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Enabling technologies for industrial energy demand management ☆

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A R T I C L E I N F O

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A B S T R A C T

This state-of-science review sets out to provide an indicative assessment of enabling technologies for reducing UK industrial energy demand and carbon emissions to 2050. In the short term, i.e. the period that will rely on current or existing technologies, the road map and priorities are clear. A variety of available technologies will lead to energy demand reduction in industrial processes, boiler operation, compressed air usage, electric motor efficiency, heating and lighting, and ancillary uses such as transport. The prospects for the commercial exploitation of innovative technologies by the middle of the 21st century are more speculative. Emphasis is therefore placed on the range of technology assessment methods that are likely to provide policy makers with a guide to progress in the development of high-temperature processes, improved materials, process integration and intensification, and improved industrial process control and monitoring. Key among the appraisal methods applicable to the energy sector is thermodynamic analysis, making use of energy, exergy and 'exergoeconomic' techniques. Technical and economic barriers will limit the improvement potential to perhaps a 30% cut in industrial energy use, which would make a significant contribution to reducing energy demand and carbon emissions in UK industry. Non-technological drivers for, and barriers to, the take-up of innovative, low-carbon energy technologies for industry are also outlined.

1. Introduction

1.1. Background

The 2007 Energy White Paper (Department of Trade and Industry, 2007) accepted that Britain should put itself on a path to achieve significant carbon reductions, mainly by adopting a range of energy efficiency measures and renewable energy technologies. Techniques for carbon capture and storage (or 'carbon sequestration') were also identified as an important element in any energy research, development and demonstration (RD&D) programme. Targets for new renewable electricity supply were set at 10% by 2010 and 20% by 2020. It is going to be difficult for renewables (principally wind power) to fill the 'electricity gap'. The UK Government is supportive of building a new generation of nuclear reactors to replace those currently undergoing, or approaching, decommissioning (Department of Trade and Industry, 2007). This, together with carbon capture and storage technologies and an increased reliance on imported natural gas for combined cycle gas turbine plants, might represent the future of the electricity supply side.

Carbon dioxide (CO_2) accounts for some 80% of the total greenhouse gas emissions in the UK (Department of Trade and Industry, 2000). On the supply side, the energy sector is responsible for around 95% of these emissions, whereas on the demand side the industrial sector accounts for around 30%. The switch from coal to natural gas stimulated by energy market liberalisation has had a favourable, but relatively short term, effect on greenhouse gas emissions. Consequently, the legally binding post-Kyoto EU target of reducing a basket of greenhouse gases to 12.5% below 1990 levels over the period 2008–2012 will require only modest governmental intervention, over and above falls in emissions stimulated by energy market liberalisation. But the UK adopted a tighter 'domestic' goal in 1997 aimed at a 20% cut in CO_2 emissions below 1990 levels by 2010. Recent trends in national CO_2 emissions indicate that it is unlikely that this national target will be met, and this has recently been recognised by the UK Government. However, in the medium term, even greater carbon reductions will be required in order to stabilise the global climate system. The Royal Commission on Environmental Pollution (2000), for example, has argued that the UK should take the lead, by adopting a target of reducing CO_2 emissions by some 60% from 1997 levels by about 2050. The UK Government is presently committed, through its 2007 Energy White Paper, to developing a sustainable energy economy in the 21st century and

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☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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to taking a lead in reducing CO_2 emissions among the industrialised countries (i.e. those of the Organisation for Economic Co-operation and Development). An aspirational target of reducing these emissions to 60% of their existing figure by 2050 has been adopted in line with the Royal Commission on Environmental Pollution recommendation. The only way in which this fall could be achieved is by significantly reducing primary energy consumption to 45–75% of the present demand (Hammond, 2003), depending on the energy technology mix (fossil fuels, nuclear power or renewable energy technologies). This requires the widespread adoption of energy-saving measures across the economy that, in turn, would necessitate action by many individual stakeholders.

It is in this context that this state-of-science review sets out to provide an indicative assessment of enabling technologies for reducing UK industrial energy demand and carbon emissions out to 2050. In the short term, during the period that will rely on the adoption of current or existing technologies, the road map and priorities are relatively clear. But the prospects for the commercial exploitation of innovative technologies by the middle of the 21st century are highly speculative. Emphasis is therefore laid on the range of technology assessment methods that are likely to provide policy makers with a guide to the potential for improvements. Key among the appraisal methods applicable to the energy sector is thermodynamic analysis: energy, exergy and 'exergoeconomic' techniques. They provide an indication of the maximum improvement potential available from different enabling technologies. These approaches are supplemented by useful techniques such as environmental life-cycle assessment (LCA), environmental cost–benefit analysis and the generation of cost curves.

1.2. Character of the industrial sector

The industrial sector in the UK is the only one that has experienced a significant fall of roughly 40% in final energy demand since the first oil price shock of 1973/1974 (see Fig. 1). This was in spite of a rise of over 40% in industrial output in 'value added' terms. However, the consequent aggregate reduction in energy intensity (MJ/£ of gross value added) masks different underlying causes:

- *End-use efficiency*: It has been estimated (Engineering Council, 1998) that around 80% of the fall in industrial energy intensity between 1965 and 1995 was induced by the price mechanism.
- *Structural changes in industry*: The relative size of the industrial sector has shrunk, with a move away from heavy industries (Hammond, 1998), particularly in manufacturing and mining, as well as the adoption of more energy-efficient technologies (like electric arc processing). Many industrial sub-sectors have undergone major rationalisations, thus enabling significant energetic and financial economies of scale.
- *Fuel switching*: Coal use in UK industry has declined steadily since the early 1960s in favour of 'cleaner' fuel (Hammond, 1998; Hammond and Stapleton, 2001). Oil use also fell rapidly from 1973 onwards, with a couple of step changes associated with the two price hikes in the early 1970s and early 1980s (see Fig. 1). Both natural gas and electricity consumption increased to market shares of some 25% and 33%, respectively. They are cleaner, more readily controllable and, arguably, cheaper for the business concerned.

