation of chemical firms range from quite small plants (of a few tonnes per year) in the *fine chemicals* area, where high purity is required, to giant ones in the petrochemical sector [55]. Batch production is employed by SMEs where small quantities of chemicals (up to around 100 tonnes per annum) are required. In contrast, continuous plants are typically used in cases where a single, or related group of, products are demanded with plants of several thousands to millions of tonnes per year [55]. They often produce intermediates which are converted via downstream processing into a wide range of products, such as benzene, ethylene, phenol, and polyvinyl chloride (PVC) from petrochemical refineries or via ammonia plants [55].

Opportunities and challenges decarbonisation in the UK *Chemicals* sub-sector have been evaluated:-

- Currently-available *best practice technologies* (BPTs) will lead to further, short-term energy and CO_2 emissions savings in chemicals processing, but the prospects for the commercial exploitation of innovative (or 'disruptive') technologies by mid-21st century are far more speculative [48,55].
- The chemicals sector has long been the largest owner of energy generating plant in UK industry. Most of this generation arises from CHP plant providing significant outputs of surplus electricity exported to the grid or other industrial sectors [48,55]. There are a number of non-technological barriers to the take-up of such technologies going forward.
- The attainment of significant falls in carbon emissions over the period out to 2050 will depend critically on the adoption of a small number of key technologies [e.g., CCS, energy efficiency techniques, and bioenergy], alongside a decarbonisation of the electricity supply [48,55].

3.4. Other material sub-sectors

Other industrial sub-sectors have been evaluated in a similar manner to those above, e.g., iron & steel [48] and pulp & paper [56]. There projected energy use and carbon emissions out to 2050 have been incorporated into the technology roadmaps for selected energy-intensive UK industries reported in Section 5 below.

4. End-use energy demand and emissions associated with infrastructure and products

4.1. Construction

The UK construction sector has annual emissions associated with the embodied energy required to produce all the materials within the region of 43–62 Mt a year [57] (over 10% of the UK's total emissions). Increasingly, strategies to reduce the energy demand of buildings and infrastructure extend beyond the operational use to include the upstream energy demand for production of materials used in their construction. There is growing evidence for a range of options to reduce industrial energy demand by changing practices within the construction sector. These include the use of alternative materials (see, for example, Section 3.2 above), eliminating excess use of materials through improved design and manufacture, and increased re-use and recycling. A number of scenarios have been developed by Giesekam et al. [58] to evaluate the potential future embodied GHG emissions in UK construction. Factors such as the energy mix required to produce electricity, future infrastructure demand, and efficiency gains could all have a significant effect on the level of emissions. However, even with lower demand for new infrastructure and decarbonisation of the electricity grid would not reduce the embodied emissions in line with national carbon targets. Further reductions are needed that consider the issues mentioned earlier such as design, material choice and production processes. Fig. 5 illustrates the embodied emissions associated with future

