Advanced Review

Industrial energy use and carbon emissions reduction: a UK perspective

Paul W. Griffin,[1] Geoffrey P. Hammond[2] and Jonathan B. Norman[1]*

Progress in reducing industrial energy demand and carbon dioxide (CO_2) emissions is evaluated with a focus is on the situation in the United Kingdom (UK), although the lessons learned are applicable across much of the industrialized world. The UK industrial sector is complex, because it may be viewed as consisting of some 350 separate combinations of subsectors, devices and technologies. Various energy analysis and carbon accounting techniques applicable to industry are described and assessed. The contributions of the energy-intensive (EI) and nonenergy-intensive (NEI) industrial subsectors over recent decades are evaluated with the aid of decomposition analysis. An observed drop in aggregate energy intensity over this timescale was driven by different effects: energy efficiency improvements; structural change; and fuel switching. Finally, detailed case studies drawn from the *Cement* subsector and that associated with *Food and Drink* are examined; representing the EI and NEI subsectors, respectively. Currently available technologies will lead to further, short-term energy and CO_2 emissions savings in manufacturing, but the prospects for the commercial exploitation of innovative technologies by mid-21st century are far more speculative. There are a number of nontechnological barriers to the take-up of such technologies going forward. Consequently, the transition pathways to a low carbon future in UK industry by 2050 will exhibit large uncertainties. The attainment of significant falls in carbon emissions over this period depends critically on the adoption of a limited number of key technologies [e.g., *carbon capture and storage* (CCS), energy efficiency techniques, and bioenergy], alongside a decarbonization of the electricity supply. © 2016 The Authors. *WIREs Energy and Environment* published by John Wiley & Sons, Ltd.

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INTRODUCTION

The industrial sector accounted for almost one-third of world primary energy use and approximately 25% of world carbon dioxide (CO_2) emissions from energy use and industrial processes in 2005.[1] High growth in production and energy use have been seen in the emerging economies, such as India and China, with China being responsible for 80% of worldwide growth in industrial production over the past 25 years.[1] In contrast, the UK has seen a reduction in industrial energy use whilst continuing to increase output in economic terms.[2] It accounts for some 21% of total delivered energy and 29% of CO_2 emissions. Industry is also very diverse in terms of manufacturing processes, ranging from highly energy-intensive (EI) steel production and petrochemicals

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*Correspondence to: j.b.norman@bath.ac.uk

[1] Department of Mechanical Engineering, University of Bath, Bath, UK

[2] Department of Mechanical Engineering and Institute for Sustainable Energy and the Environment (ISEE), University of Bath, Bath, UK

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processing to low-energy electronics fabrication.[2] 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 subsectors, devices and technologies can be identified[2]; 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.[2] Despite significant improvements in the energy intensity of manufacturing in the *United Kingdom of Great Britain and Northern Ireland* (UK) (defined as *energy use per unit of economic output*), considerable reductions in the CO_2 emissions are still required. The UK *Climate Change Act* 2008[3] has put into law an ambitious long-term target of an 80% reduction in 'greenhouse' gas (GHG) emissions by 2050 compared with 1990 levels. If industrial emissions remain steady they would grow from approximately a quarter of the UK emissions in 2010 to over half of the allowed emissions under the 2050 target.[4] Economy-wide emissions targets are therefore likely to require a reduction of approximately 70% from industry.[4] If historical growth of the sector continues, then a range of options will be required to make the necessary reductions. This would include falls in energy intensity, through fuel switching and improved efficiency; the widespread use of bioenergy and the electrification of processes; and the use of carbon capture and storage (CCS).[4]

Issues associated with anthropogenic global warming and climate change, as well as with energy security, are of worldwide concern. Consequently, British attempts to reduce and decarbonize energy demand must be seen as part of an international effort. The lessons learned from the path to decarbonization that is taken by the UK industrial sector will also be applicable elsewhere in the industrialized world. Energy demand reduction consists of both energy efficiency improvements and behavior change.[5] 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 or pounds sterling). But consumers could also be encouraged to reduce their energy use by changing their service demands.[5] 'Smart' technologies can, e.g., 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 peaks typically in the morning and evening. This profile may be smoothed, and the overall power requirement lowered, by shifting flexible tasks in industry to off-peak times. The present study builds on work by Dyer et al.[2] commissioned by the UK *Government Office of Science* (GOS). The range of assessment techniques for determining potential energy use and GHG reductions are initially discussed. The wider UK industrial landscape is assessed with the aid of decomposition analysis in order to identify the factors that have led to energy and carbon savings over recent decades. Two subsectors of UK industry are then examined in terms of their energy use and GHG emissions, as well as their improvement potential: 'Cement' processing and 'Food & Drink' production. They are both important users of energy; representing EI and nonenergy-intensive (NEI) subsectors, respectively.

ASSESSMENT TECHNIQUES IN AN INDUSTRIAL CONTEXT

Background

Sustainable development (SD) implies the balancing of economic and social development with environmental protection: the so-called 'Three Pillars' model.[7] In the long term, Planet Earth will impose its own constraints on the use of its physical resources and on the absorption of contaminants, whilst the 'laws' of the natural sciences (such as those arising from thermodynamics) and human creativity will limit the potential for new technological developments.[7] SD is a process or journey toward the destination of 'sustainability.'[7] It is a key concept when examining energy use and associated emissions, and has foundations in engineering, economics, ecology and social science (see, e.g., Hammond and Winnet[7]). Therefore, the use of multiple techniques to examine various aspects of sustainability is sensible when assessing different technologies. Such techniques may yield informative quantitative measures or an improved qualitative understanding. Dyer et al.[2] reviewed technology assessment methods applicable to the industrial sector, including integrated appraisal methods, thermodynamic techniques, environmental life-cycle assessment (LCA), and environmental cost-benefit analysis. Hammond and Winnet[7] argued that such appraisal methods can play an important evaluative role as part of an interdisciplinary toolkit within a general systems framework. The discussion here builds specifically on the work of Dyer et al.[2] to demonstrate how these, and additional, techniques can be applied for estimating future energy use and GHG emission levels from industry.

In order to provide the information required for an assessment of improvement potential within the industrial sector a number of steps must be taken. The current state of energy use and emissions within the various subsectors needs to be examined as an initial step, along with the identification of the processes used and outputs produced. Once the baseline is well understood potential technologies for reducing energy use and emissions need to be assessed, both in terms of the contribution that can be made to reducing emissions and the likelihood of realizing this potential. This section examines the basic approach that can be taken to an assessment of the industrial sector, as well as the identification of some of the techniques available to determine baseline energy use and potential energy saving technologies.

Top–Down Versus Bottom–Up Approaches

There are broadly two approaches to modeling the industrial sector, top–down and bottom–up, as illustrated in Figure 1 (adapted from Dyer et al.[8]). A top–down approach splits industry into subsectors, usually based on available statistical data, and uses these data to determine energy use, output, energy intensity, and other measures for which data are available. Whilst this approach has the advantage of covering a large proportion of energy demand, the limits imposed by the level of disaggregation available from industry-wide statistical sources means that the conclusions that can be drawn from top–down studies are often only indicative in nature. A bottom–up approach, by contrast, would typically focus on a single industrial subsector and disaggregates the energy demand indicated by industry-wide statistical data sources. Thus, energy use is separated into lower order subsectors, processes and manufacturing plants. The data used for a bottom–up study will come from more specific information sources, such as trade associations, company reports, and case studies. Such a bottom–up study, therefore, can be useful in terms of presenting more accurate findings,[8] although it will be limited in the breadth of its application.

A hybrid approach, taking aspects of both top–down and bottom–up models is possible, with detailed bottom–up studies, set within a top–down framework. Using this approach would normally entail focusing on a number of subsectors for the bottom–up study, with the remainder of the sector being treated in a generic manner. Subsectors that use a large amount of energy are obviously prioritized for bottom–up studies. Additionally, subsectors that use energy in a relatively homogeneous manner are easier to analyze and this may also be considered when selecting appropriate subsectors. For subsectors that are not the subject of detailed bottom–up modeling, a focus on the potential reduction in emissions through widely used, 'cross-cutting' technologies can be useful. An example of this approach is the *Usable Energy Database* (UED),[9,10] produced by the present authors for the UK industrial sector as part of the research program of the *UK Energy Research Centre* (UKERC).

Thermodynamic Analysis

Thermodynamic methods provide an indication of the quantity (enthalpy) and quality (exergy) of an energy flow.[2,7,8,11,12] 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 subsector or process provides allows the theoretical minimum *specific energy consumption* (SEC), the energy use per physical unit of output, to be calculated.[13] The definition of this energy service is important. De Beer[13] considers the energy service for steel making. A broadly defined energy service such as production of a material with certain properties, e.g., strength, allows a consideration of alternative materials, whereas specifying simply the making of steel allows options such as scrap utilization to be considered.[13] A narrowly defined energy service, such as making steel from iron ore, further limits the scope of improvements to those that produce virgin steel.[13] 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 establishment of a minimum theoretical SEC serves as a comparison of where current technology performs and where the limit for improvement lies. Whilst it is recognized this limit will not be reached in practice it can still be insightful in indicating where departures from this optimal occur.[2] Energy and exergy analysis[2,7,8,11,12] can indicate those areas where inefficiencies occur within the constraints of the existing system, as well as the improvements that may be possible. Indeed Hammond and Stapleton[11] present the maximum theoretical improvement, or energy saving, potential across the

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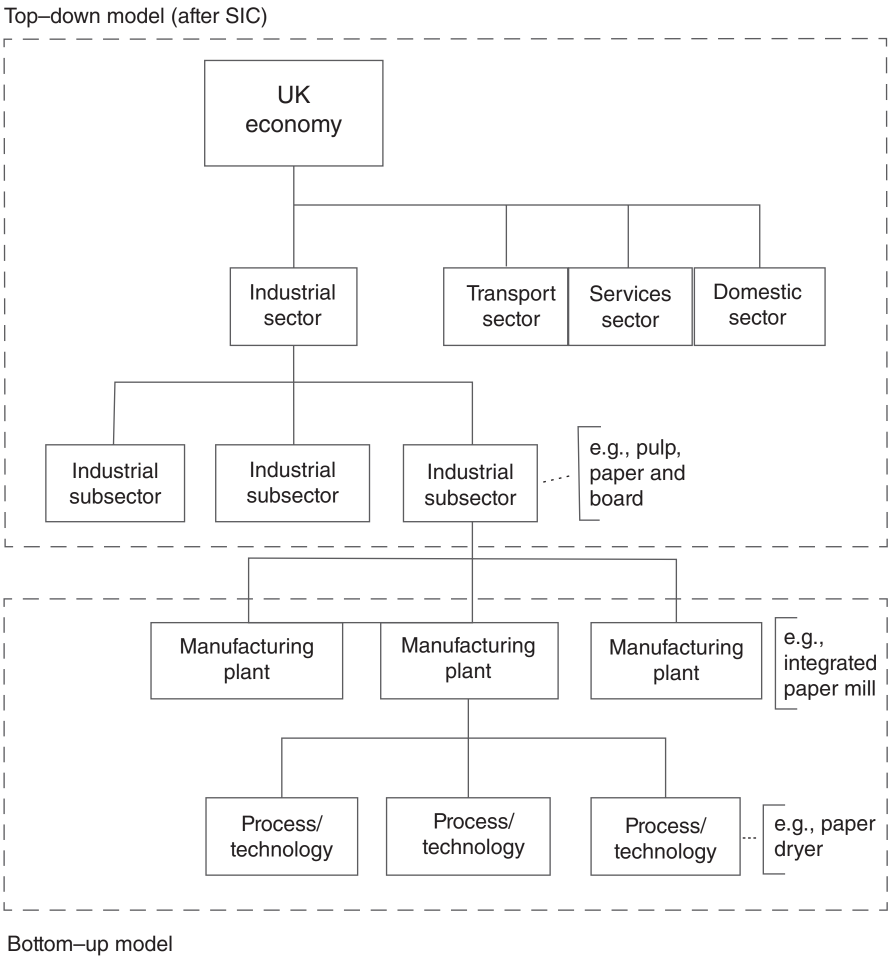

FIGURE 1 | Top–down and bottom–up model schematic. (Reprinted with permission from Ref 8. Copyright)

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,[2,7] this has widely been referred to as the 'energy efficiency gap' and the 'energy efficiency paradox.'[7,15] This is illustrated schematically in Figure 2, which depicts the economic and technical barriers (as well as the thermodynamic limits) that must be faced in securing energy-efficiency savings in practice.[7,15] Roughly, this implies 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%.[2,7] This suggests the thermodynamic analysis can provide a valuable signpost to where technologies can have the greatest impact.