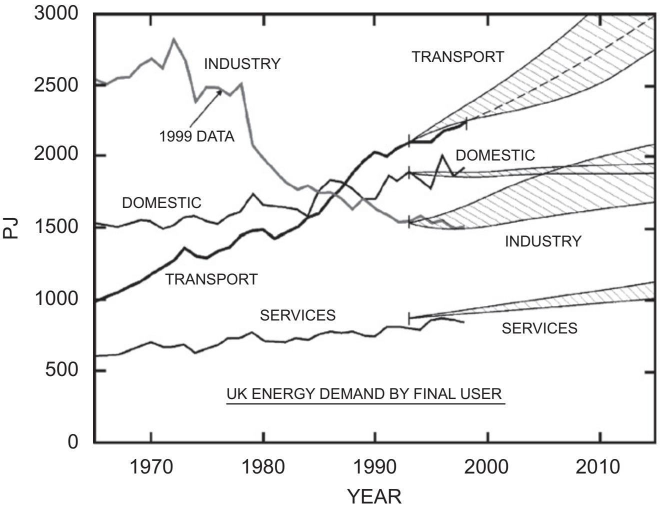

Fig. 1. UK energy consumption by final-user sectors: *hatched area*, EP65 projections (Hammond, 2000).

The industrial sector is very diverse in terms of manufacturing processes, ranging from highly energy-intensive steel production and petrochemicals processing to low-energy electronics fabrication. Whereas the former typically employs large quantities of (often high-temperature) process energy, the latter tends to be dominated by energy uses associated with space heating. Future Energy Solutions and the Carbon Consortium (2005) identified around 350 separate combinations of sub-sectors, devices and technologies in their recent study of the potential for carbon reduction from UK industry. Each combination offers quite different prospects for energy efficiency improvements and carbon reductions, which are strongly dependent on the specific technological applications. 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. Conversely, certain behavioural or good-practice measures are suitable for adoption across the board precisely because of their explicit independence from the type of technology employed.

In the period up to 2030, the European Commission expects that the EU25 economy will continue to be more focused towards 'high value added' products, which are less material- and energy-intensive, as well as undergoing restructuring in favour of services (European Commission, 2002). It believes that the potential for reducing CO_2 emissions emanating from industry is likely to be limited. Others take a more optimistic view: see, for example, Hammond and Stapleton (2001) and von Weizsacker et al. (1999). Best available electrical technologies and heat pumps have been proposed by the Commission as attractive and cost-effective options, while acknowledging that this will incur additional costs over and above the baseline scenario out to 2010; perhaps 14–30% for energy-intensive industries and 9–21% for others.

2. Technology assessment techniques

2.1. Integrated appraisal of energy systems

Methods for the appraisal of industrial energy systems and their environmental valuation play an important role in the context of sustainability assessment. They are at the heart of methods for quantifying economic and social costs and benefits, as well as the direct ecological impacts that are an inevitable side effects of material 'progress'. Concepts such as the physical life cycle of products and processes (Azapagic et al., 2004; Burrows et al., 1998), and the need for clearly defined system boundaries, are key elements in environmental problem solving. However, some economists would claim that methods from their 'normative' discipline can be extended to incorporate all of society's environmental concerns. In contrast, engineers and environmental professionals have at times argued that economic techniques (such as cost–benefit analysis) may well obscure the impacts of different courses of action, and that decision makers consequently become less well informed rather than the reverse. Aggregate decision criteria, for example, often conceal the weighing of various impacts. In contrast, the sort of 'descriptive' tools for analysis that emanate from the engineering and physical sciences can provide alternative insights that complement those from economics. These include thermodynamic (energy and exergy) analysis and environmental LCA. A range of interrelated environmental project appraisal techniques were recently examined by Hammond and Winnett (2006) in order to determine their relative merits. They argued that many of the environmental appraisal methods can play an important evaluative role as part of an interdisciplinary toolkit within a general systems framework. Nevertheless, caution needs to be used when adopting economic and engineering analysis techniques so as to ensure that they are fit for their sustainability purpose.

2.2. *Thermodynamic constraints on energy systems*

In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This idea is based on the First Law of Thermodynamics, that is, the principle of conservation of energy, or the notion of an energy balance applied to the system. It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting', which was developed in the 1970s in the aftermath of the oil crisis. This analysis is performed over the entire life cycle of the product or activity from 'cradle to grave'. It has since been widely used by academics and UK government departments and agencies, including the Energy Technology Support Unit at Harwell (subsequently Future Energy Solutions). However, it needs to be employed with some care, as the whole-life or 'gross energy requirement' may not necessarily be the most appropriate criteria for assessing energy-related projects. It takes no account of the energy source in a thermodynamic sense. Electricity may be regarded as an energy carrier having a high quality, or 'exergy', because it can undertake work. In contrast, low-temperature hot water, although also an energy source, can only be used for heating purposes. Here, the parameter known as 'exergy' (explained in more detail by Hammond and Stapleton, 2001), which stems from the requirements of the First and Second Laws, signifies the maximum useful work obtainable from an energy system at a given state in a specified environment. It provides a basis for defining an exergy efficiency, and can identify exergetic 'improvement potential' within energy systems. Exergy analysis is popular in Europe and North America, as is a version that combines it with cost analysis: so-called 'exergoeconomics'. Pioneering studies were undertaken in the USA by Hatsopoulos et al. (1978) and Gyftopoulos and Widmer (1982). More recently, Hammond and Stapleton (2001) found that significant efficiency gains could be obtained in the UK by focusing attention on making better use of space-heating systems, improving the operating efficiency of power plant, and reducing thermodynamic losses in transportation systems that are presently dependent on internal combustion engines. Over a timespan of a little more than 30 years, the overall exergetic improvement potential for the country has risen by about 15%, but this steady increase hides major changes in terms of the decline of industrial energy consumption and the inexorable climb of transport energy demand.