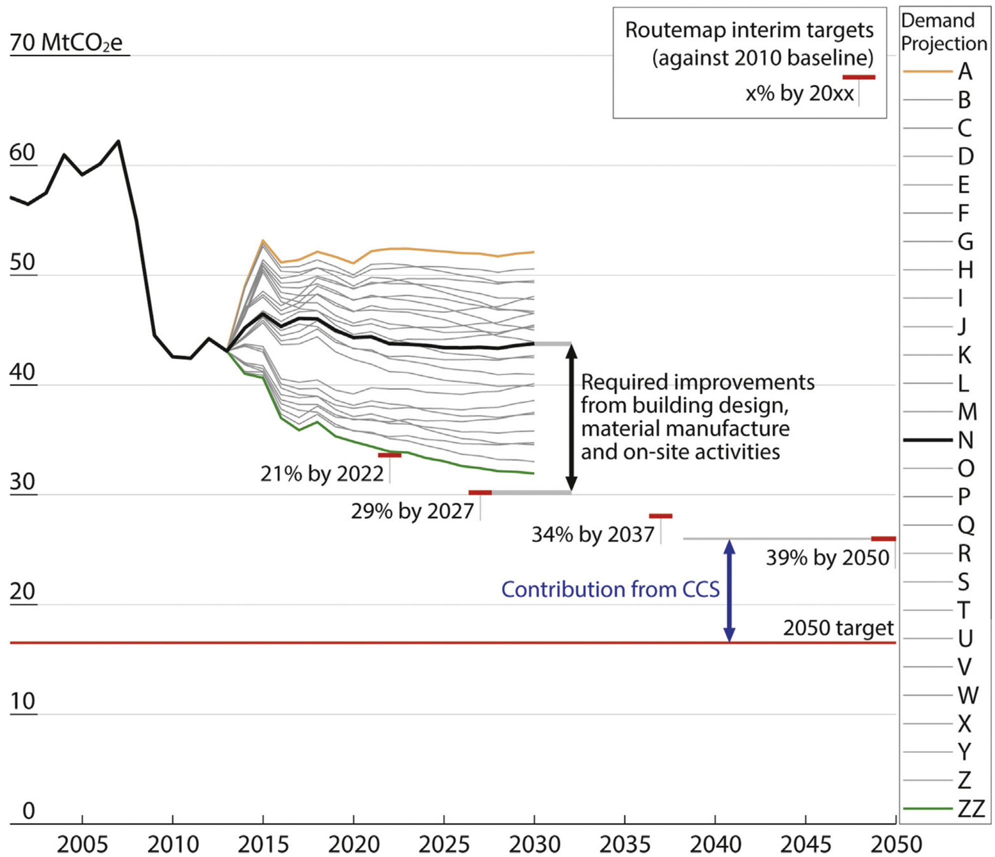

Fig. 5. Future projections of embodied emissions from UK construction 2001–2030, including projected improvements in carbon intensity of electricity supply. *Source:* Giesekam et al. [58].

demand for construction for a wide range of scenarios [58]. Subsequent results [59] found a disparity between present company-based *carbon targets* and the range of possible trajectories. Giesekam et al. [59] illustrated the impact of different methodological assumptions and highlighted the critical features for an appropriate response. They argued that a cross-industry dialogue is needed to establish a suitable response to deliver both a widely-accepted, construction sector target trajectory and a corresponding plan for its delivery.

A parallel study [57] was undertaken in order to comprehend the views of experts from the construction sector on the key barriers to a range of options that would reduce its embodied emissions. This elicited a number of perceived inhibitors: high cost, ineffective allocation of responsibility, industry culture, and the poor availability of product and building-level carbon data and benchmarks [57]. Opportunities to overcome such barriers include early engagement with professionals along the supply chain during the planning phase of new buildings and infrastructure, better availability of accurate LCA data on the different material options, and the effective use of whole life costing.

Overall insights and lessons from such studies can be summarised, for example, as:-

- The embodied GHG emissions associated with constructing buildings and infrastructure are becoming increasingly important with the operational energy use of buildings decreasing.
- There are many options available to address the embodied emissions associated with energy-intensive materials that need further investigation and a greater recognition within industrial energy policy/strategy.

4.2. Food & Drink

The *Food & Drink* sub-sector produces a wide range of products, making use of many different processes [15,47]. The analysis of the sub-sector therefore presents a challenge akin to that of examining the whole of manufacturing. So a detailed analysis of the processes and products that represent large uses of energy were studied, together with a more generic approach taken to the rest of the sub-sector. The latter examined the potential for improvements through cross-cutting technologies. Energy demand in the UK *Food & Drink* sub-sector can be split into thirteen product groups or sub-sectors as shown in Fig. 6. This grouping is a combination of three and four digit SIC codes, and is based on knowledge of the processes and products employed within the groupings; data limitations; and how the sub-sector is disaggregated for other purposes, such as the requirements of the UK *Climate Change Agreements* (CCAs) between the British Government and the industry. Fig. 6 indicates that a number of sub-sectors dominate the *Food & Drink* sub-sector with the top five energy using sub-sectors comprising approximately 60% of the total energy demand. Another *Pareto-like* insight. There is clearly some uncertainty about the accuracy of energy demand data at this high level of disaggregation. Low temperature processing dominates the *Food & Drink* sub-sector. Drying and separation, as well as space heating also contribute to the demand at the low temperature end of the energy cascade [15,47]. A large proportion of this heat is supplied by steam systems. The UK *Food and Drink Federation* (FDF) estimate 49% of the sub-sector emissions arise from boilers, with another 27% from direct heating [15,47].

The approach taken by Griffin et al. [15] was to focus on cross-cutting technologies that could influence a number of product groups, particularly in regard to the supply of low temperature heat. This included the improvement of steam system efficiency, as well as the increased use of both CHP plants and heat pumps. Thus, the insights and lessons from this evaluation of the *Food & Drink* sub-sector can be summarised as [15,47]:-