Decomposition Analysis

A decomposition analysis separates the effect of different factors contributing to changes in energy demand or energy-related GHG emissions over time. With suitable data, it can be applied to the whole industrial sector or to a subsector. Hammond and Norman[16] used a decomposition analysis to examine changes in the energy-related carbon emissions of UK manufacturing from 1990 to 2007. The effects of changes in output, structure, energy intensity, fuel mix, and the emissions factor of electricity respectively on GHG emissions were examined. Kim and Worrell[17] undertook a decomposition analysis of the iron and steel subsector in various nations as an example of applying the technique to a single subsector. Griffin et al.[18] utilized a decomposition analysis as part of an evaluation of the opportunities for the reduction of GHG emissions in the UK cement sector.

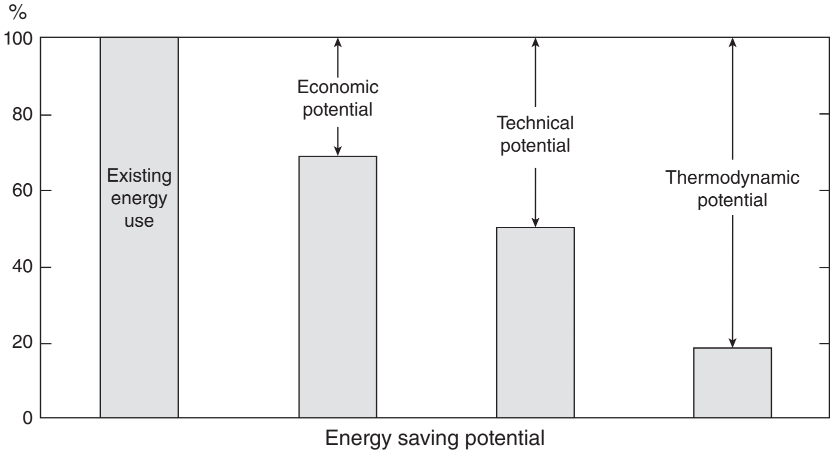

FIGURE 2 | Energy efficiency gap between theory and practice.[7]

Examining the underlying reasons for previous improvements in emission levels and energy use through decomposition analysis helps understand how these earlier gains were realized, and whether a similar approach will yield further improvement in the future.[16] Technical improvements can improve energy efficiency, and hence decrease the energy intensity. This was found to have the greatest influence on UK industrial energy-related GHG emissions between 1990 and 2007.[16] However, other factors can also make important contributions. The recent (2008) economic downturn or 'recession' led to a decrease in output in many industrial subsectors, and so reduced energy demand and associated emissions. Whether production will 'bounce-back' to prerecession levels is an important consideration in looking at near-term emissions going forward.

Other Engineering Approaches

There are a variety of other engineering-based appraisal techniques that can provide complementary insights into the principal methods summarized above. The simplest is probably 'mass and energy networks,'[2] which is based on the fundamental principles of mass and energy conservation. Variants of mass and energy networks that are common in chemical or process engineering have been extended to deal with complex processes involving reactive systems and multi-phase flows.[2] One technique that has been widely adopted is so-called 'pinch' analysis or technology. This is a method for analyzing 'heat exchanger networks' and process plant to yield optimal configurations.[19,20] It was extended and commercially exploited in the UK and beyond by Professor Bodo Linnhoff (formerly at what is now the University of Manchester in the UK), after which it was incorporated under the generic title of 'process integration.' Comparative studies have been undertaken to evaluate the results of exergy analysis with pinch technology. For example, Wall and Gong[21] examined a case where heat exchanger networks could be employed along with heat pumps. They concluded that pinch analysis was inadequate in that situation and recommended the adoption of 'exergoeconomic' optimization.[22] In addition, various methods of system optimization can be employed to optimize the performance of refrigeration equipment, power plants, pumps, fans, and the like. These methods are diverse, embracing economics, equation fitting, search methods, system simulations, steady-state simulation, dynamic programming, geometric programming, dynamic behavior of thermal systems, and calculus methods of optimization, as well as probabilistic approaches to design (see, e.g., Ref 23).

Embodied Energy and GHG Emissions in Materials, Infrastructure, and Products

In addition to the energy use and emissions at a manufacturing site, a product will have upstream or 'embodied' energy[a] and carbon emissions resulting from material extraction, transport, and theearly stages of production.[24–26] 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[24,25]), which examines energy and carbon emissions on a 'cradle-to-grave' basis using process LCA,[26] and UK input–output (IO) table models (such as those developed by the *Stockholm Environment Institute*, based at the University of York[27]). 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. Therefore, 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, would not be a favorable choice. This approach of considering indirect emissions is similar to environmental LCA,[2,7,26] 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.

An additional, related issue is that of 'carbon leakage.' 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. No net fall in emissions may result, if the boundary of the analysis is drawn beyond the UK borders.[28] This carbon leakage may involve an overall rise in emissions, compared with 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, e.g., in the UK.

Economic Analysis

The idea that prices reflect economic value led to the development of the techniques of economic analysis for the assessment of both private and public sector investment.[7,29,30] *Financial appraisal* evaluates the costs and benefits of any project, program, or technology in terms of outlays and receipts accrued by a private entity (household, firm, etc.) as measured through market prices.[31] It omits environmental externalities, or any costs or benefits that may occur beyond the firm or private individuals (i.e., consumers).[7] Therefore *economic cost-benefit analysis* (CBA) is applied to take a society-wide perspective, with a whole systems view of the costs and benefits. It can provide an important input into the evaluation of many projects that have significant impacts on the environment. In such cases it is necessary to internalize some of the costs and benefits that might otherwise be viewed as being external to the market. This valuation process is uncertain and potentially controversial, often relying on the determination of shadow prices. In mainstream environmental economics, time is routinely dealt with by discounting. Costs and benefits in monetary terms are progressively discounted for future years in order to allow for the 'time value of money.'[29] Investment appraisal results in the determination of a single decision criterion; typically either the *net present value* (NPV) over the project life, the corresponding discounted cost-benefit ratio, or some related parameter. In dealing with risk, economic analysis generally assumes a world of calculable probabilities. Thus, a probability distribution for the decision criterion, such as the discounted cost-benefit ratio, is obtained if uncertainty is explicitly taken into account.[7]

CBA accounts for private and social, direct and indirect, tangible and intangible costs, and regardless to whom they accrue and whether or not they are accounted for in purely financial terms.[31] A further distinction between *financial appraisal* and *CBA* is in the use of the discount rate to value benefits and costs occurring in the future. Financial appraisal uses the market rate of interest (net of inflation) as a lower bound, and therefore indicates the real return that would be earned on a private sector investment.[7] CBA employs the so-called 'social rate of discounting,' and therefore assigns current values to future consumption based on society's evaluation of the trade-offs involved. The real market rate of interest is subject to continuous fluctuations depending on many economic parameters.[32] Economic CBA for public investment in the UK often adopts the current 'test discount rate' of 3.5% employed by the British government for investment appraisal purposes.[29] In contrast, a recent study by the management consultants *KPMG*[33] found that the average UK cost of capital after corporate taxes amounted to 7.9%.

Drivers and Barriers to Industrial Energy Demand and GHG Emissions Reduction

The Drivers for Change

The business environment in which new processes or technologies are developed and brought to market is a crucial factor in determining their rate of market penetration.[2] It is therefore worthwhile examining the circumstances under which the user (typically, but not always, a firm) will decide whether to adopt these processes or technologies. There are two principal drivers in industry behind the adoption of energy demand management measures, namely costs and legislation. Energy costs represent a large proportion of operating expenditure (often as much as half) for EI subsector, whereas for NEI subsectors they are an order-of-magnitude smaller than this (only around 5%).[2,8] Hence, this driver is much stronger within the EI industries. In addition, environmental legislation typically punishes firms for polluting, by imposing fiscal penalties on the burning of fossil fuels. On a European scale, the European Union (EU) *Emissions Trading System* (EU ETS, formerly known as the EU Emissions Trading Scheme) is a 'cap and trade' policy, which aims to create a market for carbon.[2,8] The allocation of permits is based on the projected emissions for particular industrial subsectors. However, there remain significant weaknesses in the EU ETS that need to be addressed if it is to be effective, including the method for allocating the permits. The latter has been criticized because some EU member states initially proffered liberal estimates of their projected emissions for inclusion in their national allocation plans (NAPs).[8] This enabled them to obtain more permits than they would otherwise be allocated. It has also been suggested that the total number of permits allocated was too high,[8] and that the frequency of information disclosure was too infrequent.[8] This gave rise to market ignorance in relation to the oversupply of permits, and hence trading took place on a false premise. Additional drivers for energy demand reduction include competitiveness within the marketplace, associated intangible benefits [such as the delivery of *Corporate Social Responsibility* (CSR) requirements] and fiscal support from third parties.[8] The benefits of energy demand management measures via other areas can also be significant, e.g., improvements in productivity (see Ref 34). In fact, the nonenergy benefits are often greater than the value of the direct energy savings.[8,35]

The Barriers to Change

There are several barriers preventing firms from adopting enabling technologies for energy demand management.[2] These are often diverse with the main barriers being hidden costs, management focus on 'core business' issues[36] (such as production output), lack of information, and (in some cases) the availability of capital.[37–40] Many result from a lack of specialist knowledge on the part of the firm. So they include, *inter alia*, economic market and nonmarket failures, the investment costs associated with new plant, as well as a certain degree of management inertia. Jaffe and Stavins[15] highlighted some market failures associated with the public good of information, in particular its nonrival and nonexcludable properties, which for energy-efficiency technologies is a significant barrier to uptake. Perhaps the most significant nonmarket failures are those of hidden costs and access to capital, together with imperfect information, they are amongst the highest barriers.

Lack of information is consistently cited as one of the main barriers, particularly lack of submetering.[39] It is generally a greater problem for the NEI subsector of manufacturing, for whom energy use is not of as great importance as for the EI industries.[40] There is some disagreement over whether lack of capital is really a significant barrier.[37,39,40] Sorrell et al.[40] found hidden costs and access to capital were the main barriers in an extensive survey of barriers to industrial energy demand reduction with access to capital most significant in relation to small- and medium-sized enterprises (SMEs).

The potential for energy saving opportunities in the NEI subsector of manufacturing is often underplayed by energy policy makers.[36] In contrast, the EI subsector is generally easier to analyze, but the NEI subsector comprises a significant proportion of overall energy use. It is therefore thought that the potential for relative savings in the latter subsector may be greater than in the rest of industry[36]: the NEI subsector is responsible for 38% of the manufacturing sector's final energy demand in the UK. Cross-cutting technologies are likely to have greater relative impact in this subsector.[36] Policy instruments can also act to increase the effectiveness of drivers to adopting energy efficient technology, or to remove the barriers.

THE INDUSTRIAL LANDSCAPE

Character of the Industrial Sector

The current situation in regard to energy use in UK industry and its recent historic development can obviously influence the potential for future improvements. Thus, since the 1973 oil price 'hike,' industry has been the only sector of the UK economy to have experienced a dramatic decline in final energy demand of roughly 50% in the period 1973–2007[41] (prior to the global economic slump of 2008). This was in spite of a rise of some 15% in the real *gross value added* (GVA) of industry over the same period.[42] The consequent drop in aggregate energy intensity (defined as *energy use per unit of economic output*) is driven by different effects:

- *Energy efficiency*: A large part of the decline in industrial energy intensity can be attributed to energy efficiency improvements; an estimated 80% of the fall in industrial energy demand between 1970 and 1995 resulted from this.[43]
- *Structural change*: The relative size of industrial subsectors has changed with a transition away from EI industries.[44]
- *Fuel switching*: Coal and oil use has steadily declined in favor of 'cleaner' fuels, such as electricity and gas.[44] These 'cleaner' fuels can be used with a higher degree of control and so are

> more efficient than alternatives. Additionally, when examining primary energy demand, the increase in the efficiency of electricity generation (largely caused by fuel switching in favor of natural gas) will have the effect of lowering primary energy use.

