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Industrial energy efficiency: Interdisciplinary perspectives on the thermodynamic, technical and economic constraints

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Industrial energy efficiency

Interdisciplinary perspectives on the thermodynamic, technical and economic constraints

Russell C. McKenna

A thesis submitted for the degree of Doctor of Philosophy
University of Bath
Department of Mechanical Engineering
March 2009

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Abstract

Overreliance on energy from fossil fuels is unsustainable because of their regional depletion and associated environmental impacts. The British industrial sector accounts for around one fifth of final energy demand and one third of carbon emissions nationally. This thesis attempts to quantify the potential for industrial energy efficiency from the current baseline, by adopting thermodynamic and economic perspectives.

The methodology involves a top-down analysis of energy trends within the manufacturing sector to determine the baseline against which changes are measured, leading to bottom-up case studies which explicitly consider the detailed mechanisms affecting energy demand. Top-down analysis highlights the diversity between industrial sectors, for which a sectoral classification based on process homogeneity is proposed. It also enables the long term, systemic potential for efficiency improvements to be estimated and identifies the barriers to uptake.

Bottom-up case studies are better suited to identifying the sectoral potential in the short to medium term. Firstly, the technical potential for heat recovery from industrial sectors is quantified by recourse to thermodynamic quality and spatial considerations. Secondly, an energy and exergy analysis of a glass furnace enables a distinction between avoidable and unavoidable losses, leading to the identification of economic savings. Thirdly, a process integration study at a pulp and paper mill based on a pinch analysis and optimisation of a heat exchanger network highlights economic efficiency improvements.

This thesis demonstrates that realising the full industrial energy efficiency potential requires improvements to public policy intended to overcome market-related barriers, especially the EU Emissions Trading Scheme and the Carbon Trust, with additional scope for a mandatory efficiency standard relating to motors. Energy efficiency has to part of a company's overall strategy to be effective. Future work should focus on heterogeneous sectors and the broader effects on industrial energy efficiency of globalisation and the shift towards services.

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The affluent earth was not only pressed for the crops and the food
that it owed; men also found their way to its very bowels,
and the wealth which the god had hidden away in the home of the ghosts
by the Styx was mined and dug out, as a further incitement to wickedness.

Ovid, *Metamorphoses*, 1.137:140

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List of abbreviations

Abbreviation	Meaning
AEA	AEA Energy and Environment
BERR	Department for Business Enterprise and Regulatory Reform (previously DTI)
CCA	Climate Change Agreement
CCL	Climate Change Levy
CCGT	Combined Cycle Gas Turbine
CCP	Climate Change Programme
CHP	Combined Heat and Power
CO ₂	Carbon Dioxide
CPI	Consumer Prices Index
DEFRA	Department for Environment, Food and Rural Affairs
DPP	Discounted Payback Period
DTI	Department for Trade and Industry (now BERR)
DUKES	Digest of UK Energy Statistics
EAS	Energy Audit Series
ECA	Enhanced Capital Allowance
ECUK	Energy Consumption in the UK
EE	Ecological Economics
EEIR	Energy Efficiency Innovation Review
EKC	Environmental Kuznets Curve
EMAS	Eco-management and Audit Scheme
ERE	Environmental and Natural Resource Economics
ETSU	Energy Technology Support Unit
EU ETS	European Union Emissions Trading Scheme
FES	Future Energy Solutions
GCC	Grand Composite Curve
GCV	Gross Calorific Value
GER	Gross Energy Requirement
GHG	Greenhouse Gas
GVA	Gross Value Added
HEN	Heat Exchanger Network
HEX	Heat EXchanger
IAG	Interdepartmental Analysis Group
ICT	Information and Communication Technology
IETS	Industrial Energy Thrift Scheme
IIED	International Institute for Environment and Development
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
IRR	Internal Rate of Return
ITP	Industrial Technologies Program
LCIP	Low Carbon Initiative Programme
LCPD	Large Combustion Plant Directive
LCTA	Low Carbon Technology Assessment
LDPE	Low Density Polyethylene
LZC	Low and Zero Carbon Technology

Abbreviation	Meaning
MFP	Multi-Factor Productivity (same as TFP)
NCV	Net Calorific Value
NEB	Non-energy Benefit
NISP	National Industrial Symbiosis Programme
NPV	Net Present Value
OEF	Oxford Econometric Forecasting (now Oxford Economics)
ONS	Office for National Statistics
PA	Process Analysis
PEC	Primary Energy Consumption
PS	Polystyrene
PVC	Polyvinyl Chloride
RCEP	Royal Commission on Environmental Pollution
RPI	Retail Prices Index
SEA	Statistical Energy Analysis
SEC	Specific Energy Consumption
SER	Specific Energy Requirement
SIC	Standard Industrial Classification
SME	Small and Medium sized Enterprise
STP	Standard Temperature and Pressure (0°C and 1atm)
STPR	Social Time Preference Rate
TER	Theoretical Energy Requirement
TFP	Total-Factor Productivity (same as MFP)
UEP	Updated Emissions Projections
UKERC	UK Energy Research Centre
UK	United Kingdom
UMIST	University of Manchester Institute of Science and Technology
USDOE	US Department of Energy

Nomenclature

Symbol	Definition	Units
A	Area	m ²
A _{c,wall}	Area of wall for convective heat transfer	m ²
C	Capital cost	£
c _p	Specific heat capacity	J/kgK
C _x	Fraction of fuel x in fuel split	-
D _i	Excess energy in block i of HEN	-
E	Energy	J
E _T	Total site energy consumption	J
E _{Tf}	Total site fuel consumption	J
E _x	Exergy	J
F	Correction factor for cross-flow heat exchangers	-
f _c	Combustion emissions fraction	-
f _{cond}	Specific condensation factor	-

Symbol	Definition	Units
f_{el}	Electricity fraction of fuel split	-
f_L	Lang factor	-
g	Acceleration due to gravity	m/s^2
h	Specific enthalpy	J/t
h_c	Cold side heat transfer coefficient	W/m^2K
h_h	Hot side heat transfer coefficient	W/m^2K
H	Enthalpy	J
I	Investment	£
IP	Improvement potential	-
K	Capital	£
K_T	Overall sector emissions factor	kgC/J
K_x	Emissions factor of fuel x	kgC/J
L	Labour	£
LF	Load factor	-
m	Mass	kg
\dot{m}	Mass flow rate	kg/s
P	Pressure	Pa
Q	Heat or economic output	J or £
\dot{Q}	Heat flow	W
r	Discount rate	%
R	Revenue	£
s	Specific entropy	J/kgK
S	Entropy	J/K
S_{conv}	Empirical convective heat transfer coefficient	$W/m^2K^{5/4}$
T	Temperature	K
$\Delta T_{lm,cf}$	Logarithmic mean temperature difference	K
U	Heat transfer coefficient or internal energy	W/m^2K or J
V	Volume	m^3
w	Humidity ratio	-
W	Work	J
Y	Equipment capacity	kg/s
Z	Vertical height	m
ε	Emissivity	-
η_c	Combustion efficiency	-
σ	Stefan-Boltzmann constant	W/m^2K^4
λ	Thermal conductivity	W/mK
Θ	Carnot factor	-
Ψ	Exergy efficiency	-

1 Introduction

1.1 *Background to sustainable development*

Over the past few decades a general awareness has emerged that many of humankind's activities are unsustainable. Although this realisation came to the fore mainly in the 1960s and 1970s, such ideas are not new. In the 18th Century Malthus (1798) and the classical economists believed that it was impossible to improve human welfare in the long term, and Jevons (1866) famously predicted the imminent exhaustion of Britain's indigenous coal reserves. More recent concerns about the sustainability of human activities were especially provoked by publications such as Hardin's (1968) *Tragedy of the Commons*, which discussed the implications of a rapidly increasing population with access to the same finite resources (Appendix A2.1). Several years later *The Limits to Growth* study was carried out, which predicted that a business-as-usual scenario would be confronted by physical and ecological limits within a century (Meadows et al., 1974). In 1983 the World Commission on Environment and Development (WCED) was established to formulate a Global Agenda for Change (Frears & Hicks, 2008a). The WCED's (1987) activities culminated in the publication of *Our Common Future*, also known as the Brundtland Report, which attempted to address the apparently conflicting objectives of ensuring economic growth whilst protecting the environment. Although most concepts of sustainable development are multifaceted, one widely recognised aspect is that of inter- and intra-generational equity adopted in the Brundtland report (ibid.). Most if not all concepts of sustainable development or sustainability incorporate a consideration of the varied interactions between economic activity and the physical, ecological, environmental and social systems in which it occurs.

1.2 *Energy and the environment*

The relationship between energy (use) and the environment plays a central role in concerns about sustainability. Energy has underpinned human development historically and has been particularly crucial in the rapid industrialisation during the past few centuries (Smil, 2003). Technological innovation has been inextricably linked with the evolution of energy systems, which is clear from the large number of General Purpose Technologies (GPTs, chapter 2) that are energy technologies, such as the steam engine, the internal combustion engine, and electricity generation (Lipsev et al., 2005).

Around 90% of the primary energy used today, and indeed since the beginning of the 20th century (Nakicenovic et al., 1998), is harnessed from non-renewable fossil fuels¹ that are being exhausted at a rate far faster than they were formed (IEA, 2008). This problem is compounded by the fact that these fuels are unevenly distributed around the world, which has consequences

¹ Non-renewable within this thesis refers to the timescale upon which these fuels are formed being far greater than the human timescales involved in consuming them. Renewable resources are therefore those energy flows that, apart from geothermal energy, are directly or indirectly derived from current or recent flows of solar and gravitational energy (IEA, 2004a).

in terms of energy access and security. Furthermore, the exothermic reaction of combusting these hydrocarbon fuels in air (or oxygen) releases carbon dioxide (hereafter CO₂) as well as other polluting oxides (nitrous, sulphur etc.). CO₂ is a so called greenhouse gas (GHG) because it contributes to the greenhouse effect, in which incident solar irradiation is trapped within the atmosphere, leading to a temperature increase (Boyle, 2002).

It is widely held by scientists and climatologists that the greenhouse effect is being exacerbated by human activity. The Intergovernmental Panel on Climate Change (IPCC, 2009) was established in 1988 in recognition of this belief. In 1992, the United Nations Conference on Environment and Development in Rio de Janeiro established the United Nations Framework Convention on Climate Change (UNFCCC, United Nations, 1992), and in 1997 the Kyoto Summit amended this Framework and developed the Kyoto Protocol (United Nations, 1998). The IPCC (2001, 2007) since found that the global average surface temperature increased over the 20th Century by about 0.6°C and since the late 1950s by 0.1°C per decade. Over the latter timescale snow cover and ice extent has decreased, and the global average sea level has risen. Significantly, the IPCC (2001) detected a “discernable human influence” on global climate and identified a causal link between rising anthropogenic GHG (mainly CO₂) emissions and global surface temperature increases.

1.3 Climate change policies and targets

The Kyoto Protocol commits the UK to reduce emissions of a basket of six GHGs by 12.5% by 2008 to 2012, based on 1990 levels. The government’s national target for abatement of CO₂ emissions is a 20% reduction on 1990 levels by 2010. The Kyoto target has been met and exceeded, but without additional measures over and above current climate change policy, the latter target will narrowly be missed in 2010 (DEFRA, 2006c, p.26, para. 17).

The Royal Commission on Environmental Pollution (RCEP, 2000) suggested that the UK should in fact strive for a reduction in CO₂ emissions of some 60% (on 1997 levels) by around 2050, corresponding to an upper limit for the concentration of CO₂ in the atmosphere of 550ppm. More recently Stern (2007) found that the economic cost of unchecked climate change exceeds the cost of mitigation, and concluded that the stabilisation target for GHGs should be in the range 450-550ppm of CO_{2e}². Although Stern’s study (ibid.) was rather controversial because of the extreme values employed for key input variables such as the social discount rate (Appendix A1.5), the lower end of this range is widely believed to correspond to a temperature rise of 2°C by 2100 (IPCC, 2007), and was therefore employed by Bows et al. (2006, p.9) in their modelling of decarbonisation scenarios. They concluded that the UK should in fact aspire to a 90% reduction in CO₂ emissions by 2050, corresponding to a 70% cut by 2030. These and the recommendations of the Climate Change Committee (CCC, 2008), that the UK should aim at an 80% cut, culminated in the Climate Change Act (HM Government, 2008). The Act legally

² CO_{2e} is carbon dioxide equivalent, which is obtained by multiplying the Global Warming Potential (GWP) of a greenhouse gas by its mass (Choudrie et al., 2008).

commits the government to this 80% cut and became law in 2008, but there has been some speculation about the consequences and culpability if this target is not met (The Economist, 2008a). In addition, the precise role of each sector of the economy in meeting this target has not yet been defined, although the CCC (2008) made some recommendations.

The fact that over 90% of CO₂ emissions are associated with energy conversion and use (DEFRA, 2006a) means that any strategy aimed at meeting this 80% target should necessarily be focussed on energy. In order to develop a strategy that incorporates the whole energy system, including supply and demand sides, it is useful to have a framework within which to work. The House of Commons Environmental Audit Committee (1999, para.24) defined an energy hierarchy³ to act as a framework for energy policy, which ranks the approaches to decarbonising energy use according to their relative sustainability and the ease with which they can be achieved:

1. Energy demand management and end-use efficiency;
2. Energy supply from renewables;
3. Combined heat and power (CHP) and fossil fuels; and
4. Nuclear power.

The primary area where attention needs to be focussed is therefore on reducing demand and improving efficiency at the point of use.

1.4 Aims, challenges and scope

This thesis is concerned specifically with the industrial sector. This sector has significantly reduced its energy demand over the past few decades, mainly due to improvements in energy efficiency, and to a lesser extent structural changes and output effects (DTI, 2002b, p.32, cf. chapter 4 in this thesis). It also plays a key role in the economy due to the linkages it has with other sectors, both within the UK and internationally. Many of its outputs are intermediate products for other sectors, and all of them find use in other parts of the economy, such as within the domestic and transport sectors. In addition, Britain has a long history of international pre-eminence in manufacturing which began with the first Industrial Revolution.

The general aim of this thesis is **to quantify the extent to which it is technically and economically possible to improve industrial energy efficiency⁴ from the current baseline.** Economical in this context means conforming to the economic criteria that firms typically apply to energy efficiency projects. Technical indicates potential that is physically possible with current technology, but is not (necessarily) economical. The current baseline refers to the status

³ Others have proposed similar energy hierarchies, such as the IET (2007). The main difference is whether demand reduction and energy efficiency are grouped under the same heading. In the IET framework they are distinct, whereas in the hierarchy adopted here they are two facets of the same point: addressing current demand.

⁴ Throughout this thesis the terms efficiency and productivity are used synonymously.

quo at the time when this research was carried out⁵. The aim may be developed further to claim that it is possible to improve energy efficiency through three main means, namely behaviour, technology and policy. There is evidence that strong drivers exist for firms to undertake energy efficiency measures. The harder drivers are environmental legislation and energy costs, but there are also softer drivers in the form of corporate social responsibility (CSR) and other intangibles. Evidence also suggests that barriers to energy efficiency exist, which prevent the theoretical potential being realised in practice.

Hence the general aim of this thesis is to quantify the potential improvement in industrial energy efficiency, both now and in the future, whilst taking into account these technical and economic barriers. This general aim requires an understanding, from an interdisciplinary perspective, of the current and historical energy productivity of British industry, and an assessment of the potential for improvement from the current status quo. Implicit within this interdisciplinary approach is the combination of insights from the fields of thermodynamics and economics. The emphasis is therefore placed on the feasibility and usefulness of combining approaches from different disciplines, as well as on using these approaches to analyse the industrial sector. One facet of this research is to qualitatively explore and assess the ways in which perspectives from thermodynamics and economics can provide superior insights into the performance of industrial systems, compared to a situation in which these approaches were used in isolation. Another facet involves quantitatively determining the potential for energy saving in industry and understanding the reasons why opportunities are not being realised.

The research supporting this thesis has substantially affected the latter's objectives. In particular, macroeconomic analysis of the industrial sector as presented in chapter 5 is of limited use in determining the improvement potential for individual sectors and sites. This sort of top-down approach is better suited to analysing industrial performance retrospectively and understanding the reasons for (or decomposing) changes in energy demand, as well as identifying the systemic possibilities for energy efficiency improvement in these sectors in the long term. It is not able to identify the precise means through which this might be realised, however. Instead bottom-up studies, which take into account the heterogeneous nature of sectors, are required. These micro – or in some cases meso⁶ – level studies are able to account for process-specific determinants of energy use that are overlooked from a macroeconomic perspective. In other words, studies based on this detailed approach enable an understanding of the mechanisms that actually determine energy use, rather than just the effect they have as manifested in the overall energy demand.

The selection of specific sectors to study in such detail is itself part of the research problem, as it is largely dictated by data availability. As discussed in chapter 3, there has been a paucity of attention devoted to industrial energy analysis in the past few decades. In conjunction with

⁵ The manufacturing sector's output has been and is being significantly affected by the global financial crisis following the credit crunch of 2007 (The Economist, 2009b). The baseline for this thesis is taken as the status quo in 2005/2006, and no account has therefore been taken of these recent events.

⁶ That is, neither at the macro (economy or sector) level, nor at the individual process level, but in between, where whole industrial plants/sites are the functional unit.

widespread concerns about commercial confidentiality, this firstly means that current industrial data is difficult to obtain and, secondly, that companies in general are reluctant to engage in studies with academia. This is compounded by the fact that most energy-intensive industries have their energy use professionally managed because it represents a significant proportion of their operating costs (chapter 5). The consequence is that the focus of specific bottom-up studies is dictated by the willingness of trade associations and/or companies to cooperate and the availability of relevant data.

The scope of this thesis is as follows. Firstly, the research is confined to all energy transformation processes occurring within the manufacturing sector in the UK⁷. The manufacturing sector in this context includes all activities classified under Section D of the Standard Industrial Classification (SIC), but excludes electricity generation activities in centralised power plant (ONS, 2003). Secondly, the scope is limited to identifying the potential for energy efficiency improvements, and is not concerned with implementing them. The methodological scope of this thesis is confined to the fields of economics and thermodynamics, and therefore excludes some of the subtle contextual factors which some have argued are crucial in effecting a decarbonisation of the economy (Reason, 2008). This thesis attempts to reach an appropriate compromise between such extremely anthropocentric approaches that focus on cultural, social and political issues and purely technical ones.

1.5 Objectives

Having outlined the general aims of this thesis, attention is now drawn to the specific objectives below, through which the aims will be achieved.

- (i) To discuss relevant approaches emanating from the fields of thermodynamics and economics, and to highlight the problems with the neoclassical concept of production (chapter 2)
- (ii) To review applications of thermodynamic and economic techniques to industrial energy systems (chapter 3).
- (iii) To define energy efficiency, discuss its measurement and associated problems, and to identify the means of increasing efficiency (chapter 4).
- (iv) To identify drivers for and barriers to increased energy efficiency, including theoretical frameworks and empirical evidence (chapters 4 and 5).
- (v) To analyse the industrial sector from a macroeconomic perspective, using a variety of interdisciplinary tools, in order to determine and understand current and historical energy trends (chapter 5).
- (vi) To estimate the long term potential for energy efficiency improvement through systemic optimisation (chapter 5).

⁷ The terms “manufacturing” and “industry” are used interchangeable in this thesis, except where the usage of the latter is intended to refer to a business activity such as “the telecommunications industry”.

- (vii) To apply relevant methodologies to industrial energy systems in order to determine the short term technical and/or economic energy efficiency improvement potential (chapters 6, 7, 8).
- (viii) To discuss the results of these detailed studies and the suitability of combining their respective methods in the wider context of the preceding chapters (chapter 9).
- (ix) To discuss the limitations of this research (chapter 9).
- (x) To draw conclusions and highlight areas for future work by relating the discussion in chapter 9 to the original aims and objectives outlined here (chapter 10).

2 Thermo-economic background

Drawing on the introduction to economics and thermodynamics given in Appendix A2, this chapter serves two main purposes, relating to objective (i) in the previous chapter. The first is to discuss relevant interdisciplinary applications of economics and thermodynamics, and assess their ability to provide a better understanding of energy systems in general. The second is to discuss the interrelation between technological change, energy efficiency and economic growth, and to highlight some of the problems associated with understanding this relationship. These two related aspects are dealt with in turn below.

2.1 *Some thermo-economic insights*

This section explores some of the attempts at integrating economics and thermodynamics in order to overcome some of the limitations of the neoclassical view. To begin with, a brief critique of the neoclassical economic framework is presented, which builds on the background discussion in Appendix A2.1 and prefaces the remainder of this chapter. This is followed by an overview of ecological economics, which can be seen as one attempt to overcome the restrictions of neoclassicism and incorporate more satisfactory environmental and welfare considerations. This leads into discussions of the application to economics of conservation principles and the Entropy Law⁸, followed by an assessment of alternative theories of value.

2.1.1 Critique of neoclassical economics

The obsession with growth is a major problem with the neoclassical paradigm. It is well known that human welfare and happiness are dependent upon more complex factors than wealth (Appendix A2.1.1). Although these two measures generally increase with income, there is a limit of about \$10,000 above which the happiness/income correlation ceases to apply (Common & Stagl, 2005, p.198). Once people have enough to meet their basic needs, the marginal increases in welfare and happiness to be gained from additional wealth are minimal. Notwithstanding this strong criticism, some economists believe that growth can in fact solve the environmental and distributive problems not satisfactorily addressed by the conventional model. Their theory is known as the Environmental Kuznets Curve (EKC), because it is based on the Kuznets curve relating inequality to income per capita. In this case, the curve relates environmental quality to income per capita, and the hypothesis is that environmental degradation will level off and then decrease again as a country develops. The basis for this is that, as economies become more services focussed, the energy- and carbon-intensity of the economy decreases, in addition to the population having more wealth on average to spend on improving environmental quality (ibid., p.247).

⁸ The terms Entropy Law and Second Law are used synonymously within this thesis to refer to the Second Law of Thermodynamics.

Whilst this occurs on a national scale, a developed, post-industrial economy still consumes goods and services that have relatively large amounts of carbon and energy embodied in them. The embodied CO₂ in imports to the UK is actually increasing the nation's overall consumption-related emissions, whereas the indigenous emissions show a different picture (Wiedmann et al., 2008). This theory is therefore flawed because it does not account for one country's development leading to a redistribution of emissions globally but not actually reducing them. Furthermore, the theory presupposes that all countries will eventually develop into service (or information) based economies which do not have any heavy industry. Manufacturing output must be superfluous in such a scenario, or be produced in Otherlands, the hypothetical country which van Gool (1997) showed to have low overall exergy efficiencies (chapter 3).

The second argument, of higher affluence resulting in increased expenditure on improving the environment, holds little more weight than the first one. It is predicated on the assumption that environmental degradation is a reversible process. In many cases this is not the case, so regardless of how much is invested in attempting to restore the environment the changes cannot be reversed. The assumption of reversibility in energy conversion processes also contravenes the Second Law of Thermodynamics; all material and energy transformation processes involve unavoidable irreversibilities. Pasche (2002) has also analytically shown that long-run sustainability is not concomitant with a positive growth rate. Hence the EKC hypothesis does not make a satisfactory case for adhering to the high growth course that has been followed in the recent past.

Other criticism has been made against neoclassical economics at a fundamental level. For example, what basis does it have in reality and how can it justify the complex models that it employs based on such tenuous assumptions? Wiener (1964, cited in Daly, 1992, p.4) takes this to the extreme when he bemoans the way in which economists "dress up their rather imprecise ideas in the language of the infinitesimal calculus...a sham and a waste of time". It is a scathing indictment, but the essence of it carries some weight: economics has long looked to mathematics for precision where in fact it is concerned with imprecise and abstract phenomena. The above point also relates to fundamental misnomers in economics; the language employed does not reflect the physical process to which it relates (Daly, 1992). So, for example: growth itself implies reaching maturity; consumption implies reaching satiety; and production actually refers to transformation. In none of these examples does the actual phenomenon live up to its economic namesake.

2.1.2 Ecological economics (EE)

The shortcomings with the neoclassical model discussed above are some of the main drivers behind the development of ecological economics (EE). In contrast to Environmental and Natural Resource Economics (ERE) ecological economics (EE) has evolved from an explicit consideration of the principles of physical science, in particular ecology. ERE can be considered as an extreme interpretation of the neoclassical paradigm and is essentially a branch of welfare economics, with the two objectives of valuing and managing environmental assets that are

otherwise externalities (Cropper & Oates, 1992). EE on the other hand has evolved from a coalescence of ecology with economics, but also contains elements of thermodynamics, ethics and other social sciences, and is therefore broader and more encompassing in its coverage than ERE. It is not involved purely in attempting to correct for market failures, rather has a completely different framework and therefore embraces such diverse topics as green accounting, sustainability and environmental Kuznets curves (Ma & Stern, 2004). EE is considered a transdisciplinary field in the sense that it embraces areas studied by the sciences of ecology and economics, yet transcends them to offer another related but different perspective (Common & Stagl, 2005, pp.4-5). EE began to emerge in the late 1980s, based largely on the ideas of the economists Daly (1992) and Georgescu-Roegen, and the ecologist Odum (1970), as well as others. There have also been significant contributions from earlier writers such as Soddy, Lotka and one of the chief exponents of utilitarianism, John Stuart Mill (van den Bergh, 2000, p.2). All of these writers had strong interests outside their own field and were in some way dissatisfied with elements of their own discipline.

For Daly this was in the form of a general frustration with the neoclassical model and its emphasis on growth as the underpinning factor in improving human welfare. Instead of the obsession with “more is best” he favours a situation in which “enough is best”, within what he calls a Steady-State Economics framework (Daly, 1992). He further criticises mainstream economics as in the face of ecological scarcity it simply demands more ingenious technological “fixes” – that is, higher productivity, achieving more with less. The second main ground for his criticism is that what is provided (the output) by the economic machine is not what is required by the consumers who use it – what he calls *existential scarcity*. In other words, the activity of the system is misplaced because it does not, in fact, improve peoples’ wellbeing, rather persuades them to purchase what they do not need. Daly argues that we need to concentrate on moral growth and qualitative improvements rather than quantitative growth. He stresses the relatively short time-period over which long-run growth has occurred, when considered in the context of the history of mankind, suggesting that growth is in fact the aberration and stability the norm (ibid., p.18). Indeed, Smith himself referred to what later became known as the “stationary state” by Mill and others, although he did not explain the transition from growth to maturity in *The Wealth of Nations* (Deane, 1978, p.36).

Odum was chiefly concerned with applying the ecological “systems” concepts to other areas, including economics and energy systems. His best-known work was probably his book *Environment, Power and Society* (Odum, 1970), especially as it is regarded by many as providing much of the stimulus for the development of energy analysis (IFIAS, 1974, pp.11-12). He also made what is thought to be one of the first valuations of an environmental resource when his work in the Gulf of Mexico provoked him to attempt to quantify the human impacts on metabolism in the area (Kangas, 2004). This provided the foundation for the application of valuation methods to the environment in both ERE and EE. One of Odum’s main contributions to EE is his concept of the pulsing paradigm, which refers to the way in which ecosystems undergo pulsing behaviour, when production and consumption rapidly increase, before falling off again. Such spurts can be caused by external events or shocks such as storms or may be

internally mediated as in the case of predator-prey cycles. Odum et al. (1995) postulated from these phenomena that such pulses occur at all scales within the earth's ecosystems, and that the steady-state condition is the exception rather than the rule. This analogy between natural and economic science is one of many in the field of EE and, if a valid one, implies that the solution to the insatiable appetite for growth might be a reduction in production and consumption within the economic system or a "prosperous way down" (ibid.). Odum's other legacy for the field of EE is the concept of EMERGY, or embodied energy, which is the total solar energy embodied in a product or service, traced back to the sun. This is discussed in more detail in Appendix A2.2.2.4.

EE is therefore more aligned with classical economics than the neoclassical school, at least in the sense of emphasising the importance of land and its productive power. It emphasises the importance of the individual, society and sustainability instead of the pure satisfaction of consumer needs in order to maximise utility. The Malthusian classicists were ostensibly wrong in their prediction that the long term prospects for improving the welfare of humankind were quite poor, which is seen as one of the main reasons for the demise of the tradition in the latter half of the nineteenth century (Common & Stagl, 2005, p.3). Their assertion has arguably been borne out by experience, though, given the very large global inequalities in wealth distribution and human wellbeing that now exist. The basis on which such a conclusion was based, however, is as sound now as it was then: the arithmetically rising production capacity is incompatible with a geometrically increasing population, which implies a finite carrying capacity for the planet. The precise capacity is flexible to some degree because of the role that technological progress can play in improving productivity (section 2.2), but ultimately it is still finite.

2.1.3 The Entropy Law, conservation principles and metaphors

Several practitioners have drawn parallels between the fields of physics – especially thermodynamics – and economics. Georgesgu-Roegen (1971) contended that the economic process – that is, the transformation of natural resources into forms of capital for consumption and then, ultimately, into waste – obeys the Second Law of Thermodynamics. Mirowski (1989) argued that the field concept of value in neoclassical economics owes itself mostly to the conservation laws (in particular of energy and matter) emanating from the physical sciences, and energy can therefore be seen as analogous to utility or value. There are clearly close synergies between these two ideas, and this section therefore explores them together.

To say that the physical processes involved in the economy obey the Entropy Law is to state the obvious because all physical systems must do so. The novelty lies in applying the Second Law of Thermodynamics to the whole economic "machine" rather than just its physical components. The economy not only employs low entropy/high exergy material and energy inputs, and produces high entropy/low exergy outputs, but can also be understood by analogy to physical systems in the way it processes information, value and other abstract entities. The application of the Second Law to the economic process explicitly acknowledges the finite resources and

limited assimilative capacity of the environment discussed in section 2.2. Georgescu-Roegen therefore attempted to integrate thermodynamic limits into the neoclassical model. Mirowski (1988, p.821) suggests that he has been misunderstood by economists as an advocate of the energy theory of value, mainly because of their lack of understanding of the diverse areas which he touches. In fact Georgescu-Roegen strongly rejects the energy theory of value and the aligned energetics and neo-energetics schools (ibid.).

The crux of Georgescu-Roegen's (1971) argument is that the analogy between neoclassical economics and classical mechanics is crucial if the true nature of the economic process is to be understood. He has generally been keen to point out the nature of the economic process, in particular the fact that the economic system is not an isolated one. Another criticism Georgescu-Roegen (1971, p.322) levelled against the economic science is that it is not, strictly speaking, a theoretical science, because it suffers, as all human creations do, from the subjectivity of the institutional context. That is, the theoretical framework of economics evolved in a relatively wealthy, industrialised context, which is one reason why it does not apply out of this context. He cites examples of non-capitalist settings where the standard model does not apply, such as a monk who actually maximises his personal utility by eschewing the riches and frivolities of a capitalist society.

At the extreme, Georgescu-Roegen (1971) wanted to formulate a Fourth Law of Thermodynamics, which would govern the conservation of matter. He hypothesised that matter too, as well as energy, could be irreversibly degraded, and therefore required a property which reflected this "quality" content. But material dispersion occurs mainly due to processing activities that lead to scrap generation. It is in fact energy, and not matter, that ultimately provides the resource constraints for production (Ayres, 1999; Cleveland & Ruth, 1997). The economic machine requires pure commodities (e.g. fuels, minerals, metals), which invariably occur in nature combined with other materials. To obtain pure forms of these materials, it is necessary to invest energy and capital resources. As materials move through the economy, their purity generally increases along with the amount of capital that has been "invested" in this purification process – the "embodied" capital. Hence what Georgescu-Roegen interpreted as a degradation of materials is essentially a concentration process, in which the desired material is extracted from its naturally occurring form. There is a significant difference between this process and one in which materials tend to degrade because of some kind of diffusion gradient. It is therefore hard to reconcile this concept with the physical principles which underpin economic resource conversion processes. There does not seem to be scope for a Fourth Law to reflect the quality of matter because this is effectively equivalent to its (chemical) exergy.

Mirowski's (1989) central argument is that when the field of neoclassical economics was developed it adopted wholesale some of the key principles from the natural sciences, especially conservation principles. Moreover, it adopted these principles without a proper understanding of what they meant or the reasoning upon which they were based, mainly out of a desire to give economics more credibility and an unshakeable foundation in the laws of nature. The fact that the context from which conservation principles were taken was not understood is not so

important, but the fact that it was not tailored to the field to which it was applied is crucial. Had this been the case, argues Mirowski (*ibid.*, p.398), then a whole trench of neoclassical economic theory would have been more easily comprehended in the conceptual framework of this metaphor. The principle seems to have been adopted out of some extrinsic appeal rather than because it was intrinsically applicable to the economic system. The consequence is that if it had been applied with a better understanding, the outcome would have been much more useful. Mirowski (1989, pp.197-202) identifies four paradoxes associated with this blinkered adoption of scientific principles:

1. **Scientific tools were adopted as legitimacy for economic research**, as methods were borrowed without being properly understood, with little apparent discussion of their appropriateness to economics – instead the consensus was taken for granted.
2. **Conflation of the Kantian concepts of mind and world**, essentially manifested in the mistaking of a subjective experience of the world (the mind) with what the world actually is. This is also known as confusing the map for the territory, originally identified by Koryzbski (1995).
3. **Re-evaluation of the relationship between mathematics and the physical world**, especially in the context of our ability to take measurements.
4. **Shift in the notion on theory and the way it develops**. Theoretical development in the physical sciences moved away from attempts at complete closure and began to recognise the usefulness of imperfect models of reality simply as a tool in their own right.

Granted that neoclassical economics inherited its field theory of value⁹ (or utility) from physics, what are the implications for the neoclassical model? Mirowski does not purport to be proposing alternatives; instead he attempts to highlight what the key questions are (*op. cit.*, p.401). The implications for neoclassical economics seem to be that field concept of value is inadequate for several reasons. In particular, the notion of utility or value as some kind of field concept that is conserved has no basis in reality because of the way the metaphor migrated across disciplines. Furthermore, the neoclassical model does not go any way towards explaining production, because goods and services are produced in reality, and not utility, value or energy (Gordon, 1991). The crux of the problem, which well reflects the paradoxes quoted above, is the failure of the neoclassical school to adopt the cornerstone of all physical conservation principles, that of the conservation of energy, the First Law of Thermodynamics. Utility or value is not conserved, in fact quite the contrary: it is created by the economic system and might be considered as the actual purpose of the system as whole – it is certainly the purpose of individual economic agents within the model, whether individuals or firms. This leads to the question of how better the analogy might be adopted or developed from physics, in

⁹ The field theory of value or utility asserts that these phenomena in economics are metaphorically concordant with energy as understood from a physical perspective (Mirowski, 1989, ch.5). The utility field is therefore a multidimensional space, whereby the number of dimensions relates to the number of commodities, and in which agents attempt to maximise their utility by optimising their consumption of available commodities.

a more holistic manner, in order to preserve its integrity. Hence attention is now drawn to alternative theories of value which might stand to overcome some of these inconsistencies.

2.1.4 Alternative theories of value

The predecessor to the neoclassical field theory of value – i.e. the classical view – was a substance theory, which treated value as an intrinsic part of a commodity like land or materials, rather than an abstract, continuous entity as in the neoclassical view (Deane, 1978, p.116). This has its roots in the land theory of value advocated by the Physiocrats, and later in the dichotomous framework of Adam Smith. The latter included the two concepts of value as embodied labour and as labour commanded by trading something in the marketplace, which Smith was not able to reconcile with one another (Patterson, 1998). These concepts persisted for some time until the Utilitarians equated the value of goods with the pleasure derived from consuming them, thus developing the concept of utility and diminishing marginal utility¹⁰.

One problem with the substance theory is that value or utility does not exist by itself; it is only when the economic system extracts, processes and distributes something that it even begins to have a value. Hence why, in enabling and driving the industrialisation and rapid economic growth of the last few centuries, private property rights have been essential. Without private property there is neither an incentive for the individual or firm to improve anything nor a basis upon which to start increasing value. It is only with private ownership that economic value can be said to exist, because without property the whole concept of and necessity for trade disappears. The substance theory of value is therefore limited because it does not reflect the abstract nature of value as something that only exists in the presence of goods or services and a market (demand) for them. This theory fails to recognise the complex nature of value, which is often associated with intangibles such as brand loyalty and cannot easily be decomposed into its constituent elements. It is also affected by such abstract notions as the endowment effect, whereby consumers place different values on goods or services depending upon whether or not they own them (The Economist, 2008b).