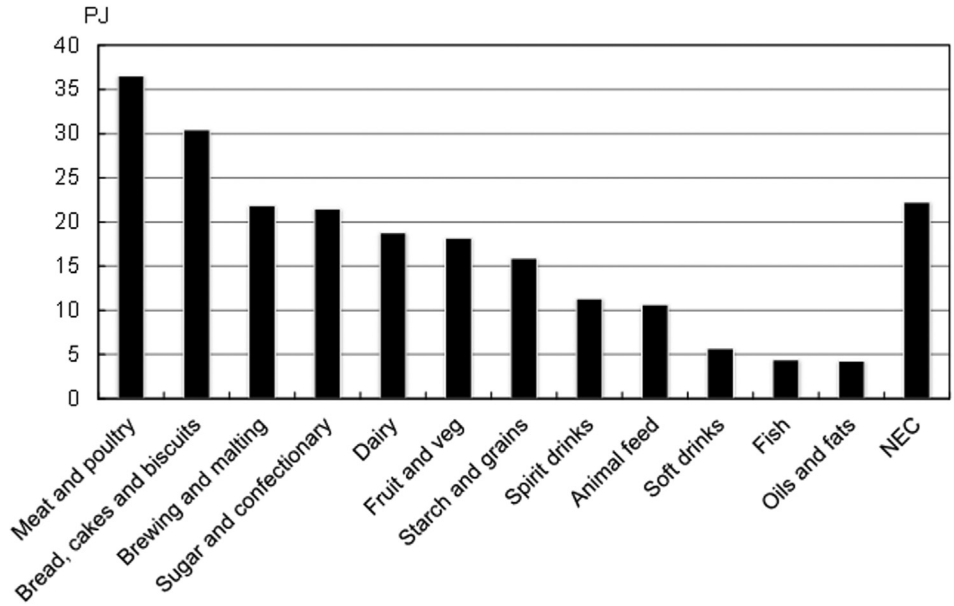

Fig. 6. The primary energy demand for products from the *Food & Drink* sub-sector. NEC – not elsewhere classified. *Source:* Griffin et al. [15].

- It is generally risk adverse in nature, there is strong focus on product quality, and stringent safety requirements which have led to an increase energy demand in recent years [15]. The customer base of the sub-sector tends to be dominated by a few large retailers (e.g., 'supermarket' chains), meaning that margins are small and there is little capital for innovation.
- Product life-cycles can be short and so flexibility of equipment is vital, which will often harm efficiency [15]. Large-scale adoption of technologies is made difficult by the diverse and fragmented nature of the *Food & Drink* sub-sector. Additionally, many food processing sites are small (92% of such businesses in Europe being SMEs) with efficiency improvement tending to be slower in these smaller businesses.

5. UK technology roadmaps of energy-intensive industries out to 2050

5.1. The context

A set of selected '*technology roadmaps*' have been developed in order to evaluate the potential for the deployment of the identified enabling technologies in UK energy-intensive industries out to 2050. They combine individual roadmaps for the pulp and paper, lime, glass, and brick sectors [48,56]. The extent of the potential resource demand and GHG emissions reduction was therefore estimated and projected forward. Such roadmaps represent future projections that match short-term (say out to 2035) and long-term (2050) targets with specific technological solutions to help meet key energy saving and decarbonisation goals. A bottom-up roadmapping approach has been adopted, based on that previously used by Griffin et al. [15,46,55,56] to examine the impact of UK decarbonisation in the cement [15,46,48], chemicals [48,55], pulp and paper [48,56], and iron and steel [48] industrial sub-sectors (for greater detail see Griffin [48]). Thus, their content was built up on the basis of the technical *improvement potentials* associated with various processes employed in the individual industry sectors [15].

5.2. Scenario definitions

The identified improvement technologies for the selected UK EI industries were incorporated into a technology roadmap framework through a series of scenarios [15,46,55,56]. The baseline year for the framework was taken as 2010. Full details of the both the 2010 baseline and the *Best Available Technology* (BAT)/*Best Practice Technology* (BPT) improvements can be found in the thesis of Griffin [48]. BPTs represent the 'best' technology that is currently in use, and therefore economically viable [55]. This can be distinguished from a *Best Available Technology* (BAT), which includes proven technologies that may not yet be economically viable. Four future scenarios were then devised in order to demonstrate this approach [15,46,48,55,56]:-

- ***Low Action*** **(LA).** This scenario describes a path with only slight improvements going forward. No further investment is made in additional process technology improvements, and efficiency is only improved incidentally through the replacement of retired plants.
- ***Reasonable Action*** **(RA).** All identified efficiency technologies are installed by 2025, and retired plants are replaced with best practice ones by 2030.
- ***Reasonable Action including CCS*** **(RA-CCS).** This scenario is based on RA, but includes CCS. Biomass co-firing with CCS may, of course, mitigate upstream emissions on a full life-cycle basis, because of potential 'negative emissions' [60], i.e., it sequesters carbon emissions from fuel combustion. This is something that will need careful study in future studies.
- ***Radical Transition*** **(RT).** This scenario explores a boosted or radical version of the *Reasonable Action* (without CCS) scenario.