In the period 1990–2007, it was found through the decomposition analysis by Hammond and Norman[16] that 'energy-intensive' subsectors gave rise to relatively smaller reductions in GHG emission reductions and energy intensity improvements than the rest of industry. This was thought to be partly due to low energy prices throughout the majority of this period, which reduce the impetus toward improving energy efficiency in EI subsectors. In contrast, from 1973 to 1990 higher relative prices caused the EI subsector to invest in energy efficiency. This potentially left fewer remaining cost-effective opportunities, or 'low hanging fruit,' for improving energy efficiency, and hence limiting improvement post-1990. A general slowing of industrial energy intensity improvements has been observed in both the UK and more widely in other developed nations.[45,46] 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) programs,[47] especially within the EI subsectors. As a result of these trends, there is expected to be relatively larger energy improvement potential in NEI subsectors of industry, particularly in 'SMEs.'[36] This does not mean that the improvement potential in EI subsectors has 'run its course,' but that larger interventions and major changes to the current system may be required to secure significant improvements, rather than relying on relatively small, continual changes.[16]

Subsector 'GHG' Emissions

The GHG emissions from the UK industrial sector split by subsector[5] are illustrated in the pie chart presented as Figure 3. This includes emissions from energy use (including those indirectly emitted from electricity use) and process emissions. Subsectors with significant process emissions are steel, chemicals, cement, aluminum, glass, ceramics, and lime. Information on energy use,[48] emission conversion factors,[49] and process emissions[50] were combined to construct Figure 3. It reveals that a number of subsectors that dominate GHG emissions from the industrial sector, and suggests priorities for bottom–up studies. The post-2008 economic recession in the UK (and globally elsewhere) has resulted in the closure of some large plants, this should be considered when viewing the data presented in Figure 3 (which refers to 2007). In regard to large energy users, the Teeside integrated iron and steel works was mothballed in February 2011,[50] it then changed ownership, and the blast furnace was relit in April 2012,[50] but (at the time of writing) was again closed in 2015. There have also been plans to cut jobs and production at the Scunthorpe integrated iron and steel works. Additionally, two of three aluminum smelters have been closed, or closure is planned. The long-term future of such plants, and how much capacity other plants may change in response, is currently uncertain. The closure of these major industrial facilities must be set against the background of a general economic slowdown with significant closures also seen in the cement and paper subsectors. However, the relative importance of subsectors depicted in Figure 3 in terms of manufacturing sector GHG emissions is not expected to have changed significantly from 2007 onward, with the exception of the aluminum subsector (where the bulk of energy demand may disappear).

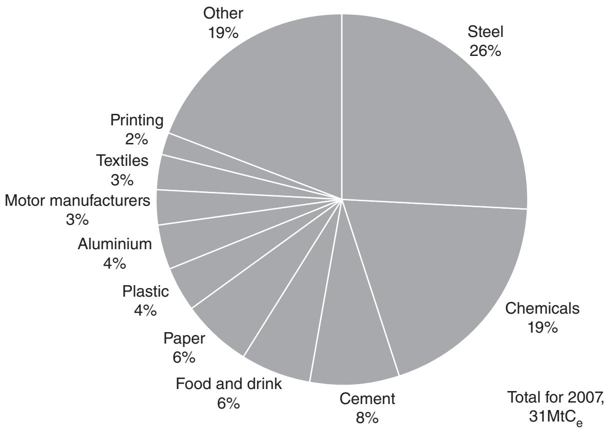

FIGURE 3 | Greenhouse gas emissions from UK manufacturing, 2007.

Subsector Variation

The diversity of manufacturing processes, ranging from highly EI steel production and chemicals processing to NEI electronics fabrication,[2] presents a substantial variation in the main challenge to an energy analysis of the industrial sector. As previously indicated, this can be split into 350 separate combinations of subsectors, devices, and technologies.[2] Thus, the EI subsector typically employs large quantities of (often high-temperature) process energy, whereas its NEI counterpart tends to be dominated by energy uses associated with space heating. So this

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variation in energy use also produces differences in the significance of energy use in the various manufacturing subsectors. Energy intensity, the percentage of costs represented by energy and water usage, and the mean energy use per enterprise for the different UK industrial subsectors are illustrated in Figure 4. A high value in any of these measures suggests that the subsector is EI (see previous work for further explanation of this approach[17]). An EI subsector is more likely to have implemented energy savings. Consequently information on energy use and improvement potential is often more readily obtained in such subsectors. An additional consideration when analyzing subsectors is their homogeneity in terms of energy use and the processes used throughout the subsector. An initial disaggregation of subsectors usually takes place at a top–down level based on available national data. But the subsectors may have considerable heterogeneity in output and intrasector variation in energy use. Further disaggregation into subsectors using similar processes will then be needed for a bottom–up energy analysis.

EXAMPLES OF SUBSECTORAL STUDIES

The Context

The various appraisal techniques discussed above have been applied to the *Cement* and *Food & Drink* subsectors as exemplars of EI and NEI industrial subsectors respectively.[b] Data presented in Figure 3 indicate that these subsectors emit comparable levels of GHGs, although their attitude toward energy saving GHG mitigation may be very different, with the Cement subsector typically placing much greater importance on its energy use. Because of these differences, and in order to illustrate the range of techniques available for assessment, the *Food & Drink* subsector was undertaken using a broader, top–down approach, whilst the *Cement* subsector is investigated in a bottom–up manner. A fuller picture of the UK industrial sector can be obtained via the UKERC industrial UED.[10,14]

Food and Drink Subsector

Energy Analysis of Food & Drink Production

The *Food & Drink* subsector produces a wide range of products, making use of many different processes. The analysis of the subsector therefore presents a challenge akin to that of examining the whole manufacturing subsector. So a detailed analysis of the processes and products that represent large uses of energy was studied, together with a more generic approach taken to the rest of the subsector. The latter examined the potential for improvements through cross cutting technologies. Energy demand in the UK *Food & Drink* subsector can be split into thirteen product groups or subsectors as shown in Figure 5. This grouping is a combination of three and four digit *Standard Industrial Classification* (SIC) codes, and is based on knowledge of the processes and products produced within the groupings; data limitations; and how the subsector is disaggregated for other purposes, such as the requirements of the UK *Climate Change Agreements* (CCAs) between the British Government and the industry. Figure 5 indicates that a number of subsectors dominate the *Food & Drink* subsector with the top five energy

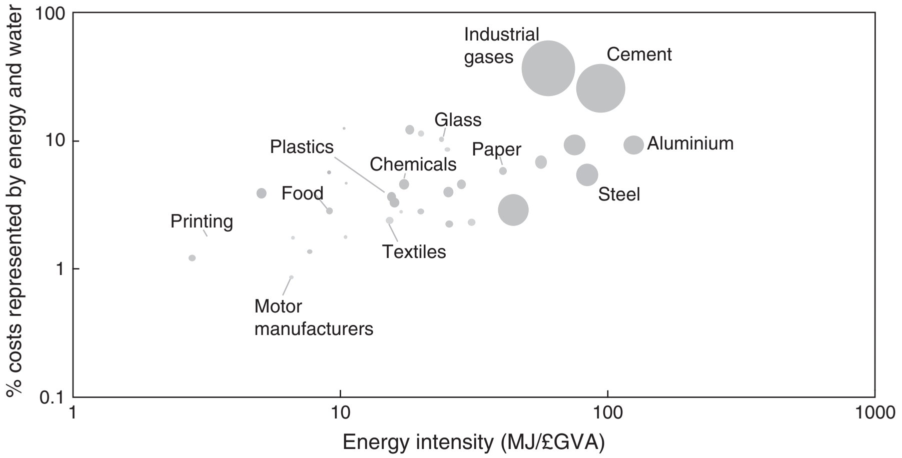

FIGURE 4 | Primary energy intensity, percentage of costs represented by energy and water, and mean primary energy use per enterprise (represented by the area of the data point). Sources: 2007 subsector data adapted from a range of statistical sources.[5,18,36,48]

using subsectors comprising approximately 60% of the total energy demand. There is clearly some uncertainty about the accuracy of energy demand data at this high level of disaggregation. For this reason, the totals shown in Figure 5 represent the mean for the period 2002–2006, with the highest and lowest energy demand over this period removed in order to filter the effect of any year-to-year fluctuations.

The energy intensity of the various products within the *Food & Drink* subsector is illustrated in Figure 6 (in a similar manner to that used to depict the energy intensity of the whole of UK industry in Figure 4). Again the data employed are the mean of that in the period 2002–2006, with the highest and lowest results (or outliers) for this period disregarded. Despite the variability of energy use seen throughout the *Food & Drink* subsector, it is actually less than that observed over the whole of the UK manufacturing sector (see Figure 4, and note the log scales used). Approximate energy flows within the *Food & Drink* subsector, from primary fuels through to end uses, can be depicted with the aid of a 'Sankey diagram': see Figure 7, based on 2006 data taken from two UK Government publications: the *Digest of*

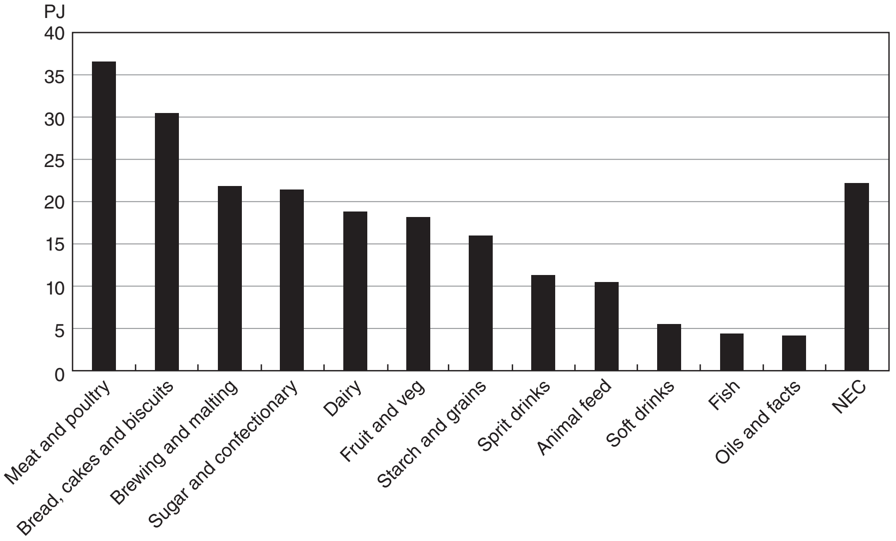

FIGURE 5 | Primary energy demand for subsectors of food and drink. Totals shown are for 2002–2006 disregarding the highest and lowest energy demands over this period.[48]

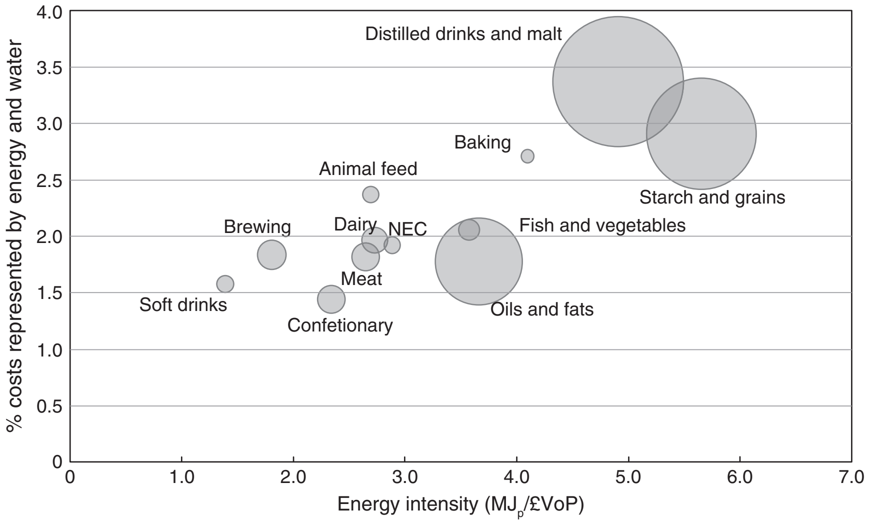

FIGURE 6 | Primary energy intensity, percentage of costs represented by energy and water, and energy use per site (represented by the area of the data points). Sources: 2007 data adapted from a range of statistical sources.[5,18,36,48]

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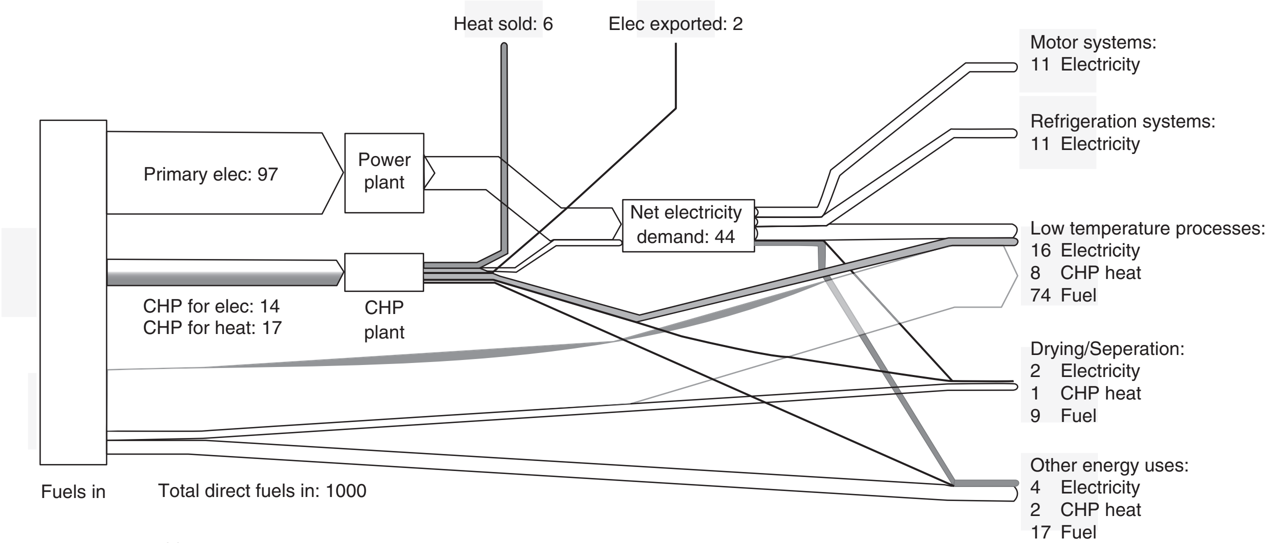

Vast majority of fuels natural gas
Distribution losses associated with fossil fuels not included
Conversion and distribution losses associated with power and CHP plant not shown.
All flows in PJ.
Flows less than 0.5PJ omitted, flows rounded to nearest PJ

FIGURE 7 | Energy flows through the food and drink subsector in 2006.