One alternative to the substance theory is the social theory of value, which refuses to be constrained by any invariant or conservation principle based on natural or scientific laws. There is no way of formalising such a theory in reality, because in attempting to reflect the abstract and ethereal nature of value as a concept it abstains from being constrained by the physical world. That is not to say that this theory eschews all forms of invariants, instead that it locates them in social institutions such as those concerned with accounting conventions, property rights and even money itself (Mirowski, 1989, p.400). The intricacies of such a theory are beyond the scope here though.

Another concept that does deserve closer attention is the energy theory of value. The idea that energy might in some way be related to the concept of value has a substantial history, dating

¹⁰ Strictly speaking, the predecessors to the utilitarianist theory of value also exhibited diminishing marginal returns, but this does not seem to have been explicitly formulated before Mill, Walras and Jevons (Patterson, 1998).

from the mid-nineteenth century. Mirowski (1988) traces the development of the theory from its early beginnings, although arguably the true formulation of a parallel between energy and value was not reached until the 1920s when Lotka (1922) attempted to reveal the biophysical foundations of economics. He essentially proposed that there are two key implications of biological evolution for energy systems: firstly, that evolution tends towards a maximum energy throughput if energy supplies are abundant and, secondly, that where energy supply is short, evolution will favour systems that are more efficient. The implication is that the economic system should react in the same way. Around this time Soddy (1961, cited in Mirowski, 1988) was one of the strongest advocates of an energy theory of value, but his limited mathematical abilities (which he himself admitted) and unsophisticated monetary theorising (he was a chemist by background) meant that he was barely credited for this insight in his lifetime.

In the 1930s the Technocracy movement paid renewed attention to energy use, perhaps partly due to the crash of 1929 and the ensuing Great Depression. Mirowski (1988, p.815) refers to an American survey of industrial energy consumption that was carried out in units of energy rather than money, because dollars were a “rubber yardstick”. This and the following assertion that mechanisation disrupted the economy, leading to widespread unemployment, can be related to Kümmel et al.’s (2002) complaint that the productive power of energy is overlooked in neoclassical economics, as it is not given the proper weighing in production functions. Whereas the latter relates specifically to multi-factor productivity measurements (MFP, section 5.2.3.3), the problem of fluctuations in monetary value are part of a more general problem in relating economic measurements value to the underlying physical quantities concerned (further discussed in section 4.2).

The energy theory of value did not become any more than a straightforward analogy until the 1970s, when mainly engineers attempted to quantify precisely the nature of the relationship between energy and value. These theories were still not successful, mainly because of the way in which they treated energy as an embodied value substance, and due to the reliance on input-output matrices that themselves are in economic units. The associated analysis invokes circular reasoning along the lines that the energy content can be inferred from the cost, which in turn depends on the energy content (Söllner, 1997, p.185). In essence, though, the concept remained the same, i.e. that the true value of a good or service should reflect its embodied energy content.

The proposition that energy can be used as a proxy for economic value is based on the supposition that these two variables are closely related to one another – that is, that the energy content of goods and services is directly proportional to their value. Furthermore the ratio of energy content to prices has to be constant in all instances – except when the economic value is itself deemed to be inaccurate. Supposing there is some relation between energy content and value seems to be quite reasonable, especially within the industrial sector where the energy content (embodied energy) of goods increases as they pass through the system in the same way that their value increases (Roberts, 1982). However, this does not necessarily occur in the same proportion at each stage and this analogy cannot easily be transferred to the financial services

sector, where value is often added through borrowing and investment activities that neither make a tangible difference to the capital being processed nor embody additional energy in it. Hence the energy theory of value, whilst having some intrinsic logical appeal, appears to break down upon closer scrutiny. It also suffers from the same problem as substance theory rejected above, in that value only exists, or begins to exist, when energy is harnessed. That is, the inherent value of materials in the ground is not reflected until they are extracted and the energy within them is employed. One crucial implication of this is that the only way value can be created is within the energy industry, because this is the sector which transforms primary into secondary energy.

Problems are also encountered in attempting to develop the energy theory of value into an applicable framework which could improve or even replace the neoclassical concept. Energy and materials are flow inputs to the production process, and capital and labour are stock inputs. Söllner (1997) contends that whereas the former become embodied in the good or service, the latter present difficulties in terms of how they should be treated. For example, how should the value of labour as a production input be accounted for, and should the energy value relate to the actual manpower required directly, or does it also need to consider the indirect, nutritional energy content of the food consumed? These questions essentially relate to the issue of boundary conditions, such that at the extreme one draws a very wide boundary and traces a solar energy as far back as the sun (i.e. EMERGY, see Appendix A2.2.2.4).

There is no simple solution to this conundrum, but one possibility would be to consider labour, too as a flow rather than as stock. As an input to production labour is effectively a power, i.e. a rate of energy conversion. If labour were considered as a flow input then this problem might be partially overcome, whereby the value of labour (energy) becomes embodied in the good or service being produced. The question of how to account for the capital inputs to production is even more difficult to address. If an energy theory of value were extant, capital transformations would be in units of energy, but there would still be a large, heterogeneous capital stock already in existence and measured in economic units of money. This presents the further problem of converting this economic value to energy value by using the appropriate conversion factors. Such factors would have to be determined based upon the embodied energy of the material, the year of production (i.e. the energy mix), and other intangible factors, such as the fact that this capital stock exists and does not require manufacture.

Patterson (1998) also notes the difficulties associated with incorporating physical mass flows into any energy theory of value because their value lies not in their energy content, rather in their physical and chemical properties as materials. Whilst distinguishing between two types of energy theories of value, namely one in which energy is the sole proxy for value versus one in which the embodied energy in products serves as an indicator of the value of goods, he notes that both are faced by this mass flow problem and therefore impossible to establish other than axiomatically. Nevertheless, this need not write the energy theory of value off in its entirety. There is much to be gained from better understanding how energy (and other factors) affects value.

Dissatisfaction with the energy theory of value has led some practitioners also to invoke the Second Law of Thermodynamics, and to reflect upon the relationships between negentropy (order) and value. Negentropy can be equated with structure or information, and the economic system itself is partly concerned with adding information or structure. Hence why Roberts (1982, p.172) has explored the relationship between information and value, arguing that there are useful generalisations to be made about very broad classes of economic activity. Indeed, it could be argued that information or structure in goods and services is what makes up for the residual component of value not accounted for by the embodied energy.

Another argument frequently cited against an energy theory of value is that it takes no account of the difference in quality between different fuels, but the different price of fuels per unit of energy content itself arguably reflects this difference in quality. Along with the considerations of entropy generation and irreversibility discussed above, this issue of energy quality has led some to suggest an exergy theory of value (e.g. Dincer, 2002, p.143; Gaggioli, 1983), which explicitly reflects the quality of energy streams. This concept suffers from the same shortcomings as the energy theory of value, however, in that it does not, indeed cannot, reflect the non-physical, abstract and intangible qualities which are currently associated with the monetary value system. Although Lozano & Valero (1993) previously claimed that “there is no doubt that the origin of every cost lies in the irreversibilities of the process”, Valero (2006, p.179) recently summed up his discussion of exergy accounting thus:

“The thermodynamic equivalence of irreversibilities has no counterpart with its money value nor the value itself. I prefer to burn natural gas for heating purposes than the same amount of exergy in Picasso’s paintings. The source of value of a Picasso painting is not related to the irreversibilities involved in creating it.”

The value inequality between the fuel and the painting is of course a subjective one, but the Picasso painting could easily be replaced by something of significant value to the individual in order to make the same point. The apparent contradiction between the two statements of Lozano & Valero (1993) and Valero (2006, p.179) is resolved, however, if the equivalence between the exergy cost and the economic cost is rejected. There is no doubt that physical processes have irreversible exergy “costs” associated with them, and that these are often related to economic costs, but the conflation of these two concepts can lead to a misunderstanding. Whilst some practitioners explicitly advocate an exergy theory of value, others are interested in quantifying the economic cost of the exergy destructions and losses – the distinction should be maintained.

The energy and exergy theories of value have had limited application because of their only partial ability to reflect the true value that individuals and society place on goods and services. Whilst there are general correlations between the energy (and exergy) content of goods or services and economic value, such relationships break down upon closer inspection. This informal relationship can offer a better understanding of the contribution of (embodied) energy

towards value, but does not seem able to reflect the other, mainly intangible, aspects of value. The fact remains that energy is not satisfactorily represented within the neoclassical framework (section 2.2.2), but it appears that specifically energy and exergy theories of value are not able to ameliorate this. The discussion thus far has focussed on the theoretical implications of alternative value theories, and has therefore overlooked the logistical complexity which would surround any attempt at changing the reigning value system, but this should also be a consideration in any pragmatic evaluation.

2.2 *Economic growth, technological change and energy efficiency*

The roles of technological change and energy efficiency in economic growth are the subject of much continued debate. Much work in the past few decades has attempted to delineate this complex relationship and thus better understand the role that energy plays in production. This section highlights the main problems in this regard and discusses some of the potential solutions.

2.2.1 *Accounting for technological change*

The neoclassical general and partial equilibrium model outlined in Appendix A2.1 does not incorporate an explicit theory of technology and its associated progress (von Tunzelmann, 1995, p.72). Instead, it focuses on the substitution between capital and labour, the two inputs for production, and the way in which the production function can be optimised within technological constraints. Technological change is implicitly accounted for through modifications to the production function (shifts onto different production frontiers) over time. Solow (1957) famously decomposed changes in output over time into contributions from quantitative and qualitative changes in factor inputs (capital and labour) and technical change, defining the latter as being any change which resulted in a shift in the production function¹¹. Essentially, the technical change was incorporated into Equation A1 in Appendix A2.1.2 by treating the empirical constant Q_0 as a time dependent function $Q(t)$. Technical change is not necessarily an improvement in productivity, but merely reflects the fact that the production process changes over time due to developments in technology and modifications to the technology mix.

In analysing the contribution of technical change to productivity growth, Solow (ibid.) explicitly accounted for differences in technology across periods, which had previously been overlooked. Rather than simply apportioning economic growth to increases in the capital- and labour-intensity of manufacturing, a fraction of growth could be related to this technical change, he argued. He demonstrated, with data for the American economy (excluding agriculture) over the period 1909 to 1949, that the doubling of gross output over this period was mostly due to technical change and only in small part (12.5%) due to increased capital input. He showed that it was possible to distinguish between shifts along the same production function and shifts of

¹¹ The terms technical change and technological change are employed synonymously within this thesis.

the entire function itself. This decomposition led to the development of multi-factor productivity accounting (see section 5.2.3.3).

There remains some ambiguity surrounding the Solow residual, however, because although it supposedly *accounts* for technical change, it does not *explain* it. It measures something associated with technical change, but precisely what is unclear. Lipsey and Carlaw (2004) suggest three mutually exclusive definitions of the Solow residual from the economics literature: technological change; only the “free lunches” associated with technological change; and at best our ignorance and at worst nothing we can identify. The main reason for this ambiguity is the expenses associated with technological innovation over and above the R&D costs. These also include costs associated with installation, acquisition of tacit knowledge and learning by doing – together defined as development costs, and including the costs associated with undertaking risk by investing under uncertainty, otherwise known as the costs of entrepreneurship. The “free lunches” that are measured by TFP according to the second definition are spill-over effects associated with investing in uncertainty. That is, they are only realised *if* the risk-taking pays off and is economically worthwhile.

According to the second definition above, TFP measures only the productivity benefits associated with technological change, but not these additional development costs. By this rationale, zero TFP does not imply zero technological change, but that the marginal returns on investment in R&D of new technologies are the same as those for investing in existing technologies. In this case, whilst the TFP would indicate otherwise, there has still been technological change. The difficulty thus presents itself of how to measure the change, and to this end Lipsey et al. (2005) suggest that it cannot be inferred from any *current margin*. Instead, it would be manifested in the difference between the time path of GDP if technology had remained constant and its actual path, which in practice might be measured by reference to some business as usual (BAU) scenario. Quantifying this counterfactual is clearly not straightforward though.

Hence the neoclassical view of technological change is that it corresponds to changes in productivity which cannot be explained by – or are not due to – modifications in the relative combination of factor inputs, in particular labour and capital. The earlier economic growth models required a large proportion of productivity change to be attributed to this residual, which in Solow’s (1957) case was of the order of 90%. In an attempt to reduce the proportion of growth that had to be attributed to the residual, economists adopted models with further explanatory factors covering such things as changes in quality of input factors and in the employment mix. But these new models still did not ultimately *explain* the underlying process of technological change, rather lumped the effect of such changes into increasingly abstracted factors, which still went no further towards an explanation than the original Solow residual (Fagerberg et al., 1994).

The common theme running through the neoclassical growth models is the concept of technological change as something which occurs exogenously to the economic system and

which is therefore by definition elusive and implicit. Many have seen the exogenous treatment of technology's contribution to growth as a key problem and one of the main reasons for its intractable nature. Several attempts have therefore been made to incorporate an endogenous theory of technological progress into economic growth models, in what was essentially a reversion to Schumpeterian principles, including the idea that innovation by private firms ultimately drives the growth process. Whilst scientific advances represented an exogenous source of technological change within these models, it could also occur endogenously through inducements such as high prices of factor inputs. Such considerations have resulted in the development of endogenous growth theory in the last few decades, based largely on the work of Lucas and Romer (Winnett, 2007). A further limitation of the neoclassical perspective on technological change is its failure to consider such empirical processes as learning by doing and learning by using. These are notions which have been borrowed from the science of psychology and introduced into economics, chiefly by Arrow (1962, cited in von Tunzelmann, 1995, p.73). The inclusion of such experiential variables in the body of work concerned with production and economic growth has meant that productivity improvements due to advancements along a learning curve can at least be qualitatively, if not quantitatively, encapsulated.

2.2.2 Accounting for energy's role in production

Both neoclassical and endogenous growth models place very little emphasis on energy as a factor of production – and therefore growth – because, compared to labour and capital, energy typically accounts for a relatively small share of total production costs. The popular Cobb-Douglas function (according to Equation A1 in Appendix A2.1.2), for example, does not explicitly account for energy inputs, which are implicitly included in capital and labour inputs. This has led many practitioners, in particular ecological economists, to develop models which reject the assumption that the productivity of each factor input is proportional to the share of that input in the value of output. Instead, the productivity of each input is estimated directly from generalised production functions, known as KLEMS functions because of their explicit consideration of capital (K), labour (L), energy (E), materials (M) and services (S), which are able to reproduce historical trends very well without attributing any part of growth to technological change. These models differ from those of the neoclassical school in one or both of two main respects. Firstly, they attempt to account for the differences in thermodynamic quality (exergy) between energy carriers and, secondly, they consider the various productive powers (output elasticities of production) of these energy carriers (Sorrell, 2009).

For example, Ayres and Warr (2005) demonstrated that an exergy-augmented production function can accurately reproduce productivity growth in the USA over the period 1900 to 1970, and Warr et al. (2008) employed a similar approach to the UK over the period 1900 to 2000. In both of these cases the authors conclude that physical work plays an important role in the production process, alongside labour and capital. Whereas an energy-augmented production function still requires the invocation of a residual factor, exergy-augmented production functions seem able to accurately replicate long term economic growth without recourse to residuals of TFP. The shortcoming of a production function based on labour, capital and

exergy seems to be that it cannot accurately account for technological progress which is not heavily dependent on exergy flows. The crucial example of this is the ICT revolution which, although drastically increasing quality of life (or output), has not until recently led to large productivity increases (Ayres & Warr, 2005). Where value creation is augmented by quality changes rather than absolute changes in output, exergy as a production factor is limited in its explanatory powers. Nevertheless, these studies seem to indicate that improvements in thermodynamic conversion efficiency and quality of energy over time provide a suitable proxy for quantifying productivity increases without recourse to exogenous technological change.

Other production functions such as the LINEX and energy-augmented Cobb-Douglas have been used to empirically measure the differences in productive powers between energy carriers (Warr et al., 2008, Hall et al., 2001, Beaudreau, 2005). The LINEX function is so called because it depends linearly on energy and exponentially on capital, labour and energy. It is more precise in reproducing historical trends because of its time-dependent marginal productivities, which correspond to the dynamic substitution of factors under technological change (Hall et al., 2001). As well as allowing technical change to be explicitly observed through changes in the production function itself, the LINEX also allows the production factors of the respective inputs to be determined at each time-step in the dataset. The energy-augmented Cobb-Douglas function separates out energy as another input to production and thus recognises the importance of energy as a resource input, but still retains the constant elasticities of substitution and technology for all time periods of the Cobb-Douglas.

Beaudreau (2005) used an electricity-augmented Cobb-Douglas function to reconstruct economic growth in the USA, Germany and Japan, finding that the output elasticity of electricity was around 0.50 for all three countries, with capital and labour output elasticities lower than in previous studies. Kümmel et al. (2007, 2002) employed the LINEX function to accurately reconstruct empirical economic growth data for the same three countries, similarly concluding that the productive power of energy was around 0.50 in all three cases. The authors note that energy is given a production weighting (in energy augmented Cobb-Douglas functions, say) of about 5%, which does not account for the disproportionate output reductions in the USA as a result of the 1970s energy shocks – estimated at 1%, whereas the expected change due to the cost-share weighting of energy input should have been just 0.25% (Kümmel, 2007, p.2). Both Beaudreau's (2005) and Kummel et al.'s (2007, 2002) studies reproduced economic growth trends with very small residuals, implying that the productive power of energy plays an important role in technological change. Such studies suggest that the marginal productivity of energy inputs is around an order of magnitude larger than their cost share of the inputs (Hall et al., 2001).

These novel attempts to understand the mechanisms behind economic growth do not provide a panacea, however, because the empirical evidence is limited and has been somewhat contradictory. Berndt & Wood (1975) found that energy is only a minor factor of production, but this could be due to the time period studied (i.e. 1947 to 1971), which was before the oil price hikes and the resulting focus on energy efficiency. The LINEX function also exhibits some

strange characteristics, such as its increasing marginal returns and variable marginal productivities (Sorrell, 2009). Hence caution needs to be exercised when interpreting these results.

2.2.3 Further problems with the production function

There are some more general problems with neoclassical (Cobb-Douglas) production functions, such as their assumption of constant output elasticities and failure to consider different technology combinations. Fisher (1971) demonstrated, by employing fictitious economies with only one output, that the Cobb-Douglas only happens to be a good fit to empirical data because in most cases labour's share of production appears to be roughly constant. This implies that the Cobb-Douglas produces the correct results, but for the wrong reasons: "an aggregate Cobb-Douglas production function...does well in wage prediction not because wages are truly generated by it but because the behavior of labor's share just happens to approximate the stylized fact generated by such a function..." (ibid., p.306). Aggregate production functions in general and the Cobb-Douglas in particular appear only to be applicable as long as labour's share of capital remains roughly constant. The apparently coincidental applicability of the Cobb-Douglas must be related to its lack of theoretical foundations at the micro level; there is no reason why it should apply in practice, aside from the fact that it is mathematically convenient and produces empirically accurate results.

Another crucial aspect of the neoclassical production function is that production factors are considered substitutable for one another, within limits implied by the essentiality condition. Output can only be produced when one or more resource inputs are non-zero. If output cannot be produced without a specific input then strict essentiality is said to apply to that input. In this case, regardless of the increase in non-essential inputs, production is not possible unless the essential input becomes non-zero. Essentiality is clearly a close depiction of reality, because inputs are inevitably required to produce goods and services, and in some cases these inputs are essential – energy is always required, for example. It is still theoretically possible though, to produce a constant level of output (of products and/or services) by substituting inputs, provided the elasticity of substitution of the production factors is sufficiently high. The substitutability aspect of the production function is less indicative of reality, though, because the implication is that natural resources can be substituted by a suitable amount of capital in another form, something which Ayres (1998, p.204) has criticised because it directly fails to acknowledge – actually contradicts – the First and Second Laws of Thermodynamics. He suggests that one solution to this problem would be the dematerialisation of the economy, such that in the future no, or very few, virgin materials are used. Certainly this aspiration to "close the loop" of material flows through the economy is a central tenet of many definitions of sustainable development, but it would not in itself correct the problem with the production function. Treating energy as a substitutable input for labour and capital fails to recognise the crucial role that it plays, and does not reflect the reality in which energy is irreversibly used and dissipated. Rather, it defeats the object of having two factor inputs if they are substitutable; one might as well just have one. Furthermore, the distinction between flow and stock resources is

overlooked here, yet their dimensionality is different (Daly, 1992, p.108). The fund is ultimately used to process the flow, and this distinction might be better reflected in the model.

A related failure of neoclassical production functions is their failure to account for the finite resources employed as natural capital. Söllner (1997) highlights the omission of natural limits to economic growth as well as important interdependencies. The conventional schematic of the economy has capital inputs “appearing” from and waste streams “disappearing” into whatever ether surrounds the economic system (Figure A1 in Appendix A2.1.1). This ether is in fact the global ecosystem, which acts as source and sink, respectively, for all inputs to and outputs from economic processes, as shown in Figure 2-1. The conventional assumption was that resource scarcity is reflected by prices, which are determined based on the demand for them in a given time and place (Munby, 1976). Inefficient and imperfect markets mean that this is not always the case, however, such that a more explicit consideration of finite resources is required by the production function.

If the standard production function is modified to consider fixed and non-renewable resources (land and fossil fuels respectively), the consequence is a race between technological progress and the growth drag associated with these resources (Jones, 2002, ch.9). This growth drag has two components. Firstly, increasing population puts pressure on the finite stock of natural resources which, due to the diminishing returns associated with these fixed factors, results in a per-capita growth rate that is proportional to the population growth rate. Secondly, the rate at which non-renewable resources are used slows growth at a rate proportional to their share in production. Hence positive levels of per-capita economic growth require technological progress to offset these diminishing returns. At the margin, with zero technological change, per-capita growth decreases in proportion to population growth. At the other extreme, with high levels of technological change, it is theoretically possible for the share of non-renewable resources in production to approach zero. In fact, this is what the empirical evidence suggests occurred throughout the twentieth century (ibid.), which partly explains why the relative price of energy has decreased.

The problem with the definition of the economic system – more specifically, the context within which the system operates – has received significant attention in the literature. In particular, Georgescu-Roegen criticised Solow’s and Stiglitz’s work on economic growth, emphasising the lack of natural resource inputs (and their finite nature) to the Cobb-Douglas production function. Solow is alleged to have said, during a lecture series on the subject, that “the world can, in effect, get along without natural resources...” (Daly, 1999a, p.77). His argument was essentially that, because of the substitutability of the inputs to the production function, one can make up for a lack of resources with other, equivalent inputs. He cites evidence for the substitutability between exhaustible and renewable or reproducible resources, but seems to overlook the central issue, namely the finite nature of natural resources. Some twenty years after this criticism Solow responded, but did not directly address the issues raised, nor did he attempt to answer the questions posed, and didn’t mention Georgescu-Roegen (Daly, 1999b). In addressing five questions centred around the debate and raised by Daly (1999a, note 5), Solow

gave some brief peripheral answers but did not concede any problems with the neoclassical model.

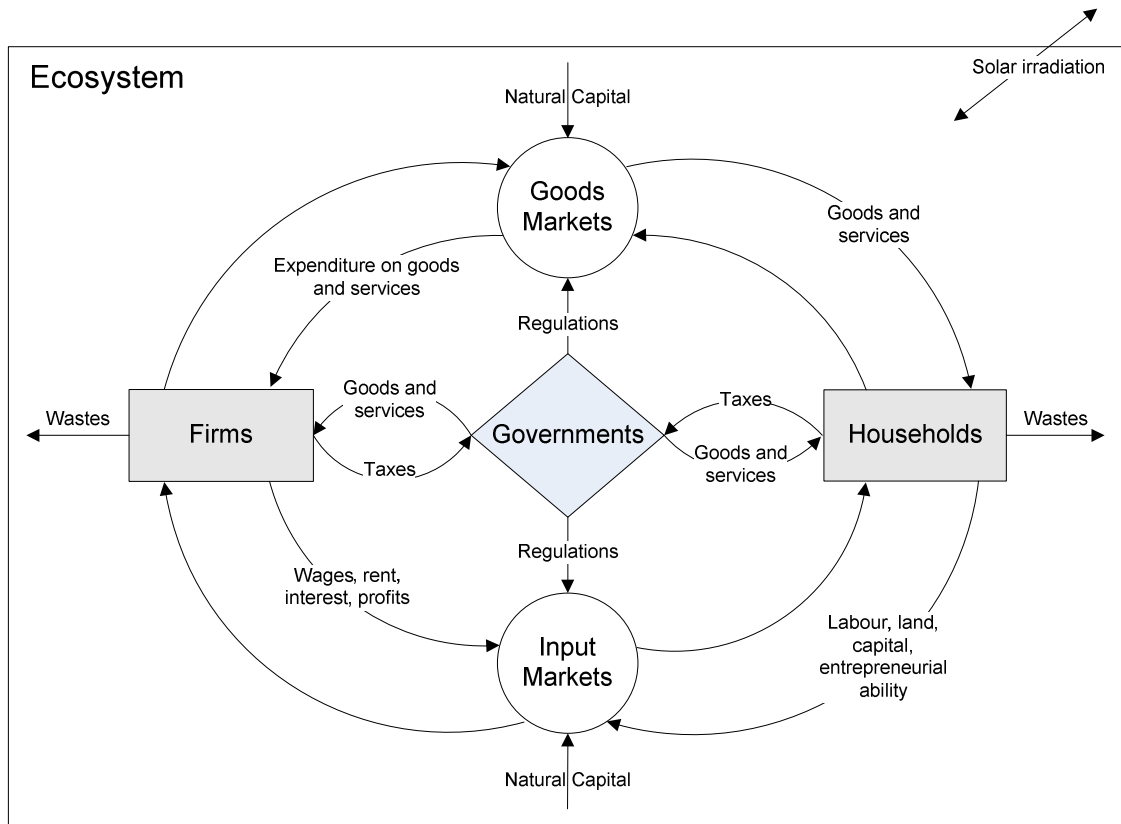


Figure 2-1 – Revised concept of the economic system (after Daly, 1999c)

2.2.4 The S-E framework and GPTs

As well as modifications to the production function discussed above, these fundamental flaws in the neoclassical framework have led to more drastic attempts at reform. One novel approach is that of the Structuralist-Evolutionary (S-E) model, which focuses on the uncertainty facing a firm when making decisions about optimisation of factor inputs, and also the time variable which is absent from most neoclassical formulations of the production function – but which also plays a crucial role in a firm’s strategic decisions. The most crucial consequence of the firm’s uncertainty, perhaps, affects the certitude with which it can know where the isoquants within factor space lie (Lipsev et al., 2005, pp.50-54). The act of shifting within factor space itself has uncertain costs and time associated with it, because devoting resources to a shift in production has opportunity costs that are not reflected by the standard model.

The crucial point is that the nature of factor space and the isoquants within it are affected by the firm’s decisions. As well as having an inherent amount of uncertainty at any time, the process of changing production configurations itself affects the factor space in such a way that it is not acceptable to view such a change as simply moving along an isoquant (Amendola et al., 2005). In the neoclassical production function the firm can choose any point in factor space, and can move between points without incurring any costs. By contrast, with the S-E production

function, the firm only knows its past trajectory for certain and, whilst it has estimates and wishes for its future trajectory, the future path is uncertain. In fact the best information available about future technological changes to the firm is often in the form of historical trends in a relevant parameter – a pertinent example of which is Moore’s (1965) law, which suggests the doubling of microprocessor speeds approximately every two years. In addition, any changes that the S-E firm makes to its production configuration will incur costs that are not considered by the neoclassical function.

The S-E framework is distinct from the neoclassical one in the way that it attempts to get inside the black box of technological change, which in neoclassical terms is only observable by the results it produces. Instead, the S-E framework further develops the models of endogenous technological change discussed above, by incorporating risk and uncertainty, and often dealing explicitly with the relevant economic, political and social structures. Whereas general equilibrium models are often based on assumptions about perfect information and foresight, the S-E framework considers uncertainty to be a central element in innovation, with innovation seen as a process of “groping into the unknown” (Lipsey et al., 2005). The high level of risk associated with investment in R&D can be understood by considering that the failure rate for such projects can be as high as 90% (Twiss, 1986). Finally, the path-dependency and context-specificity of innovations are also crucial aspects of the S-E model, reflecting its attempt to grasp the “lumpy”, heterogeneous nature of reality, rather than the smooth, homogeneous world of general equilibrium. Clearly the alternative S-E formulation of the production function represents a more accurate depiction of reality, but it does suffer from immaturity and an apparent lack of empirical testing.

A central part of the S-E framework is concept of General Purpose Technologies (GPTs), which can generally be defined as widely applied technologies which have caused (or stand to cause) the nature of the economic system to be drastically altered. The concept of GPTs reflects the universality of certain technological systems (such as energy systems) and the way in which developments (improvements) in such technologies can and do have far reaching impacts on a systemic scale, rather than just affecting individual products or processes. The theoretical framework within which GPTs are best understood and modelled remains a relatively open area of debate (Helpman, 1998). Lipsey et al. (2005, pp.97-99) define four characteristics of a GPT:

1. They **improve** in interrelated ways with time;
2. They have a **range of uses**, through a proportion of the economy;
3. They have a **variety of discrete uses**; and
4. They result in **spillovers**, which are effects in other areas resulting in indirect improvements.

There are many examples of GPTs, and their far reaching effects on their economies are well known. One particularly relevant GPT in the present case is electricity, which will serve well as

an example to illustrate the above characteristics¹². Firstly, the thermodynamic efficiency of electricity generation and distribution greatly increased over the first few decades of the twentieth century, such that the price of a unit of delivered electricity has commensurately decreased over this time. Secondly, even if one only considers its application as a power source for lighting systems, the pervasive use through all sectors of the economy is clear. Thirdly, although electricity was originally used mainly for lighting applications, it is a very versatile energy carrier, which can be used for motive power applications as well as heating and lighting. Fourthly, the spillovers from electricity have arguably been as far reaching as this GPT itself, whereby the obvious example is the ICT revolution, for which electricity has been *the* power source. The consequence of GPTs for economic growth and productivity is that, because of their fundamental effects on the economy, these technologies can be used to understand the residual of technological change – especially over periods when this is large.

Another important consequence of the S-E framework is its rejection of the productivity paradox – that is, the notion that productivity growth must result from technological change (Lipsey, 2002). Growth economists expect to see such a productivity change when a GPT is introduced, but a GPT is very rarely, if ever, recognised at the time of its introduction to the market, as it takes time for it to have a transforming effect. Bresnahan and Trajtenberg (1995), who seem to have first used the term GPT, recognise this inability to spot an emerging GPT as a problem, particularly because it stands to restrict its impact. Productivity changes do not necessarily imply the presence of a GPT or, vice versa; the presence of a GPT does not imply a productivity change – and certainly not at that time. Higher rates of technological progress do not necessarily enhance the uptake of new technologies (Van Soest & Bulte, 2001). Diffusion is slowed by the fixed costs of the newer technology, so that as long as the full cost of developing and operating with the new technology is greater than the running costs of using existing technologies (whose capital costs are largely sunk), then the new technology will not be adopted. The rate of diffusion is often heavily dependent on exogenous shocks to the system, such as the oil price hikes in the 1970s that led to rapid increases in energy efficiency (IEA, 2004b).

2.2.5 Technological diffusion

The analysis of technological diffusion attempts to determine the relationship between the innovation and uptake of new technologies, and make qualitative and quantitative enquiries into the reasons for varying rates of diffusion between firms, products/services and geographical/economic regions. Theoretical attempts to model diffusion have roots in epidemic theories, which were originally concerned with the spread of diseases. Schumpeter first applied these theories directly to the field of economics, and was also responsible for the Schumpeterian

¹² Electricity was discovered much earlier than it was widely exploited as an energy carrier. The key enabling innovation for the electricity revolution was the dynamo, but the discussion that follows focuses on electricity as the GPT rather than the dynamo itself. It could be argued that electricity is in fact the result of a combination of enabling GPTs, but the focus here is on an illustrative example.

trilogy of technological change, which distinguishes between three aspects of change (Stoneman, 1995, pp.2-3):

1. **Invention** – generation of ideas;
2. **Innovation** – application of ideas; and
3. **Diffusion** – commercialisation of products/services.

Non-linearity is a crucial characteristic of this scheme, whereby at each stage selections are made, such that only a fraction of the ideas are ultimately applied, and even fewer come to market. Also, there is a continuous feedback mechanism, whereby revenue streams from new products are reinvested in further R&D activity. The anticipated returns from the diffusion of new innovations are a major driving force behind its development in the first place. In many cases the innovation process leading to successful products or services has involved the application of a technology outside the field for which it was intended, which runs contrary to the traditional and widely accepted idea of a demand-driven process, where technology evolves to meet a demand. An example is petroleum, which was first introduced as a medicinal agent and lubricant in the early 19th century (Duffy, 1983). The degree to which a company or sector is active in technological development can be measured by the amount of investment in R&D in relation to its output. On this measure, the pharmaceuticals sector is the most dynamic sector in the UK, closely followed by aerospace and ICT (ONS, 2008b).

Empirical evidence suggests that market penetration of a technology over time follows an approximately sigmoidal, exponential distribution (Stoneman, 1995, p.269). The diffusion period, measured as the time between first use and use by 95% of the potential market¹³, can vary widely between technologies and areas, but it typically lies in the range 5-50 years (ibid., p.6). Langley (1984a) found that an innovation requires on average 18 years to achieve 50% penetration of its potential market (with a variance from six to thirty years), and that diffusion tends to be faster if the innovating industry is concentrated in a small number of firms or establishments. The most simple models of diffusion rest on the assumption that the only determinant of technology uptake is information about it: if economic agents are aware of (the availability of) a new technology, and it is relevant to their needs (they are within the potential market), then they will adopt it. Information about technology spreads between agents at a rate proportional to the remaining number of potential users. Thus the empirically observed exponential curve is obtained, with asymptotes at zero and maximum (i.e. 100%) diffusion. The assumption that new technology is adopted purely because it is known about is clearly somewhat dubious, and this is the main criticism of these simple models of diffusion. The lack of response to innovation is not always due to ignorance on the part of the firm though (Duffy, 1983, p.362). More often, firms apply strict economic project-appraisal criteria, and conclude that the investment is not economically feasible, or encounter some other barrier (see section 5.5). In an attempt to overcome this limitation, epidemic models have been developed to

¹³ There does not seem to be a formal definition of the potential market. It is a notional construct corresponding to the estimated number of firms or individuals which could make use of (or gain utility from) a product or service.

incorporate uncertainty with respect to technologies. The uncertainty is assumed to reduce over time as a result of learning from experience, but such models are also limited in their accuracy due mainly to their static nature.

More complex, dynamic models incorporate supply side (as well as demand side) factors. Rather than being based on quite passive economic agents, who await the arrival of some new information and act accordingly, these models tend to incorporate more proactive agents who actively engage in the activity of information seeking, which has basic rules and costs associated with it. These supply-demand interaction models can also produce the observed diffusion profiles already observed and documented. In addition, these models are more capable of defining a welfare-optimal diffusion path, which is not possible if the supply side is not incorporated (Stoneman, 1995, p.278). There are further benefits from extending the model's scope in this way, including a treatment of technology which improves over time and a consideration of product variety as endogenous rather than predefined.

A large area of interest with these diffusion models is in attempting to make forecasts about future technological change and emerging GPTs. However, as mentioned above there is great uncertainty associated with making predictions about the future based on present trends, and a GPT is almost always unrecognisable whilst still nascent. Twiss (1986) acknowledges these uncertainties but considers it possible to detect trends towards future innovation and the environment into which innovations will be launched. Technological forecasting rests on the fundamental assumption that technological progress is not random, rather follows some kind of trend, and can therefore be determined by plotting temporal developments in some relevant parameter. This parameter is typically related to functional, technical or economic performance. Clearly, this assumption is open to criticism; the *ex ante* identification of the current situation on an idealised sigmoid is neither immediately obvious nor necessarily possible. Depending on this location on the s-curve, the future trends might well differ – only the middle portion of the curve is linear – and this approach overlooks the impact of exogenous shocks. As a first order estimate of likely future technological developments within a field, however, past trends often represent the best information available.