In order to analyse energy usage and its effectiveness within the UK industrial sector, Hammond and Stapleton (2001) subdivided the multitude of processes into four broad categories: low-temperature ($T_p < 394$ K), medium-temperature ($T_p = 394$–692 K), high-temperature ($T_p > 692$ K), and mechanical drives. Typical energy and exergy efficiencies in these categories are illustrated in Fig. 2. These are end-use values; obviously the net energy and exergy efficiencies would need to account for losses in power generation. Consequently, the use of electricity to power mechanical drives is not as attractive as it appears, but is largely a necessary engineering requirement. Knowledge of fuel and electricity shares in each of the process categories enabled them to estimate the thermodynamic inputs and outputs associated with the industrial sector. They showed that exergy losses in industry, as a proportion of the energy input, are rather smaller than in either electricity generation or the domestic sector. Nevertheless, there is still considerable scope for thermodynamic improvements in industry.

The background studies on energy efficiency and energy productivity prepared for the UK Energy Review by the Cabinet Office's Performance and Innovation Unit (PIU) in 2002 recognised that the thermodynamic findings of Hammond and Stapleton (2001) represent the maximum theoretical improvement, or energy saving, potential (see Chapman and Eyre, 2001). But the

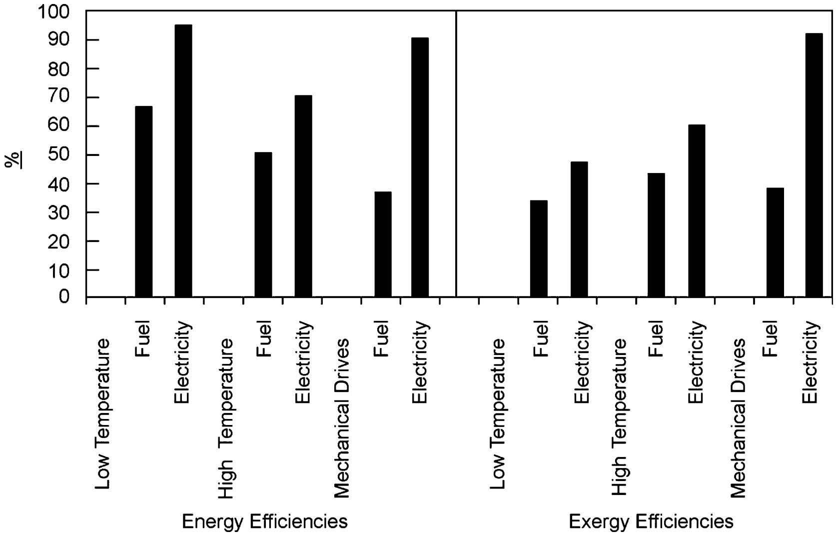

Fig. 2. Thermodynamic efficiencies of industrial processes (Hammond and Stapleton, 2001).

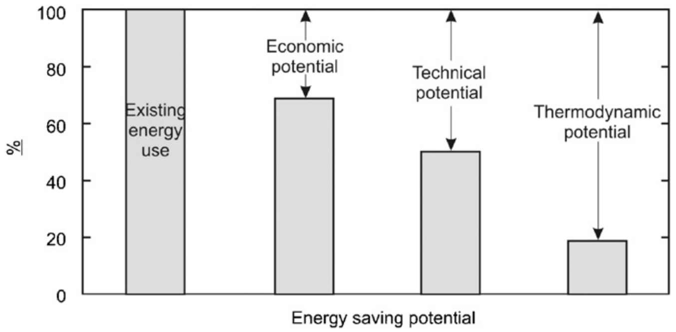

Fig. 3. The energy efficiency gap between theory and practice (Hammond, 2004b; Hammond and Winnett, 2006).

PIU team highlighted the distinction between such an optimum and what can feasibly be achieved in practice. In the economics literature, this has widely been referred to as the 'energy efficiency gap' (Jaffe and Stavins, 1994) and the 'energy efficiency paradox' (DeCanio, 1993, 1998; Van Soest and Bulte, 2001). This is illustrated schematically in Fig. 3, which depicts the economic and technical barriers (as well as the thermodynamic limits) that must be faced in securing energy-efficiency savings in practice. Roughly, this implies that, although the thermodynamic (or exergetic) improvement potential is 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%. Notwithstanding this, the PIU team (Chapman and Eyre, 2001) argued that the current level of energy services could be secured using just 20% of the energy used presently; something that suggests very great scope for innovation in energy efficiency over the longer term.

2.3. *Environmental LCA*

The aim of the LCA is to identify opportunities for environmental improvement by detecting the areas with the most significant impacts. This improvement potential can then be examined as part of the design process. In 1991, the Society of Environmental Toxicology and Chemistry (SETAC; see Fava et al., 1991) established a framework for LCA, comprising four main stages, that follows a logical sequence through goal definition and scoping, inventory analysis, impact assessment, and recommendations for improvement. There are many technical issues that need to be addressed during the conduct of LCA (Azapagic et al., 2004; Hammond and Winnett, 2006). These include the definition of system boundaries, the quality of data available, and the way in which the results are normalised. The goal definition process is very important as part of the planning stage for an LCA study. Gathering data for the inventory can be a time-consuming task, as many companies see such data as either confidential or simply do not have the sort of detailed records needed for a credible whole-life study. The impact assessment is still undergoing refinement; the concepts employed in the SETAC methodology have been largely incorporated in the ISO 14040-44 standards.

LCA is still in the development phase, both in Europe and North America. The process of tracing the life-cycle environmental impact of a product or activity is complicated. It is greatly assisted by the use of spreadsheet programmes, and several special-purpose software packages have become commercially available. The initial stages of LCA, those related to scoping and inventory analysis, can be regarded as well defined and understood. However, the later stages, including the processes of normalisation and valuation, are subjective, and many different methods are currently in use. This leads to inevitable problems when the results of impact assessments are interpreted. Nevertheless, the use of LCA is still one of the more scientific environmental management tools. Clearly, much more research is needed to refine LCA methods and to make them more robust (Azapagic et al., 2004; Hammond and Winnett, 2006). It is critically important that LCA studies are peer reviewed. This is normally undertaken as part of the refereeing process when the results of studies are submitted for publication in the scientific and technical media. Unfortunately, many industrial studies are not subject to a similar level of rigorous evaluation. There is consequently a need for government departments and agencies with an interest in the application of LCA techniques over a range of products and systems to establish a 'college of peers' for this purpose (Hammond and Winnett, 2006). This could have a very real and near-term effect on improving the reliability of LCA studies.