UK Energy Statistics (DUKES)[51] and *Energy Consumption in the UK* (ECUK).[52] The dominance of low temperature processing within *Food & Drink* is clear. Drying and separation, as well as space heating (included within 'Other energy uses' in Figure 7), also contribute to the demand at the low temperature end of the energy cascade.[12] A large proportion of this heat is supplied by steam systems. The UK *Food and Drink Federation* (FDF) estimate 49% of the subsector emissions arise from boilers, with another 27% from direct heating.[53] For comparison, the US *Food & Drink* subsector uses an estimated 52% of delivered energy in steam systems.[54] Assuming 50% of delivered energy is used in steam systems, this relates to 81 PJ using the data in Figure 7, which therefore amounts to 69% of heat demand. Direct heating then accounts for 37 PJ, or 23% of delivered energy.

The emphasis in the present study was on the food processing stage. However, Tassou et al.[55] provide a valuable summary of energy demand over the whole *food supply chain* (FSC): across agriculture, food processing, retailing, domestic preparation, and food disposal. Their state-of-the-art review examines the technological opportunities for reducing energy consumption, and brings together a substantial amount of information from multiple and very practical sources. It notes that the FSC is responsible for approximately 18% of total UK energy use, 176 $MtCO_{2e}$ emissions, and 15 Mt of food waste. They therefore examined the literature on energy consumption and emissions from each part of the food chain, as well as outlining approaches for demand reduction which appeared promising. In agriculture, even though energy use is moderate compared with the other parts of the whole FSC, Tassou et al.[55] contend that energy savings of up to 20% can be achieved through renewable energy generation and the use of more efficient technologies and 'smart' control systems. In fact, the sustainable intensification of agriculture and field operations, not explicitly discussed in this piece, has a huge potential to reduce energy demand across the FSC.

In food processing, Tassou et al.[55] argued that energy could be saved at the processing plant level by optimizing and integrating processes and systems to reduce energy intensity, e.g., through better process control, advanced sensors and equipment for on-line measurement, and intelligent adaptive control of key parameters. Likewise, they proposed the minimization of waste through energy recovery and better use of by-products. These findings are similar to those from the UKERC-funded industrial energy use study (Griffin et al.[10,14] that examined the *Food & Drink* subsector in terms of improvement potential from heat pumps, energy management and heat recovery, and other cross-cutting measures (such as motor and boiler systems). Tassou et al.[55] note that, in the food retail sector, significant progress in energy efficiency has been made in recent years, but that there still exists potential improvements in the efficiency of refrigeration systems, 'heating, ventilation, and air conditioning' (HVAC) and refrigeration system integration, heat recovery, and amplification (again analogous to that suggested by Griffin et al.[10,14]) using heat pumps, *demand-side participation* (DSP), system diagnostics, and local *combined heat and power* (CHP) systems and tri-generation. Tassou et al.[55] also identify energy saving opportunities from the use of low-energy lighting systems, improved thermal insulation of the building fabric, integration of renewable energy sources, and thermal energy storage systems. They observe that energy consumption in catering facilities is primarily the result of cooking and baking, refrigeration and HVAC systems. Here energy demand reduction can be achieved from the use of more efficient equipment, as well as via behavioral changes with respect to type of food consumed, food preparation practices, and environmental conditions in the premises.[5]

Tassou et al.[55] noted that, in terms of home energy savings, food consumption is affected by many factors, including food availability, disposable income, urbanization, marketing, religion, culture, and consumer attitudes. Inevitably, there is further work to be done in this complex area. Changes in energy/resource use in one part of the supply chain can impact in other parts, e.g., because of the interconnectedness of the FSC. Thus, better demand forecasting by retailers could impact on resource use in agriculture and food waste reduction in the FSC overall.[56] Nevertheless, Tassou et al.[55] believe that significant energy savings can be achieved from the use of more efficient appliances and food preparation methods (such as microwave technology, rather than oven cooking), as well as changes in consumer diets and behavior. They contend that all these factors should be taken into account in devising new approaches and technologies to effect reductions in energy demand and resource use along the whole food chain.

Because of the variability in energy use across the *Food & Drink* subsector (as displayed in Figures 6 and 7) the approach taken for the present study 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 includes the improvement of steam system efficiency, as well as the increased use of both CHP plants and heat pumps. Cross-cutting technologies that are not explicitly examined include improvements to motor systems (such as those used for producing refrigeration and compressed air), lighting, and space heating (although space heating has some common ground with the discussion of low temperature heating here).

Steam Systems

Steam systems in US industry were found to have an average efficiency of approximately 55%.[54] 20% of the energy input is lost in the boiler, 15% in distribution of the steam, and 10% in converting the steam energy to other forms of energy.[54] The overall efficiency and losses of steam systems are thought to be similar in the UK. There is obviously considerable variation is the corresponding figures; thermal efficiency of the boiler unit can range from 55 to 85%, depending on the age of the boiler and fuel used.[54] The distribution losses associated with the steam system depend not just on the insulation levels and equipment used, but also the size of the site and the distances steam is transported. The conversion losses are partly dependent on the final use of the steam. There are a number of options available to improve the performance of a steam system. Based on information from a number of sources,[53,57,58] these can be split into low- and medium-cost options for the boiler and opportunities relating to the steam system. Low-cost savings involve monitoring energy use and efficiency, as well as undertaking basic maintenance to preserve performance. In contrast, medium-cost savings involve the purchase of new equipment, and may include:

- *Flue-gas heat recovery:* the recovered heat can be used in the preheating of combustion air, or feed-water (using an 'economizer').
- *Installation of a flue gas damper:* this prevents heat loss through the flue when the boiler is on standby.
- *Variable speed drive motors:* boilers often have a forced draft combustion air fan. Replacing the fixed speed motor with a variable speed drive can offer significant savings.[57]
- Maintaining high levels of insulation around the boiler and other components in the steam system.
- Treating water to remove substances that can reduce efficiency and prematurely corrode the boiler.
- *Optimize boiler blowdown:* boiler blowdown is the flushing of the boiler to remove deposited solids. Too frequent blowdown wastes energy, too infrequent leads to inefficient performance.

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Heat can also be recovered from the blowdown operation.

Options for the steam distribution system, rather than the boiler itself, include:

- Leakage checking
- Ensuring good insulation levels throughout the system
- Identifying and removing redundant pipework
- Steam traps, used to remove condensate from the system require regular maintenance or can lead to large losses if stuck open
- Condensate recovery
- Decentralization of the steam system. If the system is used to transport steam long distances it may be more efficient to use two or more smaller boilers at different locations than one large centralized boiler. Similarly if different pressures of steam are required by different processes matching the supply and demand of steam by using multiple boilers can save energy

In the longer term, boilers can be replaced with more efficient units, which should not be oversized. Additionally a new boiler purchase offers the opportunity to replace the existing unit with one utilizing a less carbon-intensive fuel.

A combination of the technologies discussed can be retrofitted to an existing system, and might save 10–20% of current steam demand in the UK *Food & Drink* subsector.[53] This potential is available immediately and economically in most cases. A new boiler can reduce energy use by 25% or more.[53] Factors such as availability of capital, and windows of opportunity to retrofit technologies without disturbing production may form barriers to realizing the potential. Using information from the energy flow diagram displayed in Figure 7 above, an improvement of 10–25% in steam systems would save 8–20 PJ/year, assuming the fuel saved is natural gas. This relates to 408–1020 $ktCO_2$; adopting a carbon intensity for gas of 51 $ktCO_{2e}/PJ$.[49]

In some cases, the best option for improving energy efficiency of a steam system is by replacing the steam system with an alternative.[58] A heat pump can also be used to supply low temperature demands. Likewise, a CHP plant offers considerable potential for improvement over a separate steam system and grid electricity. Much of the potential for CHP lies in replacing demand that is currently supplied by steam systems.

Combined Heat and Power

Conventional power generation—that is the combustion of fossil fuel to produce heat, raise steam, and drive a turbine—involves considerable inefficiencies. A modern *combined cycle gas turbine plant* (CCGT) has a First Law efficiency of perhaps 55%[2] (with further losses involved in the transmission and distribution of electricity). These losses typically arise from heat being rejected to the external environment. A CHP plant (also known, particularly in the US, as cogeneration) makes use of the surplus or 'waste' heat that arises during power generation, so improving the overall energy efficiency of the plant. These plants require a relatively constant heat demand to operate effectively. Industrial processes can often provide such a demand. 5.9 GW_e of 'good-quality' CHP (GQCHP) was installed within the UK in 2010[59] approximately 50% of this was within the manufacturing sector.[51]

The thermal output of CHP plants is normally steam and/or hot water, which is suited to many of the demands of the *Food & Drink* subsector with its large use of steam systems and hot water for cleaning. *Food & Drink* also holds potential for an extension of CHP into '*combined cooling, heat and power*' (CCHP, or 'trigeneration'), where a cooling load is also provided via an integrated absorption chiller powered by low temperature heat. Substantial use of refrigeration within the subsector makes this technology viable. Other areas of industry can also benefit from CCHP, including for cooling in *air conditioning* (A/C) systems—e.g., for large computing systems. Thus, CCHP is not limited to those areas of manufacturing that traditionally use refrigeration. However, the economics of additional cooling capacity over a CHP plant are marginal, and the CHP installation would normally have to be justified based on just the heat demand.[60] So, although greater energy savings may arise from trigeneration, it is unlikely to increase the overall potential in terms of heat and power from CHP in the industrial sector.

There was 390 MW_e of installed CHP capacity in 2010 within the UK *Food & Drink* subsector. A study of potential for increased CHP[60] by the UK *Department for Environment, Food and Rural Affairs* (Defra) estimated an economic potential for 1033 MW_e of additional capacity in the subsector from 2005 to 2010. This Defra study[60] assumed 100% uptake of economic opportunities and so would not be reached in practice. In reality, the installed capacity within the *Food & Drink* subsector fell by 18 MW_e[51] from 2005 to 2010. The effect of the post-2008 economic recession in closing existing sites, and discouraging investment in CHP plants, is

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likely to have been a significant effect. CHP plants require a large capital investment and are often seen as risky.[60] CHP plants also require a long-term guaranteed heat demand to be attractive. Consequently, with the risk of closure or reduced capacity at many manufacturing sites (due to the economic downturn), the appeal of CHP plants is declining. There is therefore a large unfulfilled potential for economic CHP plants. A clear long-term price signal, such as provided by the UK *Climate Change Levy*, the UK 'carbon price,' or the EU ETS, would also facilitate the uptake of CHP and other similar capital intensive energy-saving technologies.

In the present work, the technical potential for additional CHP capacity was estimated using individual site-level data on energy demand by temperature band, covering those sites involved in the EU ETS.[61] This covers approximately 50% of total energy demand in the *Food & Drink* sector, including the largest energy consuming sites. The constraints shown in Table 1 were obtained using information on CHP characteristics from the Defra study.[60] These tabulated parameters are representative of a range of CHP technologies available. They suggest that virtually all heat demand at these sites represented in the EU ETS can be supplied by CHP (less than 1% of heat demand would be unsuitable for this purpose). Such sites would have a total capacity of 690 MW_e. Obviously a range of technical, economic and other barriers would inhibit the installation of CHP plants at all these sites. However, the current analysis does illustrate the suitability of the *Food & Drink* subsector for the take-up of CHP technology. The potential found here is still significantly less than that estimated as 'economic' in 2010 by Defra[60]: 1033 MW_e of additional capacity. This indicates that CHP can find uses not just in the large energy-using sites included in the EU ETS, but also throughout the subsector. The Defra study[60] estimated the energy output from the CHP opportunities in *Food & Drink* would total 11 TWh of heat and 8 TWh of electricity. This implies a heat to power ratio of 1.3:1 and a load factor of 88%. To calculate the energy and emissions savings, here it was assumed that the CHP plants would be run on natural gas with an efficiency of 75%. This is compared with an alternative system of a CCGT with an efficiency of 55% and a transmission and distribution efficiency of 90%, coupled with a natural gas-fueled boiler with an efficiency of 80%. The deployment of these CHP systems would thereby save some 4.6 TWh (16.6 PJ) of natural gas in the UK; equivalent to 854 $ktCO_{2e}$.