Before a technology stands to make a significant impact in the marketplace, there are several key stages of its development, which progressively increase its potential for market penetration. FES (2005) identify five of these phases as shown in Figure 2-2, and suggest that the middle part of the innovation chain is not as well supported as it could be. In fact the FES investigation highlighted the apparent existence of a significant policy gap in the centre of the innovation chain for developing technologies (*ibid.*). The result of this is that many technologies in the UK are not satisfactorily developed – if at all – beyond the pure R&D stage, through prototyping, demonstration and on to commercial manufacture. Whilst these technologies might have a large potential for application, this lack in funding means that they are either abandoned at the R&D stage or insufficiently developed before the commercial stage. In both cases the technologies stand little chance of becoming highly adopted. This lack of support in the innovation chain was recognised by the establishment of the Environmental Innovations

Advisory Group (EIAG, see section 4.3.3.1 on manufacturing strategy) to address these weaknesses. The latter seem greatest at the demonstration and scaling-up to market stages, such that many opportunities are exploited overseas rather than in the UK (DTI, 2006a).

The lack of support for demonstration and prototyping activities is identified as an opportunity to expand the scope of the Carbon Trust’s Technology Acceleration Scheme (Future Energy Solutions, 2005). In addition, demonstration schemes are largely funded by R&D grants, but because of the large cost of such projects, the funding bodies can be reluctant to make capital available. Industrial sponsors should step in at this stage, to reserve R&D funds for work which itself involves pure research. The government’s Energy Efficiency Innovation Review (EEIR), for which the FES study was undertaken, acknowledged the need for an holistic, systems-based and coordinated policy framework in order to increase the rate of energy efficiency technology innovation and commercialisation. This framework needs to (HM Treasury et al., 2005, pp.21-22):

1. **Increase the rate of deployment** of existing technologies and measures by providing a long-term, stable signal to the market;
2. **Incentivise product improvement** and applied, commercially-driven research with significant private investments;
3. **Develop the necessary skills** at all levels to ensure the steps from the design through installation to operation are not compromised.

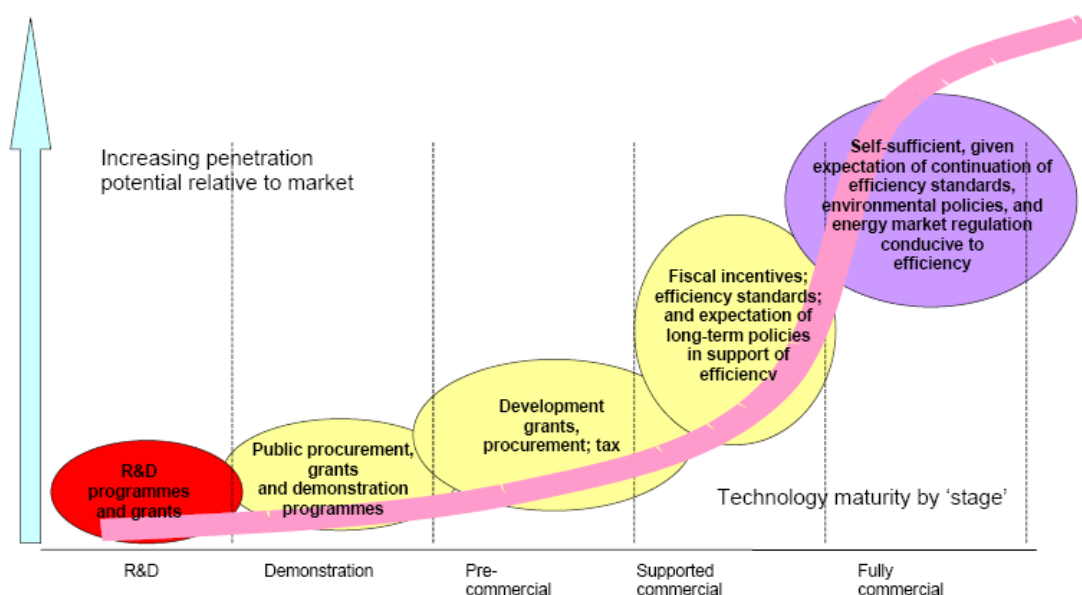


Figure 2-2 – Stages of invention, innovation and diffusion policy (Future Energy Solutions, 2005, p.51)

2.3 *Summary and conclusions*

A review of some thermo-economic insights found many instances of ideas being “borrowed” between thermodynamics and economics. In most cases the borrowing has been by the latter from the former. In general, the most successful approaches have involved the actual integration of two (or more) disciplines, such as is the case for the transdisciplinary field of ecological economics. The problem with borrowing ideas is that they are so often taken out of context and therefore misunderstood or misapplied. On the other hand, in many of the cases discussed above, whilst there has been no real paradigm shift, it is exactly this application of ideas out of context that has enabled a different understanding of an existing problem. The many problems with the neoclassical paradigm can be understood from a thermodynamic perspective. Apart from to suggest that the model should better reflect natural and physical constraints, though, these insights do not lead directly to a solution.

For example, conservation principles were only adopted by analogy by neoclassical economics, but the role of conservation of energy in particular and thermodynamics in general was overlooked. The application of conservation principles to value or utility were not valid, however, as these quantities are abstract ones which are not necessarily conserved. Geogescu-Roegen made an analogy between the entropy law and the economic process, which is useful as a way of thinking about, and understanding, the economic process, and provoked the field of thermo-economics. Alternative theories of value have been unable to account for the relationship between energy, which is conserved, and value, which is often not. The energy and exergy theories of value break down upon closer inspection because abstract constituents of value are not affected by either of these two physical parameters. Nevertheless, these measures do have a role to play in understanding the nature of value, especially for energy intensive materials whose economic value increases in significant proportion to the amount of energy or exergy embodied in them.

The contextualisation of the economic system as a self-sufficient entity is flawed, and does not account for the unidirectional nature of time for the system. This is manifested in the standard (Cobb-Douglas) production function’s failure to account for the non-substitutability between energy and other inputs, as well as the finiteness of natural resources and the assimilative capacity of the environment to absorb wastes. The constant returns to scale implied by output elasticities that sum to unity means that production can never take place without at least some of all the inputs. The asymptotic nature of the function means that the quantity of each input can become infinitesimally small, however, which does not reflect reality where a minimum amount of energy or materials is required, for example. With output elasticities summing to less than one the isoquants are shifted in factor space and the asymptote is at some minimum value. The latter is arguably a better reflection of reality, in which efficiency gains and substitution are only possible up to a point, such as the thermodynamic SEC of a process, which could not be achieved (or bettered) without contravening the laws of thermodynamics. Modification of the standard production function to account for non-renewable resources implies a race between technological progress and growth drag due to the finite nature of these

resources. At the limit, technological change can offset this growth drag, but only within limits defined by the output elasticities. The output elasticities of production given to energy are an order of magnitude lower than empirical evidence suggests they should be for several industrial economies. The role of improvements in the exergy content of energy flows in economic growth also appears to be significant, but is overlooked by standard models of production. Both of these oversights have been accounted for by non-standard production functions that have relatively small residuals and therefore do not recourse to technical change, but the evidence is limited and contradictory in some cases.

Furthermore, the production function fails to explicitly account for technical change in improving the efficiency of production processes. Attempts to incorporate technical change into production functions are able to account for but not explain it: what it actually is remains ambiguous. The fact that the residual in many MFP measurements is very large has resulted in alternative models of economic growth in which technology features more fundamentally. These include endogenous growth models and the Structuralist-Evolutionary (S-E) framework which rejects neoclassical foundations. It is built around the central concept of GPTs and the way in which they underpin long-term growth. Empirical evidence suggests that diffusion of technologies follows an approximately sigmoidal path, from R&D through to fully commercial stages. Whilst the technological development chain in the UK has a strong science base in universities, there appears to be a lack of application of this knowledge through demonstration and pre-commercial stages to commercial deployment (IPTS et al., 1998). This lack of application has been identified as being due to a lack of funding and would therefore benefit from additional support.

3 Applications of industrial energy analysis

This chapter reviews applications of thermodynamic techniques to industrial energy systems and thus places this research in context. As stated in the Introduction, the data availability has been a limiting factor that has necessitated a focus on specific sectors. In each case a review of the literature is presented as an introduction to chapters 6 to 8 inclusive. Hence the purpose of this chapter is not to make the case for studying specific sectors, rather to review the application of relevant methodologies to industry in general. The emphasis is thereby on studies relating to the UK, except where similarities in the process or methodology make other work relevant. The background and assumptions for the methods discussed can be found in Appendix A2.2, where the distinction between statistical energy analysis (SEA) and process analysis (PA) is made.

3.1 Energy analysis

3.1.1 Statistical energy analysis (SEA)

There has been a paucity of Statistical energy analysis (SEA) focussing on the industrial sector in the past few decades, which seems in part due to the privatisation of the government's Energy Technology Support Unit (ETSU). Under the auspices of the then Departments of Industry and Energy¹⁴ industrial energy analysis was carried out by the Energy Efficiency Office and ETSU. In the 1970s and 1980s several detailed studies of industry were undertaken.

The most extensive study of the industrial sector was indubitably Langley's (1984a, 1984b) survey of energy use and energy efficiency potential estimations out to 2000. This project covered the entire manufacturing sector (excluding refineries) and examined individual sectors in significant detail. The basic approach was to determine the SEC of each sector in the base year, 1980, along with the best practice SEC (which may or may not be the most efficient site in the sector, depending upon other technical constraints on production). Past trends in the SECs were analysed to explain how reductions were made due to specific technological developments, such as continuous casting of steel and the dry process for cement manufacture. These trends were extrapolated where potential was deemed to remain for further improvements, and the scope for completely new technologies was accounted for through estimated rates of development and market uptake.

Whilst the study (*ibid.*) did not provide a full set of energy demand projections, it did estimate the future SEC trend in each sector based on the likely developments in capacity, technology and plans for investment; the key findings of the work are summarised in chapter 4. The estimated developments in SEC failed to account for the drastic improvements in energy efficiency made by industry in the past three decades or so, such that they overestimated the industrial energy consumption out to 2000. This illustrates the sensitivity of such broad studies to their specific assumptions. In this case, Langley's (1984a) assumption of an annual 1.5% GDP

¹⁴ Both since conglomerated into the Department for Trade and Industry (DTI), and renamed the Department for Business Enterprise and Regulatory Reform (BERR) in 2007.

growth rate from 1980 to 2000 failed to account for the recessions of the 1980s and 1990s, when GDP growth and UK manufacturing output growth both slumped drastically, becoming negative for several periods (OEF, 2001).

Two other significant bodies of work focussing on the industrial sector around this time were the Industrial Energy Thrift Scheme (IETS) and the Energy Audit Series (EAS). The IETS was a comprehensive study of all manufacturing sectors carried out between 1978 and 1984, which produced data on energy consumption, processes employed and facilities. The EAS was a similar initiative but less comprehensive, focussing instead on specific industrial sectors and with the objective of auditing individual sites. The common theme in these two programmes is that they collected data from industrial plant, through site audits, and thereby benchmarked whole sectors. This enabled firms to compare their performance and thus better understand their position in the sector as a whole. It also allowed actual SECs to be determined, and the difference between these and the theoretical minimum to be explained, and relevant energy saving opportunities recognised. For a large number of industrial sectors these two projects, the IETS and the EAS, represented significant data resources during the 1980s. Almost thirty years later the industrial landscape has changed somewhat and this data is no longer accurate (chapter 5).

The DTI's Energy Papers also paid substantial attention to the industrial sector:

- *Energy Savings for Some Large Firms* (DTI, 1974), which includes case studies of qualitative improvements in energy efficiency, past and present, especially in large petrochemicals companies;
- *Energy Conservation R,D&D* (DTI, 1978), which outlines an energy strategy for the UK during the approximate period 1980 to 2000, with the appendices focusing on industrial conservation prospects and some generic technologies for process improvement;
- *Energy Conservation Investments in Industry – An Appraisal of the Opportunities and Barriers* (Armitage Norton Consultants, 1982), which attempted to identify existing conservation measures, the potential for further measures to be implemented, and the barriers to uptake.

In addition, Energy Paper 64 examined industrial energy markets in detail, breaking down industrial energy use into four digit SIC sectors and fuels (DTI, 1994). All of these Energy Papers are applications of, or incorporate to some extent, SEA. They are based on or include macroeconomic data on industrial energy use, which has either been inferred from national accounts or captured in tailored surveys. Most of these studies employ the IETS and/or EAS data to some extent, which in some cases provides the quantitative aspect of an otherwise qualitative survey.

It is probably fair to say that public-funded, government-led studies of the type discussed are no longer as common as they once were. Most of this work was carried out before the mid 1990s, when ETSU was privatised, mainly becoming Future Energy Solutions (FES) and later

renamed AEA Energy and Environment. The Carbon Trust's remit includes some of ETSU's former activities, such as the publication of Energy Consumption Guides (ECGs) and Best Practice Guides (PBG) relating to specific sectors. Many of these publications are now dated though, and the Carbon Trust's work is mainly focussed on individual firms rather than whole sectors (section 4.3.3.3). This lack of attention to industry is no doubt also due to the relative decline of heavier industries in the UK. Hence why Dorling et al. (1989) criticised the government's *laissez faire* approach to industry and the general low priority given to efficiency. By analysing the energy use in a large manufacturing plant with an annual fuel bill around £10million they identified significant energy saving opportunities. They found that the ventilation load was much greater than the fabric load, so that halving the number of air changes per hour would reduce the total rate of heat loss more than would be achieved by implementing a comprehensive set of insulation modifications. Another useful conclusion was that industry in general is a sector where large energy savings can be made relatively easily, because energy use in industry is controlled by fewer people than in other sectors. The population of industry, in terms of functional units, is much smaller than the domestic sector, for example ¹⁵. The counterargument is that industry is not as homogeneous as the domestic sector, so that such a broad brush approach is not appropriate.

Lucas (1979) has argued that the statistics compiled at the level of the firm for the paper industry were not being used as the basis for analysis. He makes the distinction between six different types of SEA depending on the respective definition of the system (country, site or machine) and the choice between inter-temporal or inter-spatial analyses. He also highlights the general problems associated with obtaining accurate and current data, which is largely due to academics not having any *locus standi* within industry and closely relates to the findings of this research as mentioned in the Introduction. International differences in performance in the paper sector can be explained through different industrial structures, but economies of scale in production did not seem to be exploited in all countries (op. cit.).

Broader work has been carried out by Ray and Morel (1982), who related energy use to output in the UK from 1900 to 1980, in order to reveal the extent of energy efficiency measures. Based on surveys of large energy managers in industry, local government services and financial managers in large firms, they identified energy efficiency measures since 1973 (i.e. the first oil price hike) and the likely evolution of these measures into the future. The potentially biased nature of the sample was highlighted by the authors: because only firms with energy managers were contacted, they are clearly already putting resources into some form of energy management. Their focus was on the traditionally heavy industries, such as chemicals, iron and steel, and paper. Based on the sample they identified general shifts away from coal and oil towards gas and an increased use of electricity in industry (cf. section 5.2). These trends were typical of industry at this time, although the survey underestimated their scale. This is mainly thought to be because of atypical nature of the sample, which was heavily biased towards

¹⁵ The BRE (2002) refers to 1.7 million non-domestic (i.e. industrial, commercial and public) properties in England and Wales, of which details of the floor area and building type are known for 1.3 million. This is compared with around 25 million domestic buildings in 2005 (Utley & Shorrock, 2006).

larger, energy-intensive firms. At the time of the survey, the authors concluded, firms had only just begun to invest significant amounts of capital in energy efficiency projects; up to then the measures had been mainly concerned with housekeeping and fuel switching.

More recently, applications of SEA to UK industry seem to be sparse. Farla (2000, esp. ch.2) has developed some physical energy efficiency indicators to track changes in productivity at the sector level in the Netherlands. The main advantages of physical indicators over economic ones are their consistency in aggregation and their independence from price fluctuations, but they are often constrained by data availability (see section 4.2). Ramirez (2005) employed similar indicators in her study of the Dutch food and drink sector and broader analyses of the dairy (Ramirez et al., 2006a) and meat (Ramirez et al., 2006b) sectors in four European countries (France, Germany, the Netherlands and the UK). The UK Dairy industry is atypical within the four studied because of the high proportion of liquid milk and fresh milk products used (over 50%, compared to 19% in France, 28% in Germany, and 16% in the Netherlands), but it is difficult to gain an indication of the absolute magnitude of the sector in the UK from this study because most of the data has been normalised. According to both uncorrected and corrected efficiency indicators the UK has experienced the largest increase in productivity across these countries over the period 1990 to 2000. For the uncorrected and corrected indicators the UK underwent an average annual change of -3.1% and -3.8% respectively (in terms of primary energy consumption). The low energy intensity of this sector in the UK, compared with those of the other European countries, is due to the small amount of processing activities which occur within it. The fact that the two indicators are very similar for the UK illustrates the small variation in product mix over this period. Two factors have caused the reduction in these indicators for the UK: the concentration (or rationalisation) process, and fuel switching to natural gas (Ramirez et al., 2006a). Across the EU, dairy production is generally concentrated within a few large companies. This is typical of the food and drink sector, which has experienced significant rationalisation in the past few decades. For example, in the period from 1985 to 2000, the number of dairies in the UK reduced from 336 to 102, whilst average output per dairy increased from 45 to 105 thousand tonnes of milk (ibid.).

The UK meat industry has also undergone a significant rationalisation, from 835 bovine and 703 porcine slaughterhouses in 1987 to 395 and 308 respectively in 1997 (Ramirez et al., 2006b). In the period from 1990 to 2001 the PEC of the Meat industry in the UK has grown at around 2.9% p.a., with a significant fuel shift away from solid fuels towards natural gas during this time. For all four countries, there was an increase in the energy efficiency indicator over the period studied. In the UK, this increase was around 14% over the period from 1990 to 2001. The authors (ibid.) suggest that the main reasons for increases in energy consumption within this sector were a general trend towards more energy-intensive poultry and pork slaughtering (instead of cattle), and the tendency to produce more processed cuts of meat (for example, vacuum packed, fully trimmed products, and pre-cooked, ready to eat products). The latter, *ceteris paribus*, naturally increases the energy demand of the sector, but should also logically imply a corresponding reduction in the energy demand of the commercial and residential sectors.

Ramirez et al. (2006b, pp.1711-1712) cite three main reasons for the analytical focus on energy-intensive sectors of the manufacturing sector in general: significant reductions in energy consumption can be achieved by focussing on a few energy-intensive sectors; detailed information on energy use is available for these sectors; and the energy-intensive sectors tend to have a limited diversity in terms of products, technologies and processes. The latter point is developed further in the context of characterising industrial sectors in section 5.2.2. Notwithstanding this focus, Ramirez et al. (ibid.) conclude that it is methodologically practical to develop energy-intensity indicators for heterogeneous non-energy-intensive sectors. However, data availability is a major limiting factor within these sectors, in light of which a more active cooperation with industry in this area has been recommended.

Having reviewed some pertinent applications of SEA to UK industry, attention is now turned to the main data sources currently amenable to SEA, in order to assess their suitability for such an analysis. The main data sources are the Digest of UK Energy Statistics (DUKES, BERR, 2007) and the Energy Consumption UK publication (ECUK, DTI, 2002b¹⁶). DUKES includes industrial energy use by broad two digit SIC sectors, and other related data such as the capacity and output of CHP units by sector. ECUK is more detailed, but at the expense of lower accuracy because of the way the data is based on the Annual Business Inquiry (ABI, ONS, 2008a) and then scaled up to correspond to DUKES (which is based on fuel suppliers' receipts). ECUK therefore relates industrial energy use by main fuel types at the four digit SIC level, but also contains data on energy consumption by end use.

There are therefore gaps in the national statistics themselves, upon which any SEA of the industrial sector would naturally be based (i.e. without recourse to proprietary data). The main areas which are lacking relate to the end uses of energy in industry, the breakdown between electricity used for heat and power respectively, and the temperatures at which industrial energy is used. The end-use data published in ECUK (DTI, 2004a) is also based on survey data, so suffers from the problem of inaccuracy cited above. Furthermore, although the data is broken down by end-use category, it does not distinguish between the fuel (or electricity) which is used to meet these demands¹⁷, and it is not clear precisely how the categories are defined. For example, the distinction between, and precise definition of the end uses Low Temperature Process and High Temperature Process is not even known by the BERR staff who publish this data (Knight, J., Energy Markets Units, BERR, pers. comm., May 2007 and September 2008). The data seems to be supplied to BERR by AEA, with limited transparency regarding its compilation.

Related to the lack of data on end-use data is the problem in determining precisely how electricity is used. The breakdown of energy use by fuels for individual industrial sectors is given in DUKES and ECUK, but it is not possible to infer from this exactly what the electricity

¹⁶ The corresponding tables are updated annually, one year in retrospect.

¹⁷ This was true for all years until the time of writing. The most recent ECUK data includes the contribution of different fuels to these end uses for the first time (BERR, 2008e).

is used for. Some of the end uses detailed in ECUK can reasonably be assumed to be electricity uses, such as Motors, but others such as Space Heating and Drying/Separation are much less clear. There is a strong incentive, from thermodynamic and economic perspectives, to better understand the split between electricity used for heat and that used for power applications. This is because of the thermodynamic and implicit economic inefficiency associated with generating electricity in a centralised power plant with around 2/3 losses overall, only to then use the electricity for heat¹⁸.

The final area where data is sparse relates to the temperatures at which energy is used. This can be said about the economy in general, as well as for industry in particular. Apart from the two end uses mentioned above relating to industrial processes, there is scant data available about the temperature at which energy is used in industry. It seems that neither BERR, which administers and publishes the national energy statistics, nor AEA, which provides this end use data, has temperature demand profiles for the industrial sector (Haydock, H., AEA Energy and Environment, pers. corr., May 2007). From a thermodynamic point of view it is desirable to understand this because it is the temperature in relation to the environment or dead state which determines the exergy of an energy flow.

In summary, the application of SEA to UK industry in the past few decades has been quite limited. There was a lot of activity in this area in the 1970s and 1980s, but interest seems to have dwindled since this time, due in part to the privatisation of ETSU and also no doubt due to the relative decline of heavy industry in the UK. Since this time, SEA studies which have included the UK within their scope have done so on a broader, European, or at least cross-country level. There is therefore significant scope for applying SEA to the industrial sector. In addition, there are four main areas in which the data relating to industrial energy use could be improved in the UK: highly disaggregated energy use by sector and/or site; data relating to end-uses of energy; the distinction between electricity used for power and heat; and the temperature at which energy used (a so-called temperature demand profile).

3.1.2 Process analysis (PA)

Many applications of process analysis (PA) have been made to industry in the last three decades or so. The early studies by Chapman (1975), Chapman and Mortimer (1974) and Chapman et al. (1974) focussed on evaluating the energy implications for certain policies, in this case a new family of nuclear reactors for electricity generation. The method has also been widely applied to individual industrial sectors and processes, such that a detailed review of its application to all industrial sectors is beyond the scope here. Instead, as stated in the introduction to this chapter, specific literature reviews are given in the relevant chapters (7-9). Here the emphasis is on teasing out the common threads from the application of PA to diverse industrial sectors and processes.

¹⁸ This is only the case with the current centralised electricity generating plant, and overlooks the potential (future) impact of large scale CHP and/or decentralised electricity generation upon the overall grid efficiency.

Applications of PA to industry are as varied as the industrial sector itself. Studies have, however, tended to focus on the energy-intensive industries, including iron and steel, chemicals, refineries, and petrochemicals, as well as non-metallic minerals and pulp and paper. The scope of these studies has varied from the very broad, covering a whole sector, to the narrow focus upon one type of process in a specific subsector. The scope obviously dictates the level of detail for any given analysis, so a broad approach is not usually able to provide insights into specific process plant, and detailed ones suffer from the inability to consider macroeconomic trends.

PA has been applied to global or national sectors, with little emphasis on the UK specifically. Taking the iron and steel sector as an example, attempts to analyse energy use in the sector have been focussed on the Basic Oxygen Furnace (BOF) route because it accounts for the vast majority of global capacity and therefore energy consumption in the sector (IEA, 2007). Nevertheless Worrell et al. (2001) examined the potential energy and carbon savings within the US primary *and* secondary iron and steel sectors, by combining PA with costing of the individual energy flows, and a capital cost estimation of the suggested savings. Many of their recommended savings have simple payback periods smaller than a year and very large (i.e. greater than 200%) internal rates of return (Appendix A2.1.3). Many of the technologies are applicable to the UK sector but it is not clear to what extent, due to the different size and structures of the two sectors. Worrell (1994, ch.3) has also done a PA of a specific integrated steel plant in the Netherlands, which involves a very similar approach to the US study mentioned above.

In addition, several broad studies of the US iron and steel sector have been carried out under the auspices of the US Department of Energy's (DOE) Industrial Technologies Program (ITP). These include an analysis of the theoretical minimum energy requirement for producing steel (Fruehan et al., 2000) and an assessment of the marginal opportunities for energy savings in the sector (Stubbles, 2000). Other studies have focussed on benchmarking the industry by analysing current trends and estimating the potential for specific technologies to improve energy efficiency (US DOE ITP, 2009). There is therefore a lot of activity under the DOE's ITP concerned with understanding the iron and steel sector in the US, which involves both applying PA to current and historical data and speculation about the likely evolution of future trends. The lack of such government-funded programmes for the UK might be attributed to the relative size of the sector: US steel production is approximately ten times larger than that of the UK, with around 20 integrated steelworks operating 40 blast furnaces in total (Energetics, 2000) compared to 3 and 7 respectively in the UK (chapter 6).

For the UK Michaelis and Jackson (2000a, 2000b) have done a similarly broad study, which focussed on the macroeconomic mass and energy flows through the sector, in order to chart the trends over the period 1954 to 1994, and attempt to make tentative projections out to 2019. They employed material flow analysis (MFA), a type of PA that applies a mass balance across the system of interest. The authors conclude that the exergy demand in the Iron and Steel sector will probably continue to decrease by 15-74% of 1994 levels by 2019.

There seems to be a lack of process-specific studies focussed on the UK but, contrary to national or industry-wide surveys, studies of individual process plant are highly transferrable. Hence an analysis of a blast furnace or basic oxygen furnace (BOF) anywhere in Western Europe is applicable, to some extent at least, to any other similar unit within the same region. For example, Ziebig et al. (2008) have shown that there are energy and carbon saving opportunities through employing the COREX process¹⁹, along with CO₂ removal and a CHP unit. Ziebig and Stanek (2006) have performed a system analysis of the complex relationships between operating parameters within an integrated steelworks based on energy and exergy considerations, concluding that such an approach is crucial if the true saving potential in these plants is to be realised. Rasul et al. (2007) have also modelled the blast furnace operation based on data from an Indian plant and shown that there are potential energy savings through an increase in the hot blast temperature, reducing the coke ash level and increasing the sinter volume in the charge. Hence none of these studies focus on the UK specifically, but clearly have insights which are relevant to the UK sector.

For other industrial sectors a similar trend emerges. Worrell has published extensively about applications of PA to industrial sectors. For example Worrell et al. (1994a) examined the energy consumption trends by key industrial sectors across the EU, by focussing on processes each responsible for over 1% of the 1988 primary energy consumption in this region. These included oil refining, paper manufacture, ammonia synthesis, cement and steel production, which together accounted for about 18% of total EU PEC in 1988. The study therefore included these processes in the UK, where they accounted for around half of the industrial PEC. Worrell et al. (1994b) and Worrell and Blok (1994) also used a similar approach to study the energy saving potentials in the plastics and nitrogen fertiliser sectors in the Netherlands. These two studies derive SEC measures for these two sectors, but it is clearly specific to the Netherlands at this particular time.

Some trends emerge despite this relatively small and selective survey. Firstly, there have been very few published applications of PA that have focussed on UK plant in the past few decades. Secondly, most firms in energy-intensive industries have in house teams or consultants who focus on optimising their energy and production systems, which explains why the results of such studies are not always to be found in the open literature. These sectors do not engage with academia unless there is a specific need on their part (Eglinton, D., ExxonMobil, and Stace, G., Dairy UK, pers. corr., March 2006). Most of the studies reviewed above have focussed on specific systems (either global, regional or national) in specific time periods. Whilst there is a certain degree of transferability associated with process- or technology-specific analysis, this depends on the degree of similarity between systems.

¹⁹ This process eliminates the need for coking and sintering because coal and lumped iron ore can be used directly (Siemens VAI, 2007).

3.2 *Exergy analysis*

One of the earliest macroscopic applications of the exergy method was performed by Reistad (1975) for the United States in 1970. He calculated the First and Second Law efficiencies of a range of energy conversion devices, including generators, motors, boilers, engines and heaters. Some appliances have approximately equal efficiencies based on First and Second Laws, because they mostly have energy inputs and outputs that are available. Large differences between the two efficiencies were noted for, in particular, large steam boilers, gas and oil furnaces, electric and gas hot water heaters, which is due to the low availability of the output energy streams (the large temperature difference between the supply and demand exergies).

The largest exergy loss for a coal-fired electricity generation plant occurs in the steam generator as a result of the irreversible combustion at high temperatures (*ibid.*), which was more recently confirmed by Hammond and Stapleton (2001) in their study of the UK energy system. The energy losses are largest in the condenser, however. If the availability losses in the steam generator can be reduced, there will be a commensurate reduction of the energy losses in the condenser. Thus the irreversibilities in the steam generator are a major cause of restricted exergy efficiencies in steam-electric power plants (Reistad 1975).

Reistad goes on to analyse the availability flow through the US economy. Although he acknowledges the difficulty of determining an overall efficiency for the industrial sector, because of the many different uses of energy and the requirement of knowing the temperature and amount of heat used for heating applications, he arrives at an effectiveness for the sector of 36%. Although energy flow charts (Sankey diagrams) for the economy demonstrate that around half of the input energy is wasted, available energy flow diagrams (Grassmann diagrams) paint a much bleaker picture. In this case, they indicate that over 75% of the supplied available energy is not effectively utilised. Furthermore, these availability diagrams show what Reistad (1975) has called the true thermodynamic performance of the energy system, although this point is debatable because the exergy efficiency is always constrained by large exergy destructions wherever combustion processes occur. The exergy destruction is due to the irreversible, entropy-generating nature of combustion, and results from the chemical reaction itself and the internal mixing/heat transfer process (Bejan et al., 1996). The distinction between avoidable and unavoidable destructions and the means of ameliorating the latter are discussed in chapter 9.

Wall (1987, 1990) has also applied exergy analysis to whole economies, in Sweden in 1980 and Japan in 1985 respectively. In both of these studies Wall extended the exergy concept out from the relatively closed heat and power technology field to cover all energy and material conversions in society. For Sweden in 1980 the exergy flows through society were determined with inaccuracies of 5% for electricity and 20% for heat flow to houses and other premises (Wall, 1987). The total exergy conversion is 2539PJ with a net output of 500PJ, indicating an exergetic efficiency for the whole system of around 20%. The greatest exergy losses in the system occur in the conversion of various energy sources into heat at room temperature (space

heating). By estimating the exergy content of space heating energy at around 5% (based on a harmonically varying ambient temperature variation), Wall suggests that the physical demand for exergy for space heating is 19PJ, much less than the total exergy supply of 500PJ. By looking at the exergy flow through nuclear fuel to electricity to heat, he also calculates the overall exergetic efficiency (using a Light Water Reactor, LWR) to be 1.6%. Thus the scope for increases in the exergetic efficiency of energy conversion processes appears to be significant, and to this end Wall advocates an exergetic resource accounting framework.

The study of Japanese exergy flows in 1985 is very similar, with a total exergy conversion of 18EJ and a net output of 3.8EJ, indicating a slightly higher exergetic efficiency in this case of 21% (Wall, 1990). The exergetic efficiency for space heating in the Japanese society (ambient temperature difference of 10°C) was calculated to be lower than that for the Swedish one, at 3%. In this case, too, Wall therefore advocates the use of resource budgeting, along with building technology to decrease the demand for space heating.

In relation to these two studies, Ayres (1998) has argued that due to the convention employed by Wall in these studies, the exergetic efficiencies estimated are very liberal. Ayres believes that, if the final exergy conversion processes – from primary into useful exergy – were also taken into account, then the exergetic efficiencies would be just a few percent. This does, however, approximately correspond to the values quoted above for final use of exergy in space heating applications. Regardless of whether or not these overall exergy efficiencies are liberal, though, they are generally much lower than the corresponding energy efficiencies, which in all cases is due to the low exergetic efficiencies of irreversible combustion and heat transfer mechanisms. Low overall exergy efficiencies do not necessarily imply a large scope for improvement, because in all cases a large temperature difference is required in order for heat transfer to occur. Hence both energy and exergy efficiencies should be considered.

Alvarado and Iribarne (1990) applied exergy analysis to determine the minimum theoretical energy requirements (TERs) of the production processes for copper, wood pulp and steel in Chile in 1986. The actual SECs for these three processes were calculated to be 25.6, 23.7 and 24.2 GJ/t respectively, compared to TERs of -90.6, -12.6 and 6.2 GJ/t. Thus there is a theoretical potential to make the first two processes self-sufficient in energy terms, as well as to improve the efficiency of the third one. For copper this is increasingly being facilitated through sulphuric acid co-production (the latter is highly exothermic). Pulp and paper production can deliver an energy surplus if the most energy efficient techniques are employed (Regestad, 1987, cited in Alvarado & Iribarne, 1990). Regarding steel, the estimated minimum is in close agreement with, but seems lower than other studies (e.g. Fruehan et al., 2000). The theoretical potential for making processes self sufficient should be considered with some care, however, because there are often technical, economic or other reasons why this is not possible in practice (section 4.4).

Others have applied exergy analysis with a higher resolution in the industrial sector. Most notably, Rosen (1992) carried out an energy and exergy analysis for four main sectors of the

Canadian economy – residential-commercial, industrial, transportation, and utility – in 1986. The five industrial sectors with the highest energy intensity have been identified, and a representative process from each examined. Together these five industries accounted for approximately half of the energy use in 1986. The study focuses on process heating and mechanical processes which together accounted for 81% of the industrial energy consumption in this year. Processes were categorised into low, medium and high temperature, whereby the respective temperature bands were $T_p < 394\text{K}$, $394\text{K} < T_p < 672\text{K}$ and $T_p > 672\text{K}$. Rosen (op. cit.) concludes that the largest differences between energy and exergy efficiencies in the Canadian economy are due to heating processes, where high quality energy streams are applied to meet low quality demands. In particular, the industrial sector's relatively high exergetic efficiency (compared to the residential-commercial and transportation sectors) is due to the high temperatures employed for many industrial processes (i.e. above 672K), which utilises much more of the fuel's (chemical) exergetic content. The five sectors selected have overall energy and exergy efficiencies in the range 62-82% and 32-52% respectively. Interestingly, the sectors with higher energy efficiencies do not have higher exergy efficiencies. Rosen and Dincer (1997) applied a similar methodology to Turkey in 1993, where the three most significant industries were identified as iron and steel, cement, and chemicals/petrochemicals, together accounting for approximately 60% of total industrial energy use. They reached similar conclusions relating to the energy and exergy efficiencies for these sectors.

The general conclusion for the industrial sector from these two studies seems to be that there is a large improvement potential because of the low exergy efficiencies. However, as already noted there are irreversibilities associated with the combustion process which are not well understood and which cannot be avoided. In this regard, Caton (2000) applied Second Law Analysis to the combustion process within an internal combustion engine. His treatment is purely analytical, and obtains the fraction of the fuel's availability destroyed due to the irreversible processes as a function of temperature, pressure and equivalence ratio for octane-air mixtures. The implication of his analysis for internal combustion processes is that combustion should be conducted at higher temperature in order to minimise the destruction of the fuel's available energy. There are other considerations associated with higher temperature combustion, though, including higher temperature exhaust gases and therefore higher thermal availability, as well as higher concentrations of nitrous oxides in the exhaust. Further, he showed that the exergy losses in this idealised combustion process were 5-25%.

Hammond and Stapleton (2001) recently applied the exergy concept to the UK energy system. This study covered a period of over thirty years, from 1965 onwards, and employed a sectoral approach, in which the supply side was examined in terms of the main energy sources, and the demand side separated into four energy end-use sectors: domestic, services, industrial and transport. Sector weighted exergy efficiencies of these sectors were obtained. This study contrasts with previous ones of OECD countries already discussed (Reistad, 1975; Wall, 1987; Wall, 1990; Rosen, 1992; Rosen & Dincer, 1997) in its dynamic nature – rather than taking a "snapshot" in time, it treats a period of about thirty years.