5.3. UK technology roadmap projections

GHG emissions pathways of illustrative technology roadmaps for the UK selected energy-intensive industrial sectors (pulp and paper, lime, glass, and bricks [48]) over the period 1990–2050 are illustrated in Fig. 7. (Griffin et al. [56] have displayed the energy splits and GHG emission trajectories for all four of these sub-sectors individually.) None of these sectors were identified as having viable CCS opportunities, and only the pulp and paper sub-sector was thought to have the potential for radical process transition. The aluminium sector was excluded because the last UK-located smelter of significance closed in 2012 [48]. The projected baseline will clearly be affected by industrial output, grid decarbonisation, and deployment of BPT/BAT. It was assumed that the grid will decarbonise by around 85% over the period 2010–2050 [48]. It was estimated that *EU Emissions Trading Scheme* (EU-ETS) '*cap and*

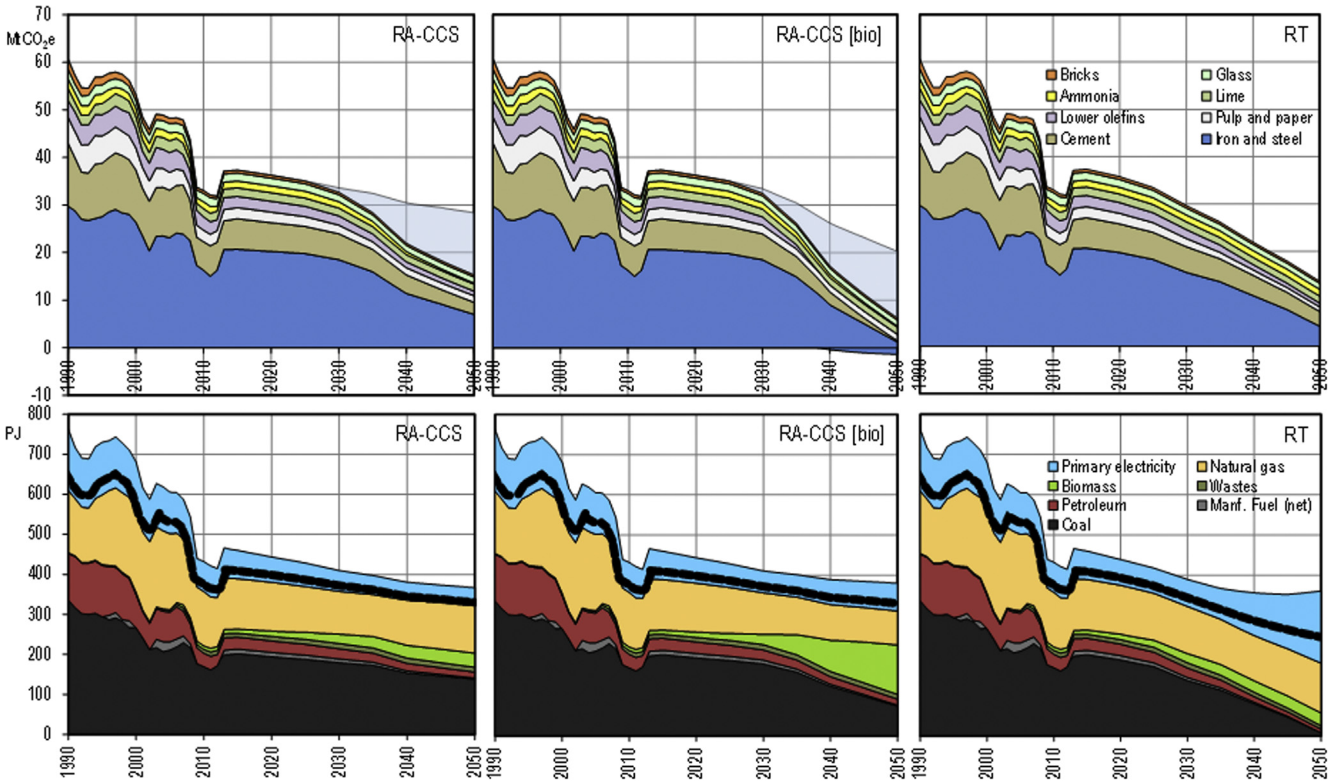

Fig. 7. Energy splits (PJ) and associated GHG emissions (CO_{2e}) in the 2050 technology roadmaps of some UK 'energy-intensive' industries under the *Reasonable Action* (RA) and *Radical Transition* (RT) scenarios: pulp and paper, lime, glass, and bricks. *Source:* Griffin [48].

trade' system covered 94% of direct GHG emissions from these energy-intensive industrial sub-sectors in 2010 [48].