LCA is a very useful approach and set of techniques, but it has several limitations at its present state of development. The methods employed only allow for the examination of global and regional impacts, and not local impacts. This can obviously bias results. The LCA study of forestry machinery by Burrows et al. (1998), for example, could only account for global and regional impacts. Local ecological damage caused by oil spills on the forest floor could not be incorporated into the methodology. However, as long as complementary studies are carried out that do take into consideration local impacts, then LCA can still be used to good effect. One of the major limitations of LCA is time and data. To undertake a full LCA study requires a vast amount of data, much of which is not within the public domain. Companies are often unwilling to part with the sort of sensitive data required for a full study (Hammond and Winnett, 2006). The use of more generalised public domain data or estimates obviously decreases the accuracy of the study. Credible databases are becoming available with the rise in popularity of LCA, and these can either be purchased as a commercial database or as part of a software package. There has been a call by the Society of Promotion of Life-Cycle Development (SPOLD) for all LCA databases to be in the same format, thereby making data transfer easier. This is taking place, but the use of LCA is still too limited to enable a practitioner to find all the information needed from a public database (Azapagic et al., 2004).

The motivations and aspirations for undertaking an LCA within industry are wide ranging. From a purely environmental perspective, the primary aim may be to identify the most environmentally significant parts of the production chain. Such an activity would allow effective targeting of abatement measures. In cases where inadequate resources are available to complete a full LCA, a screening study is often considered. Such an LCA will have reduced accuracy and detail but may be used to better understand the relative environmental impacts in a short timeframe. These must be used with caution (see Hammond and Winnett, 2006). If the results of an LCA are expected to be used in company advertising, brochures and literature, an extensive LCA is required. The ISO guidelines on LCA require that any such use of LCA data must be peer reviewed by two independent assessors.

2.4. *Environmental cost–benefit analysis*

The estimation of the broad costs and benefits is an important input into the evaluation of many projects that have significant impacts on the environment. A knowledge of the social and environmental costs is useful in identifying where the market has failed to incorporate them. This provides governments with an indication of those areas in which action needs to be taken through economic instruments (such as 'green' taxes and emissions permits) that can offset such market externalities. LCA is sometimes employed to estimate impact inventories that can then be coupled with cost–benefit analysis to yield their environmental costs. It is then necessary to internalise 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, through a variety of direct and indirect empirical methods. It is indisputable that many environmental problems, however defined, involve extended time horizons and great uncertainty. In mainstream environmental economics, the costs and benefits in monetary terms are progressively discounted for future years in order to allow for the 'time value of money'. This is a source of much criticism from environmentalists, for familiar practical and ethical reasons (see, for example, Broome, 1992). Ultimately, the application of cost–benefit analysis results in the determination of a single decision criteria; typically the net present value over the project life, the corresponding discounted cost–benefit ratio, or some related parameter. A range of techniques for the monetary valuation of environmental externalities has been developed over the last few decades (some of these were summarised by Hammond and Winnett, 2006). These might be viewed as indicating the rude health of cost–benefit analysis, but it also suggests potential weaknesses. A number of studies have recently been undertaken that demonstrate the wide variety of results that can be obtained via cost–benefit analysis, depending on the details of the methods employed (see again Hammond and Winnett, 2006).

Some of the advocates of cost–benefit analysis techniques for evaluating new projects with significant environmental impacts imply that they can be used as the sole method of assessment. There are a number of reasons for discouraging such an approach. Firstly, the various methods for valuing external costs and benefits are all open to criticism (Maddison, 1999; Stirling, 1997, 1998). The second, and arguably more important, reason for discouraging the sole use of cost–benefit analysis techniques is that they obscure rather than highlight the range of impacts that may emanate from a given project. Decision makers are presented with a single decision criteria (such as the discounted cost–benefit ratio), which actually hides many disparate environmental impacts. It is vitally important that the implications of these impacts are faced, particularly by politicians, rather than obscured by the methodology (see, for example, Hammond, 2000; Stirling, 1997, 1998).

2.5. *Other assessment techniques*

There are a variety of other appraisal techniques that can provide complementary insights to the principal methods summarised above. The simplest is probably 'mass and energy networks'. It is based on the fundamental principles of mass and energy conservation, a requirement of any chemical engineering system. Variants of mass and energy networks have been extended to deal with complex processes involving reactive systems and multi-phase flows. One technique that has been widely adopted by chemical process and mechanical engineers alike is the so-called 'pinch' analysis or technology. This is a method of analysing 'heat exchanger networks' and process plant to yield optimal configurations (see Kreith, 2000; and chapters by Kirtan Trivedi in Kreith and West, 1997). It was extended and commercially exploited in the UK and beyond by Professor Bodo Linnhoff (formerly at UMIST), after which it was incorporated under the generic title of 'process integration' (see Section 3.2). Comparative studies have been undertaken to evaluate the results of exergy analysis with pinch technology. For example, Wall and Gong (1996) 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' optimisation. Other methods for system optimisation also have a role in optimising the performance of refrigeration equipment, power plant, pumps, fans and the like. The methods themselves are diverse; embracing economics, equation fitting, search methods, system simulations, steady-state simulation, dynamic programming, geometric programming, dynamic behaviour of thermal systems, calculus methods of optimisation, as well as probabilistic approaches to design (see, for example, Stoecker, 1989).