The exergetic efficiencies obtained for electricity generation plant compare well with those reported by Reistad (1975). Energy and exergy efficiencies of coal-fired steam electricity generation in the UK are given as 35% and 34% respectively (Hammond & Stapleton, 2001); for the US, Reistad reports values of 41% and 39% respectively. The main reason for the discrepancy is the higher operating temperatures typically adopted in US power plants (Szargut et al., 1988). Thus a large potential for improvement of the exergetic efficiency of electricity generation in the UK was identified. The only ways in which this might be achieved, though, in the absence of large scale hydroelectric powers schemes, is by restricting the use of electricity to power applications and increasing the uptake of CHP plant.

In a similar manner to Rosen (1992) and Rosen and Dincer (1997), for the industrial sector end use processes were grouped into four broad categories, namely low temperature ($T_p < 394\text{K}$), medium temperature ($T_p = 394\text{-}692\text{K}$), high temperature ($T_p > 692\text{K}$) and mechanical drives, and energy end use was divided into electricity and fuel. The First and Second Law efficiencies evaluated are thus overestimates because they are end-use values, and therefore do not account for losses associated with power generation. The result is that exergy losses in industry (as a proportion of the energy input) are somewhat smaller than those in the electricity generation and domestic sectors. Exergy and energy efficiencies for the sector in the mid 1990s are reported as 46% and 69% respectively, which again suggests a significant scope for improvement of the former, but with the caveat given above that combustion processes are inherently problematic to improve (Hammond & Stapleton, 2001).

Hammond and Stapleton conclude that, in agreement with Reistad, the main exergy losses in a power plant are associated with the combustion processes and the heat exchangers. Hence improvements made at that end of the thermodynamic cycle will inevitably have the knock-on effect of increasing the First Law efficiencies. Further, they suggest that an understanding of the thermodynamics at play is more important than whether or not these improvements are actually feasible in practice. That is, one does not necessarily have to implement an exergy analysis in order to fully understand the concept. They cite early work by Chapman (1976), which noted the wastefulness associated with using nuclear-generated electricity for heating applications, rather than for power applications. There is clearly a benefit to practitioners in understanding the concept of exergy without doing detailed calculations. The main limitation of this study's coverage of the industrial sector, though, is in the rather crude end-use categories employed.

Exergy analysis has been widely applied to individual energy conversion systems and process plant, as well as to macro-level energy systems as large as national economies. It's usefulness in highlighting what is considered by many as the "real thermodynamic efficiency" has been highlighted by many studies (e.g. Reistad, 1975). However, Hammond and Winnett (2005, p.20) have argued against what is effectively an "exergy theory of value", suggesting that this may or may not be the most important factor in a given system. Instead they advocate the application of exergy analysis alongside other, more conventional, First Law techniques. Ayres (1998) also agrees that it is necessary to consider First *and* Second law analyses, in order to have

an overall indication of the efficiency of a system. The reason this is so important is that the improvement potential suggested by exergy analysis alone is often much higher than what might realistically be achieved in practice. Alone, exergy analysis does not reveal the whole picture.

3.3 *Summary and conclusions*

Applications of SEA to industry in the past few decades have been limited, which appears to be due to lack of interest from public funding bodies and the relative decline of heavier industries. In particular, since the privatisation of ETSU in the 1990s there have been very few extensive studies of industry as a whole. Some studies have included British industries alongside others in cross-country comparisons, which offer some insights into specific sectors. There are four main areas in which the data relating to industrial energy use could be improved in the UK: highly disaggregated energy use by sector and/or site; data relating to end-uses of energy; the distinction between electricity used for power and heat; and the temperature at which energy used (a so-called temperature demand profile).

A comprehensive literature review of PA applied to the British industrial sector has not been employed here because of the large variation in processes and types of studies. Instead, an attempt has been made to tease out the emerging trends in PA by resorting to appropriate examples. It seems that few applications of PA have been made in recent times to specifically UK-based plant. There are two possible reasons for this. The first is that, because PA applies to a specific unit operation or technology, the results are often transferable between sites and even countries. The second reason for the apparent lack is that energy is professionally managed by energy-intensive industries. Any studies relating to energy efficiency would not necessarily be published in academic journals unless the work was the result of collaboration between industry and academia. Work carried out in house or on a consultancy basis for industrial firms is usually subject to commercial confidentiality. Initial studies carried out as part of this research suggest that this is in fact the case for many sectors.

The review of applications of exergy analysis concluded that the method has been widely applied to both individual process plant and macro-level energy systems. The latter studies have been useful in highlighting the very low exergy efficiencies of whole energy systems, but have been somewhat crude in their treatment of end-use categories. Here also, there has been a lack of meso-level studies. The application of exergy analysis to individual processes has been partly constrained by the availability of data on the chemical exergy content of non-standard substances. For example, the method has been widely applied to combustion and electricity generation plant, but has only recently found application to specific industrial plants.

4 Energy efficiency: definition, measurement and change

This chapter presents the theoretical framework upon which subsequent chapters build. It begins by discussing the definition of energy efficiency, which is necessary if it is to be measured. Attention is subsequently drawn to the measurement of energy efficiency, before examining the ways in which this can be increased for industry, through the tripartite approach of behaviour, technology and policy. This leads quite logically into a discussion of the drivers for and barriers to the adoption of these measures, along with a consideration of the rebound effect.

4.1 Definition of energy efficiency

The term *energy efficiency* is often used without being defined, and when it is, the meaning of the term is very much dependent upon the context. Patterson (1996, p.386) notes that, although energy efficiency has an important place on the public agenda of many countries, surprisingly little attention has been given to defining and measuring the term. In the physical sciences (especially engineering) the word *efficiency* is used to refer the useful work obtained from a process or machine when related to the total energy input. It is therefore an indication of the performance of the device in energy terms, which suggests that the term *energy efficiency* is a tautology. Nevertheless, the main reason for the ambiguity is that the term is applied to system boundaries with a broad range of sizes and scopes (European Commission, 2006d, p.27). A distinction can be made between the use of the term to refer to general behaviour or practice, compared with its use to refer to a quantitative measure of performance. Here attention is exclusively focussed on the latter.

Energy efficiency relates the output from a system to the energy input to it. The different ways in which output is measured has to be reflected by any energy efficiency measures, however, and leads to several accuracy-related issues discussed in the following section. In general, any definition of the term energy efficiency has to consider several important factors, including: the energy system scale; the system boundary; the type of energy; the method of determination (i.e. measured or estimated); the nature of related indicators; the temporal characteristic (static or dynamic) and the baseline (best theoretical, best practice or inter-population benchmarking). Fawkes and Jacques (1987, p.14) suggest energy efficiency measures also need to consider the level of production plant occupancy to which the figures relate, the history of trends in these figures and the age-characteristics of the site. The plant occupancy (or load factor) and age of plant both have direct consequences for energy efficiency.

Based on consideration of the above factors, various definitions of energy efficiency have been suggested. The commonality lies in relating input to output, but there is still a degree of variation and thus ambiguity (European Commission, 2006d, pp.27-28):

- i. The ratio between output of performance, service, goods and energy, and an input of energy;
- ii. To obtain an unchanged output value at a reduced energy consumption level;
- iii. To obtain an increased output value with unchanged energy consumption;
- iv. The amount of energy consumption per unit of product/output;**
- v. The amount of energy consumed per unit of feedstock;
- vi. Energy consumption per unit of product (excluding feedstocks);

In industry the most commonly employed concept is the fourth definition above, or energy consumption per unit of output (ibid.). If output is measured in physical units, this is referred to as the specific energy consumption (SEC) or energy intensity factor. If output is measured in economic units, then this parameter is known as energy intensity, which is the reciprocal of energy productivity in the economic sense (section 5.2.3). As stated in the Introduction, energy productivity and energy efficiency are taken to be synonymous in this thesis, both being the reciprocal of the SEC or energy intensity.

This definition of energy efficiency is deceptively simple, however, because it does not explicitly define the system boundary and conventions. Of particular relevance are the conventions for dealing with feedstock energy, the efficiency of electricity generation and the use of lower or higher heating values (sometimes referred to as net and gross calorific values respectively). These assumptions are defined depending on the specific system of interest later in this thesis, so a general specification cannot be given here.

Having established the definition of energy efficiency for industry, it is well worth returning to the point above relating to a baseline. The energy efficiency of a system alone is not sufficient for an effective evaluation, rather it must be compared to a baseline so as to put it into context. Baselines therefore offer some reference datum with which to compare. The comparison can be inter-system (e.g. firm, industry, country), inter-temporal (i.e. the same system at different times) or with some theoretically-defined parameter (e.g. theoretical minimum energy requirements). It is also important that, for the sake of comparisons, system boundaries remain the same. Related to this is the fact that the best possible efficiency for a site is not always the sum of the best efficiencies of the components. This is especially the case for highly integrated process plant (e.g. chemicals), in which experience has shown that overall site efficiency is optimised by operating individual plant sub-optimally. If the baseline is in the form of a best practice or best available technology energy efficiency, this is usually taken to be either the best energy efficiency achieved within the system(s) studied or the best that could be achieved if current technology were adopted respectively.

Thus systems with different attributes cannot effectively be compared without any differences being accounted for beforehand. If a suitable correction is not possible then it stands that there can be no fair comparison of the multiple systems. Indeed, this can often be the case, such that energy efficiency studies can only be used within a limited, system-specific context. The data relating to the UK Climate Change Agreements (CCAs), for example, relates to a dynamic

population so that the aggregate results from different periods cannot be compared without considering this (Stace, G., Dairy UK, pers. corr., March 2006).

4.2 *Interdisciplinary efficiency measures*

Having defined the concept of energy efficiency as applied to industry, attention is now drawn to interdisciplinary measures of productivity. Inputs to and outputs from an economic system are almost universally measured in monetary units. Flows into and out of a physical (thermodynamic) system are typically measured in physical units of mass, volume, energy (or their time-derivatives). The consideration of energy systems of various sizes presents the problem of choosing appropriate units to measure energy efficiency, especially where the flows through the system can be measured in economic *and* physical units. Hence a variety of interdisciplinary measures have evolved to measure productivity, which Patterson (1996) has categorised into three broad types, namely thermodynamic, output-based and economic:

1. **Thermodynamic** – the pure efficiency of a specific process (dimensionless: J/J);
2. **Output based:**
 - a. Physical-thermodynamic – e.g. SEC, SER, unit energy consumption etc. (GJ/tonne);
 - b. Economic-thermodynamic – common for more aggregated systems – energy intensity or productivity (PJ/£ of GVA or GDP); and
3. **Economic** – purely economic efficiency indicators based on market prices for energy inputs and outputs (usually dimensionless: £/£).

Patterson's taxonomy originally included four separate indicator types, but the intermediate ones have been grouped together here for reasons that should become apparent. The classification is based, on the one hand upon bottom-up process analysis, and on the other hand on top-down macroeconomic analysis. The first, purely thermodynamic type of indicator indicates the theoretical efficiency of a system, usually based on highly detailed and disaggregated data. The third, purely economic indicator is obtained from more highly aggregated data. The two intermediate indicators within his taxonomy represent varying degrees of integration between bottom-up and top-down approaches. The data requirements for the various types of indicator are heavily dependent upon the level of aggregation. Thus, to determine different indicators for the same energy system, the purely thermodynamic indicators require much more data relative to the purely economic ones. This is mainly because of the high levels of detail and disaggregation associated with the bottom-up process-specific data, as shown in Figure 4-1.

The choice of physical or economic indicator depends heavily upon the data availability and the specific application; there are advantages and disadvantages of both. Physical outputs correspond directly to a quantity of good being produced; economic value only indirectly corresponds to the actual output in physical terms (alternative value theories were discussed in section 2.1.4). According to neoclassical economics, the price of a good or service is determined

by the interaction of supply and demand at one moment in time (assuming markets are efficient, in the absence of oligopolies). However, for the simple reason that the value (price) of goods tends to fluctuate, the price does not correspond to the underlying physical quantity.

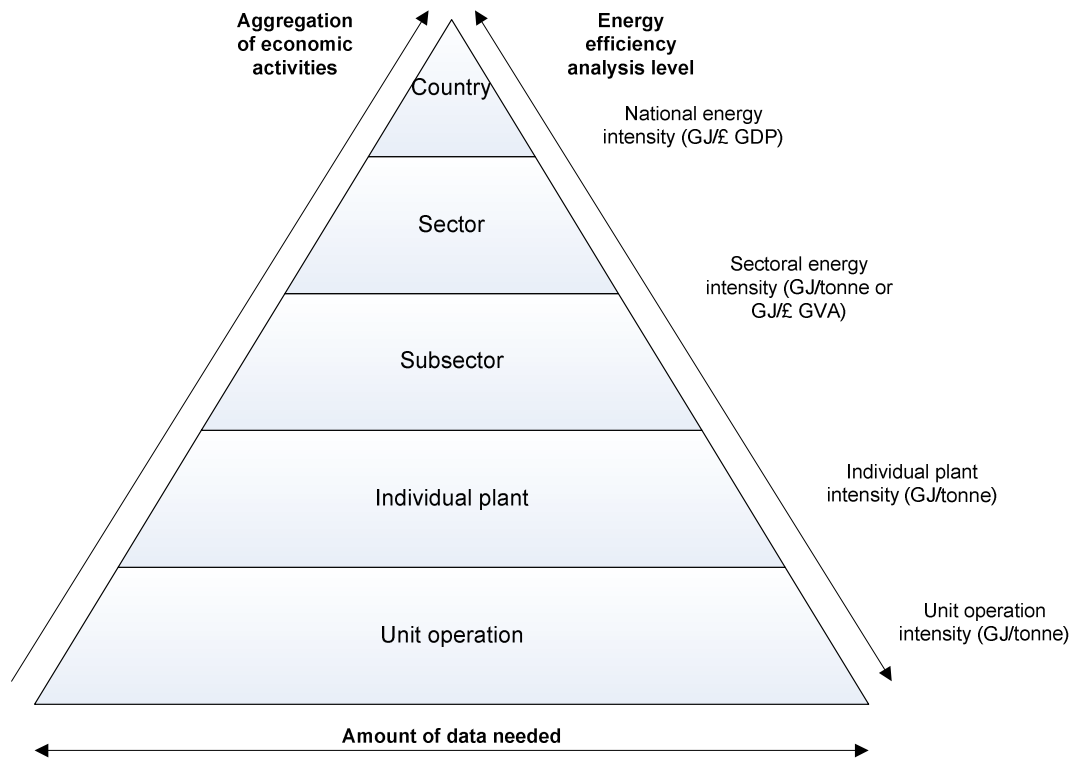


Figure 4-1 – The energy efficiency indicator pyramid (adapted from Farla, 2000, p.8)

In fact one of the main disadvantages of value-based economic indicators, compared to physical ones, is that sudden price hikes may lead to changes in the financial output, whereas the production in physical terms is not affected (Farla, 2000, p.9). Value-based indicators of energy efficiency measure not only the desired effects of the implemented energy efficiency measures, but also other, external effects. In addition, value based indicators of activity do not reflect the relevance of the product or activity mix to energy intensity within a sector. Knowledge about the mix of products or activities may therefore be especially valuable for a comparison of energy intensities between sectors with a rapidly changing output mix.

Freeman et al. (1997) critically examined the differences in output as measured by three different value-based indicators. They analysed value of production, value of shipments and value added, as well as volume of production, for several key US industries during the period 1978 to 1992. They found large discrepancies between the outputs reported by the different measures, concluding that, out of the three value-based measures, value of production appeared to be the most robust, reliable indicator. This is because this measure seemed to match the growth rate of volume of output more closely than the other measures, and it appeared less likely to exaggerate year-to-year changes in efficiency. The main problems with value-based measures were identified as (ibid.):

- **Measurement errors in price indices**, due to:
 - *Multiple prices*: short and long run, shipment, order, list and transaction prices – which price indices do not account for;
 - *Multiple goods within one industry* with one price index: structural shifts within an industry can lead to changes in value output with volume output remaining constant;
 - *Changes in data underlying price deflators*: when a major change in product definition or industry price index occurs;
 - *Quality changes*: e.g. PCs, for which the average speed has increased sharply, whilst prices have reduced; and
 - *Shipments and material deflators*: it is highly unlikely that average prices of materials and products will change at the same rate.

- **SIC related**, due to:
 - *Errors in industrial specialisation and coverage*: the degree to which value-based measures reflect the production of other goods and fail to reflect all production of a particular good; there is a direct correlation between specialisation and coverage ratios and the ratio of correlation between value and volume indicators; and
 - *Industrial redefinitions*: result in values of industrial output that are not directly comparable over time.

Physical volume indices are also far from perfect, especially in the industrial context. Non-homogeneity of products means that it is often impractical to aggregate the output from a sector. More significantly, this means that output cannot properly be measured in physical terms. In fact, often the only way to measure output in non-homogenous sub-sectors is by value of output. For example, the microelectronics industry produces a vast array of outputs, for which a specific physical unit of output is not appropriate.

Patterson (1996, p.383) also highlights the problem of overlooking energy quality with efficiency indicators. This problem might be overcome by employing exergy analysis alongside energy analysis. Patterson emphasises the importance of distinguishing between different sources and end uses of energy, all of varying quality. He also cites examples of significant discrepancies between results based on First and Second Law analyses respectively, suggesting that the problem is more acute at the micro-level because all energy inputs and outputs are typically different. For this reason, he warns against employing thermodynamic indicators in macro-level analysis, unless this problem can be ameliorated or eliminated.

The SIC related problems noted above for value-based indicators are also applicable, to a certain extent, to physical indicators. The assignment of a plant to an industrial sector within the SIC framework is largely based upon the sector in which the majority of the plant's output is classified. Whether or not this output is measured in physical or economic terms has little impact on associated errors when, for example, the main product accounts for little over 50% of

the output. Freeman et al. (1997, p.712) cite the example of the chlor-alkali industry, in which many firms produce chlorine for their own use. Also, chlorine is actually not their main product and much production of chlorine actually takes place outside the SIC of the industry.

In view of these apparent inadequacies with the conventional SIC, Beyene and Moman (2006) suggested an alternative, process-based classification of industrial activity. They note how the SIC as it stands gives no indication of the energy intensity of a firm, instead grouping together seemingly non-homogenous processes based on the end product that they produce. Beyene and Moman's study involved determining the thermal/electricity (T/E) ratio and energy intensity (measured in energy consumption per unit of sales, kWh/\$1000) for 270 plants. Across eighteen major two-digit SIC codes they identified 27 major processes with a clear, strong correspondence between the T/E ratio and energy intensities of these different processes. Any major inconsistencies or anomalies from this trend could be explained, and were mainly due to variations within the details of the process, whereby, for example, metal and plastic injection had been merged into one process.

As a result of their analysis, Beyene and Moman recommend defining a core group of processes, with sub-level being added later as necessary. They argue that a correspondence between SIC and energy profile is important because major policies, funding opportunities and utility activities all depend on this relationship. Such a process-oriented classification scheme has the potential to better identify and target industrial sectors for energy efficiency measures, by providing a more intuitive basis upon which to apply various energy analyses.

Another classification of industrial sectors is according to their degree of homogeneity. Homogeneous sectors perform the same process at all sites and typically produce just one product, with only a small amount of variation between sites. Furthermore, homogeneous sectors are generally associated with primary processing operations and are therefore energy intensive. Heterogeneous sectors produce a variety of products through diverse processes, and therefore need to be considered on an individual site basis. Upon further disaggregation heterogeneous sectors contain homogeneous sub-sectors, but in some cases this is only at very high levels of disaggregation (i.e. below the site). This classification provides the means of modelling industrial sectors/sites in chapter 6.

In light of the inherent problems associated with value-based indicators of energy efficiency, but the inability to aggregate physical indicators, Farla (2000) has developed a physical indicator that is consistent in aggregation. He has defined a physical production index from the output of a given product, which is weighted by the SEC (either the actual value in the base year, or a best practice value) of that product. The weighting factors are kept constant in all years in order to chart the frozen energy intensity development of the sector. By then relating the frozen to the actual development of the energy intensity over time, the physical indicator of efficiency is obtained. Farla has suggested that at least 90% of an industry's energy consumption should be covered by the products included in the analysis, in order that the accuracy can remain at a reasonable level (*ibid.*, p.48). The results showed large disagreements

between physical and economic indicators of efficiency (as applied to the Netherlands in this case), with year to year fluctuations (i.e. systematic errors) being smaller for the physical than the value indicators. He also noted the much larger data requirement for the physical indicators.

Value based indicators are typically favoured on a highly aggregated (e.g. macroeconomic) scale because the data is widely available in the form of national and sectoral outputs measured in GDP and GVA respectively. These data are recorded and published as part of a country's national accounts, so are current and accurate. They have the further advantage that they can be easily aggregated, because of their common economic units. Physical indicators are less readily aggregated due to their often incongruous units. Ramirez et al. (2006b) have questioned the suitability of economic-based energy efficiency indicators for measuring changes in technical efficiency, because output measured in GVA or GDP takes no account of physical output fluctuations. The choice of indicator is very important and has been shown to strongly affect the outcome of analyses (Freeman et al., 1997; Farla, 2000). In the energy debate it seems to be accepted that, wherever possible, energy efficiency indicators should be based on physical measures of output (Ramirez, 2005, p. 119). In general, though, the decision of which indicator to employ is dictated by the data availability, such that economic-based indicators are more widespread.

4.3 Methods of energy efficiency improvement

Having defined energy efficiency and discussed the ways in which it can be measured, attention is now drawn to the means through which energy efficiency can be increased. As also mentioned above, it is crucial to fully understand current consumption trends before attempting to reduce them, because a baseline is required from which to start. In general there are three types of approach to addressing energy efficiency, regardless of the context:

1. **Behavioural** measures, which involve changing practice (e.g. through better management and control), but using existing resources and little or no capital cost;
2. **Technological** measures, associated with some level of investment in new appliances or upgrades; technology may be bought off the shelf or developed by the firm itself through its R&D activities. Technology measures may be subdivided into (Langley, 1984a, pp. iv-v):
 - a. **Additional equipment measures** solely aimed at increasing efficiency;
 - b. **Replacement equipment measures**, which incur indirect efficiency gains; and
 - c. **New process technology** involving radical redesign and/or innovation.
3. **Policy-related** measures, many of which are intended to bring about behavioural and/or technological change. The focus here is on legislation as an indicator of public policy.

This taxonomy is useful not only because it separates out the different methods, but also because it highlights the complementary bottom-up and top-down approaches that can be used

by firms and governments respectively. Firms (and individuals) can change their behaviour in order to affect their energy efficiency, but drivers or incentives are required for such change. On the other hand, governments are able to put policy measures into place which provide incentives for individual firms. The intermediate area of this taxonomy that focuses on technological measures is a crucial one, for it is technological change that has enabled the industrial to drastically improve its energy efficiency over the past few decades (as discussed in section 5.1). According to the neoclassical economic perspective, it is technological change that enables increases in efficiency over and above those achieved through substitutions between and additions to factor inputs. Not all technological measures are aimed at improving energy efficiency, however. Often upgrading technology to the current state of the art can result in increased efficiency (category 2.b above), simply because newer technologies tend to be more efficient (von Weizsäcker et al., 1997, Worrell et al., 2003), but the long lifetimes of much process plant can result in technological lock-in which precludes retrofitting measures to improve efficiency. Each of the three main approaches identified above will now be addressed in turn.

4.3.1 Behaviour

According to the energy hierarchy presented in section 1.3, behavioural measures, otherwise known as good housekeeping, should be implemented before any other measures involving capital investment, because of the relative ease with which they can be affected and their relatively low associated capital cost. Behavioural measures of energy efficiency are associated with energy management, which is concerned with better measurement and control of energy systems. This involves focussing more attention on understanding how and where energy is used within a plant, and therefore being more suitably informed to make savings. The lack of awareness about onsite energy use makes this an area in which there remains significant unrealised potential (section 5.5). Furthermore, the attention given by industrialists to this activity is ultimately limited by the time and capital costs which are inevitably associated with planning and establishing the suitable system of measurement (Langley, 1984a, p.43).

There are varying degrees of energy management system; mineral oil refineries have highly complex, integrated procedure because energy costs can account for up to half of the operating costs, whereas an SME might simply have electricity and gas meters where these utilities are supplied to the site. As well as energy costs, there are many other factors affecting the scope of the energy management system, including, *inter alia*, whether the firm has a standard in place, if the company/sector is involved in long-term agreements, and whether senior management places a large importance on such activities. The first stage in setting up an energy management system is to carry out a full site audit, which involves recording the largest energy-consuming activities onsite, collecting relevant data and identifying any associated legal requirements. In most cases, at least high-level data should be available for long periods, in order to account for annual demand profiles due to changes in external temperatures and levels of production. If this information is not available then the relevant metering and/or logging equipment will need to be installed.

The above information and data can be used to determine the baseline energy consumption, against which any improvements can be measured. The appropriate energy efficiency indicators can be developed in order to track changes in productivity over time, and the areas identified on which to focus attention. Successful energy management systems all rely on the human dimension (European Commission, 2006d), so an energy or environmental manager with clearly defined roles and staff training may be required. Once the management system is established, there is a large variety of tools available in the form of software (such as the E-MAT Energy Manager's Tool developed under the European Commission's SAVE Programme), checklists, calculation methods, templates for data collection, and online tools for benchmarking and monitoring activities in an international context. These can all be used by a company to assist in carrying out the six main steps in effectively implementing a monitoring system, namely metering, targeting, analysing, accountability (i.e. apportioning responsibility), energy teams and action (ibid.).

The Eco-Management and Audit Scheme (EMAS) also allows voluntary participation by public and private organisations and provides them with guidance on establishing an environmental management system (European Commission, 2006, p.10 , p.25). For non energy-intensive industry, SMEs and in the public sector, there is thought to be a potential energy saving of 30% through cross-cutting technologies such as lighting, boilers and motors, which could be realised through an effective energy management system. New energy efficiency management schemes are also being developed under the European Commission's (2006a) Action Plan for Energy Efficiency. These will be developed along the same lines as the successful GreenLight, EuroDEEM and Motor Challenge projects, with priority given to standardised energy audits, guidelines on promoting energy-efficient products, best practice and benchmark guidebooks and education for energy managers.

There are several standards relating to environmental management, of which the most developed and detailed are the SIGMA guidelines. These guidelines include a set of guiding principles aimed at ensuring good management of the five types of capital (see Appendix A2.1.1) and accountability to stakeholders, a management framework based on a similar structure to the ISO14001 standard, and a toolkit of guidance and illustrative materials in order to help implement their guidelines (Frears & Hicks, 2008b). The Carbon Trust (2008b) also operates a scheme called the Carbon Standard (formerly the Energy Efficiency Accreditation Scheme), which formally recognises improvements in energy efficiency. Three aspects of company performance are considered for the accreditation process, including its energy management system, the amount of money being invested in energy efficiency projects and the improvements that can be demonstrated and proven.

Notwithstanding these standards, the field of energy management is a diverse and disparate one. Not all companies have a formal management system in place, and those that do differ widely in their practices. Hamblin (1996) confirms the heterogeneous approach to energy management, which is affected by, but cannot be generalised across, the sector in which a company operates. The literature on energy management reflects this diversity, being

dominated by country- or sector-specific analyses, some mainly qualitative and containing rather anecdotal evidence. For example, Hepbasli & Ozalp (2003) present the details of energy management activities in Turkey, concluding that universities and the private sector should be aware of the importance of the subject. Christoffersen et al. (2006) carried out a telephone survey of 300 firms in Denmark, concluding that less than 15% of firms in the sample undertake any kind of energy management. In addition, Jochem and Gruber (2007) report the success of local learning networks for industrial firms in Germany and Switzerland, whereby the transaction costs of energy efficiency measures and the implementation times required have been reduced through sharing experience and expertise. The efficiency measures identified were all highly profitable and the authors recommend the adoption of similar schemes in other countries.

In an empirical study of nine non energy-intensive SMEs in Germany and Denmark, Togeby et al. (1997) highlight six organisational factors describing the way in which firms work with energy efficiency. They suggest that energy efficiency is not an instantaneous event, rather a long-term process of social and technical change, which calls for a strategic orientation and a systematic approach within the companies. They also associate the companies that undertake energy efficiency activities with a certain degree of awareness about the future benefits of these activities, something which other companies perhaps lack. These benefits are over and above the purely financial savings, and include better relations with the authorities, for example. The six key organisational factors are (ibid.):

- (i) **internal know-how** in relation to technical aspects of energy efficiency;
- (ii) the **degree of decentralisation** of energy efficiency activities;
- (iii) the **dependence of activities on key actors** within the processes;
- (iv) the importance of **technical and economic arguments**;
- (v) the **embeddedness of energy activities** in similar activities concerning the environment; and
- (vi) the **importance of external impulses** and the integration of external support.

It seems that a successful energy management system is as much to do with the overall company culture as it is with the specific approaches taken to reduce energy demand. The structure of the company and the involvement of staff are key factors in making any such system effective. These and the other factors above are highly firm- and sector-specific, such that there is no cross-cutting approach to energy management apart from the general steps outlined above. It is not clear exactly why the fraction of firms undertaking energy management is so low. There are several possible reasons for this, such as barriers to energy efficiency, for which the theoretical framework and empirical evidence is presented in sections 4.4 and 5.5 respectively. Shipley and Elliot (2006) argue that (for the USA) this is certainly not because all of the “low hanging fruit” has been picked.

4.3.2 Technology

Whilst the energy efficiency measures outlined above are intended to minimise the energy consumption onsite through improved management, the next stage according to the energy hierarchy cited in section 1.3 is to employ technology to do this. There is a plethora of technological options available to industrial energy users, but in general the principle of using technology to increase energy efficiency involves upgrading existing equipment (2.a. above), replacing existing equipment (2.b.), or installing/developing completely new technology/processes (2.c.).

Several systems are prevalent throughout the industrial sector and therefore offer the potential for a crosscutting approach to energy efficiency improvements. Whilst the efficiency of individual components might be relatively high, that of whole systems is often relatively low. Optimising on a systems level has the potential to achieve large improvements in energy efficiency, perhaps an order of magnitude greater than through optimising individual components (Williams, 2007). Shipley and Elliot (2006) note that, although twenty years ago a large improvement in energy efficiency could be realised by installing a new boiler, for example, current energy efficiency enterprises need to be focussed on whole systems. The following discussion is primarily focussed on systemic technologies to improve energy efficiency. Although some examples of specific technologies are given, it is not intended to be comprehensive.

4.3.2.1 Combustion systems

Combustion processes occur in most industries, either to raise steam in a boiler (either to use directly or generate electricity through a turbine) or to use the heat directly as in a furnace. Hence a large emphasis of technological energy efficiency measures is placed on reducing the heat losses from combustion, and there are three main ways of doing this (European Commission, 2006d):

- (i) **Reduce the temperature of the flue gases**, e.g. by preheating the combustion air and/or materials or by cleaning the heat transfer surfaces.
- (ii) **Reduce the mass flow rate of the flue gases**, which can only be achieved by reducing the amount of excess air.
- (iii) **Reduce the heat losses** through the superstructure walls with insulation.

There are constraints placed on all three of these approaches to reducing heat losses. Firstly, the temperature of the flue gases has a lower limit because low temperature heat does not have many useful applications unless upgraded with a heat pump. Another consideration is the acid dew point, at which the condensation of sulphuric acid and water occurs, which is in the region 110°C to 170°C. In order to preserve the integrity of metallic surfaces from corrosion, the exhaust temperature is therefore kept around 30°C above this value.

Reducing the mass flow rate of the flue gases by removing excess air from the combustion process is limited by the stoichiometric ratio of combustion, which is required for complete combustion of the hydrocarbon fuel. This ratio is determined by the specific hydrocarbon in use, and can be calculated based on the molecular weights of the fuel and air. In addition, some (e.g. 1-2%) excess air is always desirable in order to avoid explosive environments. Combustion with pure oxygen, known as oxyfuel firing, completely eliminates the heat transfer to the nitrogen in the air which would normally be combusted. The oxygen must be produced, however, so although this technique reduces the direct energy requirements, it is no more efficient in primary energy terms (Ross & Tincher, 2004).

The heat losses through the walls can be reduced with insulation, but this tends to be installed when the furnace or boiler is commissioned. However, refractory materials used for insulation tend to deteriorate with time, so it may require replacing at a later date. Replacing or upgrading insulation therefore requires a suitable window of opportunity during plant downtime. There are also some trade-offs associated with attempting to achieve these three objectives together for one system. For example, preheating the combustion air (with recovered heat from the flue gases) to increase the flame temperature results in the formation of more oxides of nitrogen, NO_x. The “scrubbers” that remove these oxides only work in a certain temperature range. Hence the installation of heat recovery and related equipment can be complicated by conflicting objectives which can make such projects seem uneconomical, especially in the case of retrofitting.

An area which seems to be particularly promising for improving the energy efficiency of combustion systems is that of high temperature air combustion technology (HiTAC). The main feature of this technology is a novel combustion mode with a homogenous flame temperature, enabling the fuel to burn completely at low oxygen levels, which has achieved 35% higher energy efficiency to conventional jet burners (European Commission, 2006d). The technology also has lower specific CO₂ and NO_x emissions than conventional ones. Combustion takes place throughout the furnace (or vessel) with no visible flames, with more uniform radiative heat transfer and no CO detected in exhaust gases (Weber et al., 2005). In addition to these benefits, the required equipment size is smaller due to the better heat transfer, and oxygen deficient combustion produces higher First and Second Law efficiencies (Rafidi et al., 2008). One factor currently limiting HiTAC’s penetration seems to be its high capital cost.

4.3.2.2 Steam systems

Steam systems have a widespread application in industry for transporting heat, because of steam’s non-toxic nature, stability, low costs and high heat capacity. The overall potential for improvement in steam systems in UK manufacturing is estimated at around 10% (IEA, 2007, p.235). The steam system itself may further be broken down into three main components, namely the prime mover, the distribution system and the end use. The prime mover in a steam system will have an efficiency of 65% to 85% depending on the fuel type and particular configuration. For a steam system with a boiler efficiency of 80%, the overall efficiency of the

system is around 55% because 10% of the energy is lost in conversion and another 15% in distribution (Energetics & E3M, 2004, p.63). In general the best method of improving the overall efficiency of a steam systems is by using a CHP system (IEA, 2007, p.229). However, there are often reasons why this is not feasible, such as a lack of demand for electricity and economic barriers such as the uncompetitive and unstable price, known as the spark-spread, received for selling excess electricity back to the grid. CHP as a generic technology is discussed below.

Some of the main approaches to improving the energy efficiency of steam systems include (European Commission, 2006d, p.117): using economisers to preheat the feed water, which can increase efficiency by 4%; preventing formation and removing scale deposits on heat transfer surfaces; minimising boiler blowdown (i.e. removal of suspended and dissolved solids); recovering heat from blowdown; collecting and recovering flash steam and/or condensate; controlling and maintaining steam traps; insulating pipes; and reducing steam leakage. In addition to these specific measures, there are generic means to ensuring the efficient operation of distribution systems, including regular maintenance and better monitoring and control of system operation. Poorly maintained, fouled systems operate with an efficiency much lower than the 50-60% of well-maintained ones. Improved design and development of boiler plant therefore provides continuing opportunities for energy saving (Kreith, 1997).

4.3.2.3 Motor systems

Motor systems collectively include fans, drives and compressed air systems, which are ubiquitous in some industrial sectors. It is estimated that motor systems account for up to 70% of global (Williams, 2007) and European (ISR - UC, 2008) manufacturing electricity demand. The European Commission's SAVE Programme (European Commission, 2009) produced estimates for the total annual electricity savings for the UK manufacturing sector of the order of 86PJ or 24TWh (de Keulenaer et al., 2004), with the majority of this saving coming from optimisation of the overall system.

The chemicals, pulp and paper, food and drink, and iron and steel sectors all use a lot of electricity in motor systems. In the UK these five sectors account for approximately 85% all electricity use in motors systems (DEFRA, 2008b). The end uses of motor systems vary a great deal by sector. For example, the chemicals sector employs pumping systems accounting for over half of its motor systems' energy use, whereas for the food and drink sector this same proportion is accounted for by compressor systems.