TABLE 1 | Parameters for Estimating Technical Potential for CHP Plants

Minimum CHP unit (kW_e)	40
Thermal output 40–1000 kW_e	50% <100°C, 50% <500°C
Thermal output 1000 kW_e+	100% <500°C
Heat-to-power ratio	2:1
Overall efficiency	75%

CHP, combined heat and power.

CHP is clearly a more efficient method of providing heat and power than separate electricity generation and steam production in a boiler. However, if CHP is fired by fossil fuels it still leads to carbon emissions. It is therefore seen as a 'transitional,' low carbon technology by the UK Government,[59] being immediately available and economic in many cases. Whether all CHP opportunities should be pursued is a question that needs to be considered within the framework of the prospects for a low carbon future. However, fossil-fueled CHP does not appear appropriate after 2030, when a fuel switch to biomass, biogas and waste will be necessary to satisfy the 80% UK carbon reduction target[3,4] (alongside other lower temperature heating options, such as heat pumps using electricity generated by renewables[59]).

Heat Pumps

Heat pumps use an external energy source (e.g., an electric motor) to 'upgrade' heat from a lower to a higher temperature,[62] reversing the natural flow of heat from higher to lower temperatures. Lower temperature heat can be extracted from air, ground, or water sources. The industrial waste heat rejected from compressors and refrigeration equipment at 30–60°C is often suitable as a heat source for a heat pump.[63] Process heat avoids the seasonal fluctuations in temperature that affect an ambient air source, so maintaining performance during cold periods. Given that heat pumps utilize heat from a 'free' source, they produce more thermal energy output than the energy input to drive the system. The '*Coefficient of Performance*' (COP) is the ratio of thermal energy out to the energy demanded of the external source. The maximum theoretical (Carnot) COP is defined by the temperatures of the heat source and sink.[41] The COP that can be reached in practice is approximately 55% of the Carnot COP.[41] An expression for the COP of a practical device can therefore by derived as:

$$\mathrm{COP} = 0.55 \cdot \mathrm{COP}_{\mathrm{Carnot}} = 0.55 \cdot \frac{T_\mathrm{D} + 5}{(T_\mathrm{D} + 5) - (T_\mathrm{P} - 5)} \quad (1)$$

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T_D is the temperature of delivered heat and T_P the temperature of the heat source. The additional terms (±5) relate to the temperatures of the refrigerant in the heat pump. These extra terms represent the temperature difference required to drive the heat transfer between the refrigerant and the environment.

The greatest limitation in the use of heat pumps in industry is currently the temperature of the heat output. Some practitioners[62,64] have suggested that current designs allow temperatures of 100–190°C to be reached (dependent on the technology adopted); with a temperature uplift between source and sink of up to 90°C being possible. But costs are inevitably greater for those heat pumps whose output is at higher temperatures. Currently the most economic systems are based on mass-produced A/C systems.[63] These allow heat outputs up to 80°C, with 140°C expected to reach market within a few years.[63] Heat pumps can also provide a cooling demand by utilizing a heat source that requires cooling. Given the substantial cooling requirements within the *Food & Drink* subsector this application may be attractive.

In assessing the potential for heat pump usage within the UK *Food & Drink* subsector, two previous studies were examined. The *Heat Pump & Thermal Storage Technology Centre of Japan*[65] estimated that 50% of energy currently supplied by boilers in the subsector could be provided by heat pumps. This assumed temperatures of up to 100°C could be supplied by heat pumps. In the UK *Food & Drink* subsector approximately 50% of final demand is for steam systems, so this implies 25% of final energy consumption could be supplied by heat pumps. A study of heat pump opportunities within the French *Food & Drink* subsector[63] took a more specific approach using information on disaggregated heat demand and heat recovery opportunities at a subsectoral level to calculate the technical and economic potential (see Figure 2) for heat pumps utilizing heat recovery from various industrial processes. This study[63] found that the 50% share of boiler demand approach[65] appeared too high. Heat recovery opportunities and heat requirements did not necessarily match well in subsectors of *Food & Drink* processing. The French study also assumed that a higher temperature could be reached by heat pumps (140°C),[63] although these higher temperature heat pumps are not currently economical in a lot of cases. Nevertheless, they are expected to be close to market. This led to the conclusion that 15% of current energy requirements in the French *Food & Drink* subsector could technically be replaced by heat pumps.[63] Around 30% of this demand is thought to be currently economical, although this could well increase to 100% given expected future energy prices and heat pump costs.[63]

Information on the UK *Food & Drink* subsector is not available to the same level of disaggregation as its French counterpart.[63] Thus, assessments of the potential for applying heat pump technology are only indicative. If 50% of boiler input could be supplied by heat pumps, this implies that 25% of final energy requirements could be supplied by heat pumps. That represents approximately 40 PJ/year using the energy flow (Sankey-type) diagram displayed in Figure 7 above. Assuming an average output temperature of 80°C, and an input temperature of 45°C,[63] the available heat pump output from waste heat sources yielded a COP of 4.38, using Eq. (1). This requires an electrical energy input of 9.2 and 31 PJ of low-grade input heat. The refrigeration condenser can supply this in terms of 'waste heat.' In the UK *Food & Drink* subsector, there is a demand of approximately 11.5 PJ of electricity for refrigeration.[41] Estimating the COP of this refrigeration equipment to be 2.5, and assuming 70% of heat loss at the condenser, a heat pump[63] can make use of a heat source of some 28.1 PJ attributable to refrigeration.

Compressed air systems can also provide a supply of low temperature heat that is often wasted. However, there is little use of compressed air in the UK *Food & Drink* industry. Defra information[66] indicates only 1.4 PJ of demand for compressed air equipment in the *Food & Drink* subsector in 2003. Approximately 50% of compressed air input energy is available for heat recovery.[63] This means less than 1 PJ is available for use as a heat source for heat pumps. In addition, heat recovered from heating processes can be used as a source for heat pumps. Heat available at the required temperature (30–45°C) has previously been estimated as 15% of thermal end uses.[63] Heat use in the *Food & Drink* subsector was approximately 110 PJ (see Figure 7) using this 15% estimate for thermal end use from the French study[63] yields recoverable heat of 16 PJ. The above analysis indicates that there is a large enough resource of recoverable heat to supply heat pumps to fulfill 25% of final energy demand. However, as previously found in regard to the French *Food & Drink* subsector,[63] the supplies of this heat and the demands of heat pumps do not necessarily synchronized. These considerations suggest that perhaps 5-25% of final energy requirements could be supplied by heat pumps. The lower end of this range is likely to be currently economic, whilst the upper limit may become possible with developments in heat pump technology over the next decade. The subsectors of

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the French sector that indicate the highest potential for heat pump deployment were milk, sugar, and starch products.[63] A US *Department of Energy* study[67] investigating the industrial application of heat pumps identified several opportunities in the *Food & Drink* subsector. The majority of these involved the concentration of a fluid, such as that related to the production of alcohol, beer, sugar, dairy, and fruit juice or other soft drinks. This was based more on a demand for relatively low temperature heat, than the matching of suitable heat supplies with demand. A general requirement for the heating of process and cleaning water within the *Food & Drink* subsector was also identified.[67] Drying utilizing heat pumps is another area showing potential[68] where better product quality can be achieved, coupled with decreased energy demand.

The carbon savings offered by heat pumps are dependent on the emissions factor of electricity and the fuel supplying the alternative or competing (usually steam-based) system. Assuming a system operating with the COP specified above, replaces a natural gas-fueled boiler (with an efficiency of 80% and emissions factors for natural gas of 51,000 tCO_{2e}/PJ) and grid electricity of 135,000 tCO_{2e}/PJ[49] implies that for every PJ of heat demand supplied by heat pumps, in preference to natural gas boilers, 33 $ktCO_{2e}$ are saved. The associated final energy savings would be 1.02 PJ, and primary energy savings (assuming a primary energy conversion factor of 2.6[49]) would be 0.66 PJ. If 5–25% of final energy requirements are suitable to be replacement by heat pumps, then this represents 8–40 PJ; leading to a saving of 8.2-40.8 PJ in final energy demand, 5.3–26.4 PJ in primary energy demand, and GHG savings of 260–1320 $ktCO_{2e}$. Supplying the electricity from a renewable source with an assumed zero emission factor would save approximately double this amount (65 $ktCO_{2e}/PJ$), whilst if the boiler being replaced was supplied by biomass or steam was supplied by a CHP system, then savings would be even lower. Obviously, primary energy savings would be affected by the electricity mix. The economics of a heat pump installation depends on the capital cost of the system and the price of electricity (assuming an electrically driven system) compared with the existing fuel (often natural gas in the UK, as used for the calculations above). The relatively new UK *Renewable Heat Incentive* (RHI) may aid the purchase of industrial heat pumps, although it is currently limited to ground and water source installations.[69] There has been some criticism regarding the lack of support for surplus heat recovery (see, e.g., the review by Norman[36]).

Decomposition Analysis of the Food & Drink Subsector

A decomposition analysis of final energy demand in the UK *Food & Drink* subsector over the period 2001–2007 was recently undertaken by Norman.[36] He used the LMDI I methodology and disaggregated the industry into eleven subsectors or product groups; the maximum disaggregation allowed by the data available. This suggested an increase in energy demand caused by increased production, and a rather smaller increase due to shifts in the structure of *Food & Drink* (both of these effects have been relatively stagnant post-2005). The dominant effect in the reduction of energy demand was a falling energy intensity. The UK *Food & Drink* subsector is both growing, as well as steadily reducing its energy intensity. Output volume is fairly static, but there has been a move to added value products. This structural effect would indicate that such higher value added products are more EI. This is consistent with a shift toward a greater amount of processing at the manufacturing site, rather than within the home (as has been observed in the EU[70]).

In order to explain the decrease in energy intensity observed from decomposition analysis,[36] it is useful to consider the drivers and barriers to improving efficiency in the *Food & Drink* subsector, and to place this in the context of the longer-term trend of energy intensity within the broader 'Food, drink, and tobacco' subsector.[36] The *Food & Drink* subsector 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.[70] The customer base of the subsector 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.[71] Product life-cycles can be short and so flexibility of equipment is vital, which will often harm efficiency.[36] Large-scale adoption of technologies is made difficult by the diverse and fragmented nature of the *Food & Drink* subsector. Additionally, many food processing sites are small (92% of such businesses in Europe being SMEs[72]) with efficiency improvement tends to be slower at these small businesses.

Demand Reduction Implications for the Food & Drink Subsector

There are a number of barriers specific to the *Food & Drink* subsector that may limit the realization of energy efficiency improvements. These are taken from a study which was based on stakeholder inputs from a number of producers, researchers, and consultants[71] (together with an interpretation based on the present authors' own knowledge[36]):

- A small number of retailers dominate the *Food & Drink* subsector, supplier margins are squeezed, and hence capital is limited. This is intensified as food is a 'nongrowth industry,' although there is a move toward higher value added products (e.g., so-called 'ready meals').
- There is a focus on product quality and safety, as they are meant for human consumption. This leads to a risk adverse mindset in relation to process changes. Innovation tends to be product rather than process-related. Increased hygiene requirements over recent years have led to increased *energy use per tonne of product*.[70]
- Product life-cycles can be short and so the flexibility of equipment is vital; this can often harm efficiency.[36]
- Large-scale adoption of technologies is made more difficult by the diverse and fragmented nature of the *Food & Drink* subsector.

The options discussed here have all focused on supplying low temperature heat. A particular site may pursue one of the options in a less emission-intensive manner. In the near term, it might be expected that steam system efficiency improvements are pursued where economic, requiring little disruption or capital costs. The availability of fossil-fueled CHP may also be expected to increase over this period. In the longer term, heat pumps may increase in use, especially if their temperature range increases, electricity is decarbonized, and costs reduced with wider-scale adoption. Over that timescale, the take-up of nonfossil fueled CHP systems may become significant.

The approach used here to estimate savings through the various technology options for the *Food & Drink* subsector can be applied to other sectors with knowledge of steam system and low temperature energy demand. The broad nature of such an approach does lead to considerable uncertainty, but this is a feature of all energy forecasting. It nevertheless provides a useful basis for indicating where the most substantial savings may be seen.