3. The state of current technological developments

3.1. *Key challenges*

The US Climate Change Technology Program (2003) recommends focusing on energy-intensive industries. But the potential importance of the global warming problem has resulted in the case being made for a low carbon, rather than just a low-energy economy. Changes in the UK's building regulation offer a means to control the thermal performance of non-domestic new buildings, with changes in 2005 providing a further 2–8% improvement in energy consumption over the 2002 regulations (Brown et al., 2006). Steps also need to be taken in the electricity supply industry to reduce the carbon intensity of electricity production by the adoption of renewable energy and combined heat and power (CHP) plant. This would include more research into the storing of energy from intermittent renewable sources and the provision of heat networks. All these actions rely on the reduction of carbon emissions being a priority for Government and its executive agencies, as well as actions by others, down to the level of individual consumers. It would involve a market approach (Hammond, 2000), coupled with intervention by way of a portfolio of measures to counter market deficiencies: economic instruments, environmental regulation and land-use planning procedures. In order to make such an approach a practicable engineering option, it would be necessary to use systems analysis methods to optimise the energy cascade. Thermodynamic analysis will be an important technique for identifying process improvement potential. Natural Resources Canada (2003) has recognised the need for sector benchmarking to evaluate such potential against the best available technologies.

3.2. *Key technological advances*

- *Zero- and low-carbon (ZLC) energy technologies*: In order to reduce carbon emissions from industry, it is desirable to improve energy efficiency (a lower-carbon option) or employ renewable energy supplies for heat and power (generally a zero-carbon option). CHP, sometimes termed 'co-generation' or 'total energy', plant can lead to savings of 20–40% (Engineering Council, 1998), providing that the 'waste' heat from the power cycle is employed to replace that from other heat sources.
  (i) *Industrial CHP systems*: Based on a typical turbine set and operating at a power-to-heat ratio of about 0.9, CHP plants have an energy efficiency of some 80%. This contrasts with a modern, electricity-only, combined cycle gas turbine plant with perhaps a 55% First Law efficiency. CHP systems are therefore an important means of improving fossil fuel resource productivity (Hammond, 2004a).
  (ii) *Renewable energy technologies*: These are often low-efficiency devices, but ones that utilise 'income' (or 'free') energy sources that are almost zero-carbon emitters. Near-market technologies include onshore wind, landfill and sewage gas, and energy from waste plants (not a strictly

‘renewable’ source, as the waste might preferably be reduced, reused or recycled). The use of biomass in various forms, such as wood fuel, energy crops and biofuels, are likely to be of greater interest in the medium term for industries with a local supply, perhaps within a 30-mile radius of a particular site. The prices of building-embedded photovoltaic solar cell arrays will need to fall dramatically via RD&D programmes in order to be attractive. They currently have a payback period, without a subsidy, of around a century.

- *Industrial processes*: These occur in a diverse range of industries—iron and steel, chemicals, food and drink, and paper and board are among the largest energy consumers. One way of identifying developments in enabling technologies is to break them down into constituent elements or sub-processes. These can then be improved by optimising individual process types, eliminating process steps, or substituting novel manufacturing processes (such as materials fabrication and product separation). Many industrial organisations, including the Carbon Trust, adopt a characterisation of the following type:
    (i) *Combustion*: Increasing the efficiency of combustion processes (or reducing irreversibilities) has considerable scope for energy and carbon savings.
    (ii) *Materials*: R&D needs to be undertaken to optimise materials use and develop a range of durable advanced materials, via predictive tools for the discovery and development of new materials.
    (iii) *Integration*: This provides a potential basis for step changes in energy efficiency and cost effectiveness. (Thermodynamic methods, such as exergy and ‘exergoeconomic’ analysis, provide a means for the optimisation of process plant. The use of pinch technology (see Kreith, 2000; Trivedi in Kreith and West, 1997; Pretty and Rutkowski, 2001) is an alternative approach that appears to yield similar results, one brought to fruition in the UK by Linnhoff (see Section 2.5).)
    (iv) *Separation*: A range of applications exist in chemical, pharmaceutical and related industries, including crystallisation, distillation, drying, evaporation, and membrane processes. Future developments in membrane science based, for example, on a biological model for chemical transport and membrane maintenance, as well as advances in materials science and nanotechnologies, should result in improved resource productivity, doing ‘more with less’ (Wiesner and Chellam, 1999). Technological applications may result in membrane-based fuel cells for generating electricity, more compact (and lower visual impact) waste and hazardous waste treatment facilities, and improved environmental monitoring.
    (v) *Control*: Improved control and automation of industrial processes can yield significant energy and carbon reductions in many sectors.
- *Boilers and steam*: Steam is still employed to meet a significant proportion of the heat requirements in industry. The improved design and development of boiler plant therefore provides continuing opportunities for energy saving (Kreith and West, 1997). The leakage of steam downstream of boilers also gives rise to significant losses and therefore provides many opportunities for energy conservation.
- *Compressed air*: This is very widely used in industry to drive devices ranging from air-powered hand tools to pneumatic robots (Kreith, 2000). Such applications typically give rise to relatively large leakages, perhaps 10–50%, and energy costs.
- *Electric motors*: Significant improvements can be readily made in the efficiency of electric motors. They use about half the electricity consumed worldwide, but simple measures, with typical payback periods of a little over a year, can be adopted to reduce this by a half (von Weizsacker et al., 1997). These motor-system improvements include better choice, sizing, control and maintenance of the motor.
- *Heating and lighting*: These constitute a major area for improvement potential in non-domestic buildings (Brown et al., 2006; Hammond and Stapleton, 2001). Significant opportunities exist for space-heating savings via the adoption of more efficient heating plant, higher thermal insulation standards, and better environmental control. Lighting can account for some 20% of total energy end-use here, but up to 50% of related financial costs (due to the high price of electricity compared to fossil fuels). RD&D is therefore needed in innovative energy-efficient products, and then advice is required to help industrialists select best-practice lighting technologies and systems.
- *Transportation*: Industry needs to transport its output both within factories and around the supply chain to consumers. Potential opportunities therefore exist for reducing energy and carbon emissions by way of switching to high-efficiency vehicles (von Weizsacker et al., 1997) with electric or hybrid power trains, alongside improved logistics planning to reduce the need for or duration of transport.