The main reason for low motor systems efficiency is oversizing at the design and specification stage (Williams, 2007), because engineers tend to err on the side of caution with liberal safety factors when sizing individual components. For pumping applications, the power consumption of the motor varies with the cube of the rotational speed, but the flow varies linearly, hence small changes in motor speed can yield significant results (IEA, 2007, p.220). Depending upon the variability of the (pump, fan or compressor) load being met, a variable speed drive (VSD) might be appropriate. General approaches to optimising these motor systems include matching

the motor power rating to the load and using better control methods to respond to variations in loads.

For pumping applications, ways to optimise include maximising the cross sectional area of the pipe and reducing the power of the pump, as well as minimising changes in cross sectional area and direction by designing equipment around the pipes and not vice versa (Williams, 2007). These measures all serve to reduce the parasitic power load due to friction along the length of the pipes. Compressed air and fan systems can be optimised in similar ways, e.g. by locating and reducing leakages, and reconfiguring the piping to reduce the pressure loss through the system, as well as by reducing overall demand by finding alternative means to perform the same task.

4.3.2.4 Heat recovery and transport systems

Heat recovery and transport systems are widely applicable in industry because of the prevalence of heat. It is estimated that 70% of French industrial energy demand is for heat generation in some form, and furthermore, that 85% of the energy efficiency improvement potential is related to heat generation (EDF, 2007). The French and British industrial sectors have similar structures; the latter is larger overall, but France has larger iron and steel and food and drink sectors (Ministère de L'Économie de L'Industrie et de L'Emploi, 2005). By focussing on the major causes of energy waste in industry, one is better able to address technology to specific problems. Gyftopoulos and Widmer (1982, p.298) note one such cause as “the rejection of a [heat] stream at either high temperature or high pressure or both to the atmosphere”. Some of the main technologies associated with recovering and transporting heat are thus described below (Hatsopoulos et al., 1978).

- (i) **Heat exchangers** can be used to recover waste heat from hot (exhaust) gases and transfer some of this energy to the boiler feedwater, for example. They can be employed in most situations where hot and cold streams coexist, along with cooling and heating demands. Regenerators and recuperators can be used to recover heat from industrial furnaces, whereby the heat of the exhaust gases is either periodically (regenerators) or continuously (recuperators) transferred to the pre-combustion air. These devices can increase the furnace energy efficiency by 30% or more (European Commission, 2006d). Regenerators and heat wheels transfer heat from a hot stream to a material before being further transferred to a colder stream. A regenerator is stationary with respect to moving streams, whereas a heat wheel rotates between ducts containing hot and cold streams. Low temperature waste heat has applications for space heating, preheating boiler feedwater and water for washing processes. At medium and high pressures, an expander may be used to extract mechanical work from the waste streams. Furthermore, high temperature waste heat recovery is constrained by the requirements of materials to withstand such high temperatures (typically 1000 to 1400°C), as well as the often vitriolic and acidic nature of the exhaust gases. As with CHP, the application of heat recovery is largely constrained by the immediate demand for the recovered heat.

- (ii) **Heat pumps** are simple thermodynamic machines in which low temperature heat from a source is transferred to a higher temperature sink, using mechanical or high temperature heat energy. In industry there are a number of possible applications, wherever it is desirable to pump low exergy waste heat into a higher temperature environment. Kolbusz (1976) cites the examples of waste heat recovery and drying by dehumidification. Alongside several other specific applications, Lazzarin (1995) also suggests cooling and compression. Where the temperature of a waste stream is too low to be useful (i.e. 30-40°C), a heat pump can be employed to raise the temperature to around 80°C (Langley, 1984a, p.44).
- (iii) **Heat pipes** enable the transfer of heat over significant distance with a very low heat loss (entropy increase), and without the need for mechanical pumping. These may be used in combination with CHP systems in order to transport the heat to district heating schemes or adjacent industrial facilities.

4.3.2.5 Cogeneration or combined heat and power (CHP)

Cogeneration or Combined Heat and Power (CHP) can achieve very high overall efficiencies (in excess of 80%) by utilising the heat which would otherwise be wasted in centralised electricity generation. Its applicability depends chiefly on the heat to power ratio of the load; various prime movers (e.g. steam turbines, diesel engines, gas turbines) are suitable for operating at different ratios (Enviros Consulting, 2006a). This technology depends, critically, on there being a use for both outputs – this is often the limiting factor for consideration – as well as the economics of spark-spread (section 4.4).

Trigeneration or Combined Cooling, Heat and Power (CCHP) exploits the same principle as CHP, with the addition of a cooling demand. This technology is particularly applicable where there are significant heating, cooling and electricity demands, such as in airports. The combined generation of streams to meet this demands can result in very high efficiencies.

4.3.2.6 Process modifications

Switching from batch to continuous processing can increase energy efficiency. Energy requirements for continuous processing methods are lower because cooling and reheating of materials between stages is reduced, throughput is faster, equipment is smaller, and waste heat can more easily be recycled (Langley, 1984a, p.46). Continuous processing is not always applicable, however, in particular for short production runs of (one-off) products, and where quality can only be assured by a batch-wise method.

Process intensification can be achieved through a technique known as micro-process engineering, the field of chemical engineering concerned with carrying out reactions in small vessels in order to exploit the high heat and mass transfer properties due to the large surface

area to volume ratio, which can achieve more energy efficient processes. The UK has been at the forefront of the development of this approach, which results in compact and efficient designs (Hessel, 2005). Only a few examples of its successful commercial application exist, including heat exchangers, reactors and separation plant, which is why the Carbon Trust (2002) regards this approach as high risk.

4.3.2.7 Lifecycle approaches to dematerialisation

The industrial sector is unique in the sense that the products it manufactures have impacts in all other sectors where they are used. Decisions made at the design stage affect the energy use and carbon emissions associated with the product's whole lifecycle. When looked at from this perspective, the industrial sector can play a crucial role, not only in improving the energy efficiency of processes, but by considering the whole impact of its products over the entire lifecycle, from "cradle to grave". Dematerialisation and lightweighting of products is estimated to be capable of saving 1MtC per year in the UK by 2050 (Future Energy Solutions, 2005). Some of the methods involving this holistic approach are listed below.

- (i) **Recycling** can reduce the primary energy input required to process materials because the chemical processes have already been carried out, although this is not universally the case as some recycling processes are themselves energy-intensive. In addition, reliance on primary material resources and the requirements for their extraction and processing, can be greatly reduced.
- (ii) **Dematerialisation (or Factor X improvements)** has the potential to yield improvements in resource productivity, thus resulting in significant increases in industrial material and energy efficiency. Von Weizsäcker et al. (1997) have proposed factor four improvements, i.e. a doubling of economic welfare combined with a halving of resource use, whilst Klostermann and Tukker (1998) document several case studies which have attempted to achieve this. Others have gone further, by suggesting up to factor ten improvements, so called 10XE, or Factor Ten Engineering (Rocky Mountain Institute, 2007). Large per capita differences in material use between countries with the same levels of well-being suggest that there is significant scope to reduce this in some countries (IEA, 2007, ch. 10).
- (iii) **Re-use** of products, including through product recovery, and **extending product lifetimes** at the design stage, can also reduce their resource and energy requirement on a lifecycle basis, and can prevent them from being disposed of prematurely. Design for recycling and design for disassembly are two areas that are aimed at facilitating reuse and/or recycling at the end of a product's use phase.
- (iv) **Alternative materials**, which are less energy and carbon intensive, can in some cases be used instead of conventional ones to perform the same function. However, this is not always possible, particular for materials such as cement, which is so versatile and universally employed in construction.

(v) **Service providers** have more control and incentive to reduce energy consumption in the use phase of their products or services than if they were just manufacturing the product. There is more incentive for energy efficiency when, for example, an energy company is running a process rather than selling the energy for the firm to run the process itself. This has been manifested in the proliferation of Energy Service Companies (ESCOs) in recent times.

4.3.3 Policy

Policy is the third aspect of the tripartite approach to energy efficiency. It has the potential to change behaviour through legal requirements (legislation). The focus here is on legislation as an indicator of public policy. Although there may be a gap between legislation and its implementation, it is considered to be the most suitable indicator in this case. This section therefore discusses the policy framework and implications for the manufacturing sector, with a particular focus on legislation relating to energy, both at a national and European level. It is not intended to be exhaustive, rather should provide an overview. The Integrated Pollution Prevention and Control (IPPC, European Commission, 2008a) requires industrial firms to obtain licences for energy- and emission-related activities. It is not discussed here in detail because it does not concern energy efficiency specifically and its broad scope precludes a critical assessment of its effectiveness. The latter also applies to the European Packaging Waste Directive (European Commission, 2005b) and its implementation in the UK through the Producer Responsibility Obligations (Packaging Waste) Regulations 2007 (as amended) and the Packaging (Essential Requirements) Regulations 2003 (BERR, 2009).

4.3.3.1 Manufacturing strategy

Despite the dwindling contribution of the manufacturing sector to the overall economy, in specialist areas such as pharmaceuticals and electronics the UK possesses significant expertise and a strong track record in innovation (IPTS et al., 1998). The government recognised this and other strengths, whilst also acknowledging key weaknesses, in its Manufacturing Strategy of 2002 (DTI, 2002c). This document sets out the government's strategy for the manufacturing sector, by identifying the short and long term challenges facing the sector as a whole. It identified seven pillars, which are all critical to the long term success of the sector (DTI, 2002c): Macroeconomic Stability; Investment; Science and Innovation; Best Practice; Skills and Education; Modern Infrastructure; and the Right Market Framework. These pillars need not all be discussed at length here, but the third and fourth ones are of particular relevance because they encompass sustainable development and adoption of best practice (technology) respectively.

The Science and Innovation pillar is concerned with raising UK manufacturing's innovation performance by drawing on the solid science base, especially by fostering better links between industry and universities. There are two strands to this theme, involving knowledge transfer

activities and sustainable development. The latter is focussed on raising productivity levels in the sector, recognising that “not enough businesses are making this investment” (DTI, 2002c, para.3.15). The Strategy further stresses that the regulation-based approach is alone insufficient to deliver the changes needed, and that technological innovation is the only means through which the manufacturing sector can achieve these productivity increases. Knowledge transfer is delivered through the advice schemes such as Envirowise and Biowise respectively.

The Best Practice pillar is concerned with increasing competitiveness by adopting world-class practices. It aims to improve the least productive parts of an industry, which can be more than five times less productive than the most efficient ones (Haskell & Barnes, 2000, cited in DTI, 2002c), and thus bring the whole sector up to a high standard. The main activities under this pillar are the government-industry best practice fora, such as the SMMT²⁰ Industry Forum which was established in 1994. Since then the Forum has achieved significant productivity and competitiveness improvements. The success in this area led to the concept being replicated in other manufacturing sectors, including aerospace, chemicals, ceramics, textiles, metals and clothing. In addition, the Manufacturing Advisory Service (MAS) was set up to give free advice, and identify problems and opportunities for SMEs, which are considered to require most assistance as they don’t always have resources to devote themselves (HM Treasury et al., 2005). Furthermore, Innovation and Growth Teams (IGTs) have been established to convene key stakeholders and develop suitable policy, for specific sectors including automotive, chemicals, aerospace, and environmental goods and services.

In 2004 this Manufacturing Strategy framework was reviewed and the government identified the need for performance indicators against which to quantitatively and qualitatively assess progress under the seven pillars (DTI, 2004b). The sector’s spend on innovation-related activities increased over the decade from 2002, but as a fraction of GDP this was lower than in Germany and the USA. This review did not directly address the sustainable development aspect of the Science and Innovation pillar, however, apart from highlighting the establishment of the Chemistry Leadership Council. The latter was set up in response to the Chemicals IGT’s (CIGT, 2002) report to focus on innovation and science priorities, future skills needs, sustainable development and industry reputation. It is not clear how effective these IGTs have been in putting into practice any of their recommendations. For example, the website for the Chemicals IGT have not been updated in over four years and attempts to contact the authors were unsuccessful. The true effect of the CIGT on the sector is yet to be seen.

The Manufacturing Strategy was again reviewed in 2008 (BERR, 2008g). The MAS has been successful in helping business following its advice to save over £500million through the adoption of lean manufacturing techniques. The move to a low carbon economy has gained prominence in the four intervening years since the previous review, and large opportunities have been identified for manufacturing in terms of exploiting markets in environmental technologies and processes, and benefitting from the comparative advantage associated with

²⁰ The Society of Motor Manufacturers and Traders is the trade association for the automotive sector in the UK.

developments in clean technologies (Ernst & Young, 2008). There is little focus on industrial processes and/or energy systems specifically though; instead, three areas of the Strategy are to focus on nuclear energy, renewable energy, and low carbon vehicles. However, an Integrated Low Carbon Industrial Strategy, which should bring together diverse areas of government activity concerned with manufacturing, is planned for 2009. A competition for the UK's best cluster according to certain criteria has also been announced. Finally, the role of the Technology Strategy Board (TSB) in stimulating technological advances is an ongoing element of the Strategy. It has already invested in a portfolio worth over £1billion in collaborative business-business and business-academia partnership projects. Its main role is to add value by focussing on the economic benefit to the UK, however, and it neither develops energy technologies as the Energy Technologies Institute (ETI) does, nor achieves carbon savings as the Carbon Trust putatively does.

4.3.3.2 The EU Emissions Trading Scheme (EU ETS)

The EU ETS is cap and trade policy, which attempts to reduce the amount of CO₂ emitted by industrial firms within the EU by creating a market for this gas. Phase I ran from 2005 to 2007, Phase II runs from 2008 to 2012, and Phase III commences in 2013. The EU ETS applies to energy activities with a thermal rating over 20MW_{th} and the sectors manufacturing metals, ceramics and non-metallic mineral products (European Commission, 2003c), but excludes ammonia and soda ash production at the time of writing. There are current proposals for the revised Emissions Trading Directive to include, *inter alia*, ammonia, soda ash and sodium bicarbonate production in Phase III (House of Lords European Union Committee, 2008, p.22, para 120).

Companies operating under the EU ETS are given an emissions allocation which is determined for each Member State based on their National Allocation Plan (NAP). Under the present framework, the permits are mainly given away or "grandfathered" at the start of the trading periods, after which point trading on the open market is supposed to overcome deficits and surpluses. Further details about the NAP are given in chapter 6 where it has been used as a data source for modelling industrial heat loads. A case study of the cement sector is also presented in chapter 5, which relates to its performance in relation to the Scheme.

The extent to which real emissions reductions were achieved during Phase I of the EU ETS is questionable (Convery et al., 2008). The main problem seems to be the grandfathering methodology, which means that the companies are in fact not paying for their (allocated) level of emissions. A better alternative would be to auction the permits at the beginning of the trading period, which has occurred to some extent during Phase II and is being considered further for Phase III (DEFRA, 2008a). The Directive (European Commission, 2003c) sets a cap of 10% on the fraction of permits that can be auctioned in Phase II. The UK has auctioned 7% of permits in this period, but for sectors where competitiveness is not at risk the Scheme would benefit from higher levels of auctioning up to and including 100% (House of Commons Environmental Audit Committee, 2007, para.40). The Carbon Trust (2008c) found that, for a

central carbon price of €20/tCO₂ out to 2020, competitiveness was most sensitive in those carbon intensive sectors that are unable pass the carbon price on to their customers, in particular lime, cement, and to a lesser degree iron and steel. The aluminium sector would also be indirectly exposed to pass-through costs from the electricity sector if it entered the Scheme, due to the largely inelastic nature of electricity prices. There are clearly uncertainties surrounding the carbon price out into the future, and the exposure of individual sectors will depend on this price.

The overallocation of permits during Phase I was largely a result of liberal estimates of projected emissions by governments, which meant their NAPs were too generous, as was particularly severe in Germany (Gilbert et al., 2004). The frequency of information disclosure was also too infrequent (Lewis, 2006), resulting in the market's ignorance regarding the oversupply of permits until April 2006, during which time it was trading on a false premise. Ultimately this led to an excess of permits in the marketplace which caused the carbon price to plummet during the second quarter of 2006. These problems have led to consideration of a benchmarking approach to emissions allocation, which is potentially more accurate than grandfathering because it accounts for changes in output (Entec UK Ltd. & NERA Economic Consulting, 2005). Benchmarks were developed for all sectors in Phase II (*ibid.*); for two carbon-intensive sectors most sensitive to the international competition, iron and steel and cement, these benchmarks were further developed for Phase III (Entec UK Ltd., 2008). One main problem with the benchmarking approach is the heterogeneity between sectors, which means that a broad approach is generally not applicable (section 5.2.2), and benchmarks differ by sector (*ibid.*).

A related problem concerns the fraction of emissions reductions expected to be met by Kyoto credits, such as those obtained through CDM and JI²¹ projects in developing countries. During Phase II around two thirds of the emissions reduction (from BAU) is expected to be as a result of such transfers (House of Commons Environmental Audit Committee, 2007, p.30). This fraction of emissions reductions is therefore likely to be outside the EU and in the form of carbon dioxide equivalent. The Linking Directive also makes it "theoretically possible the EU ETS might not be responsible for any emissions reductions within the UK at all" (House of Commons Environmental Audit Committee, 2007, para.69).

Finally, there is the obvious problem of the EU ETS's restriction to EU Member States, and the associated risk of carbon leakage, which is the strategic relocation of a company's manufacturing capacity outside the trading region to avoid the carbon cost. There does not appear to be evidence that this has yet occurred, but the case study of the cement sector in chapter 5 suggests that it is a distinct possibility with a high enough carbon price. The sectors identified above as having competitiveness issues are also at risk of carbon leakage, and it

²¹ The European Commission's (2004a) Linking Directive amends the Emissions Trading Directive (European Commission, 2003c) to enable Member States to allow operators to use credits obtained through Kyoto mechanisms (certified emission reductions and emission reduction units) such as the Carbon Development Mechanism (CDM) and Joint Implementation (JI) to comply with their obligations under the EU ETS.

seems that a sectoral deal to ameliorate this is most likely in the cement sector (House of Lords European Union Committee, 2008, para 120). The conclusion seems to be that the EU ETS is not currently working in its intended roles, i.e. of creating a market for and ultimately reducing CO₂ emissions from industry, and that if it did there would be a risk of carbon leakage for some sectors. The latter problem could be overcome by a multilateral as opposed to unilateral trading scheme, or by some form of carbon tax on imported goods.

4.3.3.3 Domestic policy: the Climate Change Programme

The Climate Change Programme was updated in 2006 in order to maintain progress towards Kyoto targets (of 12.5% reductions in a basket of six GHGs by 2008-2012 on 1990 levels) and to facilitate convergence towards domestic targets of reducing CO₂ to 20% below 1990 levels by 2010. It includes the Climate Change Levy (CCL), a tax on energy use applied to industry, with a dispensation of 80% available to certain energy-intensive industries in the form of the Climate Change Agreements (CCAs), in return for undertaking energy saving measures towards predefined goals. Its introduction in 2001 was accompanied by a 0.3% cut in employers' national insurance contributions, intended to offset any apparent increase in taxation on the business sector as a whole.

It has been estimated that full carbon savings from the CCL in 2020 will be of the order of 3.7MtC; measures introduced in the Climate Change Programme are estimated to save around 4.9MtC in the business sector²² by 2010 (DEFRA, 2006c). The largest reduction in carbon dioxide emissions in the whole business sector was achieved in 2006 as a result of the CCL (DEFRA, 2006b). It has already achieved cumulative savings of over 16MtC and, compared with a situation where the package were not in place, is expected to result in annual savings of 3.7MtC by 2010, with an associated reduction in overall unit costs for businesses of 0.13% by 2010 (HM Treasury, 2006). Whilst the announcement effect of the CCL led attention to be focused on energy use in industry after 1999, the results from 2007 suggest that the Levy is no longer such a key driver of energy efficiency (National Audit Office, 2007).

The CCAs seem to have been very effective in incentivising energy efficiency, with estimated annual carbon savings by 2010 estimated at 1.9MtC (ibid.). There is evidence of an "awareness effect", which stimulated energy savings and explains some sectors' achievements above and beyond the (admittedly rather weak) targets (Barker et al., 2007). The overall (net) effect of the CCA/CCL package resulted in environmental benefits over a situation in which a flat rate tax was imposed with no rebate, and no CCAs (Ekins & Etheridge, 2006). Extrapolating these findings for voluntary and negotiated agreements in general suggests that such a policy measure is an effective means of incentivising energy efficiency in industry. Initially, a high enough tax is required to do this, followed by a suitable offer of a rebate on this tax for suitable measures, and culminating in negotiations with sectors to set targets. The latter may indeed be

²² Business here includes industry and commercial sector; no further disaggregation is available.

weak if, as it seems, the majority of the energy efficiency measures are undertaken due to increased awareness about them.

The Carbon Trust was created by the government in 2001 as a private company, in order to offer an integrated support programme for the uptake of low and zero carbon technologies. It is especially focussed on organisations within the public and commercial sectors, and offers support in various forms, including (The Carbon Trust, 2008a):

- **Energy audits**, which may be free for companies with energy bills in excess of £50,000 per annum;
- An **enhanced capital allowance (ECA)** scheme to provide an incentive for companies to invest in low carbon technologies;
- **Interest free loans**;
- **Expert advice** on a consultancy basis;
- **The Carbon Trust Standard (previously the Energy Efficiency Accreditation Scheme)** provides certification for businesses that commit to measuring, managing and reducing their carbon emissions;
- **Applied research**, with funding up to £250,000 available for relevant projects, and field trials of market-ready technologies and solutions.

Particularly relevant to the latter point is the recent advanced metering field trial, which identified average annual cost savings of £1,000 (and 8.5tCO₂) through advanced metering in SMEs, if the barrier of insufficient financial incentives for energy suppliers can be overcome (The Carbon Trust, 2007). At the time of writing two field trials are underway in the field of industrial energy efficiency, focussing on plastic bottle production and asphalt manufacturing, and due for completion around 2010 (Staunton, G., The Carbon Trust, pers. corr., June 2008).

The House of Commons Committee of Public Accounts (2008) assessed the performance of the Carbon Trust, finding that although it is due to meet its target of annual reductions of 4.4MtCO₂ by 2010, this is not a particularly challenging goal against the total reduction of 118MtCO₂ required by the Climate Change Programme (i.e. 20% reduction on 1990 emissions of 592MtCO₂). Overall, businesses and public sector organisations adopted less than 40% of the Trust's recommended savings in the financial year of 2006-2007, and the main barrier to adoption was identified as cost. This was particularly the case for smaller businesses (SMEs) with limited access to capital. Managers often failed to see the commercial benefits of adopting energy efficiency projects and there was a lack of time to take up and/or install the device or project.

Amongst the recommendations for the Carbon Trust are that it should collate more data on the typical energy use and costs in key sectors, in order to provide a more convincing case for the potential savings. This lack of data for specific industrial sectors is very pertinent to the present work, as there is a general paucity of data relating to manufacturing sectors, which is disaggregated and accurate enough to understand energy use and carbon emissions at the

sector level and below. The Carbon Trust is also urged to promote the Energy Efficiency Accreditation Scheme (rebranded as the Carbon Trust Standard) on the grounds that it stands to increase share values and company competitiveness in the long term. Furthermore, there seems to be a limitation on the scope of the Carbon Trust's activities because of the restrictions surrounding EU rules on State Aid. It would seem logical to target those sectors or individual businesses which are energy or carbon intensive, but the State Aid rules restrict the extent to which this is possible because it has the potential to distort competition. A related problem is that the Trust's fund managers stand to make considerable returns from investments in nascent low carbon technologies, something which needs to be reviewed regularly if experienced staff and investor confidence are to be retained. The State Aid problem meant that the Carbon Trust was not able to target the two-thirds of businesses with energy bills greater than £500,000 per year, which collectively produced around one third of all UK CO₂ emissions (House of Commons Committee of Public Accounts, 2008, p.8). There appears to be a public policy gap here: either the remit of the Carbon Trust should be modified to allow it to focus energy-intensive companies, or another organisation should be established to do this whilst not being subject to the same constraints surrounding State Aid.

The government's Cogeneration Directive sets a 10GW_e target for good quality combined heat and power (GQCHP) by 2010 (DEFRA, 2004). It is the national implementation of the European Directive on promotion of Cogeneration (European Commission, 2004b). This is highly relevant to industry because it is one of the main users of this technology: 93% of (electrical) CHP capacity is concentrated in the industrial sector (BERR, 2007, p.151). The uptake of CHP has been and remains slow, however, due mainly to economic barriers such as the spark spread and the large recent increases in gas prices, which is the fuel used for over 60% of industrial installations (Cambridge Econometrics, 2003). The installed electrical capacity of GQCHP was 5.4GW_e in 2005 (DEFRA, 2007a) and in 2007 the figure was 5.5GW_e (BERR, 2008a). It is therefore unlikely that the 10GW_e target will be met, as confirmed by revised estimates from Cambridge Econometrics (2003). The latter suggest that 8.1GW_e of GQCHP generation capacity will be installed by 2010, with a range of estimates from 7.7GW_e – 9.4GW_e.

4.3.3.4 Waste-related policy

The European Directive on Waste Electrical and Electronic Equipment (WEEE, European Commission, 2003b) came into effect in August 2005, and aims to reduce the amount of WEEE sent to landfill or for incineration by forcing manufacturers to arrange for the safe and clean disposal of their products at the end of their useful lives. The European Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS, European Commission, 2003a) has been effective since July 2006. It aims to reduce the amount of heavy metals, amongst other harmful substances, that is contained in the waste that does eventually end up being landfilled or incinerated. The scope of the WEEE and RoHS Directives is therefore limited to companies manufacturing electrical and electronic equipment.

The main impact of the RoHS for electronics manufacturers has been to affect a shift towards lead-free manufacture, involving the replacement of tin-lead alloys with lead-free alternatives (Goosey, Professor M., IeMRC Industrial Director, University of Loughborough, pers. corr., November 2008). These alternative alloys have higher melting points, which initially caused concerns that the legislation would actually increase the energy consumption of the process. Developments in the energy efficiency of process technology have meant that these concerns proved largely unfounded, however (op. cit.). Another key concern relates to the issue of “tin whiskers”, which spontaneously grow from the solder and can cause short circuits, as well as less ductile joints and higher strain due to higher differential temperature coefficients required. Finally, ensuring compliance along global supply chains seems to be very difficult, time consuming, and therefore costly.

The main problem with the WEEE has been the way in which the Directive (European Commission, 2003b) has been implemented differently in each of the Member States leading to an administrative burden (EurActiv, 2007). Secondly, in many countries WEEE is collected en masse from civic amenity sites or household collections (ibid.). As the waste is not sorted, the manufacturers contribute to a collective scheme with the fees determined by the company’s market share. Importantly, this dilutes the incentive for design for recycling because the benefit is shared with competitors.

Two domestic programmes relevant to industry are the Waste and Resources Action Plan (WRAP) and the National Industrial Symbiosis Programme (NISP). WRAP was created as part of the Waste Strategy in 2000. It is mainly funded by DEFRA, under the Waste Implementation Programme and Business Resource Efficiency and Waste programme (Brown, M., WRAP, pers. comm., Sept. 2008). It is a not-for-profit company which aims to help individuals, businesses and local authorities to reduce waste and increase recycling rates. Within the manufacturing sector, WRAP is working alongside local authorities and reprocessors to enable continued collection of plastic bottles (WRAP, 2008c). In addition, it is working with thirteen Material Recycling Facilities (MRFs) in a range of trials, including sorting high quality paper and glass on a full scale.

There are several WRAP project areas that are particularly relevant to the manufacturing sector, including activities in the container glass sector as discussed in chapter 7. In addition, WRAP (2008a, AEA Technology & WRAP, 2006) carried out an LCA of plasterboard (gypsum) and reviewed the rate of recycled paper usage in UK paper mills (WRAP, 2002). WRAP’s business plan for the period 2008-2011 involves focussing on eight key work streams within the manufacturing sector: container glass, recovered paper fibre, plastic bottles, mixed plastics, waste protocols, MRFs, electrical products and industrial products (WRAP, 2008d). The total budget for the Programme is of the order of £60million per annum for the period 2008-2009, of which around £5million is dedicated to the manufacturing sector directly (with indirect funding streams to the sector through related activities such as materials recycling and organics). WRAP is thus addressing many of the waste-related and environmental issues of diverse manufacturing sectors. In so doing it is providing a clearer understanding market trends and

barriers to change in these areas and thus enabling policy to be more effectively directed towards specific materials.

The National Industrial Symbiosis Programme (NISP) was established in 2005 in order to create commercial opportunities to exploit industrial resources, such as materials, energy, and water. NISP is also mainly funded through DEFRA's Business Resource Efficiency and Waste (BREW) Programme, and membership is free to companies, with the organisation being administrated on a local basis through twelve regional offices. Since its creation in 2005, NISP has helped to reduce carbon emissions by 4.4MtCO₂, mainly by diverting wastes streams into other industries (NISP, 2007). Related to NISP is the Landfill Tax, which requires manufacturers to pay for sending waste to landfill. It has been instrumental in encouraging manufacturing companies to reduce waste relating to their processes (O'Hare, J., Dept. of Mechanical Engineering, University of Bath, pers. corr., March 2009).

4.3.3.5 Minimum-efficiency standards

There are several policies requiring energy technologies to adhere to minimum efficiency standards that are relevant to industry. The Directive on Energy End-Use Efficiency (European Commission, 2006b) is the basis of the Action Plan for Energy Efficiency, which details the measures necessary to achieve a 20% improvement in energy efficiency by 2020 across Europe (European Commission, 2006a). The Action Plan (*ibid.*, pp.20-25) implements and amends the existing Energy End-Use and Energy Services Directive, by issuing a mandate for a European norm (EN) for energy audits, proposing more detailed metering and billing requirements and possibly establishing a centre to identify and improve emerging and existing technologies. It also proposes developing minimum efficiency requirements for new electricity, heating and cooling capacity lower than 20MW, and considering, if necessary, such requirements for larger units.

The Directive on Energy End-Use Efficiency also requires Member States to implement national Action Plans in order to meet their national target of a 20% improvement in energy efficiency by 2020. The UK's Action Plan only addresses those industrial sectors not covered by the EU ETS (DEFRA, 2007f); the EU ETS remains the government's main policy for targeting energy-intensive industries. Hence the scope of the UK's Action Plan is mostly irrelevant here, except for the introduction of the Carbon Reduction Commitment (CRC), a cap and trade emissions trading scheme covering commercial and public sectors (i.e. those outside the EU ETS). The CRC is estimated to deliver 1.2MtC savings by 2020 (*ibid.*, p.48). The non-energy intensive industrial sector is also involved in voluntary agreements within the SME sector, of which a quarter is accounted for by manufacturing businesses. The precise format and content of these agreements is still being determined at the time of writing.

Another relevant policy resulting from the European Action Plan is the Directive (European Commission, 2005a) on Eco-Design of Energy-using Products (EuPs), which applies to manufacturers of electronic and electrical products. In order to retain their CE marking, and the

right to sell their products within the EU, the manufacturers have to comply with specific EcoDesign criteria over the whole lifecycle, in particular relating to energy use. Whilst these criteria only apply during the use stage of the product's life, there are implications for the manufacturers because they must redesign the products with this in mind. The manufacturing sector is therefore affected in one of two possible ways. Firstly if products are used within the sector itself, such as boilers or motors, then these devices are covered by the Directive during their use phase. Secondly, the manufacturing sector is directly responsible for the energy consuming characteristics of products employed in other sectors, all of which are covered by the Directive. The Directive does not stipulate specific requirements for individual products, however, but establishes conditions for setting such requirements and enables them to be improved quickly and efficiently through Implementing Measures.

The main impact of the EuP for manufacturing sectors is on motor systems. These systems are mostly used to drive pumps, fans and compressors, which account for 32%, 22% and 8% of electricity use by motors in commercial and industrial applications (DEFRA, 2008b). Other applications include refrigeration, air conditioning and materials handling. The efficiency standards developed through Implementing Measures are voluntary, however, and relatively low in the EU compared to mandatory schemes elsewhere (IEA, 2007, p.223). In the UK the Market Transformation Programme (MTP) is responsible for developing evidence for the EuP Directive. The MTP (2007) found that such voluntary incentive measures have led to market penetrations of efficient motors between 10% and 20% in general across Europe, and 17% in the UK. The only way to increase the market penetration further is through mandatory minimum standards, as has been very successful in the USA. Hence why the United Nations Industrial Development Organisation (UNIDO) advocates an energy management (ISO) standard along the lines of ISO14001, which integrates energy efficiency into management systems (Williams, 2007).

Finally, in comparison to domestic hot water and central heating boilers, industrial boilers suffer from an absence of regulation in the UK (Future Energy Solutions, 2005). Their widespread use in industry to raise process water and steam means that they account for a large proportion of the energy consumption, estimated to be around 50% of the total (DTI, 2002b). However, this lack of regulation has contributed the continued use of old, inefficient boilers, which are often kept running for much longer than their design life because their limited maintenance cost are low compared with their replacement cost.

4.4 Drivers and barriers to energy efficiency

Having examined the means through which energy efficiency can be achieved, attention is now turned to the reasons why the above measures are not always effective in practice. The discrepancy between the cost-effective potential for energy saving and the actual level of uptake has been referred to as the energy efficiency gap (Jaffe & Stavins, 1994) and the energy efficiency paradox (DeCanio, 1993, 1998; Van Soest & Bulte, 2001). There is much evidence for the presence of this gap in general (ibid.) and in the United States in particular (Shipley & Elliot,

2006). The existence of this gap or lack of uptake is attributed to barriers that exist, and therefore prevent the realisation of this theoretical cost-effective potential. Whilst the presence of the energy efficiency gap is widely acknowledged, its quantification is not straightforward. In particular it depends on exactly which costs and benefits are associated with a project; if these are properly accounted for, Van Soest and Bullte (2001) suggest that the gap is smaller in practice than in theory, and that in some cases it may in fact be rational not to invest in an energy efficient technology which appears profitable from an NPV point of view. This is because of the inherent uncertainty associated with future technological progress and the (at least partly) irreversible nature of investment. Although firms forego a short-term energy (and cost) saving, in the long-term they stand to reap the cost benefits of even better (more efficient) technology. Furthermore, an unknown proportion of the gap seems to be affected by a perception bias: public opinion indicates that the fiscal and regulatory incentives in industry are not strong enough to support a more rapid uptake of energy efficient technologies and practices, but it is not been possible to prove this (Future Energy Solutions, 2005, p.80). In some cases even economists' own unwillingness to accept the evidence of shortcomings in the economic theories itself can become a barrier (DeCanio, 1998).

There are various definitions of energy efficiency or energy saving potential. Jaffe and Stavins (1994) make a distinction between the theoretical (hypothetical) maximum, the technical, and the economical potential (Figure 4-2). The former is what might be achieved according to theory, for example the theoretical SEC of a process, but that is never attainable in practice. The technical potential is that part of the theoretical potential that can be achieved with (current) technology, i.e. is practically feasible. The economic potential is that proportion of what is technically feasible that is currently economical at market prices. The market trend potential is what would be expected under a given set of energy policies, energy prices etc., and therefore reflects market imperfections and social obstacles (Jochem, 2000, p.183). The extent to which the latter two can be overcome will determine the size of the market trend potential. Finally, the welfare potential reflects the additional savings when externalities are taken into consideration. These potentials are graphically represented in Figure 4-2. The relative size of these potentials depends very much on the specific circumstances, in particular the existing government policy. The baseline in Figure 4-2 invariably already incorporates some policy measures towards energy efficiency, such that the potentials as shown are merely indicative, and do not indicate quantitative estimates.

4.4.1 Theoretical framework of barriers to energy efficiency

A broad theoretical framework therefore has to include economic, behavioural and organisational types, whereby many barriers exhibit aspects of several or all of these. For economic-related barriers it is useful to distinguish between market barriers and market failures (Jaffe & Stavins, 1994). The former refers to disincentives to the adoption of apparently cost effective technology, whereas the latter are a special case of market barriers in which the market has somehow failed to operate efficiently, and in which economists see a case for public policy intervention (Sorrell et al., 2000). The distinction between these two types of economic

barrier is not clear however, because in practice markets are neither perfect nor efficient. The neoclassical concept of a market failure is predicated on the assumption that markets *are* fully integrated and efficient. The fact that they are not leads some market failures to be classified as market barriers, which is supported by empirical evidence that markets for energy related technologies are not free from structural imperfections (Sanstad & Howarth, 1994). The implication is that hidden costs, for example, should be considered market failures because they always exist.