A comparison of the 'breakthrough' roadmaps (RA-CCS, RA-CCS [bio], and RT) {see again Fig. 7} indicates that the scope for strong mitigation measures and technologies. Radical process transition (RT) accrues fuel savings worth nearly two thirds (63%) of total fuel savings from its roadmap [48]. In contrast, deploying CCS technology involves an energy penalty and reduces consequent savings [15]. *Scope 1–2/3* GHG emissions reduction by 2050 (compared with 1990 levels) is 78% with RA-CCS, 88% with RA-CCS [bio], and 79% with RT [48]. Thus, all breakthrough roadmaps deliver on the 70% target indicated for industry in the UK *Carbon Plan* [61]. Although RT and RA-CCS decarbonise by a similar amount in 2050, the former achieves a greater cumulative emissions reduction over the period. This is because of the effect of deeper reductions from RT over the short-medium term are achieved primarily by a faster move away from EI processes and technologies.

6. Towards a more '*circular economy*' – engaging producers and consumers

Clearly changes in the use of materials to manufacture products (e.g., material substitution, light-weighting, or the use of recyclate) will lead to GHG emissions reductions. But decisions made by the final consumer (whether industry, households or government) similarly affect the amount of energy embodied in products and have the potential to reduce energy demand [1,11]. Consumption is traditionally associated with economic growth and any effort to constrain it is liable to prove controversial, although the concept of '*prosperity without growth*' [62] has recently gained some traction. Arguably, eco-efficiency will reduce resource consumption sufficiently to achieve sustainable development goals and mitigate climate change, and consequently strategies to slow throughput of materials by addressing product lifetimes have been proposed [63–65]. Having commissioned research into product lifetimes [66], the potential benefits of increased product longevity were recognised by the UK Government in its waste prevention programme [67]. Concern about planned obsolescence and the potential need to introduce regulations to ensure minimum product (or component) lifetimes were prominent in the European Commission's *Circular Economy* Package [68], whilst a growing community of academic researchers is now active in the field [69].

The impact on energy use of applying a wide range of *circular economy* (CE) approaches has recently been studied by Cooper et al. [70] in a global context, across the EU-27, and in the UK. Such approaches can be viewed as an alternative to the conventional *linear 'take-make-consume-dispose'* economic model, which attempts to minimise waste and material inputs to the economy through eco-design, recycling and reusing products [68]. However, the *Ellen MacArthur Foundation* [71] present it more broadly in terms of expanding the 'waste hierarchy', 'circling longer', or enabling cascaded use. The *Foundation* claims that these approaches increase employment, more effectively capture value, mitigate exposure to supply chain and market risks, and better develop customer relationships. A reassignment of material flows within the *circular economy* has consequently been conceptualized by the European Commission [68], and is represented schematically in Fig. 8. Cooper et al. [70] recently collated evidence on specific quantifiable CE approaches, and then calculated their combined overall supply chain impacts via IO analysis. Energy saving opportunities were found to amount to between 5% and 8% in the UK [70], which is equivalent to the total scope for other industrial energy efficiency savings. Cooper et al. [70] broke down the potential savings that could be achieved in the UK through the different subsets as illustrated in Fig. 9. These included food waste, steel production, other materials production, product refurbishment, vehicle provision, construction, and other equipment manufacture. In cases where the options were already in use (e.g., through recycling), the savings represent potential increases in their level of application. Approaches for '*getting more out*' were found to have greater potential in the UK than those

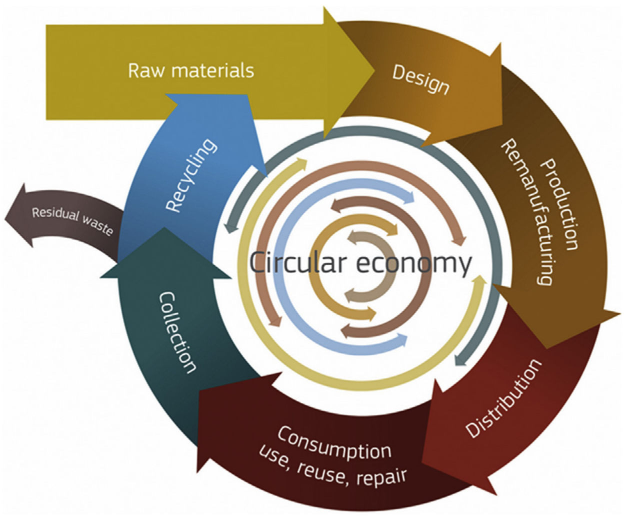

Fig. 8. Schematic representation of material flows in a more '*circular economy*'. *Source:* European Commission [68].

associated with '*putting less in*'. This partially reflects the relatively high proportion of imported products that are consumed in the UK, but also that relatively few of the British manufactured products are suitable to '*putting less in*' options. It should be noted that the results relating to steel material efficiency [70] include practices like reducing yield losses in forming. Widespread use of steel in construction, vehicles and other goods means that total potential savings associated with steel could be even higher (i.e., some of the savings that are included within the calculated results are related to other sectors, not to the '*steel*' findings displayed in Fig. 9). The relative prominence of the '*reducing food waste*' approaches relate primarily to their broad applicability [70], but some of the potential reductions in UK food waste have already been secured.