4. Future advances to 2050 and beyond

4.1. Key challenges

In the industrial sector, the EU’s Emissions Trading Scheme offers the potential to significantly reduce CO_2 emissions. Brown et al. (2006) recently noted that non-domestic buildings (including industrial and commercial structures) might provide a basis for reducing emissions by some 25 MtC by 2050; compared to 1990, a reduction of about 45%. A similar ‘baseline’ trend is expected from industrial processes, which could lead to about a 30% reduction in total carbon emissions from 1990 to 2050 (although only a 12% reduction from 2000 to 2050). The potential reduction in UK emissions between the domestic and non-domestic building stock and industrial processes is depicted in Fig. 4. Only 20% of the non-domestic building stock produces 80% of its emissions—in keeping with the so-called ‘Pareto principle’. It has been estimated (Brown et al., 2006) that the UK could achieve around a 60% reduction in its carbon emissions by 2050 from a combination of domestic buildings, non-domestic buildings and industrial processing from a 1990 baseline. This would

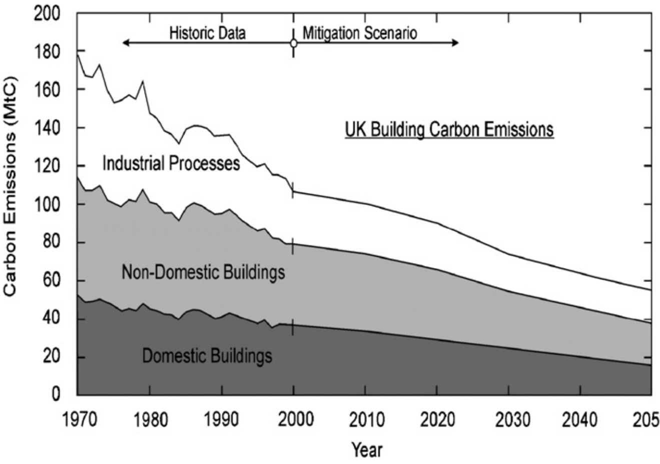

Fig. 4. Potential carbon reductions from the UK building stock, including industrial processes: a mitigation scenario (Brown et al., 2006).

require additional energy-saving measures over and above those associated with the 'baseline' projection. Thus, the potential for 'greening' the UK building stock is large, but the measures needed to achieve this would present a significant challenge to the UK Government, domestic householders and industry in the broadest sense.

The US Climate Change Technology Program (2003) has recognised that particular R&D challenges are unique to each industrial sub-sector. These include research on advanced computational tools, materials behaviour and fabrication methods, and separation processes, alongside the development of improved design methods.

4.2. Key scientific advances

4.2.1. High-temperature processes

These encompass a range of industries and activities—metallurgical processes, thermochemical cycles and the like. Clearly, any processes that take place at high temperature must have a significant potential for energy saving via heat cascading and waste-heat recovery. Thermodynamic methods, such as energy, exergy and exergoeconomic analysis, provide an important means for the optimisation of high-temperature process plant (Hammond, 2007).

4.2.2. Combustion

Manufacturing industries obtain some 85% of their energy from on-site combustion of fossil fuels (US Department of Energy, 1999). The detailed mechanisms involved in combustion processes are not well understood at a fundamental level (Hammond, 2007). Several studies have investigated the sources of irreversibility, or exergy destruction, resulting from such phenomena. It is useful to differentiate three hypothetically distinct sub-processes: (i) combined diffusion/fuel oxidation, (ii) internal thermal energy exchange (or heat transfer) and (iii) the mixing process associated with the combustion products. About three quarters of the exergy degradation is linked to internal heat conduction. In fact, chemical reactions are found to be quite efficient; the exergy efficiency of this sub-process was typically 94–97%. Advanced combustion research must therefore aim at gaining an improved understanding of these mechanisms, finding ways to secure an improvement in diffusion processes and the development of new technologies. The UK has significant expertise in this field (Carbon Trust, 2002), although long-term R&D has tailed off in recent years.

4.2.3. Advanced materials

The importance of improved materials that can withstand high-temperature processing and corrosive, or otherwise harsh, environments have been recognised both in the UK (under the UK Energy Research Centre's networking and research activities) and in the USA (US Department of Energy, 1999). Such materials have the potential to reduce energy use in refining and fabrication, lower pollutant emissions and increase component life. The US Advanced Industrial Materials Program, together with the separate Engineered Ceramics Program, has engaged with industrial stakeholders to identify user needs, although the research is mainly carried out at Department of Energy national laboratories. The Advanced Industrial Materials Program has focused on intermetallic alloys, advanced structural polymers and membrane materials. Ceramics typically perform well at higher temperatures than conventional metal alloys, but are often brittle. They can consequently suffer from catastrophic failure in service. The US Engineered Ceramics Program aims to develop structural ceramic and composite materials, including continuous fibre ceramic composites, for a range of industrial process and power generation applications. The Carbon Trust believes that opportunities exist for the UK to develop a capability in niche markets based around novel materials. The UK Energy Research Centre is developing one of its six themes in this area: Materials for Advanced Energy Systems. The Centre is focusing on developments in the computer modelling of materials (from the quantum to the continuum scale), and on methods of rapid-throughput screening.

4.2.4. Process intensification

The performance of chemical and process plant modules may be revolutionised by the adoption of a design philosophy based on the novel concept leading to size reduction. This can be achieved by re-examining from a fundamental perspective the underlying fluid dynamics and related transport phenomena—heat, mass and mixing-rate processes. The UK has been at the forefront of the development of this approach (Emeritus Professor Colin Ramshaw at Newcastle is sometimes regarded as its founding father) and it therefore holds a lead in terms of R&D. It results in compact, smaller and efficient designs; built around the compact heat exchanger as the foundation technology. This can give rise to long or short residence times as required. The design concept can provide better product quality and speed to market, reduced capital costs, improved control of process irreversibilities with more efficient energy use, and reduced waste streams and 'green' manufacture with a lower environmental footprint. Possible applications of process intensification and miniaturisation include the manufacture of advanced functional polymeric materials, nano-structured alloys and composites. But the Carbon Trust (2002) regard this approach as high risk and necessitating significant R&D effort. Only a few examples of its successful commercial application are available: heat exchangers, reactors and separation plant.