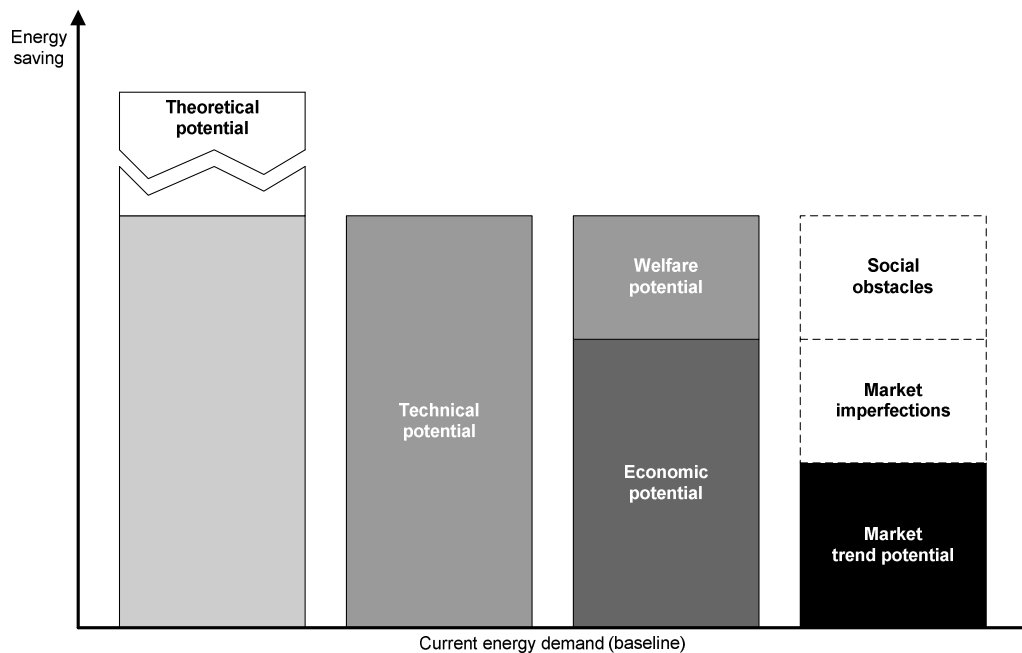


Figure 4-2 – Different definitions of energy efficiency potential
(adapted from Enquête Commission, 1991, cited in Jochem, 2000, p.183)

Economic market barriers include (Sorrell et al., 2004):

- *Heterogeneity* of the area of application, which is particularly salient in non-energy-intensive sectors of industry (such as food, textiles and machinery); one particular technology is therefore not always applicable across the board;
- *Hidden costs*, which are often overlooked in an appraisal of the project; these include the cost of downtime for installation and maintenance of equipment;
- *Access to capital*, which, if lacking, can be the limiting factor behind neglecting potential projects; the question of who should fund the project within an organisation often arises – the answer is sometimes elusive; and
- *Risk*, which is manifested in the strict investment criteria such as short payback periods demanded for projects.

Economic barriers classed as market failures are (Sorrell et al., 2004):

- *Imperfect information*, which might be in the form of a lack of information about technologies or techniques, or a presence of incomplete information, which could be outdated or inaccurate; this market failure includes:
 - *Adverse selection*, whereby purchasers select products or services (often purely) based on price, without fully appreciating either the true energy efficiency savings gained, or the relative merits of the technology compared to the alternatives;
 - *Moral hazard*, where agents are presented with an opportunity to cheat after signing a contract;
 - *Split incentives*, where the economic benefits from an energy efficiency investment are not realised by the investor;
- *Imperfect competition*, such as where monopolistic or oligopolistic firms are able to exploit their large market shares;
- *Incomplete markets*, such as when markets are not fully integrated, and the agents trading within them only represent a subset of the market population, which can contravene the condition of Pareto optimality defined in Appendix A2.1;
- *Principal-agent relationships*, which are common in large companies where there is a hierarchical structure, and are characterised by information asymmetry.

Whilst these economic barriers are important, they are all concerned with markets, but many obstacles to realising energy efficiency improvements lay outside markets. Eyre (1997) suggests that this framework fails to explain the origins and underlying structure of the barriers and how they might change in the long term – instead, it only confirms the inadequacy of the model as discussed in chapter 2. He argues for a more holistic consideration of the psychological, social and institutional aspects of energy use. The latter barriers are incorporated into the above framework, however, through recourse to the fields of organisational theory and psychology (Sorrell et al., 2004). Insights from these two fields have enabled a better understanding of the nature of bounded rationality, for example. Hence the neoclassical assumptions of utility maximisation by agents in possession of complete and perfect information, within complete markets, are all relaxed within this framework because of their imprecise depiction of real-world behaviour.

4.4.2 The rebound effect

The rebound effect is the mechanism through which improvements in energy efficiency lead to increases in energy consumption. It was first posited in relation to coal consumption by Jevons (1866), who argued that more economical use of this fuel would in fact result in an increase, rather than a reduction, in its consumption. The effect is therefore also known as Jevons' Paradox. A positive rebound is defined as an increase in energy demand due to increased energy efficiency, and is usually expressed as a percentage of the expected energy savings (Sorrell, 2009). The overall or economy-wide rebound consists of direct and indirect effects. The former was first identified by Khazzoom (1980), and relates to the increased uptake of an energy service as a result of improved energy efficiency. The ubiquitous example is of the

motorist who exploits the improved energy efficiency of his or her vehicle to drive further. Indirect rebound effects are more complex because they encompass all the ways in which apparent savings result in increased energy demand, often involving complex cross-sector linkages (Herring, 1999, 2006; Greening et al., 2000; 4CMR, 2006). For the industrial sector, an example of an indirect rebound effect is increased production resulting from improved efficiency.

In general, arguments in support of the rebound effect do not include quantitative estimates; what theoretical and empirical evidence there is contains a number of weaknesses and inconsistencies (Sorrell 2009). The emphasis of investigations for the rebound effect has – by and large – been in the domestic and transport sectors (Greening et al., 2000). The findings seem to indicate that the effect is largest in these sectors, but it is unclear whether it is actually much smaller in industry because of a lack of empirical data for this sector. What little evidence there is for industry suggests that the effect is small. However, there is little conformity amongst even these few studies, such that the scope and magnitude of the effect for industry is not yet fully understood. Furthermore, the measurements all come from short-term studies, which cannot account for changes in the firm's technologies, for example. Also, most studies have been at the level of the firm, such that industry size is inevitably neglected. In the short-run, the industrial rebound effect has been estimated as low to moderate, lying somewhere in the range 0-30% (ibid.; Bentzen, 2004). In the long-run, estimates are much less insightful, giving a wide range of estimates: the levels of direct take back depend on their ability to substitute fuel for other factor inputs. The available evidence does suggest, however, that in the majority of cases technical efficiency gains result in fuel savings, which are only slightly eroded by increases in demand. In the broader context, however, the importance of energy/exergy as a driver for economic growth (section 2.2) means that increases in energy or exergy efficiencies could be manifested as increases in growth rather than reductions in energy demand (Sorrell 2009).

4.5 *Summary and conclusions*

Energy efficiency in this context is defined as the energy use per unit (or mass) of product produced (the SEC). Interdisciplinary indicators have been widely used to analyse industrial performance from a macroeconomic perspective, but their accuracy is limited by inconsistencies in aggregation, problems in selecting the appropriate price index, and modifications to the SIC and/or product specialisation resulting in measurement errors. Such indicators are useful for identifying broad trends but the way in which the data are published means that such macroeconomic measures are by definition retrospective rather than actual.

There are three main approaches to increasing energy efficiency, including behaviour, technology, and policy. The potential for all three of these measures is limited in practice by market failures and market barriers, which can be addressed by public policy measures, as well as organisational and behavioural barriers, which cannot. Only if these barriers can be overcome will the full potential be realised or even approached. Behaviour is essentially

concerned with energy management, which appears to be varied in its application; not all firms undertake it, and the evidence of its application is somewhat anecdotal. It is certain that, to be effective, energy management has to be embedded in a company's culture, though, rather than simply being a tool which can be employed. Technology offers large potentials for improving energy efficiency, both in terms of systemic optimisation and specific technologies with niche applications. Within the former, combustion, motor, steam and heat recovery/transport systems are ubiquitously applied in industry and are therefore areas on which to focus attention.

There are various areas of public policy relating to energy use in the manufacturing sector. The Manufacturing Strategy places very little emphasis on energy and sustainability related issues; energy efficiency is addressed indirectly through attempts to improve productivity, but the long term sustainability of the sector is not well considered. The Innovation and Growth Teams (IGTs) are partly meant to address this, and the automotive team appears to have made some significant impacts on the sector, but the results of the other teams remain to be seen. There is a risk that these teams convene on a one-off basis to discuss the issues and the report becomes their main (and only) output.

The EU ETS is supposed to achieve carbon reductions in the energy-intensive industries but there are concerns, for several reasons, that it is not achieving any – or that the majority are occurring outside the EU. Auctioning more (or all) of the permits, expanding the Scheme to cover other sectors such as aluminium, and addressing the fraction of the emissions reduction in each period that can be met from Kyoto transfers should help this problem. In the broader context, though, the Scheme needs to be linked with other international trading schemes if carbon leakage is to be avoided, especially within sectors vulnerable to the carbon price such as cement and iron and steel.

The CCL and CCA package seems to be effective in delivering energy efficiency improvements. Two other key areas of the Climate Change Programme, the Carbon Trust and the 10GWe target for GQCHP by 2010, appear to have weaknesses. The Carbon Trust is not achieving many of the potential savings identified because of barriers to energy efficiency and its ability to focus on energy- and carbon-intensive firms is constrained by European State Aid laws. The CHP target will almost certainly not be met by 2010, due mainly to a lack of uptake of CHP because of poor economics (or a perception of this).

In the area of waste-related policy WRAP is very active in many manufacturing sectors, and is identifying the potential for improvements through, for example, recycling and lightweighting, as well as the reasons why this might not be technically or economically feasible. NISP is realising some of the potential savings in these areas. Minimum efficiency policies seem to be quite comprehensive in coverage, but there remains scope for a mandatory minimum efficiency standard for motors, and there seems to be a lack of efficiency-related legislation for industrial boilers and furnaces/ovens.

5 Macroeconomic analysis of the manufacturing sector²³

The purpose of this chapter is to present the UK manufacturing sector in context, by analysing the role that it plays in the economy as a whole as well as in providing goods to trade internationally. To begin with the sector is analysed in terms of output, growth rates, and energy and carbon trends. Attention is then drawn to productivity metrics, in particular energy, labour and multi-factor productivity (MFP). Subsequently the patterns of international trade in goods from the manufacturing sector are explored, followed by a case study of the European cement sector's energy efficiency and related activities in the context of the EU ETS. The empirical evidence for barriers and drivers to energy efficiency in industry is then discussed, within the theoretical framework presented in the previous chapter. Finally, a summary of energy demand projections for the industrial sector is given.

5.1 *Background to British manufacturing*

Britain was the first nation to undergo an industrial revolution based on steam, which occurred in the late 18th and early 19th Centuries and fundamentally affected the country's economic structure. This unprecedented development later spread around the world, in particular to Germany and the USA, which have arguably been two of Britain's largest industrial competitors ever since. The Industrial Revolution lasted from around 1780 to 1830, although there has been some dispute about the precise period over which it occurred. It was largely enabled by the strong population growth in the latter half of the 18th Century, which resulted in an increased mobility of the labour force, and higher output from the agricultural sector. These changes, coupled with efficiency improvements in agriculture, provided the labour force that would drive the Revolution. In addition, there were crucial external factors which brought about this fundamental change, including foreign trade and entrepreneurship (More, 1997). The latter was particularly relevant when one considers that the steam engine had been around for well over half a century. Only when James Watt invented the condenser in 1765, thereby improving the efficiency of the machine and the con-rod mechanism for transforming rotation into linear motion, was steam's widespread adoption as a prime mover economically facilitated (Lyle, 1947).

Changes within specific industries can broadly be classified as stepwise or revolutionary. These generally occurred within mass-market consumer goods industries and specialised producer (or intermediate) goods industries, respectively. Whereas many consumer goods sectors grew in size without drastically adapting their processes, several producer goods industries underwent significant technological innovation in order to grow. Indeed, such innovation was necessary to enable their development. This was particularly the case in the iron industry, which had previously used charcoal from sustainable coppices as its main fuel. When demand exceeded

²³ Some of the material in this chapter was presented at the International Conference of the Society for Sustainability and Environmental Engineering, November 2007, Perth, Australia. The case study of the cement sector in section 5.4 was published in Carbon Finance, a trade magazine. These publications are both attached in appendix A1.

supply for this fuel, and the price of charcoal therefore rose, an alternative was found in coal – in the form of coke. Such fundamental innovations were not generally widespread, however, and in the majority of industries there were steady improvements. The specialisation that was particularly prevalent in consumer goods led to the growth of an independent services sector, as ancillary operations associated with, but not absolutely necessary for, the manufacture of these goods became largely independent. Hence it was through specialisation, and the associated Smithian *division of labour*, that the services (tertiary) sector evolved as an adjunct to the manufacturing (secondary) sector, in a similar way to how the secondary sector itself evolved from the agricultural (primary) sector.

5.2 *British manufacturing in a national context*

The purpose of this section is to analyse some of the macroeconomic trends within the manufacturing sector by employing different metrics, and thus provide an understanding of the national context in which the sector operates.

5.2.1 Introduction

According to BERR's DUKES (2008a, p.14) the industrial sector accounted for around 19% of final user energy demand, or 1,309PJ of 6,891PJ in 2007²⁴. This does not include oil refining or production of coke, which are instead counted within the energy supply sector. If the energy use as coke and petroleum products within industry are included, this figure for 2005 increases to around 1,650PJ (DTI, 2007b, cf. Figure 5-4). The CO₂ emissions from the sector on an end-user basis accounted for 28% or 42.4MtC out of a total of 151.1MtC in 2005 (DEFRA, 2007b). These emissions figures are determined on an end-user basis, so that emissions resulting from the energy processing sectors (namely electricity generation and petroleum refining) are allocated downstream to the point at which the energy is used.

According to the Office for National Statistics (ONS, 2006c), the industrial sector accounted for about 13% of GDP in 2004, or 14% of total GVA (whereby the difference is due to the sum of taxes minus subsidies), as shown in Figure 5-1. This share fell below 20% for the first time in 1999 and has been declining since then (ONS, 2006c, p.23). The remainder of GDP is generated mainly by service-related activities, which account for over 65% of the total and represent the fastest growing part of the economy. In fact the largest difference in contributions to GVA over the period 1992 to 2004 was accounted for by a decline in the manufacturing sector and a growth in services. Together these two sectors accounted for almost half of total change in GVA between these two years, but their relative contributions went from being almost equal in 1992, to a situation in 2004 where the service sector's contribution was well over double that of manufacturing (ONS, 2006c, p.23). The decline of manufacturing GVA has been led by clothing-related industries and heavy industries such as iron and steel. This has been due to

²⁴ DUKES includes the construction sector in industry, so these totals are slightly different from those included in figures and discussed elsewhere in this thesis.

many factors, but mainly because of fierce competition from emerging markets that have opened up as a result of globalisation. Toll processing and trade liberalisation have also increased the degree to which the UK has to, and to a large extent is unable to, compete with cheaper imports (ONS, 2006c, p.24).

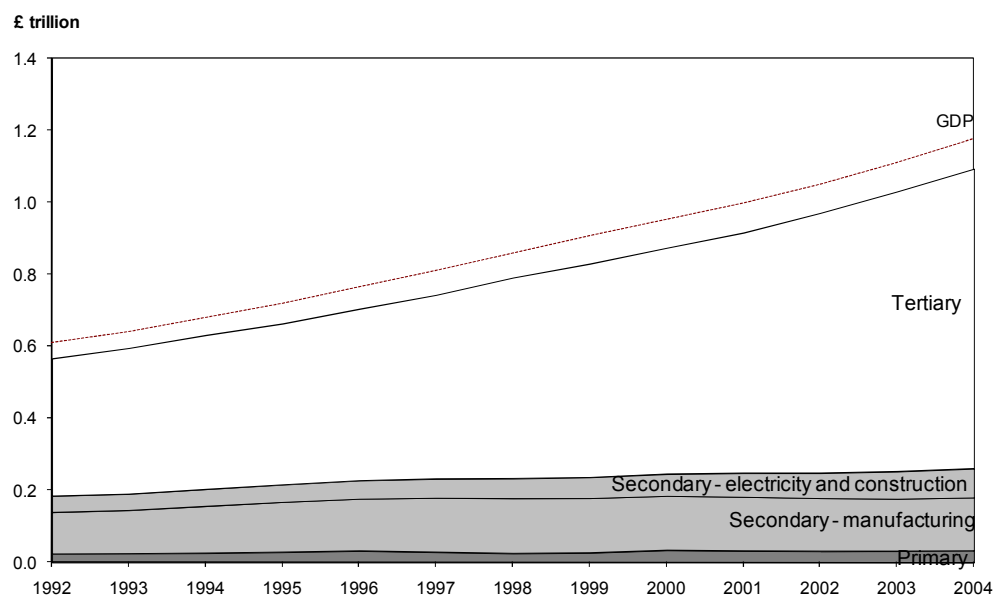


Figure 5-1 – GVA in for three economic sectors and national GDP 1992-2004

Source: ONS (2006a)

The shift towards service activities across the whole economy has been accompanied by a blurring of the distinction between secondary and tertiary activities within the manufacturing sector itself. Many manufacturers have positioned themselves as service providers rather than merely sellers of a product (DTI, 2000). Examples include aero-engine manufacturers such as Rolls-Royce, automotive companies, and so-called energy service companies (ESCOs), all of which provide the hardware and the associated maintenance necessary over the lifetime of the product. The proportion of Rolls-Royce's revenue from aftermarket (servicing) activities has increased from around 20% in 1981 to almost 60% in 2007 (The Economist, 2009a). Ford offers car servicing support, both in terms of financing/leasing and maintenance, which is an indication of the changing nature of innovation (Howells, 2000). This blurring of the boundary between services and manufacturing activities means the true role of these and other companies is misrepresented when they are classed as purely manufacturing in the national statistics (Figure 5-1). For companies like Rolls-Royce, in which service activities account for a large proportion of output, the relative reduction in manufacturing's contribution to GDP can be understood as being partly due to a delineation of the concept of what constitutes a manufacturing sector. The sector can no longer be considered as a workshop that simply makes products.

In a longer term context, the manufacturing sector is the only one in the UK that has experienced a significant fall of roughly 40% in final energy demand since the first oil price shock of 1973/74 (BERR, 2008b). This was in spite of an increase in the monetary value of

output of over 40% in real terms during this period (Engineering Council, 1998). The consequent aggregate reduction in energy intensity (TJ/£million of gross value added, GVA) masks different underlying causes:

- **Energy efficiency:** The majority of the change in industrial energy intensity is due to improvements in energy efficiency (DTI, 2002b, p.32). It has been estimated that around 80% of the fall in industrial energy consumption between 1965 and 1995 was due to this factor (Engineering Council, 1998, p.429).
- **Structural and output effects:** The relative size of the industrial sector has shrunk with a move away from heavy industries. These two effects have been relatively small within the UK (DTI, 2002b, pp.33-34, Howarth et al., 1991, Greening et al., 1997).
- **Fuel switching:** Coal use in UK industry has declined steadily since the early 1960s in favour of cleaner fuel (Hammond, 1998).

This point is worthy of further attention, hence the evolution of the fuel split for the industrial sector is shown in Figure 5-2. As well as the shift away from coal to gas (the so-called “dash for gas”) in the 1980s, there has been a steadily increasing market share of electricity use in industry over the past few decades. There was a sudden drop in industrial consumption of petroleum related products after the oil price hikes in the 1970s. In 2006 the fuel split is dominated by natural gas, electricity and petroleum products, which account for 37%, 22% and 32% of the total respectively (BERR, 2008b). The remainder is mainly accounted for by solid fuels, heat and renewable fuels.

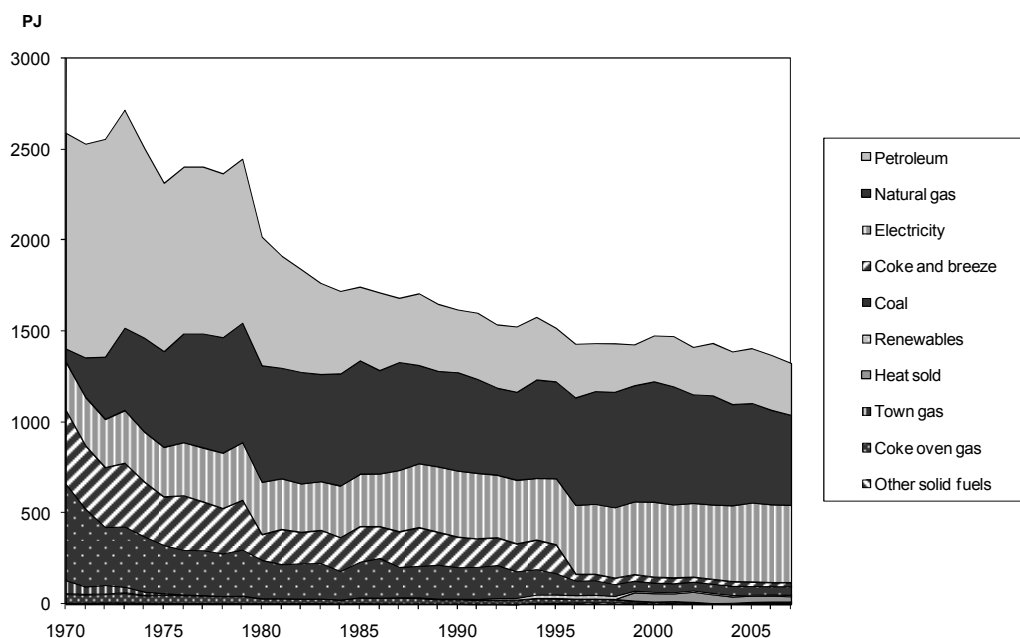


Figure 5-2 – Industrial final energy use by fuel 1970-2007

Source: BERR (2008b)²⁵

²⁵ The apparent sudden reduction in coke and breeze use from 1995 to 1996 is due to a change in methodology, whereby coke manufacture and use in blast furnaces ceased to be recorded in industrial statistics and began to be included

5.2.2 Characterising individual industries

The manufacturing sector consists of several different industries producing a large variety of products. In order to understand the causal effects driving the higher level trends, one has to examine what is occurring below the surface. This section examines individual industries from a top-down perspective by discussing their output, energy consumption, carbon emissions, resource productivity, and other related issues.

5.2.2.1 Output and growth rates

Output in GVA terms from industries at the two-digit SIC level is shown in Figure 5-3, which also includes the construction sector for reference. Although outside the scope of this research it is interesting to note the large contribution to GVA that the construction sector makes. The large growth in this sector is important because it has stimulated increased demand for the materials and products which it requires, namely steel, aluminium, cement, ceramics and glass. In general a small number of sectors account for the majority of the demand for these materials. For example, over 70% of aluminium demand in the UK is in the construction, packaging and transport sectors, whilst around 60% of steel demand is from the construction, transport and engineering sectors (Dahlström et al., 2007). According to British Glass (2004), around 90% of glass manufactured in the UK is destined for the food and drink sector as packaging (container glass) and the construction and automotive sectors as glazing (flat glass). Cement and bricks both have their primary demand in the Construction sector.

After construction, the sectors with the highest absolute value added are food and drink and pulp and paper, both with output in GVA exceeding £20billion in 2004 (in current basic prices). These are closely followed by electronics, basic metals, chemicals, transport equipment, and engineering. Together these seven sectors accounted for almost 80% of manufacturing GVA in 2004 (excluding construction).

Over the period shown (i.e. 1992-2004), the food and drink and pulp and paper sectors experienced the strongest growth in GVA, with an annual increase in output of around £0.4billion. The food and beverage sector is highly diverse, containing a large number of different activities, such that it is difficult to make general assertions about its growth, other than to say that it is a mature industry that caters mainly for a domestic market (apart from exceptions such as Scotch whisky). Its growth is therefore relatively steady and stable. The pulp and paper sector is also mature, with growth particularly strong in packaging, driven by increasing demand from the food and drink sector. It is exposed to significant international competition with imports accounting for over 60% of domestic consumption by tonnage (OEF & The Carbon Consortium, 2006). Growth is therefore mainly driven by domestic demand for

within energy transformation and supply. The actual coke use in the iron and steel sector was around 120PJ in 2007, compared to 157PJ in 1995 (BERR, 2008a, Table 2.4).

paper and board products, which peaked at 12.9Mt in 2000 and was around 12.3Mt in 2005 (CPI, 2007).

The chemicals sector has an above-average growth rate for the manufacturing sector, and is roughly in line with GDP growth of 2.8% p.a. (CIA, 2006). The majority of the sector's outputs are intermediate, so are employed within other sectors of the economy. The demand for chemicals is therefore largely dictated by domestic and overseas trends within these other sectors. In addition, the UK produces an extraordinarily large proportion (60%) of high value added speciality chemicals in comparison to other countries, such as the USA (44%) and Germany (40%) (Enviros Consulting, 2002).

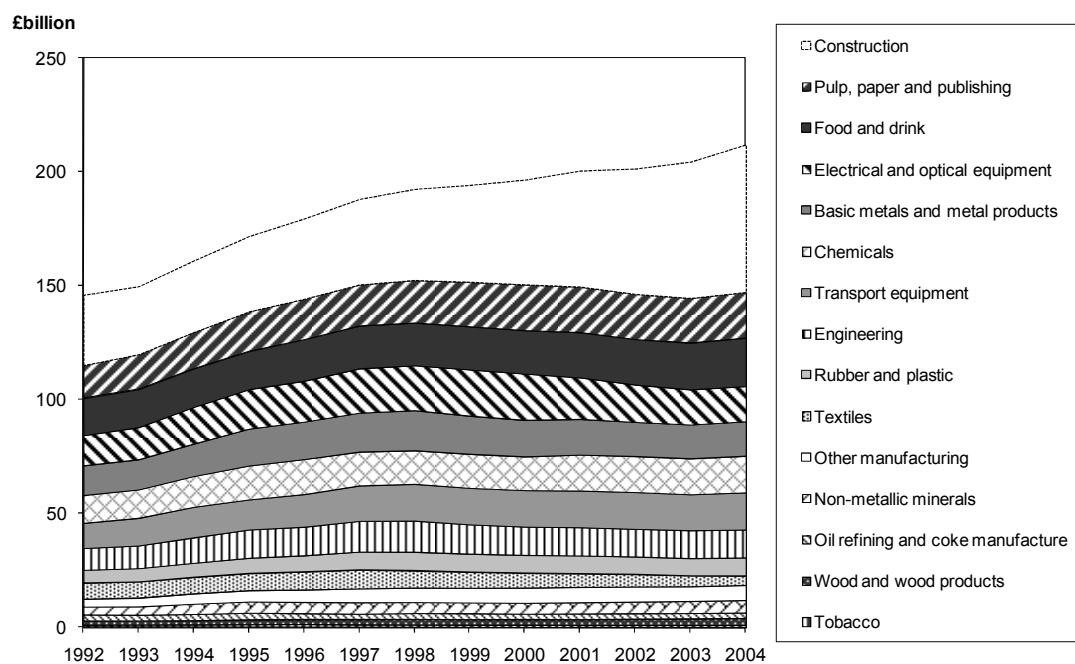


Figure 5-3 – GVA by industrial sector including construction for reference, 1992-2004

Source: ONS (2006a)

Growth in the chemicals sector has slowed in recent years. The dominance of the pharmaceuticals within this sector, which accounts for around 40% of output, is one of the main determinants of overall growth. This abatement in growth is expected to continue within pharmaceuticals for several reasons, including the increasing costs associated with bringing new drugs to market, the expiration of patents on branded drugs and the associated ubiquity of generic products, and the trend towards manufacturing overseas (OEF & The Carbon Consortium, 2006).

The relative decline of manufacturing GVA has been led by a similar trend in the textiles and iron and steel sectors. The former has undergone a steady decline for the past few decades, in the face of fierce competition from lower wage economies and the relocation of capacity into these emerging markets. UK production from this sector has fallen at an average annual rate of 4.75% since 1990 (op. cit.). The output from the iron and steel industry plunged in 1997 and

reached a low point in 2002, as the sector struggled to come to grips with the weak sterling and low prices, which led to the bankruptcy of ASW and Co-Steel (*ibid.*). However, the demand for steel is cyclical with a period of the order of five years (Dangerfield & Roberts, 2000), so it is unclear precisely how much of this reduction in total output, from 18.3Mt to 11.5Mt between 1997 and 2002 (EEF, 2007), was actually due to these factors alone. The UK imports different steel products to those which it exports, such that it cannot always remain competitive in export markets because the price of UK steel is typically higher than those in the rest of Europe (CRU Strategies, 2004). There is therefore a certain degree of vulnerability to foreign exchange rates, which the weakening of the pound against the euro in recent years has ameliorated.

There has also been a relatively strong downturn in the electronics sector, which is still recovering from the so-called “dotcom bust”, when UK output slumped as a result of a sudden drop in demand and much of the production capacity relocated overseas (OEF & The Carbon Consortium, 2006). The lowest output was recorded in 2002, since which time the sector has recovered somewhat, but it still remains at about 40% below the peak reached in 2000.

Overall, manufacturing GVA has risen from £0.12trillion in 1992 to £0.15 trillion in 2004, which correspond to a reduction from about 21% to 14% respectively of total GVA over this period (ONS, 2006a). Hence growth within the manufacturing sector remains steady, but is still consistently behind that of the economy as a whole. Neglecting the recent downturn since 2007, GDP growth has remained steady at around 3% per annum (ONS, 2007d, p.18), whereas growth in manufacturing GVA has been near zero over the period 1996 to 2004 (cf. Figure 5-1 and Figure 5-3). Over the longer term, from 1970 to 1999, manufacturing output as a proportion of GDP fell from 32% in 1970 to 19% in 1999 (DTI, 2002c, p.11). The relative reduction in output over the past decade or so can therefore be seen as part of a longer term trend.

5.2.2.2 Energy and carbon trends

The final user energy consumption by industrial subsectors is shown for the period 1990 to 2005 in Figure 5-4. It shows the consistent reduction in total energy demand for the sector as a whole over this period (clearer in the long term in Figure 5-2). Total industrial energy consumption decreased from around 1750PJ to 1650PJ over this period, a reduction of about 6%. The largest energy consuming sectors are basic metals (85% of which is iron and steel), chemicals, food and drink, pulp, paper and publishing, and non-metallic minerals, which together accounted for over half (57%, or 869PJ) of the total industrial energy consumption in 2005.

Much of the reduction in energy demand occurred within the iron and steel sector. This sector has reduced its energy consumption from 440PJ in 1990 to 260PJ in 2005, a change of some 41%. In addition to the reduction in domestic output mentioned above, there has also been an increase in the end-use energy efficiency and an improvement in the yield from the steelmaking process from 71% in 1975 to 91% in 1995 (UKACE, 2000). The reduction in output resulted from severe operational difficulties, major structural changes and falls in activity due to an adverse business climate (DEFRA, 2003).

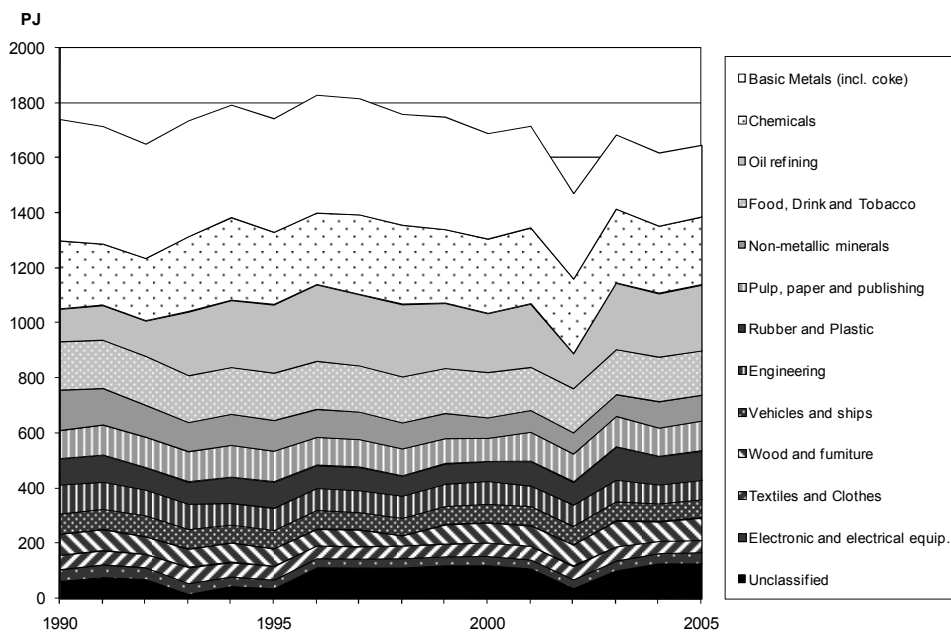


Figure 5-4 – Industrial energy consumption by sector 1990-2005

Source: DTI (2007b)

As well as the carbon dioxide liberated through the combustion of fossil fuels (so called combustion emissions), several industries release this gas directly through chemical reactions. Hence these emissions are termed process emissions, and are liberated through such processes as calcination or decarbonation, when a base compound such as calcium carbonate (CaCO_3) is thermally broken down such as occurs in lime and cement kilns, and glass furnaces. Other sources of process emissions include the decomposition of carbon anodes used in the electrolysis of bauxite solution to produce aluminium, and in the Haber process for manufacturing ammonia. The most significant industrial sources of these process emissions are summarised below (Choudrie et al., 2008):

- **Cement kilns** in the cement sector, from the decarbonation of calcium carbonate;
- **Lime kilns**, from the decarbonation of calcium carbonate and magnesium carbonate:
 - In the **merchant facilities** producing lime to sell privately;
 - In the **iron and steel sector**, where in-house lime kilns produce lime and dolomite for use as slag formers and as fluxing agents in the basic oxygen furnace;
 - In the **sugar sector**, but the carbon dioxide is reabsorbed as it forms chalk when bubbled through the melter liquor;
- **Glass furnaces**, in which calcium carbonate and soda ash (sodium carbonate) decompose to release CO_2 ;
- **Ceramics kilns**, whereby certain types of clay with high levels of carbonaceous material (e.g. Lower Oxford Clay) release large amounts of CO_2 ; there is a large variation (one order of magnitude) in the emissions factors for various raw materials (Enviros Consulting, 2006c);

- **Ammonia production** through the Haber process – CO₂ is a by-product which may be used to further produce methanol or acetic acid;
- **Integrated iron and steel works** – the main source of process-related CO₂ emissions is in the uncontrolled release of blast furnace gas and basic oxygen furnace gas (Choudrie et al., 2008, pp.116-118); controlled emissions are typically recycled and used as fuel;
- **Electric Arc Furnaces (EAF) for secondary steel manufacture** – CO₂ emissions result from the breakdown of the graphite electrodes in the furnace;
- **Aluminium production**, whereby the UK employs solely the pre-baked anode route (as opposed to the Soderberg process, with anode paste), and the anodes are burned off during the electrolysis;
- **Fermentation processes** in the food and drink industry, including bread production and alcoholic fermentation; there appears to be lack of information relating to this source and it is thought to be minor (Reason, S., Energy Manager, Food and Drink Federation, pers. corr., March 2009).

Hence analysis of emissions from industrial sectors should consider both combustion and process emissions. Whilst DEFRA (2006a) records emissions by IPCC source category for the purposes of national greenhouse gas reporting, it does not record the combustion emissions from individual sectors, except iron and steel. Hence Figure 5-5 shows the sectoral combustion emissions, which have been estimated based on the energy data in Figure 5-4 and the corresponding emissions factors for fuels fossil fuels and electricity (Choudrie et al., 2008). Figure 5-5 also shows the process emissions, and it is clear that these made up only a small proportion (10%) of total industrial emissions in 2005. The remainder of industrial emissions result from the use of energy from fossil fuels.