The Cement Subsector

Background

In contrast to the *Food & Drink subsector*, the *Cement* industry is quite homogeneous in terms of its output and can be characterized as a single, sequential process route with one product output. The vast majority of cement manufacture in the UK is of the form 'calcium silicate,' more commonly referred to as *ordinary Portland cement* (OPC). Almost all cement is manufactured for use as concrete for construction purposes. The primary raw material of OPC is limestone (calcium carbonate) and is mixed with small quantities of other minerals, such as clay and sand. The raw materials are quarried and delivered to the cement plant where their grinding and mixing is the first stage of the manufacturing process.[73] The raw meal is then fed into the kiln where calcium carbonate decomposes into calcium oxide and carbon dioxide at approximately 900°C.[74] At around 1500°C, the calcium oxide reacts with the other materials to form small nodules known as 'clinker.'[74] The clinker is then cooled and milled with gypsum, and possibly other materials, to form cement.[75]

The sector is highly energy intensive and about 90% of on-site energy demand is used to raise the kiln firing temperature to 2000°C.[76] Most carbon dioxide emissions derive not from fuel combustion, but from the decomposition of limestone. These 'process emissions' account for 60% of carbon dioxide emissions related to cement manufacture, while just over 30% can be attributed to kiln fuel combustion. The remaining 10% is emitted indirectly via the production of electricity delivered to the cement plant for mainly grinding processes.

There are small variations in the basic process route described above, which can be classed as either 'dry' or 'wet' (with semi-dry and semi-wet classifications also existing). The less EI dry process uses raw materials in dry, ground form. In contrast, the wet process adds water to the raw materials to form a slurry. This is necessary with softer forms of limestone, but demands more energy to evaporate the water from the production process.[75] The UK has 15 cement kilns located at 12 sites, with 4 kilns having closed during the period 2008–2009.[76] There are eleven dry kilns (representing 76% of capacity), three semi-dry kilns (representing 11% of capacity) and a single semi-wet kiln (representing 13% of capacity).[76] The overall SEC of kilns operating in the UK is 3.8 GJ/tonne of clinker.[76,77] Reductions in this figure, alongside alternative options for reducing the level of carbon emissions from the *Cement* subsector, are examined here. It builds on earlier work reported by Griffin et al.,[18] as well as that in the doctoral theses of Norman[36] and Griffin.[76]

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Decomposition Analysis

Energy use in UK cement kilns has dropped by approximately 60 TJ between 1973 and 2010.[76] A decomposition analysis was used here to separate the different effects contributing to the change in energy demand, these effects were[18]:

- Clinker output
- Switching between dry, semi-dry, semi-wet and wet kiln technologies (structural effect)
- SEC improvement of the different kiln technologies

A *Log Mean Divisia Index* (LMDI) methodology was again used for the decomposition analysis.[18,36,78] Information on the output, and SEC of kilns in the UK between 1973 and 2010 was extracted from an online source of information on individual kilns,[76] and aggregated to represent the UK situation. Whilst this may not represent year-to-year fluctuations in production well, it should capture trends well, and is sufficient for the purposes of the current analysis. The results of the decomposition analysis are presented in Figure 8. It can be seen that over all time periods the effect of improvements in SEC of the different kiln types represent the smallest component in reducing energy demand. In the most recent time period (2000–2010), the effect of improvements in SEC has been substantially smaller than any previous period. This indicates that a limit to the efficiency of kilns appears to be approaching. The substantial effect of switching to more efficient kiln types in the past is illustrated in Figure 8. However, now that there are no wet kiln types left in the UK, further potential for reducing energy demand in this manner is limited. Over the whole period studied here (1973–2010), there has been a falling demand in clinker, and this has greatly restricted the scope for reducing energy demand in the *Cement* subsector.

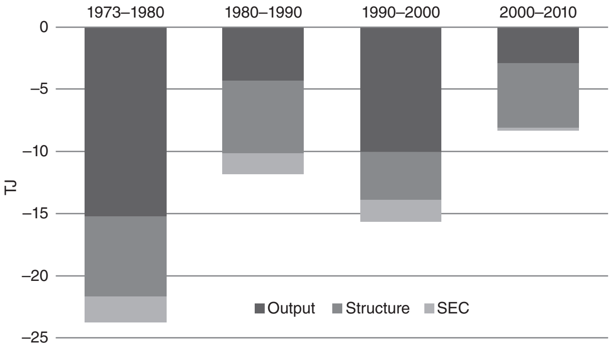

FIGURE 8 | Decomposition of UK cement kiln energy use 1973–2010 (the effects of changes in structure, output and SEC are separated).

Embodied Energy and GHG Emissions Associated with Cement

'Embodied energy (or carbon) is defined as the total primary energy consumed (or carbon released) from direct and indirect processes associated with a product or service, and within 'cradle-to-gate' system boundaries. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation, and right through to fabrication processes until the product is ready to leave the final factory gate.'[24,25] Data on the embodied properties of a wide range of construction materials (~1800 records for 35 classes of materials) have been incorporated into the *Inventory of Carbon and Energy* (ICE),[24,25] developed by the University of Bath, has been freely available for several years and used for many projects and in specialized design tools. Feedback from these users enabled the database to be refined and it continues to be developed and expanded as new information becomes available.

The formation and refinement of the ICE database took several stages. Firstly, embodied energy and carbon input data were collated. The majority of the input data originated from secondary data resources, such as journal papers, technical reports and monographs. It consisted of values of embodied energy and carbon, mainly derived from process LCA studies,[26] as well as relevant information about the data source (i.e., country of data, year, system boundaries, and report details). Selection criteria were required to assess whether each data point was of high or low quality: compliance with approved methodologies/standards (such as the ISO 14040 series); clearly defined (cradle-to-gate) system boundaries; preference for data recently sourced from within the UK; and ideally the embodied carbon values were obtained from LCA studies (otherwise from emission coefficients). Once the data had been quality rated, the 'best' embodied energy and carbon values were catalogued. The most recent version of the ICE database is v2.0.[25]

The values of embodied carbon all exclude the re-carbonation of concrete in use, which is application dependent. The majority of these concrete values in the ICE database (reproduced in Table 2) were taken from a specially developed '*Cement, Mortar and Concrete Model*.'[25] It operates using the quantities of constituent material inputs and an additional energy requirement of plant operations, transport of constituents, and a small allowance for mixing waste. These values are therefore dependent upon the

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TABLE 2 | Inventory of Carbon and Energy (ICE)[25]—Embodied Energy and GHG Emissions for Cement

Materials	Embodied Energy (EE), MJ/kg	Embodied Carbon Dioxide (EC), kgCO$_2$/kg	Embodied Carbon Dioxide Equivalent (EC), kgCO$_{2e}$/kg	Comments
General (i.e., UK weighted average) embodied energy and CO$_2$	4.5	0.73	0.74	Weighted average of all cement consumed within the UK. These data have been estimated from the British Cement Association's factsheets (see Hammond and Jones[25]). 23% cementitious additions on average
Average embodied energy and CO$_2$—Portland Cement (CEM I), 94% Clinker	5.50	0.93	0.95	This is a standard cement with no cementitious additions (i.e., fly ash or blast furnace slag). Composition 94% clinker, 5% gypsum, 1% minor additional constituents. These data have been estimated from the *British Cement Association's* factsheets (see again Hammond and Jones[25])
6–20% Fly Ash	5.28–4.51	0.88 (@ 6%) to 0.75 (@ 20%)	0.89–0.76	*Ground Granulated Blast Furnace Slag* (GGBS). See Hammond and Jones[25] for further details on material profile
21–35% Fly Ash	4.45–3.68	0.74–0.61	0.75–0.62	
21–35% GGBS	4.77–4.21	0.76–0.64	0.77–0.65	
36–65% GGBS	4.17–3.0	0.63–0.38	0.64–0.39	
66–80% GGBS	2.96–2.4	0.37–0.25	0.38–0.26	

selected coefficients of embodied energy and carbon of cement, sand, and aggregates, which are the main constituent materials for concrete (see Table 2). Fly ash, which has a lower embodied energy and carbon, cannot be used in the same high fractions as blast furnace slag. In certain circumstances, blast furnace slag could reach 70–80% replacement, which is much higher than the upper limits of fly ash.

Future Technology Pathways

There is a large wealth of information and analyses available that provide good foresight into the future opportunities for energy and emissions reduction in the cement industry. Most notably, in the *World Business Council for Sustainable Development* (WBCD) *Cement Sustainability Initiative* (CSI) and the *International Energy Agency* (IEA), via their *Cement Technology Roadmap*.[79] The latter publication illustrates a potential transition pathway for the cement subsector's contribution to an overall 50% reduction in global GHG emissions by 2050 (according to the IEA 'BLUE' scenario derived from the conclusion of the *Intergovernmental Panel on Climate Change* (IPCC) that aims to reduce global emissions by at least 50% by 2050 in order to avert a global warming temperature rise of 2°C). The roadmap is illustrated by a technology timeline based on information from 38 technology papers produced by the *European Cement Research Academy* (ECRA),[80] and the scenario analysis for the IEA's *Energy Technology Perspectives* (ETP), using the MARKAL model.[81] Although the roadmap can be utilized in providing global and regional context, it is not sufficient to inform policy at the national level. Moreover, domestic information provided for the roadmap analysis of the UK via the *Getting the Numbers Right* (GNR) database is lacking in certain key areas.[76] A UK-specific assessment is provided by the 'Carbon

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Strategy' of the *Mineral Products Association* (MPA)[82] is broadly in line with the WBCD/IEA *Cement Technology Roadmap*.[79] Three primary routes were mapped out by MPA: a focus on waste-derived fuels in the short term (out to 2020); continued increased use of waste-derived fuels, higher levels of clinker substitution and investment in 'low carbon cement' RD&D in the medium term (2030); and a vision based on the deployment of CCS technology in the longer term (2050).[82] The assessment made in this paper is independent of the industry (i.e., MPA) strategy, and aims to suggest the potential impact on energy and GHG emissions offered by the technologies and measures that could feature in the long term.

The earlier work of Griffin et al.[18] formed part of, and draws on the results obtained from, the UKERC industrial UED.[10,14] The prospects for reductions in the specific energy use and emissions associated with the UK cement industry were explored under a series of four scenarios out to 2050: characterized as '*Low action*,' '*Reasonable action*,' '*Reasonable action including CCS*,' and '*Radical transition*.' Griffin et al.[18] note that historic trends, and those expected through technological innovation indicated by these scenario projections, suggest decreasing advances being made through efficiency improvements. This is characteristic of 'energy-intensive' manufacturing,[16] where high energy prices (Griffin et al.[18] observe that energy costs typically represent 40% of operational costs for a cement manufacturer) have driven 'quick wins.' There is, according to Griffin et al.,[18] some potential for further contributions from clinker substitution and fuel switching, although such options are not without their difficulties. Clinker substitution could continue to increase somewhat without adversely affecting the properties of cement (up to a maximum of 40%, from the current level of ~30%[18]). The main clinker substitutes in the UK rely on carbon-intensive industries, blast furnaces, and coal-fueled electricity generation. Such operations may not be viable over the long term, when the national focus could well be on decarbonization, and this could influence the economic availability of clinker substitutes. Cement kilns are well suited for the use of *refuse-derived fuel* (*RDF*), or *solid recovered fuel/specified recovered fuel* (SRF), as the mineral content in such fuels is incorporated into the clinker without residual ash or heavy metal disposal being required. More broadly, OPC is well established, having a mature supply chain and being well understood for use in construction. Griffin et al.[18] therefore believe that the OPC industry in Britain is likely to take incremental steps in the long term to ensure its continued existence with the aim of supplying well-tested, familiar products to the construction industry. Nevertheless, the successful adoption of alternative cements outside the UK might act as an appropriate driver for change in this country.

Energy Efficiency Improvements

Energy demand for a cement kiln with current *best available technology* (BAT) is 2.9–3.3 GJ/t, and is provided by a six-stage preheating and precalcination dry-rotary kiln.[74] Preheating implies that heat from the end of the process is reused to preheat the raw meal coming into the kiln. The number of stages of preheating that can be used depends on the raw material composition.[73] Precalcining is also increasingly used where a secondary combustion chamber starts the calcination (the decomposing of calcium carbonate) process before entering the primary kiln.[73] No kilns in the UK currently use six-stage preheating, and so they do not employ BAT. However, all dry kilns have four- or five-stage preheating and the majority employ precalciners.[76] The average SEC for UK cement kilns in 2010 is confirmed by MPA as 3.8 GJ/ tonne clinker.[76] This figure is calculated at the subsector level and includes energy use in shut downs and start-ups throughout the year. Instantaneous energy efficiency would be higher.