4.2.5. Improved industrial process monitoring and control

Process monitoring enables energy consumption to be accurately measured against pre-determined standards (Natural Resources Canada, 2003). Industrial process control can then be employed to reduce variability in situ. It typically utilises online or at-line instruments that ideally monitor in real time. They can map the concentration–time-profiles of reactants and products in the process vessel. It consequently provides a fertile and growing area of R&D for device designers and control engineers. Recent technological advances in wireless telecommunications technology have been, and are being, applied to the development of these data capture instruments, such that many measurements can now be effectively achieved without intrusive wiring. As the penetration of wireless technology progresses, the price of the technology will decrease significantly and the rate of uptake should show a corresponding increase. The potential scope for this particular technology is very large indeed, but only if the apparent lack of awareness relating to the importance of energy monitoring in industry can be eliminated. It is one of the few technologies that can be effectively employed across industry as a whole, and therefore promises to make significant contributions to energy demand and carbon emissions reduction.

4.2.6. Factor X improvements in resource productivity ('dematerialisation')

The prospect of 'Factor 4' improvements in resource productivity advocated by Ernst von Weizsacker et al. (1997), sometimes known as 'dematerialisation', suggest that economic welfare in the industrial world might be doubled while resource use is halved, hence the 'Factor 4'. Resource productivity forms one of the components of the so-called 'IPAT', or 'sustainability', equation devised by Holdren and Ehrlich (1974) for analysing environmental disruption:

$$\text{(Environmental) Impact} = \text{Population} \times \text{Affluence} \times \text{Technology} \qquad (1)$$

Population growth in the UK has been very slow since the 1970s. Affluence, or economic consumption per person, is normally measured by gross domestic product per capita. The 'technology' component in Eq. (1) represents the environmental damage per unit of consumption. According to Meadows et al. (1992), the scope for reducing the various terms on the right-hand side of the IPAT equation is very large over a 50–100-year timescale. Table 1 is adapted from this work, although they attribute the estimates of the potential for long-term change and the associated timescales to Amory Lovins (reproduced from Hammond, 2004b). Obviously, the individual columns in Table 1 reflect global aggregate figures or averages. Therefore the focus in the industrialised world, where the population is stable, would have to be principally on resource productivity (the 'technology' element). The multiplier effect of the IPAT equation suggests that significant reductions in environmental impact (via increases in resource productivity like those indicated in Table 1) are possible overall. Improvements in resource productivity in the UK would involve a structural shift from energy-intensive manufacturing to energy-frugal services (Hammond, 2000). Britain has moved some way in this direction (see Fig. 1), with a 40% improvement in primary energy intensity since 1965. Increases in resource-use efficiency at the Factor 4 level (the UK Foresight Programme has been contemplating Factor 10 over the long term) would have an enormous knock-on benefit of reducing pollutant emissions that have an impact, actual or potential, on environmental quality. In reality, such a strategy requires a major change ('paradigm shift') to an energy system that is focused on maximising the efficiency of the full fuel/energy cycle and minimising the embodied energy in materials and products by way of reuse and recycling (Hammond, 2000).

An example of a Factor X technology is *light-weighting*, which aims to reduce the life-cycle environmental impact of products and is one of the approaches favoured by Amory Lovins for the development of his 'hypercars' (see von Weizsacker et al., 1997). It may affect the product attributes such as the appearance, weight and size of a product. These are often attributes that affect buyer decision and can therefore affect the perception of a brand and represent a business risk. There are strong arguments for light-weighting, including reductions in energy and materials costs plus industrial-waste reduction, with payback in 6–18 months. Indeed, the strategy was demonstrated in the early 1990s when a General Motors team built two four-passenger Ultralite concept cars in just 100 days (von Weizsacker et al., 1997). The cars had sports car performance and styling, with doubled efficiency and enhanced safety features. The following technological R&D issues would need to be addressed in order to make a practical reality of the light-weighting concept for affordable mass production:

- joining technology to deliver multi-material capability,
- development of specific new materials,
- metal forming and casting,
- lighter, safer assemblies,
- surface engineering,
- computer-aided design software.

There are also a number of 'soft' issues that would need to be tackled. Consumers have an important role in reversing the trend towards increased appliance waste, but they currently face economic disincentives and lack adequate product information. Legislation is therefore likely to be needed in order to encourage light-weighting.

5. Drivers of and barriers to the adoption of advanced industrial energy technologies

5.1. *The drivers for change*

The business environment in which new technologies or techniques are developed and brought to market is a crucial factor in determining their rate of market penetration. It is therefore worthwhile examining the circumstances under which the user (typically, but not always, a firm) will decide whether to adopt these technologies or techniques. There are two primary drivers in industry behind the adoption of energy demand management measures (including both technology and techniques), namely costs and legislation. Energy costs represent a large proportion of operating costs in the energy-intensive industries; often up to 50%. This, combined with recent dramatic increases in natural gas prices, means that costs represent a significant incentive for industrial energy demand management (see also Section 1.2). Likewise, environmental legislation, which 'punishes' firms for polluting, effectively results in penalties for the burning of (non-renewable) fossil fuels and the use of derived electricity. In the UK, companies are subject to the EU Emissions Trading Scheme and the Climate Change Agreements or the Climate Change Levy, as well as the recently introduced Large Combustion Plant Directive. In order for firms to comply with these quite

Table 1

The environmental impact of population, affluence and technology (adapted from Hammond (2004b) after Meadows et al. (1992), who based the estimates on those produced by Amory Lovins)

Population	Affluence		Technology	
Population	$\times \frac{\text{Capital stock}}{\text{Person}}$	$\times \frac{\text{Material throughput}}{\text{Capital stock}}$	$\times \frac{\text{Energy}}{\text{Material throughput}}$	$\times \frac{\text{Impact}}{\text{Energy}}$
Applicable tools				
Family planning	Values	Product longevity	End-use efficiency	Benign sources
Female literacy	Prices	Material choice	Conversion efficiency	Scale
Social welfare	Full costing	Minimum materials design	Distribution efficiency	Siting
Role of women	What do we want?	Recycle, reuse	System integration	Technical mitigation
Land tenure	What is enough?	Scrap recovery	Process redesign	Offsets
Approximate scope for long-term change				
$\sim 2\times$	?	$\sim 3–10\times$	$\sim 5–10\times$	$\sim 10^2–10^{3+}\times$
Timescale of major change (years)				
$\sim$50–100	$\sim$0–50	$\sim$0–20	$\sim$0–30	$\sim$0–50

stringent legislative requirements, energy demand has to be reduced. Obviously, other drivers exist, including market competitiveness, intangible benefits (such as perceived contributions to the firm's corporate social responsibility) and fiscal support from third parties (such as the Carbon Trust). However, these usually have a secondary impact on industrial companies (Carbon Trust, 2005).