The rankings of individual sectors in terms of total carbon emissions is similar to that in terms of energy discussed above. The largest carbon emitter is the iron and steel sector, which accounted for 17% or around 7MtC. This is closely followed by the chemicals, food and drink, pulp and paper, and rubber and plastic sectors, which account for 15%, 9%, 8% and 7% respectively. These five sectors together account for almost 60% of total industrial emissions.

Having looked at individual sectors in terms of total energy consumption and carbon emissions, it is desirable to go into a little more detail in order to characterise these sectors more precisely. In order to do this, attention is now drawn to the different end uses of energy within these sectors. The first point of note is that there is a large variation between the end-uses of energy in individual sectors. Generally speaking, subsectors that carry out processes in the early stages of a product's manufacturing lifecycle, so called primary processing, are energy intensive operations, many of which occur at high temperatures. In contrast, operations that occur towards the end of a product's manufacturing life tend to be less energy intensive, because they are dominated by the assembly of prefabricated components rather than their manufacture per se. As materials and products progress through the manufacturing sector, therefore, the amount of energy and carbon that is embodied in them increases, but the rate at which this increases is high at first and then less so (Roberts, 1982).

Figure 5-6 shows industrial energy demand by end uses. All of these end uses are met with a proportion of electricity which varies from around a quarter to a third. If this fraction was converted into its primary equivalent, it would be approximately three times larger based on the current electricity generation and transmission efficiency of 35% overall (BERR, 2008a). There are end uses for which electricity is necessary, such as motors and lighting, but it is also being used for low and high temperature processes, which from a thermodynamic perspective is clearly inefficient; electricity is a versatile energy carrier which could be better used for providing motive power. There are industrial applications where electricity is desirable because of its versatile nature, such as EAFs and in high temperature furnaces, but in other cases its use is unfavourable. In order to address this thermodynamic inefficiency the overall efficiency of the generation and transmission grid could be improved by exploiting higher proportions of renewable energy resources, but this is constrained by the intermittency and disperse nature of these energy sources. Another option would be to focus on the efficiency of generation, thereby utilising some of the heat, equivalent to around 60% of the primary energy input (DTI, 2005), which is exhausted to the environment in conventional centralised generators. Sweden has one of the best track records in this area, with 50% of the heat market being accounted for by district heating schemes (Euroheat and Power, 2005a).

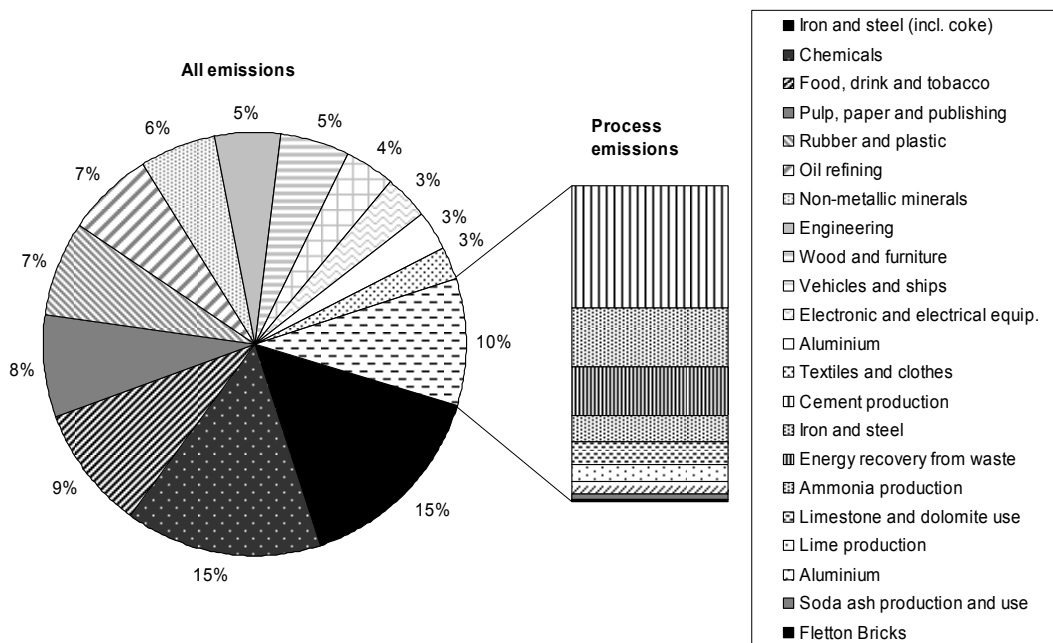


Figure 5-5 – Industrial combustion and process emissions in 2005 (total 39.3MtC)
Source: estimated from DTI (2007b) and DEFRA (2006a)

The majority of high temperature processes occur within a few industries, namely basic metals and non-metallic minerals. Furthermore, around 70-80% of these sectors' energy use is accounted for by high temperature processes. Strictly speaking this definition of high temperature is not satisfactory because above 300°C is not high temperature. The problem is that the data is not measured with enough resolution, so it is not possible to break the energy use by temperature down any more precisely. These industries have processes which occur at

around 1500°C, but are not distinguished from other sectors carrying out processes at only moderately high temperatures. This is a clear limitation of this dataset, and one which is discussed further elsewhere. Ideally, data would be available for industrial energy use in 100°C temperature bands up to around 2000°C.

The chemicals and food and drink sectors are the ones with the most diverse end uses. The former employs all the end uses shown in Figure 5-6, with low temperature processes, drying/separation and motors accounting for the majority of energy use. The food and drink sector employs around 60-70% low temperature processes, with small proportions of energy being used in other end uses. Similarly the pulp and paper sector employs energy almost exclusively for low temperature processes and drying/separation in roughly equal proportions. Finally, the rubber and plastics sector mainly uses low temperature processes in a similar proportion to the food and drink sector.

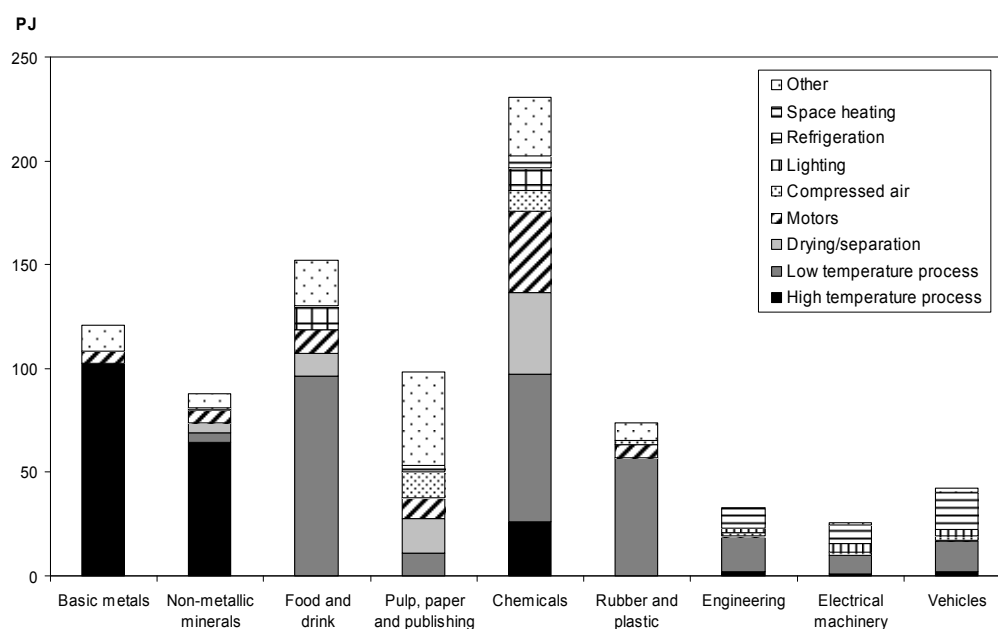


Figure 5-6 – Industrial energy consumption by end use 2006 (selected sectors)

Source: BERR (2008j), excluding SIC 23 and 37, renewables and heat sold

The electricity use in motor systems for different applications, including fans, compressors and pumps, is shown in Figure 5-7, based on the UK Motor Market Study conducted by BSRIA for MTP. The sectors using most energy in these systems are the energy-intensive ones, especially chemicals and metal products (engineering). According to this data, energy use in motor systems across sectors is due to a diverse range of uses, but it is possible to extract some broad trends. The chemicals sector uses around 70% of motor systems energy in process fans and pumps, and other applications such as materials handling and specialist machines (DEFRA, 2008b). Also in the iron and steel and engineering sectors, a large proportion of energy is used for other uses such as materials handling. The engineering sector also uses significant amounts of energy in motor systems associated with compressed air and fans. The food and drink sector

seems to use almost half of its motor systems energy in compressed air systems for refrigeration.

The general conclusions to be drawn about energy and carbon trends in industrial sectors are that, whilst relatively few sectors together account for the majority of energy consumption and carbon emissions, there is much diversity between these sectors in terms of end uses of energy. Energy intensive sectors tend to have larger overall energy demands than non energy intensive ones – this is not by definition the case, because it depends on the different structure and absolute size of the respective sectors. Furthermore, energy-intensive sectors typically use more high-temperature energy than non energy-intensive ones. The additional distinction can be made between those sectors carrying out primary processing operations (involving substantial material transformation) and those dominated by assembly activities. The latter tend to have end uses of energy that, as well as being smaller overall, consist of larger proportions of energy for space heating. This is due to the nature of this type of manufacturing, which involves assembling mainly prefabricated parts rather than making them (or the material) from scratch. A classification of industrial sectors according to the degree of process homogeneity is therefore a useful means of accounting for this diversity.

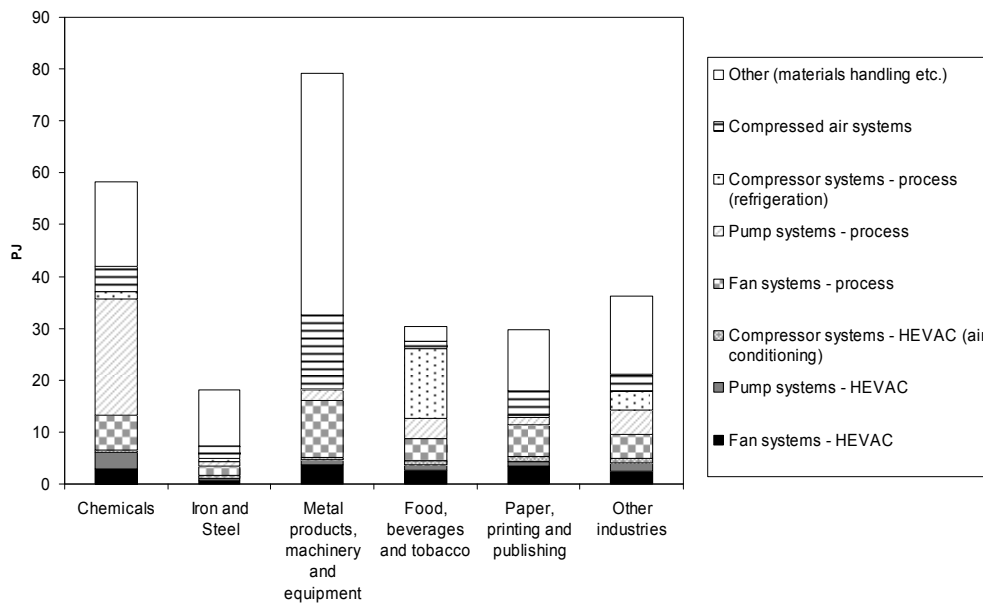


Figure 5-7 – Electricity use in industrial motor systems by sector and system type
 Source: Gainsford, C., MTP Helpline, pers. corr., September 2008

5.2.3 Productivity

The preceding section focussed on aggregated or absolute measures on individual sectors, namely energy consumption and carbon emissions, neither of which gives any indication of how well this energy is used in production. This section discusses various productivity metrics for the industrial sector. Three indicators will be discussed, namely energy productivity, labour productivity and multi-factor productivity (MFP). Capital productivity is another, similar,

metric but it will not be discussed at length here because there are substantial problems with determining the value of capital in various forms, and this measure is therefore not widely included in national statistics. In summary, these metrics are defined as follows:

- **Energy productivity**, which is the output in GVA per unit of energy input, or the inverse of energy intensity (i.e. energy inputs per unit of GVA output);
- **Labour productivity**, which is the output in GVA per unit of labour, whereby the latter is typically measured in hours worked, number of employees or number of filled jobs;
- **Multi-Factor Productivity (MFP)**, which is that productivity which is not accounted for by changes in the quality or quantity labour and/or capital inputs, and is generally thought to be closely related to technological change (ONS, 2007b).

This section discusses these three productivity measures and applies them to industrial sectors, beginning with energy productivity, then labour productivity, and finally multi-factor productivity (MFP).

5.2.3.1 Energy productivity

Measures of energy productivity for various economic sectors are not included in the national accounts produced by the Office for National Statistics, except where energy is considered as one factor in multi-factor productivity accounts such as the international EU-KLEMS programme (section 5.2.3.3). The following discussion is based on energy productivity metrics developed for industrial sectors based on their respective GVA output according to the Blue Book (ONS, 2007d) and energy consumption according to ECUK (DTI, 2007b). The energy data in ECUK has been summed across all primary fuel and electricity categories and aggregated to the two digit SIC level in order to achieve correspondence between the two datasets. The reason for not maintaining higher levels of disaggregation in the output and energy data is the inherent inaccuracies associated with ECUK. Energy productivity for manufacturing sectors alongside that for the economy overall is shown in Figure 5-8, which is plotted on semi-log axes because of the large variation in energy productivity across the manufacturing sector; over one order of magnitude separates the sectors at extremes of the energy productivity range.

The general trend across all sectors is of increasing energy productivity, which reflects improvements in the end-use efficiency with which energy is used, due largely to better technology and/or improved processes. However, this is not the sole reason for the observed changes; in many cases the underlying causes are very much sector specific, so it is not possible to make general assertions applicable to the whole of industry. Whereas some sectors exhibit consistent or smoothly transitional energy productivities, others appear somewhat “peaky”, which illustrates a limitation in both the scope and resolution of this dataset: the relatively short time period to which it relates does not facilitate the recognition of very long term trends, and the annual data points can overlook shorter term trends that occur between record years. The compilation of the ECUK dataset from the ONS Annual Business Inquiry involves scaling up a

representative survey of industries to the corresponding total (from DUKES), such that it is subject to a certain degree of noise.

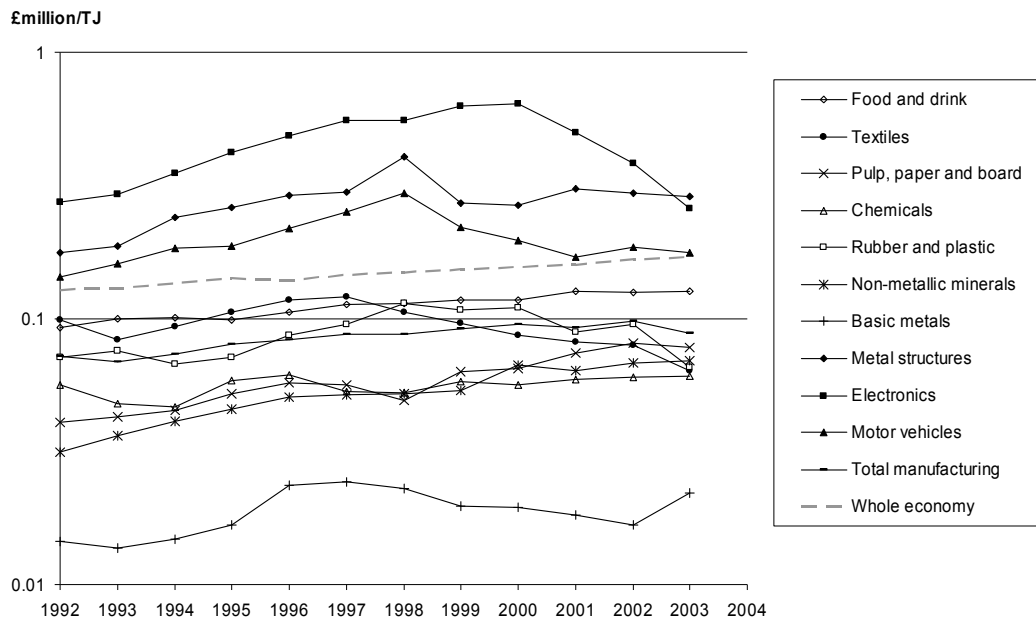


Figure 5-8 – Energy productivity for key industrial sectors 1992-2003

Source: Derived from DTI (2007b) and ONS (2006a)

The sectors with the lowest energy productivity are by definition the energy intensive sectors, especially basic metals, non-metallic minerals, pulp and paper, and chemicals. The apparently sudden change in energy productivity for the basic metals sector in 1996 reflects a change in the methodology for recording coke manufacture than an actual change. The way in which GVA data for the coke, nuclear fuel and oil refining industry (i.e. SIC 23) is aggregated means it is not possible to determine the energy productivity of coke production alone, even though it belongs almost exclusively to the basic metals sector. The energy productivity of SIC 23 alone is very low indeed, hence is not shown in Figure 5-8 because it would distort the ordinate scaling. This is probably largely due to the significant amounts of feedstock energy used within this sector. All of the outputs from the sector are fuels, so not all the energy input is actually used within the sector, rather it is embodied in the fuels. In this case it can be misleading to look at the energy productivity alone. The coke manufacture aspect of SIC 23 should be included in the basic metals sector, however.

The sectors with the highest energy productivity are generally those which carry out high value-added operations at the end of a product's manufacturing lifecycle, such as electronics, motor vehicles and metal structures. Two of the curves in Figure 5-8 rise to a peak in 1998 before tailing off again, namely motor vehicles and metal structures, but the reason(s) for this are not clear. The downturn in the electronics sector alluded to above is also evident in the reduction in energy productivity after 2000.

The chemicals sector has exhibited steadily increasing energy productivity from £56million/GJ in 1992 to £60million/GJ in 2003. This is despite a significant increase in the volume of output from £12.7billion to £16.1billion over this period. The sector is further characterised by high levels of R&D investment, which facilitates constant innovation in the form of new products and processes. Pharmaceuticals has both the highest absolute R&D investment of all industrial sectors and the highest largest increase in the past two decades, accounting for £3.3billion or 25% of the total in 2005 (ONS, 2008b). The chemicals sector as a whole (including pharmaceuticals) spent almost £4.0billion or 30% of the total in 2005 (ibid.). It is diverse in terms of the range of products manufactured and the nature of the processes employed, often employing highly complex, functionally adjacent and integrated plants, which exploit one another's resources in terms of (waste or exported) heat and materials. Hence it is the largest user of traded heat in the industrial sector, accounting for almost half of the total heat sold in 2007 (BERR, 2008a, p.27). The diversity of the sector is further indicated by the ubiquity of its products throughout society and the fact that a large proportion are intermediate products, serving to illustrate its continually important role within the economy.

The food and drink sector has also undergone significant improvements in energy productivity, from £92million/GJ in 1990 to £126million/GJ in 2003 and in spite of an increase in output from £16.3billion to £20.6billion. One reason for these effects is a significant rationalisation, which is exemplified by the brewing sector. The number of breweries has fallen from a peak of around 150 in 1980 to just 60 in 2004, which was accompanied by a disproportionate reduction in output from 65 to around 58 million hectolitres (Tighe & BBPA, 2005). Notwithstanding a change in product mix towards lager (which has a more energy intensive production process than ale, due to longer storage periods) and a shift towards smaller packaging units, this rationalisation has facilitated a corresponding reduction in specific energy consumption from over 250 to around 160 MJ/hl.

Another trend within the food and drink sector has been towards producing more highly processed food, such as ready-meals for preparation in the home, or snack foods for consumption "on the go". There has also been increased emphasis on freshness or quality as well as on health or nutritional value (Langley, 1984b). Particularly for food which is sold in supermarkets, there are stringent requirements placed on the physical characteristics of the product, which has been a driving force behind developments in processing techniques within this sector. The recent growth in health foods has evinced itself in the appearance of a niche market for special products with low salt, sugar or fat content, for example, which has grown with increasing public awareness (or perception) of the benefits and risks associated with nutrition. Also, one of the key drivers within the food and drink industry is currently legislation relating to the consumer and the environment (European Commission, 2006f). Within the meat sector this has contributed significantly to the shift towards poultry production, because of the difficulties and costs associated with conforming to porcine-related legislation.

Most industrial sectors have increased their energy productivity over the period 1992 to 2003, which in most cases is due to improvements in energy efficiency because output has actually increased over this time. The manufacturing sector has a lower energy productivity than the economy overall because of the typically energy intensive processes that occur in many sectors. The measures of energy productivity developed here are useful for comparing sectors with one another over time periods. It is also possible to broadly classify industrial sectors according to their energy productivity relative to other sectors and the whole economy. Sectors with lower energy productivity than the final energy ratio for the economy are generally energy-intensive; sectors producing high value-added goods, such as engineering and motor vehicles, are non energy-intensive.

5.2.3.2 Labour productivity

The manufacturing sector's declining share of output (in GVA terms) since the early 1990s has already been alluded to above. In fact this trend has been evident since the beginning of the previous decade, when the service sector's share of output overtook that of manufacturing for the first time (ONS, 2007b, p.88). Inspection of the labour productivity data for these two sectors reveals another picture entirely, however. Aside from a trough in the mid 1990s, the manufacturing sector's annual growth in productivity remained at around 4%, compared to less than 2% for the services sector and around 2% for the economy as a whole. In fact the general trend since WWII has been for the labour productivity of the whole economy to fluctuate around the 2% annual growth mark – that is, generally mirroring GDP growth (ONS, 2007b, p.87). The main reason for this large productivity growth within the manufacturing sector, though, is the rapid reduction in employment within the sector. The labour productivity improvements achieved within the manufacturing sector after 1980 are associated with labour shedding rather than output growth. Between 1978 and 2006 the proportion of the workforce employed in manufacturing fell from 29% to 11% (ONS, 2007a), corresponding to an actual reduction from 6.9 million to just under 3.0 million workers, whilst over roughly the same period the value of goods they produce increased by 35% (DTI, 2002c, p.11). There has been a similar trend across Europe, with multinational companies in pharmaceuticals, aerospace and electronics sectors shedding jobs (IPTS et al., 1998).

Growth in labour productivity in the past few decades has been strongest in the chemicals and engineering sectors, and to a lesser extent within the iron and steel and food and drink sectors. For the chemicals sector the growth in productivity was largely due to a rationalisation of the industry following the recession of the 1970s and a shift from basic towards speciality chemicals. The latter was evinced in the rapid growth within the pharmaceuticals sector, which retained over 10% of total world pharmaceutical exports for the latter half of the twentieth century (Broadberry, 2004, p.76). The food and drink sector has exhibited particular strength in a handful of industries, especially Scotch whisky and brewing. Whilst the former has been very successful due to a diverse range of products, the latter has ostensibly suffered from its failed attempt to adopt standardisation measures aimed at realising economies of scale (ibid., p.81).

This ultimately led to the establishment of the Campaign for Real Ale (CAMRA), a consumer group emphasising the merits traditionally brewed beers.

Productivity growth in the iron and steel sector was largely due organisation changes and a rationalisation of the industry, but technological improvements also played an enabling role. The major technological changes in the post-war period have been the shift away from open hearth and Bessemer production towards basic oxygen and electric arc furnaces for primary and secondary steel respectively. The proliferation of continuous casting from the 1970s onwards led to large energy efficiency improvements, as this method effectively replaced three process stages in the conventional means of production by turning a batch process into a continuous one (de Beer, 1998). It also drastically reduced the minimum economic scale of production and therefore enabled the growth of so-called mini-mills. The eventual privatisation of the industry in 1988, after several periods in both private and public hands already, allowed a turnaround in productivity performance as the gap with Germany was closed in the late 1980s.

In comparison to other industrialised countries, especially Germany and the USA, Britain has long been a laggard in terms of labour productivity. There is a particularly marked productivity gap between Britain and the USA, which is used by the government as a gauge of the long term prosperity of Britain and progress towards improving welfare (Kitson, 2004). The magnitude of the gap is very sensitive to the method of measurement used. In terms of output per worker, HM Treasury's favoured measure, the gap is around 45%, but in units of output per hour, the gap is 25% (EEF, 2001). Another important difference between the two countries is the structure of their manufacturing sectors. The USA's sector is much larger, having a significant domestic market demand for its goods, and the economy much more closed. The UK, by contrast, has an economy more open to international trade and therefore less resistant to fluctuations in international markets. The USA's performance in the ICT sector has been much better historically than the UK's, which has contributed in part to the gap.

Another reason for the gap is that the UK's manufacturing sector has suffered from a shortage in investment in recent decades. Two reasons for this are the volatility of the sterling exchange rate and the risk-averse nature of managers in the UK industry. Manufacturing investment growth in the UK over the past thirty years or so has been close to zero. Firms on both sides of the Atlantic highlight three main barriers to investment within the sector as the lack of demand for their products, uncertainty over future demand and the exchange rate between the dollar and sterling (ibid.).

The degree to which the USA and the UK have taken up lean manufacturing is another reason for the gap in productivity. There are barriers in the UK to an improved uptake of this approach, including attitudes to change within the firm, a lack of understanding of lean manufacturing, shortage of the right skills, and other cultural issues. There was a polarisation in the survey results between firms which had adopted lean manufacturing throughout the whole organisation and those which had not adopted it at all (EEF, 2001, p.29). The USA has

adopted this approach much more extensively, something that has its roots in the nation's manufacturing model. America adopted a model of mass production because of land abundance, which meant an abundant complementarity between human and physical capital. Hence the American model evolved, due to a lack of skilled workers, to be homogenous and capital-intensive (Broadberry, 1997). The European model, on the other hand, is virtually the opposite of this because it is labour intensive, and employs rather less physical capital. Whereas the UK has a focus on specialised production through skilled workers and tailored manufacturing lines, the USA is very much concerned with mass production methods. In fact Broadberry (1997, p.318) argues that one of the best examples of Britain's shortcoming here lies in its failure to mass produce British motor vehicles.

Around 21% of the manufacturing productivity gap with the USA is due to differences in the amounts of physical capital available for each worker, with the remainder being due to differences in skills levels and the efficiency of how different factor inputs are employed, i.e. TFP (O'Mahoney & de Boer, 2002, p.33). The differences in physical capital and skill levels of the workers are inherent aspects of the production systems in these two countries. Hence why differences in skills account for around much more of the gap with Germany, where vocational training is common (DTI, 2002c). The large proportion of the gap with the USA that is due to TFP reflects the different production methods employed in the UK and USA, and suggests that it might not be a fair basis for comparison. Perhaps productivity levels as seen in the USA are only achievable with mass-production, in which case it is invalid to compare the two systems, or at least that proportion of the gap which is due to the means of production.

In summary, manufacturing labour productivity has grown at a rate almost double that for the economy as a whole over the past two decades or so. This is mainly due to a reduction in employment in manufacturing, rather than an increase in output. There are several niche sectors that have fared particularly well in terms of productivity over this time, namely pharmaceuticals, Scotch whisky and aerospace. There is also a significant gap in labour productivity between the manufacturing sector in Britain and that in the USA, Germany and France. This gap is largely to do with the methods of production employed and the capital available, but also includes factors such as the skills levels of the workforce. The extent of the gap differs depending upon how it is measured, in particular whether it is normalised onto the hours worked as well as the number of workers. Britain attempted to adopt American style mass-production methods after WWII, but this was unsuccessful because it undermined the skills of craft workers and removed control of the production process from the shopfloor. Coupled with this was the problem of finding markets for large numbers of standardised goods, whilst Britain was also turning away from Commonwealth markets towards continental Europe. By the 1980s British manufacturing had all but abandoned American style mass production techniques in favour of customisation and skilled shop floor labour, which went some way towards closing the productivity gap with other countries.

5.2.3.3 Multi-factor productivity

Multi-factor productivity (MFP) or total-factor productivity (TFP) decomposes changes in productivity into contributions from labour, capital and a residual that is attributed to technological change. The latter is a moot point that has been much debated in the economics literature, and was discussed further in section 2.2. Nevertheless, there is a general consensus that, at least to some extent, technological change embodies advances made through R&D as well as the contribution of intermediate inputs such as materials, energy and services. Investment in other intangible assets is also included in this residual, since their contribution cannot be explicitly measured, along with a proportion of improvements in the factor inputs and an error associated with the decomposition process itself (ONS, 2007b, p.91).

The decomposition of productivity into these three components is based on the original analysis by Solow (1957), from which the residual takes its name. A standard production function is a generalisation of the Cobb-Douglas as given in Equation A1 (Appendix A2.1.2). This general equation can be used to derive Equation 5-1, in which α_K and α_L are the income shares of capital and labour respectively. The procedure for calculating the income share of labour is to sum the compensation of employees plus compensation associated with the self-employed, and the income share of capital is simply one minus the income share of labour – i.e. constant returns to scale are assumed. The MFP change is then calculated by integrating Equation 5-1 between two time periods.

$$\frac{\Delta Q(t)}{Q(t)} = \alpha_K \frac{\Delta K(t)}{K(t)} + \alpha_L \frac{\Delta L(t)}{L(t)} + Q_0(t) \quad 5-1$$

MFP data for the UK economy is administrated and published annually by ONS (2007b), but limitations on the quality-adjusted labour input (QALI) mean that the analysis can only be carried out for the whole economy and at the level of six broad sectors, one of which is manufacturing. Whilst these series are subject to some uncertainties in terms of the output measures used, particularly in the services sector, they are the most comprehensive ones produced nationally.

In the immediate post-war period labour and total factor productivity increased rapidly within the manufacturing sector. During the period 1951-1973 output, labour productivity and MFP grew at 4.4%, 4.3% and 2.9% per annum respectively (Broadberry, 2004, p.59). This trend slowed significantly in the 1970s, which reflected the overall slowdown in the economy as a whole, largely due to the oil price hikes of 1973 and 1979. After the 1970s, output and productivity growth by both labour and MFP measures accelerated again in the manufacturing sector, but this time because of reductions in employment rather than increasing output.

Over the period 1997 to 2005 the strongest (unadjusted labour) MFP growth was in the manufacturing sector, which grew at 2.3% per annum compared to 0.8% for the economy as a

whole (Table 5-1). When the adjustment is made for labour quality, the same trend is seen to a lesser degree, as manufacturing productivity grew by 1.8% per annum compared to 0.7% across the whole economy. As well as confirming the assertion made above about labour shedding being the root of labour productivity increases, Table 5-1 also shows that the output growth in spite of this was only possible because of MFP growth. In other words, output growth was only possible because the efficiency of production (i.e. how factor inputs are employed) improved significantly and thus offset the reductions in labour input.

The data in Table 5-1 is limited in both scope and resolution for individual sectors. The EU KLEMS (2007) data provides more insightful data on MFP, covering the period 1980-2005, and broken down by two digit SIC sectors. Hence Figure 5-9 shows the contributions to GVA growth for manufacturing sectors over the period from 1980 to 2005. The Figure clearly shows the reductions in labour contributions to output in all manufacturing sectors, which is particularly prevalent in the textiles sector. This sector is the only one in which the reduction in labour hours worked over this period is not compensated for by changes in the other factors of production, resulting in a drop in output.

Sector	Output growth	Capital input	Labour input	MFP growth	Labour input (adjusted)	MFP growth (adjusted L)
Manuf.	0.3	0.3	-2.4	2.3	-1.8	1.8
Whole Economy	2.9	1.1	1.0	0.8	1.1	0.7

Table 5-1 – Decomposition of output growth, average % growth p.a. 1997-2005

Source: ONS (2007b, p.93)

Figure 5-9 also clearly shows the large contribution that MFP has made towards overall output growth in the manufacturing sector compared to the market economy. This is particularly noteworthy in the energy intensive sectors, including chemicals, basic metals, non-metallic minerals and electrical machinery, whereby improvements in energy efficiency have enabled the large reduction in overall energy intensity discussed in section 5.2.1. Overall the electrical equipment sector has had the largest overall growth over this period (Figure 5-9). This is mainly due to the rapid developments in ICT in recent times, which has resulted in growing demand for electrical and electronic hardware.

The periods of heavy labour shedding have generally coincided with the recessions of the early 1980s and 1990s (OEF, 2001). For the manufacturing sector annual reductions in labour hours worked reached over 6% annually, but were generally less than 4% for the market economy. In the period after 2000 annual reductions in labour from manufacturing were quite steady at 3%, whereas the market economy has had only very small reductions in labour. If the quality (composition) of the labour is taken into account its contribution to the market economy has actually increased.

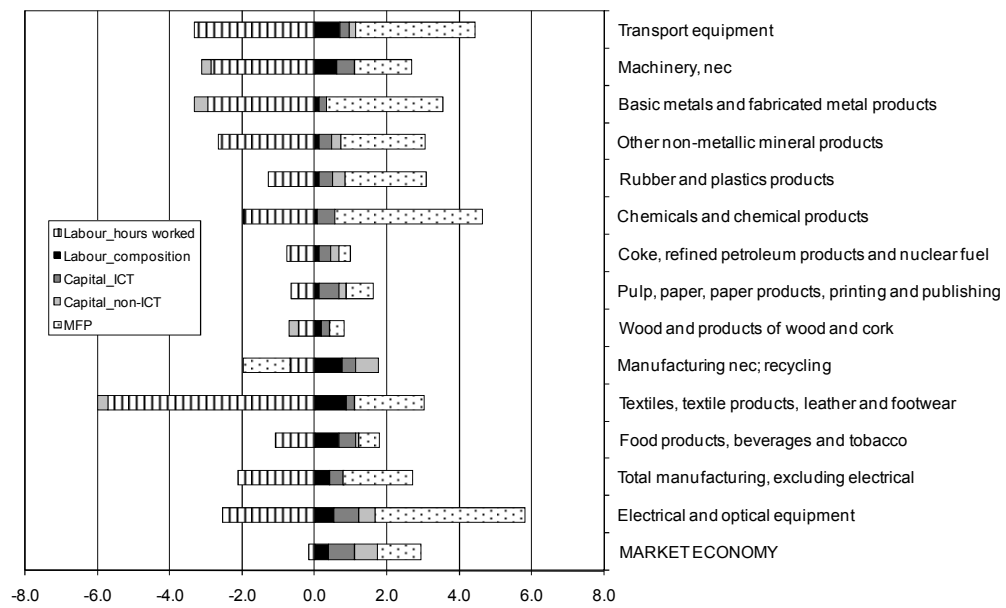


Figure 5-9 – MFP, labour and capital contributions to average annual GVA change (%), 1980 to 2005
Source: EU KLEMS (2007)

MFP is useful in this context because it allows underlying contributors to growth for these sectors to be determined. More subtle trends can be overlooked by looking at such long periods as in Figure 5-9, but it is beyond the scope here to look at time series for each and every industry. As it is, this snapshot data presents a broad picture of the trends that have occurred in the past few decades. Notwithstanding its shortcomings, MFP is a useful indicator of the contribution that different factors make to overall sector and economy growth. From this macroeconomic perspective the fact that the precise nature of the MFP is unexplained does not affect the conclusions that can be drawn from the above analysis, namely that across the manufacturing sector – and in some sectors more than others – MFP that has enabled continued output growth despite declining levels of employment. It does, however, limit what useful conclusions can be drawn about the specific nature of MFP change in the manufacturing sector. It is ostensibly impossible to distinguish between improvements made with existing technology, and those that have resulted from innovation, for example, which would be desirable in order to understand the role that new technology has actually played in the process. Having looked specifically at industrial sectors in a UK context, attention is now drawn to the international context, with a particular emphasis on trade flows.

5.3 British manufacturing in an international context

Globalisation has played a crucial role in the development of the UK's manufacturing sector, in general over the past two centuries and in particular during the past few decades. The result is that most if not all industries now operate in global markets, with a large number being dominated by foreign ownership, and significant trade flows both within and outside the European Union. In addition, many manufacturing firms have relocated in emerging markets abroad in order to take advantage of cheaper labour and capital inputs. Focussing solely on the

manufacturing sector's contribution to GVA output overlooks its importance in terms of international trade. In fact manufacturing accounts for around two thirds of UK exports by value (DTI, 2000, p.5). This subsection therefore places the UK's manufacturing sector in an international context by analysing its key trade flows and contribution to the overall balance of trade.