Much of the focus of the *circular economy* has been on recycling [68], although recent studies highlight the need for design to support "slow resource loops" (e.g., long-life products, product-life extension) alongside strategies to "close resource loops" (e.g., design for technological cycles, design for biological cycles, design for disassembly and reassembly) [72,73]. The growing field of design for behaviour change provides methods and tools to foster pro-environmental and pro-social action through the application of theories, models and approaches from the social sciences. Drawing upon the somewhat contrasting approaches of social psychology and social practice theory, researchers associated with the present co-authors have developed a *Design for Individuals and Practices Toolkit* to help designers explore interactions between users and their practices early in the design process. The aim is to capture the interrelation between individuals and specific combinations of the 'material', 'meaning' and 'competence' elements of practices in order to achieve more sustainable, product and service solutions [74]. This implies an economic model based on sharing, lending, swapping, gifting, bartering, or renting products and services that is often considered resource-efficient. By making it possible to access the use of goods without owning them, such consumption may prevent new purchases, increase the use of each product and promote reuse of unwanted possessions.

Research on product lifetimes has grown in recent years, most notably for vehicles, electrical and electronic equipment and clothing, typically associated with waste reduction and circular economy initiatives. Due to the size and weight of vehicles it has long been highlighted as a sector in which substantial reductions in material flows could be achieved through increased longevity [75]. Increasing the quality of cars through design could enable important reductions in their environmental impact [76,77], although recent evidence of significant variations in the car lifetimes across the world suggest that design may not be the only important factor [78]; systemic factors and consumer attitudes are also relevant. Moreover, products with a high energy impact during the use phase could be designed as use-intensive products [79] that might maintain the overall amount of usage while reducing longevity.

Discarded electrical and electronic equipment is a rapidly growing waste stream which has increased, in part, because advances in technology have contributed to shorter product lifetimes [64,80]. As such, *waste electrical and electronic equipment* (WEEE) has received increasing attention from policy makers [81]. Past research has revealed the large proportion of end-of-life consumer electronics disposed of through residual waste collections and destined for landfill disposal or incineration [82,83]. This represents a missed opportunity for extending lifetimes by facilitating recovery for repair or reuse, which would be preferable in the context of their high levels of embodied carbon [84] and the valuable materials that many contain.

Finally, one means of using resources more efficiently is through upcycling, the process of creating or modifying a product from used materials, components or products that are equal or higher quality or value than the compositional elements [85]. Upcycling reduces the use