5.2. *The barriers to change*

There are several barriers preventing firms from adopting enabling technologies for energy demand management. These are varied, but many concern a lack of specialist knowledge on the part of the firm. This could be information relating to the current energy consumption, the specific technology for demand management or the economic aspects of investment in such technology. In addition, there are barriers such as the limited 'windows of opportunity' for the installation and maintenance of new plant or the limited resources to undertake this type of activity (which is particularly prevalent in small- and medium-sized enterprises; see HM Treasury et al., 2005). The lack of expertise resulting from a rationalisation of the workforce and a general reluctance to adapt to changing practices can amount to barriers often associated with a degree of traditionalism (Future Energy Solutions, 2005). The latter seems to provide a minor hindrance compared with the widespread lack of specialist knowledge. That will therefore be our focus here.

Ignorance about the current energy consumption within industry on a plant level is a major inhibiter to the proper evaluation of energy-saving potential. It is important to determine the amount and type of energy usage over long periods (years at least). The starting point for energy demand management is to identify the current baseline. There is some reluctance by firms to disclose energy data to third parties. They see this as undermining their competitive advantage. But the wider availability of this type of information would enable independent analysts to suggest ways of optimising energy use in different UK industrial sectors. A lack of awareness of the available technologies by industry, and the poor understanding of the historical technological legacy issue in general, are important barriers to the uptake of energy demand reduction technologies. The most suitable time to upgrade equipment is when the existing plant is being replaced. However, if the alternatives are unknown at this time, the same or similar equipment is likely to be installed and the opportunities to realise savings are foregone.

Knowledge of the economics of energy-related projects is often a decisive factor in determining their viability. If cost data are incorrect or absent, the investment appraisal of a project cannot be affected properly. This will result in cost-effective options being neglected (see also Section 2.4). There is a common misconception that demand management incurs high costs, which seems not to take into account the relatively short payback periods associated with many of these investments (often as little as 18 months). In addition, financial grants and other support from government agencies are potentially available (including the Carbon Trust's Enhanced Capital Allowance scheme), although the take-up of these schemes by industry seems relatively low.

6. Concluding remarks

The only way the 2050 Royal Commission on Environmental Pollution carbon reduction target—60% from 1997 levels by about 2050—could actually be achieved is by significantly reducing primary energy consumption to 45–75% of the present figure. This requires the widespread adoption of energy-saving measures across the economy, and that has been acknowledged in the 2007 Energy White Paper (Department of Trade and Industry, 2007). This state-of-science review has set out to provide an indicative assessment of enabling technologies for reducing UK industrial energy demand and carbon emissions out to 2050. In the short term, in the period that will rely on the adoption of current or existing technologies, the road map and priorities are relatively clear. Here, there is a variety of available technologies that will lead to a reduction in the demand for energy in industrial processes, boiler operation, compressed-air usage, electric-motor efficiency, the effectiveness of heating and lighting systems and other ancillary uses (such as transport). But the prospects for the commercial exploitation of innovative technologies by the middle of the 21st century are highly speculative. Emphasis is therefore placed on the range of technology assessment methods that are likely to provide policy makers with a guide to progress in the development of high-temperature processes, improved materials, process intensification and improved industrial process control and monitoring. It is in these areas that thermodynamic analysis can make a major contribution to identifying where the improvement potential lies. For example, exergy analysis can provide an indication of the maximum improvement potential available from different enabling technologies. However, it is important to recognise that this 'maximum'—perhaps an 80% improvement in end-use efficiency in some cases—cannot be achieved in practice. Technical and economic barriers will limit the improvement potential to something closer to 30%. Even that would make a significant contribution to energy demand and carbon reduction in UK industry.

Recent trends in energy prices, specifically those of natural gas, and the implementation of national and European legislation have resulted in stronger drivers for industrial energy demand management technology. Innovation in ZLC technologies can secure both economic and environmental objectives. However, there still exist many barriers to the uptake of this technology, the most significant of which appears to be 'ignorance, inertia and lack of interest' (Carbon Trust, 2005). There is often poor awareness of baseline energy consumption, the specific ZLC technologies that are available and of the associated economics. Industry needs to be made aware of the portfolio of technology options that are likely to come on stream in the period to 2050. The Carbon Trust (2005) has argued for private and public support for such innovations (like those outlined in Sections 3.2 and 4.2) in order to 'move them down the cost curve to make them competitive'. Greater awareness of the importance of appraisal methods for industrial energy technologies (particularly the thermodynamic methods outlined in Section 2.2) needs to be encouraged in both the public and private sectors. The Research Councils, the Carbon Trust and the trade associations may have a crucial role to play here.

Various policy instruments will inevitably be required to encourage the introduction of energy efficiency measures in the face of market barriers. The two main candidates for intervention are economic instruments (carbon and/or energy taxes, and traded permits) and utility regulation in the wider interests of environmental protection. The Royal Commission on Environmental Pollution (2000) and others favour replacing the present Climate Change Levy with a general carbon tax based on CO_2 emitted per unit energy supplied. This should be applied upstream, where fossil fuels are first purchased, and cover all sectors. The Royal Commission argued (2000) that carbon tax revenues should then be employed to reduce fuel poverty, invest in energy efficiency measures, increase the viability of other low-carbon energy alternatives and to protect UK industrial competitiveness. The 2007 Energy White Paper advocated building and product efficiency standards, CO_2 emissions trading, tax incentives, and advice and information, alongside the EU Emissions Trading Scheme.

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