The minimum theoretical thermal energy demand required in the production of clinker is 1.65–1.8 GJ/t.[80] Additional energy is required to dry the raw materials and this increases the theoretical minimum energy demand to 1.85–2.8 GJ/t[80] depending on the moisture content of the raw material. Thermodynamic (energy and exergy) analyses[2,7,8,11,12] can indicate those areas of the process that are responsible for inefficiencies and for which losses can potentially be reduced. Kolip and Fevzi[83] have undertaken such an analysis of a plant using the dry process with a parallel flow, four-stage preheater cyclone and a precalciner. This plant represents a relatively high level of technological advancement. The First Law energy efficiency of the plant was found to be 51%, whilst the exergy efficiency was 28% (using a datum or 'dead-state' temperature of 298 K). The SEC of the process was 3.4 GJ/t clinker, which is comparable to the current performance of UK dry process kilns. The greatest energy losses in the plant were found to be associated with the stack gas (21% on input energy, at 1100°C), the discarded air from the cooler (12% of input energy at 240°C), and the heat losses from hot surfaces (10.2% of input energy). On an exergy basis, the stack gas losses represent 17% of input exergy and the discarded air from the cooler 3%; the low temperature of the cooler air decreasing its importance on an exergy basis. The irreversibilities in the process totaled 48% of exergy input and were mostly due to combustion and chemical reactions.[12] Such irreversibilities are unavoidable. This analysis therefore highlights two streams that, although unlikely to be reduced, could be reused and improve overall efficiency. The stack gases in particular hold potential. A six-stage preheating kiln would also improve recycling of heat and provide options for reuse, including heat-to-power technologies. It is thought there is little realistic potential for improving on the current six-stage preheating BAT.[73]

Existing opportunities for kiln conversion or replacement measures include semi-dry to dry and semi-wet to dry processing. There are no emerging radical redesigns leading to significant efficiency improvement reported by the ECRA.[80] A new kiln type based on 'fluidized bed technology' (FBT) is under development and, based on the latest demonstration plant operating in China,[84] could reduce fuel requirement by up to 0.3 GJ/t compared with rotary kilns.[80] Improvement potentials for the UK cement industry were calculated here by summating differences in instantaneous efficiency of different technological options. The results are summarized in Table 3, where 'best practice technology' (BPT) refers to the best performing kiln operating in the UK at present. Based on 2010 output, bringing the industry to BAT performance would accrue an energy saving of 3.15 PJ/*per annum* (pa), while reducing energy related GHG emissions by about 0.3 $MtCO_2$-eq/pa.

There is particularly low potential to reduce industrial emissions as efficiency measures do not tend to dominate the incidence of process emissions. The subsector is already very technically efficient. Indeed, nontechnological factors have an arguably more important influence. For example, market conditions that affect the kiln operation typically reduce efficiency by 0.15–0.3 GJ/t clinker,[80] which is greater than the difference made by installing an additional preheating stage. Moreover, dryness of raw material is an important factor in achieving the number of BAT preheater stages in the first place. Some dry kilns will not be able to be converted due to their location. This is likely to lead to kiln closures and replacements in drier regions before the subsector reaches BAT level. FBT could improve upon BAT but, as the technology is still under development and kilns are unlikely to match the capacity of rotary kilns,[80] it may only take up the smaller share of subsector capacity in the future.

Fuel Switching

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 alternative fuels (wastes, including biomass material) thereby resulting in lower emissions.[80] The fuel split supplying kiln heat in the UK cement subsector in 2010 is illustrated in Figure 9, and the associated fuel emission factors are presented in Table 4. Against the 2010 mix, a complete switch to waste fuel would reduce subsector emissions by 15.1%. Cement kilns are well placed for the disposal of waste fuels as the mineral content in fuels is incorporated into the clinker. Consequently, there is no residual ash and heavy metal disposal as would arise if disposed of in an incinerator.[77] The substitution of the present coal input with oil or natural gas would lead to emission reductions of 6.8 and 12.1% respectively. However, alternative fossil fuels are not economically attractive in the UK, particularly in a subsector for which

TABLE 3 | Impact of Future Actions on Energy Efficiency in the UK Cement Subsector[76]

Action	Subsector Efficiency Improvement (%)	Subsector Energy Demand Reduction (%)	Subsector GHG Emissions Reduction (%)
Replace semi-wet kiln with BPT	5.3	4.5	1.8
Replace semi-dry (Lepol) kilns with BPT	1.7	1.4	0.6
Upgrade/replacefour-stage dry kilns without precalciners with BPT	1.3	1.1	0.5
Upgrade/replace four-stage dry kilns with precalciners to BPT	0.4	0.3	0.1
Convert subsector to BPT	8.6	7.4	3
Convert subsector to BAT	12.6	10.8	4.4
Convert subsector to FBT	20.5	17.6	7.1

BAT, best available technology; BPT, best practice technology; FBT, fluidized bed technology.

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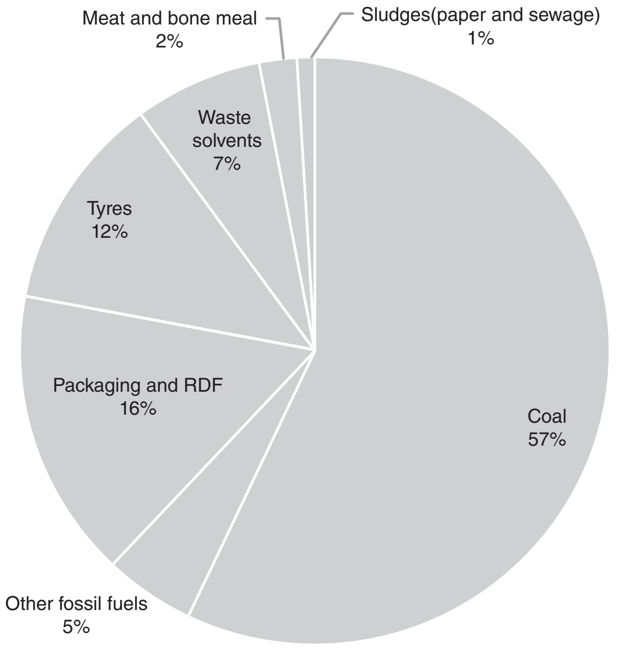

FIGURE 9 | Fuel split for heating of UK cement kilns in 2010.

TABLE 4 | CO_2 Emission Factors of Cement Fuel Options

Fuel	CO_2 Emission Factors ($kgCO_2/GJ$)
Coal	105.1
Oil	76.4
Gas	55.9
Alternative fuels (waste)	44.2
Biomass	37.2

Source: Derived from the IEA Cement Roadmap[79] and ECRA 'Look Ahead.'[80]

cheap coal of lower quality than the power sector is regarded as sufficient.[80] Alternative fuels can be 20-25% less carbon intensive in terms of direct emissions when compared with coal.[77] It should be noted, however, that as disposal of waste fuels may otherwise involve their incineration or landfill, the life-cycle emissions of using the waste fuels in the kiln may be closer to zero.[77]

Over the past decade, the UK cement industry has focused on utilizing waste for fuel, and this trend is likely to continue into the medium term.[82] Kilns can technically run on 100% waste fuel, but such high substitution rates require tailored pretreatment and quality control of the waste supply.[81] The main firing of a kiln requires a fuel having a *Calorific Value* (CV) (or *Heating Value* in North American usage) of at least 20–22 GJ/t.[80] Applying CV ranges per waste type, defined by the *European Commission* (EC),[72] to the waste split in 2010 gives a weighted average CV of 17–25 GJ/t. Combined with a coal CV of 26.2 GJ/t, the minimum waste CV requirement would imply a possible substitution level of 44%. This is only an incremental improvement on the present substitution level of 38%.

The UK cement industry has a target of 50% waste fuel substitution by 2020.[85] The MPA 'Carbon Strategy'[82] stipulates the continuation of this trend out to 2030, and the long-term upper assumption by the CSI for developed countries is 60%.[80] A waste substitution rate of 50–60% would lead to direct emission savings of 2.9–5.4%. However, this level could potentially be raised further as part of a potential synergy with efficiency improvement. Modern kiln precalciners demand 60% of fuel input at process temperatures lower than the main firing temperature.[80] This would enable at least a 60% waste fuel input at present quality together with a much higher proportion of biomass waste (typical CV of 10–18 GJ/t), which has a 15% lower emissions factor than the average waste mix. Some two-thirds of UK kiln capacity uses precalciner technology. Ultimately, the achievement of these waste substitution levels have significant political and legal implications.[80] The UK is committed to the EU and other international agreements. Likewise, a recent review by the UK's *Committee on the Medical Effects of Air Pollution* has deemed the burning of waste-derived fuels as safe for the local environment.[86] However, step-change improvements in waste management must follow before significant additional achievement down this pathway can realistically be achieved.

Feedstock Substitution

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. In the UK around 16% of the cement supplied to standard EN 197–1:2000[87] is nonclinker material, i.e., *Ground Granulated Blast Furnace Slag* (GGBS) or *Pulverized Fly Ash* (PFA).[82] Unlike many of the continental EU member states, 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.[76] This is arguably a more appropriate configuration as clinker and cement substitutes tend to require less transportation and the concrete producer can optimize the final product; thus reducing waste, energy use and additional handling.[76] The UK has a clinker substitution rate that is estimated to be 28%.[82] The upper boundary of the potential long-term global average

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for clinker substitution according the CSI is 35%.[80] Presently clinker substitutions vary considerably depending on the region, with the European market producing at above average levels. An increased substitution level to 35–40% would result in a *Cement* subsector emissions reduction of 6.7–11.3%.

GGBS and PFA are by-products of integrated iron and steel plants and coal-fired power stations respectively. In 2010, the UK operated five blast furnaces[88] and 28% of electricity supply was met by coal[51] indicating a reasonable domestic supply. However, future scenarios, such as *Pathway Beta* of the *2050 Pathway Analysis*[89] *produced by the UK Government's Department of Energy and Climate Change* (DECC), in which no CCS is deployed would put more pressure on both the blast furnace route steel production and coal-fired power stations to shut-down their operations. Importing the equivalent of a 40% substitution rate (at 2010 production levels) would dramatically extend the transport distance of about 4.5 Mt of substitute materials. Thus, feedstock substitution has some indirect dependency on the *Cement* subsector CCS pathway. Notwithstanding this, the extent to which clinker is substituted will affect the properties of the final cement product, and is therefore sensitive to market barriers. Clinker substitution rate in cement and concrete is ultimately determined by the end user in the construction industry, and is consequently subject to constraints imposed by economic and safety factors.

CO_2 Capture and Storage

CCS describes a process in which CO_2 from power plants or industrial process gas streams is captured and transported through pipelines to large underground geological formations, such as depleted oil and gas reservoirs or deep saline aquifers.[89] The technology is currently under development on a large-scale but, if proven, could potentially be retrofitted to cement plants, preventing both combustion and process emissions entering the atmosphere. The most promising CCS technology options identified here are postcombustion and oxy-fuel technology.[90] Precombustion technology is less suitable due to the need in clinker production to capture process emissions which make up the larger part of subsector emissions. A detailed study on these options was prepared by *MPA Cement* (then the *British Cement Association*) in 2008 for the IEA *Greenhouse Gas R&D Program*, based on a hypothetical modern dry kiln in Scotland.[91] A more specific study on postcombustion, focused on an actual cement plant in Norway.[92] Drawing on these studies and on the IEA cement technology roadmap[79] has enabled estimates of future costs to be made.[76] Each technology is characterized in Table 5, where the figures should be treated with great caution as no full-scale demonstration projects have yet been deployed and R&D is ongoing.[76]

Postcombustion 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. Variants include chemical absorption, membrane technologies, carbonate looping, and mineral adsorption. Chemical (amine) absorption is seen as the most promising of these and many pilot and demonstration projects for the power sector have been launched to date, with commercialization anticipated post 2020. Two important aspects for CO_2 capture in cement plants, relative to power generation plants, are their poor economies of scale and absence of large amounts of low-grade heat, which might be utilized to drive the process. A significantly large amount of additional energy is required for solvent regeneration during the process that separates the CO_2 for transport. This leads to a SEC of around 3 GJ/tCO_2, and direct emissions from the UK cement subsector in 2010 of 0.89 tCO_2/t clinker. The application of this technology would increase the 3.8 GJ/t average kiln consumption to about 6.5 GJ/t. Oxy-fuel technology involves the combustion of oxygen and recycled CO_2 instead of air, resulting in a relatively pure CO_2 exhaust for capture. It is envisaged that commercial availability could occur by 2025.[79] Retrofitting is unlikely as it would necessitate the rebuild of most of the existing plant's core components. Oxy-fuel combustion could, however, be confined to the precalciner in modern kilns, in which case capture of plant emissions is limited to about 60%.