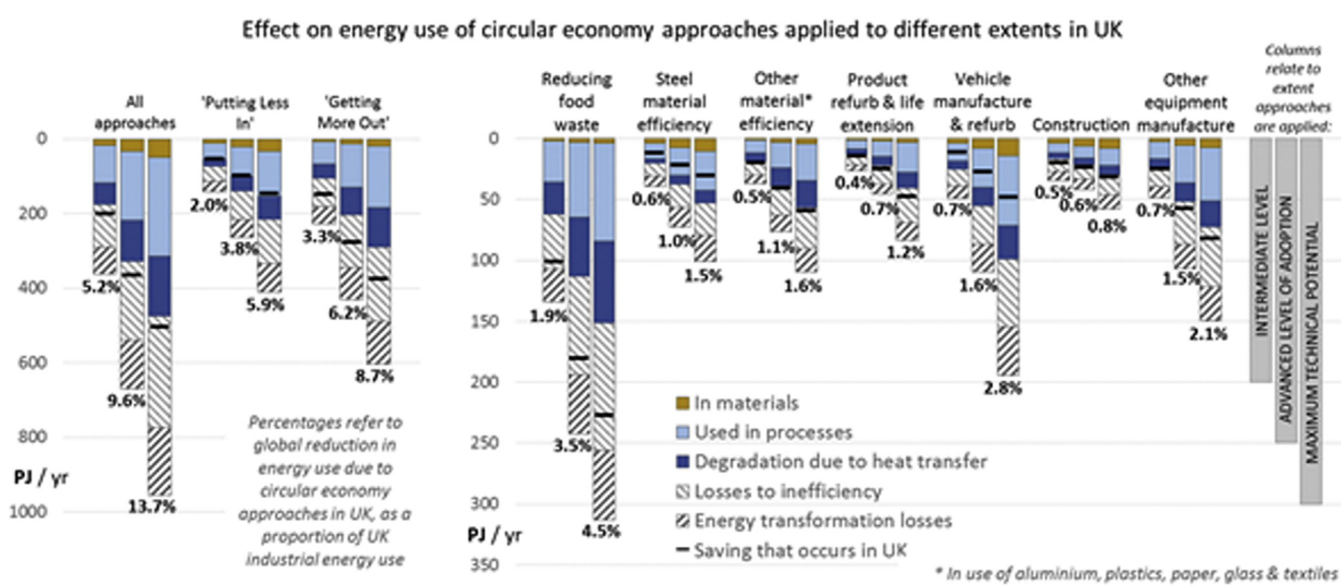

Fig. 9. Reduction in energy use possible for the UK through different subsets of '*circular economy*' interventions. *Source:* adapted from Cooper et al. [70].

of raw materials for production by extending the lifetimes of used materials, components and products; it thus increases material efficiency [11] and reduces industrial energy consumption [1], contributing to reducing GHG emissions. Its other potential benefits are reducing solid waste (or, at least, delays the addition of waste to landfill) and cost savings and new profit opportunities. Upcycling appears to have potential to create high attachment leading to product longevity. Past research in upcycling has focused on fashion industry and plastic recycling. Relatively little attention has been paid to upcycling in households despite apparent growth in practice among the general public.

The key insights and lessons from these studies can be summarised, for example, as:-

- Much of the focus of the *circular economy* has been on *recycling* [68], although there is a need for design to support multiple loop strategies [73]: "slow resource loops" (e.g., longer lasting products and product-life extension) alongside strategies to "close resource loops" (e.g., design for disassembly).
- *Circular economy* approaches have the potential to make significant energy savings that are complementary to other energy efficiency measures and equivalent to their potential [70]. The approaches exhibiting the greatest potential energy savings are often those that can either be applied broadly or relate to relatively concentrated flows of goods or services. For example, some options to reduce food waste can be applied to a large proportion of the existing food waste, whereas some of the options to improve resource efficiency in manufacturing or construction are specific to particular processes.
- *Upcycling* – the process of creating or modifying a product from the materials used, components or products (of equal or higher quality or value than the compositional elements) – aids the employment of resources more efficiently [85]. It reduces the need for raw materials by extending the lifetimes of the materials, components and products. This can increase material efficiency, whilst reducing industrial energy use and GHG emissions. Solid waste (or delays waste to landfill) can also be reduced, thereby resulting in cost savings and yielding new profit opportunities. Thus, upcycling appears to have potential to create high attachment leading to product longevity.
- Reductions in materials consumption will have implications for the kind of products purchased by consumers. A major survey of UK consumers is being undertaken that will reveal the extent to which consumers are satisfied with how long products currently last. Research in the vehicles sector is exploring whether using products more intensively, as in the case of car sharing, could reduce the number of cars needed to provide the service required (i.e., mobility).

7. The role of publics, society and decision-makers in achieving transitions in UK energy and materials

Traditional research on mitigation of GHG emissions has focused on direct consumption of energy (how we supply energy, what types of fuel we use, and how we use them, etc.). The role that materials and products might play in energy demand reduction is far less well studied. It might be argued that a step change in reducing the energy expended by UK industry can only come about if we are able to identify new ways of designing, using, and delivering products, materials and services. Before firm recommendations can be made to decision-makers regarding the combined technical and social feasibility of new products and material strategies, a fundamental set of research questions will need to be addressed [86]. These concern how various publics will respond to innovative proposals for product design, governance and use. For example, more energy efficient products may need to operate differently or look very different, while a significant shift from an ownership model to a service delivery model (e.g., direct car ownership to car clubs and rental) can also deliver considerable material efficiency and energy demand reduction.

Pigdeon et al. [87] recently examined some of the critical issues concerning the design and conduct of public deliberation processes on energy policy matters of national importance. In order to develop their argument, they employed as an illustrative case study, some of their earlier work on public values and attitudes towards future UK energy system change. They note that national-level policy issues are often inherently complex; involving multiple interconnected elements and frames, analysis over extended scales, and different (often high) levels of uncertainty. It is their view that facilitators should engage the public in terms of 'whole systems' thinking at the problem scale, provide balanced information and policy framings, and use different approaches that encourage participants to reflect and deliberate on the issues. This approach was subsequently applied to examine socio-technical imaginaries associated with low carbon housing policies [86]. Further research, partnered with *the Green Alliance* (an UK charity and independent think tank focused on ambitious leadership for the environment), is combining qualitative and quantitative social science methodologies – in particular expert interviews and workshops, deliberative research and a *Great Britain* (GB) wide national survey. A series of four two-day workshops with members of the public (n = 51) have utilised such deliberative and narrative techniques to explore the possibilities for a low material future [88]. These led to the development of a set of socio-technical scenarios and materials based on interviews with industry and policy experts that embraced a number of different strategies, such as: increased product longevity; product service systems; remanufacturing and producer responsibility; collaborative consumption; eco-packaging; waste management systems; more efficient use of existing materials; and carbon taxes [88]. It was found that the discourse surrounding new resource efficient business models echo many of the essential values people want to see in terms of system level changes (such as reducing waste, better use of finite resources, achieving energy affordability and security etc.). Therefore there is hope that in many cases they may be embraced by the wider public, although any new business model will need to align with a public vision of an affordable and secure future. This research by Pidgeon and Cherry [88] highlights some of the core values that would need to be satisfied by effective material demand reduction strategies. Those that limit perceived autonomy and freedom of individuals may prove particularly challenging. An innovative aspect of this research is a set of targeted policy engagement activities where the researchers have been holding workshops, interviews and other forms of direct stakeholder involvement, exploring the implications of the findings about public views with key decision-makers in UK businesses, policy and the political sphere (including Parliamentarians through the *Green Alliance*'s 'Climate Leadership programme for MPs').

Cherry and Pidgeon [89] recently undertook a linked study for the UK *Government Office for Science* in which they examined innovative business models for designing, using, and delivering products and services that will potentially lead to radical reductions in embodied carbon/energy, but could result in profound social challenges. They explored two examples of resource-efficient business models: *Product Service Systems* (PSS) and *Collaborative Consumption* (CC). PSS focuses on service provision rather than on product sales. This will provide a good quality and experience at an affordable price, whist reducing waste and resource use. It shifts ownership patterns, but retains consumers' behaviour and product use practices. On the other hand, CC encompasses a broad range of peer-to-peer approaches: internet selling, renting, swapping, sharing and gifting products and services. These may have more radical implications for the way in which consumers conduct their lives or interact with other citizens and businesses. Cherry and Pidgeon [89] conclude that there is a need for much better understanding of the utilisation of new consumption practices, and how they might enhance or disrupt the provision of a service. They also suggest that the UK Government has a role in incubating new resource-efficient businesses, at the same time as offering consumers a simple alternative that improves their lifestyles.

8. Concluding remarks

It has been argued that reducing industrial energy demand could make a substantial contribution towards the UK Government's goal of significant (80%) decarbonisation by 2050 [2,3], whilst simultaneously improving productivity and creating employment opportunities. This sector of the UK economy accounts for some 21% of total delivered energy and 29% of CO_2 emissions [15,16]. The focus here was on the complexity and diversity of the industrial sector with an emphasis on the situation in the UK. 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. This gives rise to significant 'industrial complexity'. Nevertheless, the lessons learned are applicable across much of the industrialised world. Some element of sectoral aggregation is therefore inevitable in order to yield policy-relevant insights [1]. In order to determine the scope for industrial energy use and CO_2 emissions reduction a number of top-down and bottom-up energy analysis and carbon accounting techniques have been assessed [16].

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 globalization [31–34]. In the short term, a variety of currently-available technologies (BATs) will lead to further energy demand and CO_2 emissions reduction in manufacturing, but the prospects for the commercial exploitation of innovative technologies out to the middle of the 21st century are far more speculative [15,46,55,56]. However, the attainment of significant falls in carbon emissions depend critically on the adoption of a limited number of key technologies [e.g., CCS/*carbon capture and utilisation* (CCU), energy efficiency and heat recovery techniques, and biomass], alongside a decarbonisation of the electricity supply. Efficiency gains can be made in industry, including in the use of heat and improvements in processing. Changes in the use of materials needed to manufacture products (such as material substitution, light-weighting and '*circular economy*' interventions) can also lead to emissions reductions [9,69]. Finally, altering the way the final consumer (industry, households or government) use products, such as via product longevity and shifts from goods to services, will lead to energy demand reductions [62–64,68,83]. New models of ownership and value extraction are also developing [89], including platforms for selling or disposing of second-hand articles, sharing ownership of goods, and recycling unwanted products. However, it is unclear whether these platforms are generating a more '*circular economy*', or whether they are acting to increase overall consumption. The reality may involve a mixture of both outturns. Thus, the challenges, insights and opportunities associated with industrial decarbonisation over the transition towards a low-carbon future in the UK have been described with the purpose of providing a valuable evidence base for industrialists, policy makers, and other stakeholders.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.applthermaleng.2018.03.049.

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