Unfavorable location and relatively low kiln capacity of most existing plants represents a significant barrier for CCS deployment in the UK *Cement* subsector. Kilns with capacity below 4000–5000 tonnes/day (t/d) are considered by IEA unlikely for CCS deployment due to relatively high specific costs.[79] Average kiln capacity in the UK subsector is just over 2000 t/d with the only eligible candidates, based on this condition, being the site at Rugby. However, this plant is located inland and away from identified UK CCS cluster regions (see Figure 10). Generally speaking, the current trend of increasing average kiln capacity will need to continue in order to achieve the appropriate economies of scale. Its projection into the future is indicated in Figure 11, based on an extrapolation of average kiln capacity

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TABLE 5 | Summary of CCS Technology Performance and Costs for the Cement Industry

Technology Options	Specific Energy Consumption (GJ/tCO_2 captured)	Energy Demand Increase (GJ/t)	CO_2 Reduction (%)	CAPEX (£m)	OPEX (£m)
Postcombustion	3.6–5.2	2.8–3.9	85	90–240	24–87
Oxy-fuel combustion (retrofit)	0.79	0.44	62	188	33
Oxy-fuel combustion (new kiln)	1.9	1.7	95–100	280	Unknown

Source: Data derived from Hegerland et al.[92] and Kuromochi et al.[93]

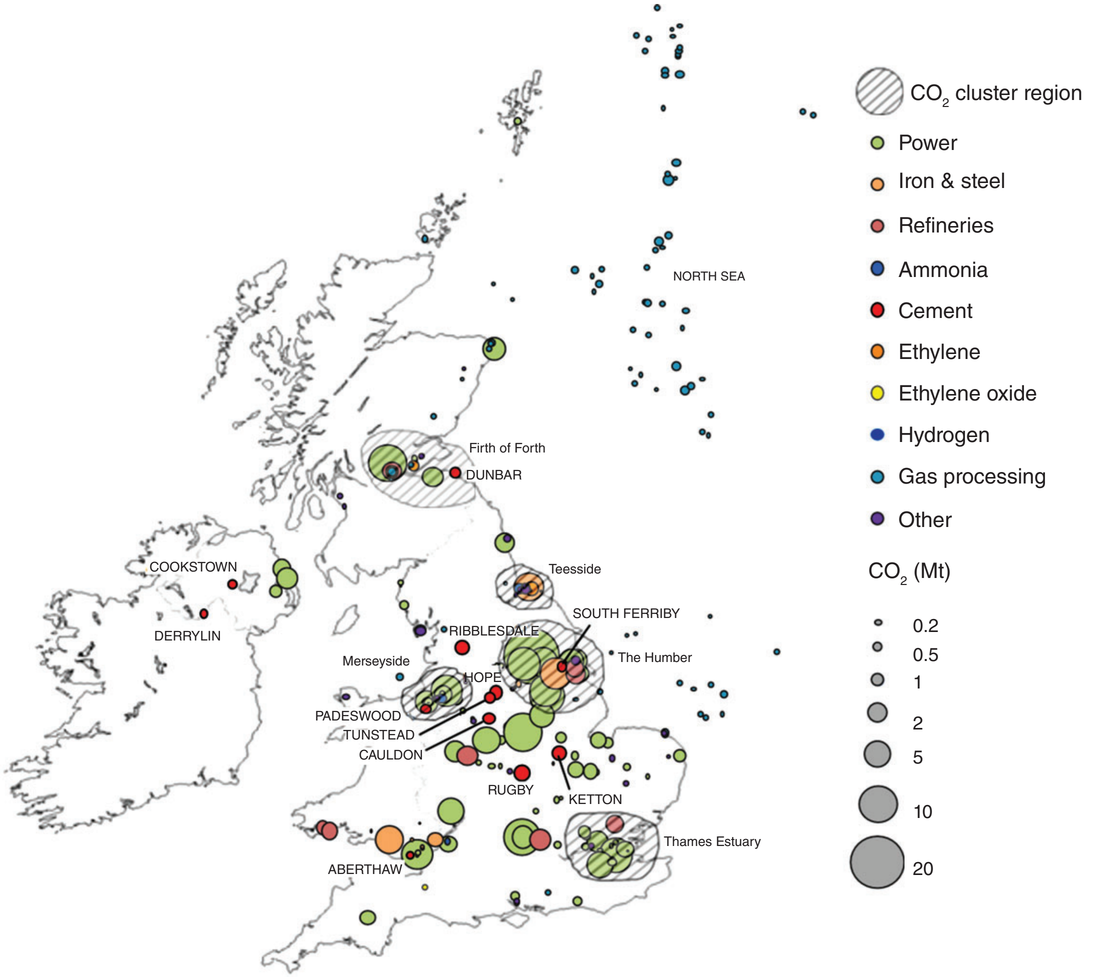

FIGURE 10 | Distribution of CO_2 point sources and CCS cluster regions in the UK.

data since 1973 (using standard linear regression) along with a logistic diffusion model represented by Eq. (2):

$$C = \frac{L}{1 + ae^{-bt}} \tag{2}$$

where C is average kiln capacity and t denotes time here. L, a and b are constants related to the upper limit, the position along the horizontal axis, and the steepness of the graph, respectively. Average kiln capacity in the UK is assumed to saturate at 6,000 t/d. Though kilns of over 10,000 t/d capacity exist in other parts of world, this figure is deemed more appropriate to the size and structure of the UK cement market. It is also the reference case for large plants used by ECRA in their assessment of future technologies.[80] The graph shows that average UK kiln

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size may be 3,500 t/d in 2030 and 5,000 t/d in 2050, meeting 2010 capacity with 8 and 6 kilns respectively. Therefore historical trends indicate that a 50% CCS enabled sector is likely to be met by just three kilns.

The locations of CCS cluster regions in the UK and their proximity to existing cement processing sites is indicated in Figure 10. If the cluster regions identified for storage under the North Sea and the Irish Sea[94,95] are considered, then existing candidate sites for CCS include Padeswood, South Ferriby, and Dunbar. However, only South Ferriby has a large enough raw material reserve to warrant such a long-term investment.[94] Clearly, the location of future CCS enabled plants will have to be considered carefully, balancing the cost of transporting CO_2 with the cost of transporting raw materials. Either way, this presents substantial economic barriers[96] along the UK roadmap for CCS deployment.

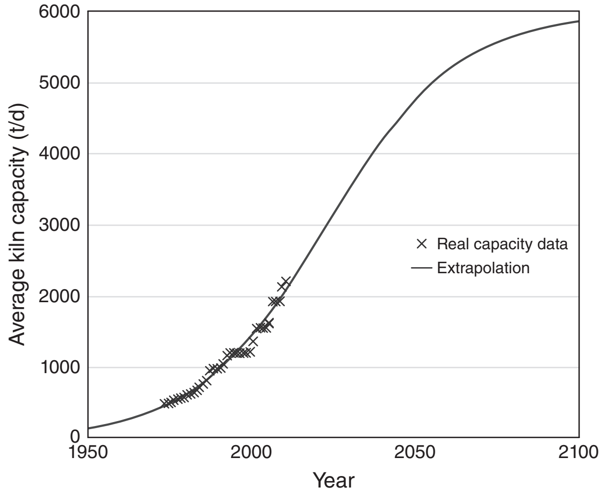

FIGURE 11 | Logistic curve forecast of average UK cement kiln capacity.

Product Substitution

In recent years there has been considerable interest in the development of novel low energy, low CO_2 cements as an alternative to OPC. The range of options have been well characterized and assessed,[97,98] and MPA have commented on the potential implications for the UK Portland cement industry.[99] The most promising products that have been identified are summarized in Table 6. Other notable options are being developed by other commercial firms, but detailed product or process information has not yet been published for these.[18,76]

OPC is a familiar, well-proven, easy-to-use, safe, strong, and durable product with abundant and widespread raw materials, low production costs, and well-established process technology, supply chains and markets. All the alternatives reviewed here will require years of further development before they can be considered serious candidates for substituting OPC on a mass-scale. Even if they reach property and cost parity with OPC, it will take a number of years to overcome regulatory barriers and establish new standards regimes and construction codes.

The construction industry is characteristically wary about unfamiliar products and Europe is more restricted by regulation than other markets, such as China and Australia.[100] Existing EU and US standards have essentially been shaped by Portland cement and concrete manufacturing bodies for over a century.[101] They are prescriptive and do not recognize the mechanical properties or chemical paradigms

TABLE 6 | Summary of Alternative Cement Technologies[18,76]

Product	Cement	Principle Raw Materials	Claimed Emissions/Energy Reduction	Process Temperature (°C)	Degree of Technical Change/Stage of Development
Novacem™ (Novacem, UK)	Magnesium oxide	Olivine, Serpentine	60–113%/50%	700	Radical/pilot demonstration
E-Crete™ (Zeobond, Australia)	Alkali-activated (Geopolymer)	Kaolin, Industrial wastes (e.g. PFA and GGBS)	80–90%/85%	Room temperature (Metakaolin: 800)	Radical/small-scale commercialization
Celitement™ (Celitment, Germany)	Partially prehydrated Calcium silicate hydrate	Limestone, Quartz	50%/28%	150–210 (Quicklime: 1000)	Radical/pilot demonstration
Aether™ (Lafarge, France)	Belite-calcium sulpho-aluminate-ferrite	Limestone, Kaolin, Gypsum	20–30%/15%	1225–1300	Major/Industrial scale demonstration

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of other cement systems. The *European Committee for Standardization's* cement committee (CEN/TC51) is starting to look at the challenges of validation arising from emerging alternative cements.[76] However, the very proponents of these materials may question the authority of CEN/TC51 (a Portland cement-based committee) to provide guidance which goes further than Portland compositions.

Despite various sources presenting alternative cements as the optimal pathway,[100,102] they appear a less serious pathway in the IEA cement technology roadmap[79] and the UK cement industry's (MPA) *Carbon Strategy*[82]; it is clear that the Portland cement industry intends to stay in business into the long term with the aim supplying well tested, familiar products to the construction industry.[99]

CONCLUDING REMARKS

Progress in reducing industrial energy demand and carbon dioxide (CO_2) emissions has been evaluated in the present study. This sector in the UK accounts for some 21% of total delivered energy and 29% of CO_2 emissions. 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 EI steel production and petrochemicals processing to low-energy electronics fabrication.[2] 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 subsectors, devices and technologies can be identified[2]; 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 industrialized world. Some element of sectoral aggregation is therefore inevitable in order to yield policy-relevant insights.[5] 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 described and assessed. The contributions of the EI and NEI industrial subsectors over recent decades was evaluated with the aid of decomposition analysis. An observed drop in aggregate energy intensity (defined as *energy use per unit of economic output*) over this timescale was driven by various effects: energy efficiency improvements; structural change (the change in nature of industry with a transition away from EI industries); and fuel switching (away from coal and oil use toward cleaner and more readily controllable fuels, such as natural gas and electricity). In addition, the 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.[2]

It is widely recognized that data on industrial energy use and the potential for GHG emissions reduction are arguable weakest in respect to the various UK end-use demand sectors.[5] Consequently, the *UK Energy Research Centre* (UKERC) recently commissioned research aimed at providing better information in support of the industrial modeling needs of UK 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.[5] This has resulted in the development of an industrial 'UED' by Griffin et al.[10,14] (which can be interrogated via the UKERC Energy Data Centre, in terms of the background documentation[10] and spreadsheet data[14]). Bottom–up studies were undertaken for 'Iron & steel making,' 'Chemicals processing,' 'Cement manufacture,' the 'Food & drink sector,' and 'Paper production.' Together they account for about 65% of CO_2 equivalent (CO_{2e}) from UK industry. The approach and challenges to a UKERC-supported study of each of these subsectors was often unique. However, the general approach taken to each subsector was to identify the 2010 baseline energy use and GHG emissions, and then to in order to determine the improvement potential offered through the application of BATs against this baseline.[10,14] A top–down view of industry was also taken in order to evaluate how the modeled subsectors fit within industry as a whole. In addition, cross-cutting technologies that might offer improvement potential were examined. Certain behavioral or good-practice measures are suitable for adoption across the board, precisely because of their explicit independence from the type of technology employed (see, e.g., Ref 2). Cost information is not explicitly included in the UED,[10,14] but the technical information can be utilized by cost-optimal, whole systems, energy-economic models, such as *UK TIMES*.[5]

Finally, two detailed case studies were presented to illustrate the potential for reducing energy use and CO_2 emissions in the *Cement* subsector and that associated with *Food & Drink*. They account for some 8 and 7% respectively of UK industrial process GHG emissions (see Figure 3), and represent examples of EI and NEI subsectors respectively.[16] In the short term, a variety of currently available technologies 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.[2] Nontechnological barriers to the take-up of such technologies have also been highlighted. Consequently, the transition pathways to a low carbon future in UK industry by 2050 exhibit large uncertainties. 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 utilization (CCU), energy efficiency techniques, and biomass), alongside a decarbonization of the electricity supply.

NOTES

[a] A confusion has arisen in the literature by the use of the term 'EMERGY' that is sometimes also described as 'embodied energy.' In reality, it can be argued that EMERGY reflects the 'availability of energy' (exergy)[2,7,11,12] to make a resource, product or service, and is pathway dependent.

[b] Thus, one industrial subsector ('*Cement*') represents EI industries, whilst the other ('*Food & Drink*') reflects NEI industries. Other UK industrial subsectors are reported in the UKERC industrial 'UED.'[10,14] Nevertheless, many of the 'cross-cutting technologies' discussed below apply quite widely across industry, not just to *Cement* and *Food & Drink*.

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