With the long term trend away from heavy manufacturing there has been an associated move away from the UK being a net exporter to becoming a net importer of goods. The trade balance in goods has been consistently negative since 1992, when it was about £13billion, increasing to £60billion in 2004 (ONS, 2006c, pp.50-53). In services alone there has been a trade surplus over this period, which has increased from £6billion to £26billion. Hence the trade deficit in goods and services overall increased during this period from £7billion to £35billion. This overall trade deficit reduced up to 1997, when growth in net trade of services exceed that for goods, after which time the overall surplus increased rapidly, due mostly to the underlying growth in the trade deficit for goods.

There are several reasons underlying this growing trade deficit, including weak global demand for UK exports over this period and a weakening of sterling (in particular against the dollar and the euro). The low demand for UK exports has been exacerbated by several shocks around the global economy, including the Asian crisis of 1997 and the recession on the USA in 2001. Weak demand for UK manufacturing exports is illustrated by the fact that the large trade deficit in goods and services in 2004 was mostly due to the trade deficit in the manufacturing sector. In this year the net trade in goods and services from manufacturing was £67billion (i.e. imports) versus £42billion (i.e. exports) from the services sector (ONS, 2006c, p.78). Hence the difference of £25billion accounts for the majority of the trade deficit in goods and services, of £35billion, in that same year.

Over the period 1994 to 2004 there has been a consistently higher level of trade in goods and services with the EU than with countries outside of the EU. This is also the case for trade in goods alone, whereby from 1998 to 2007 around 60% of exported goods from the manufacturing sector have consistently been destined for countries within Europe. The main destinations for exported goods are the USA and EU countries (esp. Germany and France), and the main sources of imports are EU countries, the USA and China (ONS, 2007c, p.133). During this timeframe the total exports from manufacturing have increased from around £150billion to £200billion. Imports have shown a very similar trend, with around 60% being sourced from within the EU, and their total value increasing from about £170billion to £270billion over this period. However, this obscures underlying shifts in trade balances between individual sectors, which can only be revealed through closer inspection.

A useful method of analysing international trade, rather than looking at absolute values of trade flows, is to employ import penetrations and export shares (ONS, 2006c). The import penetration is defined as the fraction of total demand which is met by imports. Similarly, the export share are defined as the percentage of total supply that is provided by exports. These

measures give an indication of the significance of international trade in relation to a sector's total output, as well as the demand for output from this sector. They enable a normalised comparison of multiple sectors because distortions due to the absolute size of sectors are removed. At the extreme, an export share of 100% means that all supply is exported. Conversely, an import penetration of 100% means that all demand is met by imports.

The export share of the manufacturing sector as a whole has changed little since 1990, during which time it has remained at around 45% (ONS, 2007c). The import penetration of manufacturing as a whole has increased, however, from below 50% in 1992 to more than 60% in 2004. The proportion of these imports from EU and non-EU countries is almost exactly the same as for the exports. The growing import penetration of the sector as a whole reflects a general trend of declining output in specific industries in face of fierce competition from abroad, where many have relocated in order to take advantage of a cheap and abundant labour force.

The largest increases in import penetrations over the period 1992 to 2004 have been in the tobacco, clothing, textiles, leather, basic metals, automotive, office machinery and radio and TV equipment sectors. Overall the sectors with the highest import penetrations in 2004 were leather, clothing, office machinery and radio and TV equipment, which were all at over 80%. Sectors with very low import penetrations include printing and publishing (around 10%), and non-metallic minerals and fabricated metal products (both in the region 25-30%). One of the reasons for this is that it is uneconomical to transport these relatively low value materials over large distances. In terms of export shares, basic metals has increased from about 50% in 1992 to almost 75% in 2004, whilst chemicals has steadily increased from 65% in 1992 to a peak of 75% in 2003, before dropping off to about 73% in 2004, the last year for which data is available. These two sectors had the highest export shares in 2004. Electrical machinery has also undergone a steady increase in exports, from 45% in 1992 to 55% in 2004. The export shares of several sectors appear to have been fairly constant over this time period. For example, the food and drink and pulp and paper sectors have an export share of around 25%, and the automotive sector is steady at 50%. Other sectors have experienced downturns in their export shares over this period, including, most notably, office machinery, tobacco and fabricated metal products. There has been much change in the tobacco sector as consumption has decreased, largely due to sharply increasing prices in the UK and increasing awareness about the health implications leading to a reduction in demand. As for many other sectors, manufacturing capacity has relocated overseas to lower wage economies, in some cases nearer to the market for their products. The textiles, clothing and leather sectors have also shifted a lot of capacity abroad into cheaper labour markets. This trend is one that is common in developed economies, and it has been exacerbated by the Multi-Fibre Agreement (MFA), which had previously limited imports from developing economies (OEF & The Carbon Consortium, 2006, p.34).

In absolute terms, the imports for the automotive sector are the largest in the whole manufacturing sector, having risen from £23.5billion in 1998 to £39.3billion in 2007. The vast majority (over 80%) of these imports come from countries within the EU. Automotive exports

are the second largest absolute exports across manufacturing, and they rose from £16.4billion in 1998 to £24.2billion in 2007. Similarly, over two thirds of exports are consistently destined for markets within the EU. The consequence of these changes has been a large increase in the sector's trade deficit: in 2004 apparent consumption was more than double domestic production. The sector has benefitted from inward investment from Japan, Europe and the US (e.g. Honda and BMW in Swindon, Nissan in Sunderland). However, this has partly been offset by several plant closures, such as Ford in Dagenham, Vauxhall in Luton and Rover in Birmingham (OEF & The Carbon Consortium, 2006, p.32). The rising import penetration can be attributed to the weakness of sterling against the euro, and increasingly fierce competition from emerging economies in east Europe and Asia.

In basic metals the UK tends to export higher value bar products and fabricated products, whilst importing lower value flat ones (CRU Strategies, 2004). With import penetrations and export shares at over 70%, the sector is clearly heavily dependent on international trade. The surge in exports from this sector in recent years is probably due to a return to full production after job cuts and down time for maintenance in past years. The sector's international competitiveness has improved in recent years due to restructuring. Hence imports to the sector have almost doubled from £7.9billion to £15.3billion from 1998 to 2007, whilst the proportions from inside and outside the EU have remained at about half the total. Over the same period, exports from the sector have more than doubled from about £6.4 billion to £15.0billion. About sixty percent of these exports consistently went to destinations inside the EU.

The chemicals sector has the second largest absolute imports after the automotive sector, and the largest absolute exports. Similar to basic metals, the chemicals sector tends to export mainly higher value speciality chemicals (sold on the basis of performance) and consumer products (sold on the basis of brand), whilst importing basic commodity chemicals. It is also one of the few manufacturing sectors to consistently have a trade surplus. The sector's import penetration has increased from below 50% to over 60% between 1992 and 2004 whilst the export share has also increased from 65% to about 75%. Around 70% of imports are sourced from within the EU and about 60% of exports are destined for markets within the EU. It is difficult to draw detailed conclusions about the sector as a whole because of its sheer size and diversity, but it is clear that pharmaceuticals is one of the most important sectors. Many pharmaceuticals companies have relocated manufacturing capacity overseas, which will contribute to the growing import penetration and potentially also reduce the sector's export share as less output is available for export. Another complicating factor in analysing trade flows within the chemicals sector is that a large proportion of the demand for its products comes from other sectors of the economy (i.e. intermediate products). Hence the use of its products is often obscured by further transformation processes, such as fertiliser in the agricultural sector or bleaching chemicals for the pulp and paper sector, rather than in end uses.

In summary, the UK has a large trade deficit in goods, which is mainly due to the relative decline of the manufacturing sector and domestic demand for manufactured goods therefore being met from abroad. Consistently higher levels of trade are undertaken with countries

inside rather than outside the EU: approximately 60% of imports and exports come from or are destined for countries within the EU. The distribution of UK exports has changed little over the past decade or so, but UK manufacturers are increasingly identifying emerging economies as growth opportunities for the future (BDO Stoy Hayward, 2007). The key growth areas in China are metals, chemicals and electronics – also fields in which the UK possesses significant expertise.

Since the early 1990s the export share of manufacturing as a whole has remained steady at about 45%, whilst the import penetration has risen from 50% to 60%. The highest levels of trade occur within the automotive, electronics, chemicals (especially pharmaceuticals) and basic metals sectors, which are all high value added sectors. Lower levels of international trade occur within lower value added sectors such as non-metallic minerals because it is not economical to transport these products and they are usually manufactured close to demand (IPTS et al., 1998). Several industrial sectors export higher value added goods and import more standard/basic ones, which demonstrates the UK expertise in a few key sectors.

5.4 Case study: energy efficiency in the European cement sector²⁶

Having examined the international context in which industry operates, this section presents a case study of the European cement industry, based on in-depth interviews carried out in early 2007 with senior representatives from five of the world's largest cement manufacturers, namely Lafarge, Holcim, Heidelberg, Cemex, Italcementi, and Cembureau, the trade association for the European cement sector. Lafarge is the largest cement company by turnover, with Holcim and Cemex in close competition for second and third position. Heidelberg and Italcementi are both significantly smaller companies, which is shown along with details of the individuals interviewed in Table 5-2. The positions of the interviewees are all very senior within the companies (most sit on the executive board) and were established between 1999 and 2007. The companies' annual reports and environmental reports were also used as a primary data source.

The overall objective of the study was to gain an insight into the European cement sector's strategy to improve energy efficiency and reduce carbon emissions in the context of the EU ETS. The methodology involved grouping responses from the interview transcripts under broad headings, working iteratively towards a summary matrix summarising the positions of the firms and their respective activities. Whilst the interviews were inevitably subjective to a certain degree, the views expressed therein by the respondents were taken to be closely aligned with those of the firm. The exception was when the speaker explicitly indicated that he is speaking in a personal rather than professional capacity. Direct quotations have therefore only been made when the view of the firm is being expressed.

Like most sectors, during Phase I of the EU ETS the cement sector had an overallocation of emissions permits. There was an uneven distribution across Europe, however, with a generous

²⁶ This case study was published in Carbon Finance magazine, November 2007, as shown in Appendix A1.4.

permit allocation in Eastern Europe but a very stringent one in the West. The majority of the firms manage their emissions allocations centrally, which means taking an overall balance across Europe. Allocations can also be transferred in space (between plants and countries) and time (between trading periods). The company representatives seem to think the method of allocation is flawed because it is based on previous performance, so heavily polluting plants are rewarded and efficient ones are penalised. Nevertheless, Cembureau concedes that Phase I was “business as usual” for the sector, with no evidence of plant closures due to the Scheme – although some have reduced output.

Firm	Total turnover (€m)	European turnover (€m)	Total cement output (Mt)	Name	Position
Lafarge	17000	6967	123	Vincent Mages	VP, Climate Change Initiatives
Cemex	12986	5845	98	Bruno Vanderborght	VP, Climate Change Protection
Holcim	11876	5489	113	Rob van der Meer	Director, EU Public Affairs
Heidelberg	7803	4230	75	Luis Trevino	Director, Energy and CO ₂
Italcementi	5000	3612	56	Xavier Blutel	Group VP, Environmental Affairs
Cembureau	-	-	-	Claude Lorea	Technical Director

Table 5-2 – Production (2005) and interviewee data for European cement sector case study

Source: Published company sustainability and annual reports

In terms of environmental strategy outside the EU ETS, all firms have set voluntary specific emissions targets for 2010. Figure 5-10 shows the targets and progress towards them for an average across the five firms. Lafarge was the first to set a target, in 2001, and is the only firm to have targets relating to both net and gross emissions (whereby the difference is accounted for by alternative fuels considered to be carbon neutral). On average the firms do not appear likely to meet all of their targets. In real terms the best performers have been Lafarge and Holcim, though, who have both reduced their specific emissions from 0.75tCO₂/t cement in 1990 to around 0.65tCO₂/t in 2005. Italcementi is the only company to have increased its CO₂ emissions intensity over the past ten years, and Cemex also looks unlikely to meet its target of 0.60tCO₂/t by 2015.

Energy efficiency is very expensive to improve in the cement sector. New plants are always the most efficient and improvements to existing plants are limited to within a few percent of the design efficiency. Hence the two main means of reducing the environmental impact of cement are through alternative materials and alternative fuels. The former involves reducing the amount of clinker in the finished cement, known as clinker factor reduction or material substitution. There are two main alternatives to clinker in cement, blast furnace slag and pulverised fuel ash (PFA) or fly ash. Alternative fuels include organic waste, animal feed and biomass, and result in emissions savings because these fuels are considered carbon neutral over

their lifecycle. Material substitution is by far the most efficient means to reduce cement emissions. Around 60% of emissions in cement manufacture are process emissions, with the remainder being combustion related. Material substitution affects both of these sources, but fuel substitution only affects the fuel-related emissions; it has no effect on the process-related emissions.

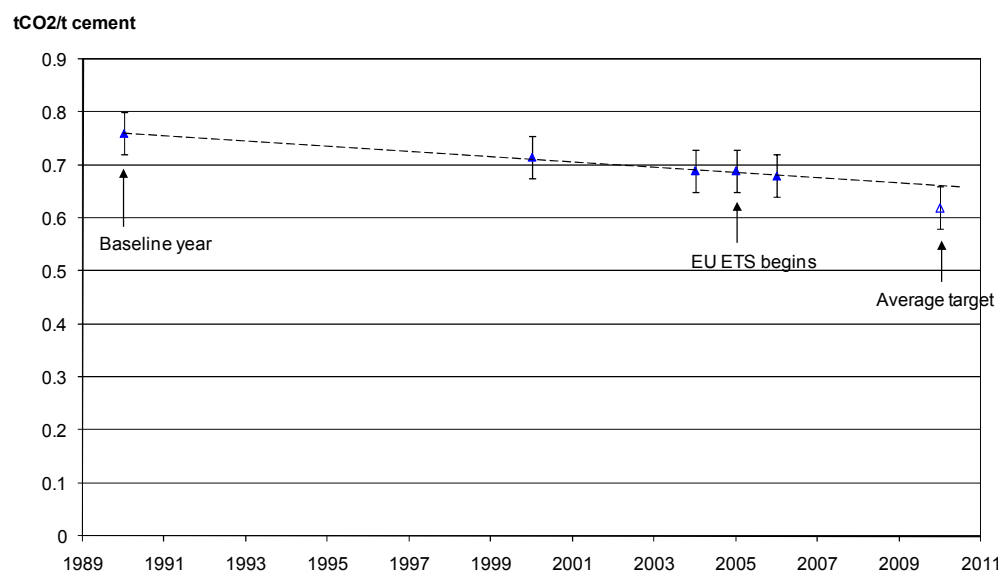


Figure 5-10 – Reported specific net emissions based on the mean value over five companies

Source: Published company sustainability and annual reports²⁷

Companies vary in the degree to which they are pursuing these two routes. The market leader for material substitution is Holcim, with around 16% alternative materials being used in its cement in 2006, whilst most other companies are using approximately 10%. Heidelberg is the market leader in use of alternative fuels with around 16% of its total fuel input in 2006 reportedly coming from sources such as biomass, tyres and plastics. These methods of reducing emissions are limited though, as material substitution cannot exceed about 75% for slag and 25% for fly ash. Although this figures seem far from their present values, companies reported market constraints on obtaining these materials. Quality is the limiting factor for fly ash: it is often contaminated and requires further processing before it can be used in cement. Italcementi also report that many of its customers are willing to pay more for a higher clinker content, which acts as a limit to its material substitution rate. Slag, on the other hand, appears to be limited in supply: only those companies with long term contracts have a guaranteed supply. Interviewees were reticent on this matter, but Lafarge has certainly secured long term contracts with steel manufacturers and Holcim owns and operates slag granulation plants at a couple of steel companies, such as Arcelor in France and Salzgitter in Germany.

In the long term the industry's ability to use these alternative fuels and materials will depend on their availability. The interviewees estimated an average carbon price during Phase II of €25/tCO₂, perhaps even reaching €35/tCO₂. The mid-point of these two values, €30/tCO₂,

²⁷ Average in 2004 based on four companies.

corresponds to a price increase in the finished cement of about 30%. Lafarge suggests that customers will not accept such price increases because of the elastic nature of demand for cement. This has led to speculation that the sector will relocate production capacity outside Europe, but many of the firms say this is not their intention. Most cement is currently sold within a 250km radius of where it is manufactured because it is not economical to transport it over land, but at a carbon price of about €30/tCO₂ this becomes economically feasible. If cement was imported from developing countries such as China and India, the overall emissions would increase because of those resulting from transport. The EU ETS might therefore make an import tax or quota necessary for imported cement, which would not necessarily reduce overall emissions, but would address the competitiveness issue.

A less radical scenario might be that European plants do not close, but no additional capacity is built either. Another obvious solution is to change the way the EU ETS operates for the European cement industry. Cemebureau, along with most of the firms, favours a worldwide benchmarking approach instead of grandfathering. Benchmarking rewards efficient operation, and is therefore seen as more equitable means of distributing permits. Any new scheme should also be global in scope, by either including the OECD and major developing countries or protecting countries in the lead on CO₂ reduction from competitive distortions. In the long term it is not technically possible to significantly reduce emissions from cement manufacture with current technologies. For drastic emissions reductions, new technologies such as Carbon Capture and Storage (CCS) and power-intensive cements will be required.

5.5 Empirical evidence of drivers for and barriers to efficiency in industry

The theoretical framework in which barriers can be understood was presented in section 4.4.1. This section discusses empirical evidence for the existence of these these barriers, and drivers, from the literature and primary sources encountered whilst carrying out this research.

The two main drivers behind the adoption of energy efficiency measures in industry are costs and legislation (Levine et al., 1995; Future Energy Solutions, 2005; Williams, 2007). It is desirable to reduce energy costs but legally imperative to conform to legislation. Energy costs are heavily sector-specific and may account for up to around 50% of the overall operating costs in refineries (European Commission, 2006d). Over the last few decades, however, the fraction of energy costs as a share of production costs has reduced significantly (DTI, 1994; Worrell, 2004). Clearly energy costs are much higher for energy-intensive sectors, and have been emphasised by recent large increases in natural gas prices, which is the main fuel of the industrial sector (BERR, 2008i). Legislation, some of which was discussed in section 4.3.3, can affect many aspects of a firm's activities. Conforming to legislation incurs costs, either directly, for purchasing tradable emissions permits and/or technology, and indirectly through the associated administrative burden. The latter is particularly significant for SMEs, which do not always have the necessary resources available (HM Treasury et al., 2005). Additional drivers

do exist, including competitiveness within the marketplace, associated intangible benefits (such as corporate social responsibility, CSR) and fiscal support from third parties such as the Carbon Trust but these are usually secondary in industry (The Carbon Trust, 2005b).

In their study of energy conservation potential for the UK, Ray and Morel (1982) identified the three most important barriers to undertaking energy conservation measures as low profitability, lack of investment and management attitudes. The first two points are clearly economic in nature and are closely related, because if projects are considered to have low profitability then there will not be a high level of investment in them. The criteria for profitability were defined as a payback period of 2-3 years, equivalent to a rate of return of 25% or more, which is approximately the same as the investment criteria employed in industry today (Eichhammer, 2004). Compared to the general cost of capital and return on investment in the economy as a whole, this profitability is very stringent. It can therefore be argued that the investment criteria themselves are a barrier, as they preclude cost-effective energy efficiency measures. In other words, the energy efficiency gap (section 4.4) between what is theoretically economical and what is actually taken up (market trend potential, cf. Figure 4-2) is larger than widely recognised. Nevertheless, industry *does* employ such investment criteria, and whilst the possibility of a notionally wider efficiency gap is acknowledged, it lies beyond the scope of this thesis to quantify it.

The importance of management attitudes should not be understated. As discussed in section 4.3.1, energy management systems depend to a large degree on managerial and organisational factors. A company's management structure and overall strategy clearly have an impact on its evaluation of and perspective on energy efficiency projects. If energy efficiency is a central aspect of its strategy then it becomes embodied in important company decisions, just as competitiveness and profitability are. In fact Cooremans (2007) hypothesises that the lack of strategic focus on energy efficiency is precisely the reason for its lack of uptake, which is confirmed by preliminary empirical results. She also emphasises the cultural aspects of energy use, such as its centralised provision, invisibility in both supply and use, and commoditisation, which result in its importance being somewhat overlooked. The cyclical and groping nature of decision-making can be understood as just one stage in a complex individual, organisational and contextual process – a concept which cannot be reconciled with the linear, rational one of utility-maximising neoclassical agents (*ibid.*, cf. Appendix A2.1.1). Furthermore, organisational-behaviour analyses of energy conservation emphasise the importance of power and incentive distribution in decision making, and highlight the need to focus on institutional issues (Cebon, 1992).

It seems that the majority of barriers are, in fact, of this non-technical nature (ISR - UC, 2008), relating rather to the human capital that is responsible for industrial energy systems rather than the practical realisation of savings through behaviour, technology or policy. It is probably for this reason that the evidence for barriers to energy efficiency is highly diverse with only a few common threads. Fawkes and Jacques (1987) found that the lack of uptake of energy-efficient technologies has no single or common feature in the dairy and beverage industries. This

finding was confirmed for the non energy-intensive sector in Sweden by Rohdin and Thollander (2006), who concluded that cost and risk associated with disruptions to production, hassle and inconvenience were some of the main barriers. Some of the initial correspondence with trade associations and companies carried out for this research also supported this emphasis on the human elements (Bainbridge, A., MEUC, pers. corr., April 2006).

Ray and Morel (1982) also identified evidence for the split incentive problem in their study. Energy managers often do not have the authority to commission projects relating to energy conservation, so need to obtain approval from management beforehand. In other words, the decision makers within the firm are not those people who understand the potential benefits of the project, although they are the ones likely to benefit directly if and when it proves to be a profitable investment. Overcoming this problem relies largely on the energy managers' ability to persuade management that the project is worthwhile. In many cases the projects will be competing for finance from other areas of the firm, such as marketing and production, which might be given precedence.

A form of the split incentive problem was also encountered during this research. Stakeholders with a vested interest in understanding energy demand (e.g. trade associations) did not have the necessary information to do so, and those with the information (e.g. companies) did not always have the resources required to do so – which is particularly the case in SMEs (HM Treasury et al., 2005). Even within a company itself, the relevant information on energy use is often not available. Furthermore, it is crucial to contact the correct person within an organisation, but on making initial enquiries this is not always possible. It is no coincidence that those cases in which the enquiry could be directed at a specific person were the most fruitful ones in terms of developing industry-academia relationships.

Worrell et al. (2003) suggest that the assessment of energy projects should be based on the evaluation of all the resulting energy and non-energy (or productivity) benefits. Some common non-energy benefits include cost reductions due to reduced material use, less waste and lower water consumption, and lower emissions of air pollutants. Although it might be quite straightforward to identify these impacts, their quantification can prove problematic, especially in the case of new technologies, with which there is typically little experience. The authors themselves admit this difficulty, especially when the benefit is not directly linked to productivity, in which case assumptions are needed to translate the benefit into a comparable cost figure. Further, the values of quantified productivity benefits often come from a published case study or a limited number of observations, such that the accuracy of the figure is questionable. The crucial point, though, is that there are real non-energy benefits to be gained from energy efficiency and Pye & McKane (2000) suggest that these are often greater than the energy benefits.

As part of their study of emerging energy efficient technologies carried out for the Energy Efficiency Innovation Review (EEIR), FES examined the drivers and barriers specific to industrial energy efficiency. As their findings are based on one of the most recent and

comprehensive studies of energy efficiency in industry, relating specifically to the UK, they deserve to be quoted at length (Future Energy Solutions, 2005, pp.53-57). The barriers have been identified as (ibid.):

- **Focus on production:** many companies are highly focused on production and do not give any priority and, as a result, time, to energy efficiency activities;
- **Availability of capital:** most companies have limited capital for new projects and look for short payback periods;
- **Low risk approach:** naturally, companies want to minimise risk, and this applies when it comes to the reliability of process plant and the quality of product. New equipment/design carries with it an unknown quantity in terms of reliability, and hence is viewed as a risk. The potential rewards have to be very high to make the perceived risk worthwhile;
- **Lack of staff/de-skilling of work force:** there is a trend towards reducing the numbers of professional staff employed within UK companies. Those that are left have increasing workloads and tend to be less qualified. This has the result that staff have little time to support/develop new projects and may not have the technical know-how;
- **Off-shoring:** importing of skills and hardware results in UK-based staff lacking skills and knowledge of their process plant/machinery, making it harder to fix or maintain products let alone upgrade them to improve efficiency;
- **Fragmentation of the UK science base:** many universities are reducing their facilities and resources necessary for R&D activities. This reduces the pool of 'experts' in the field, and makes carrying out R&D projects more difficult. The lack of test/pilot facilities exacerbates the difficulty of testing and evaluation;
- **Windows of opportunity:** Many ideas require radical changes to sites and with plant 'update time' being as low as four days per year in order to maximise production, there is little opportunity to work on improvements. This is particularly the case in the process industries where downtime is expensive (ISR - UC, 2008). It also seems to be a particular problem in SMEs (HM Treasury et al., 2005).

Clearly the empirical evidence suggests a large diversity of barriers, many of which can be understood within the theoretical framework of Sorrell et al. (2004). The complex and multifaceted nature of many of the barriers means that they are often not straightforward to address, because they affect multiple layers of management and areas of business activities. Whilst exploring the reasons for all barriers working in the same, negative direction (i.e. towards lower efficiency), Eyre (1998) highlights this complexity and suggests four common themes to many barriers. One of the themes is centralisation, which means that decisions about

energy use are made centrally, with a systematic bias towards to the supply side. Instead, he argues, regulation should address the demand side as much as the supply side because there are strong economic arguments for doing so (ibid.). Centralisation is manifested within industry as split-incentive and principle-agent barriers defined in section 4.4.1, whereby the management structure of a firm itself acts as a barrier. Another theme is commoditisation, which relates to the way in which energy is traded as a commodity despite the diversity amongst energy systems. This commoditisation hinders the development of efficient markets in energy efficiency because it treats public goods such as social inclusion and energy security as secondary issues (op. cit.), but it seems to be less applicable to industry specifically. The third theme is the complexity of the purchasing process for energy services, whereby energy institutions have developed to promote network growth and security of supply rather than efficiency. The fourth theme is the dichotomy between producer and consumer, whereby expenditure at the point of consumption is not perceived as a productive investment. These cross-cutting insights into the nature of many barriers certainly bolster the argument that regulation should equally be focussed on the demand side, but some are less relevant to industry specifically.

Sandberg (2004) and Eyre (1997) suggests that the complexity of energy systems can itself be seen as a barrier – what Eyre (1997) calls the “meta-barrier”. Whilst firms recognise the need for “a more comprehensive view of energy efficiency in investment decisions”, they do not devote the necessary resources to such activities, often because they are not considered to be core business activities. Sandberg (2004) identifies this lack of resources as being the primary driver behind the development of energy cooperation between companies, such as for district heating schemes and ESCOs. It is also the stimulus behind what he argues is a requirement for decision-making support in industrial companies. Energy efficiency is not seen as an end in itself, but a means through which to achieve economic and environmental benefits. Certainly, as identified in section 4.4.1, these are the main reasons for firms undertaking energy efficiency activities.

Whilst many studies have found evidence for barriers, some have concluded that, in fact, most energy-efficiency projects are actually implemented if they are cost effective. The DTI Energy Paper 50 contains extensive empirical evidence for drivers and barriers, resulting from industrial surveys of around 274 companies in the early 1980s (Armitage Norton Consultants, 1982). The general conclusion of this study was that, in most cases, the cost-effective potential energy savings had been realised. However, lack of information about suitable energy-efficient technologies was also highlighted as a prevalent barrier. In many cases, the trade associations contacted as part of this research did not have the relevant energy data relating to their members, or they were not willing to disclose it for reasons of commercial confidentiality.

FES (2005, p.80) also suggest that potential is in fact being taken up, contrary to public perception, and that the real issue is whether the *rate* of uptake can be increased. This is supported by evidence that several sectors have indeed made significant energy efficiency improvements in recent decades. In particular, the brewing industry is one of the most efficient

in the world and has reduced its SEC in delivered energy terms by around 50% since the 1970s (Tighe, A., BBPA, pers. corr., April 2006).

Perhaps the most significant market barriers are those of hidden costs and access to capital, which have been often cited in the literature as reasons given (e.g. in energy audits) for not undertaking energy efficiency measures. Of the market failures, imperfect information appears to be by far the strongest barrier, as well as one which might benefit from a public policy intervention. These two barriers – i.e. those of hidden costs and access to capital – were similarly recognised in the British Government’s Energy Review in 2006 (DTI, 2006b). The information often relates to specific technologies too (Armitage Norton Consultants, 1982). Jaffe and Stavins (1994) and Sorrell (2004) also highlight some market failures associated with the public good of information, in particular its non-rival non-excludable properties, which means that it cannot be supplied by a private market and contributes to its imperfection.

Finally, a more general barrier is the limited perspective taken when assessing different energy efficiency options, as this is often done on a technology rather than system basis. This is illustrated by the fact that, because operational budgets are typically separated from capital budgets in companies, energy use – often the largest single lifecycle cost for such systems – is not considered at the time of purchase (IEA, 2007, p.231). With this in mind, the following section presents empirical evidence for the potential for energy efficiency improvements through systemic improvements.

5.6 *Systemic potential for improving industrial energy efficiency*

This section attempts to gauge the technological potential for improving energy efficiency in the industrial sector based on published estimates and widely accepted scopes for systemic improvements. It begins with a discussion of the systemic potential across key energy systems and through lifecycle approaches such as recycling and fuel substitution, before identifying the scope for individual industrial sectors. Similarly, within each of these areas, the focus is at first on general or global opportunities, before focussing on Europe and the UK in particular.

Attention is firstly drawn to the broad industrial systems highlighted in section 4.3.2. Most of these estimates are based on those of the IEA (2007) unless otherwise stated. The IEA’s Energy Technology Perspectives (ETP) has estimated the reductions in industrial carbon emissions achievable by 2050. Around half of the necessary total global reduction of MtCO₂ is due to energy efficiency measures, including large contributions from motor and steam system optimisations, as well as better heat recovery and use for power generation (Gielen & Taylor, 2007). For motor systems it is estimated that the global improvement potential is some 20% of the current baseline, based on the opportunities for system optimisation outlined above (IEA, 2007). The estimated potential for motor systems in the UK is also 20%, corresponding to 50PJ/yr of electricity or around 12% of industrial electricity use in 2006 (BERR, 2008a). The Motor Challenge project estimated that the potential for motor systems in the UK is in fact around 86PJ/yr (de Keulenaer et al., 2004). For steam systems, the global potential energy

efficiency improvement is estimated at 10%, which in for the UK similarly corresponds to 50PJ/yr.

For various reasons, including the reliability of data, the large differences between systems and the variability in operation, there does not appear to be a consensus on the global CHP potential. For Europe a figure of 75GW remaining (heat) potential within the industrial sector has been suggested by the Chapnet CHP project (Minnett, 2004, cited in IEA, 2007, p.244), but this should be treated with caution. Cambridge Econometrics (2003) suggest that the majority of CHP growth will be in the chemicals and other industry/power generation sectors. Although the government's target will almost certainly not be met by 2010, DEFRA (2007a) estimates that the *additional* economical potential for low to medium temperature industry in 2010 will be 5.4GW_e, rising to 6.8GW_e in 2015. There is also an estimated 1.4GW_e potential in high temperatures industries by 2010, especially refineries and LNG terminals. Pöyry (2008) have identified around 13.9GW_e (+/- 2.5GW_e) of additional technical potential for large scale CCGT CHP opportunities in locations where the demand is accounted for by a cluster of industrial premises. One of the sites identified, Seal Sands in Teeside, has been earmarked and planning permission awarded for the development of a 1.0GW_e CHP unit (Professional Engineering, 2008).

The opportunities for recycling in industry are quite significant on a global scale, but barriers such as the reduced material quality (paper can only be recycled six times, for example), which results in more material being required to perform the same function, must be taken into account. Often the market for a recycled product does not exist, so there is no basis for comparison in energy or carbon terms, such as is the case for plastic lumber. Notwithstanding these barriers, the technical potential for recycling of all materials available is estimated to represent a saving in global industrial energy use of 2-4% (IEA, 2007). The largest parts of this potential are from municipal solid waste (MSW) and packaging materials. This potential is not yet economical for various reasons, mainly because of the costs associated with recovery operations, which might change if the carbon price rises drastically. In addition, there is an additional driver in the lack of land available for landfill, which is currently the main incentive for increased recycling rather than concerns about energy or carbon emissions. There is also an imbalance in the distribution of this recycling potential: the majority is located in non-OECD countries. Europe as a whole already has a relatively high material recovery and recycling rate of around 30%, such that further marginal improvements are much more difficult than in countries with much lower rates (ibid.).

An alternative to recycling of waste materials is to use them as a fuel. This is particularly attractive with MSW and plastics (excluding PVC), which can be processed into fuels with a relatively high calorific value and used to displace fossil fuels in boilers and kilns. The estimated global industrial energy saving potential from incineration of these materials is of the order of 2-3%, depending upon the specific combustion technology, especially whether or not CHP is used. Incinerators in the UK have a very low (16.5%) efficiency, because they are used solely to generate electricity (op. cit.).

Having examined some of the systemic potential for industrial energy efficiency improvements, attention is now drawn to the opportunities that exist for individual industrial sectors. Table 5-3 shows some estimated global and European improvement potentials based on various sources. There is a large variation in the estimated savings for each sector due to the different time scales, geographical scopes and assumptions employed, as well as whether the potential is defined as being theoretical, technical or economical. However, there still seems to be a general consensus that for most sectors there is the potential for at least a 10% improvement in energy efficiency, and in some cases much more.

Given the broad nature of the global and European estimates of energy savings given in Table 5-3, these estimates should be kept in context. It would be unreasonable to impose such estimates onto UK industry because it is atypical in nature and because this broad potential cannot be realised equally between individual countries. Indeed, the distribution of the savings will depend to a large extent on the policy measures introduced or already in place in these regions as well as the stage of technological development at which industries find themselves. For example, the largest potential for energy efficiency improvements in the cement industry are thought to exist in regions where technology is not state of the art, such as China and the Former Soviet Union (Price & Worrell, 2006).

The potential for energy efficiency improvements in UK industry was assessed by Langley (1984a, 1984b, 1987) and his team at ETSU in 1980, in one of the most extensive studies of UK industry in recent decades. The study employed a highly disaggregated technological approach in order to determine the overall technical and economic potential for energy savings in each major process of the UK manufacturing industry by 2000. Further, it attempted to estimate the likely uptake of these measures in this period as well as comparing the findings to the energy projections of 1982 (Department of Energy, 1982, cited in Langley, 1984a, p.69). The headline conclusions of the study were that (Langley, 1984a):

- The estimated energy saving potential through energy efficiency measures by 2000 was estimated to be 21-25% of the consumption which would otherwise occur.
- These techno-economic estimates are within the technical potential of 29% identified by Energy Paper 32 (DTI, 1978).
- In both high and low growth scenarios, additional equipment make the largest contribution and together with management measures account for over half the potential savings.
- Due to the large amount of process energy used in the energy-intensive sectors, the overall improvement in energy efficiency is greatest here;
- Nearly two orders of magnitude separate the subsectors with the largest and smallest energy intensities.

With the benefit of hindsight it is clear that Langley's (ibid.) projections were too high. Even the low growth scenario was overoptimistic, as it failed to anticipate the extent of energy

efficiency and structural change in industry (section 5.2.1). The implication for the estimates in Table 5-3 should be treated with caution because of the uncertainty surrounding such data.

Source	IEA (2007)	Jochem (2000) ²⁸	Eichhammer (2004) ²⁹	Other	
Scope	Global	European	European	Savings	Source
Base year	2004	1995- 1997	2000		
Target year		2020			
Sector					
Food and drink		>15	6-12		
Iron and steel	11-18 (tech.)	13-20	15	11-20	US economical potential (Worrell et al., 2001)
Aluminium	15		21		
Chemicals	25-32	>10	8-27	30-50 ³⁰	Global petrochemical industry, theoretical potential (Neelis et al., 2006)
Refineries		7-10	25-32	10-20	US economical potential (Worrell & Galitsky, 2005)
Pulp and paper	33-37	50	21-24	75-90 ³¹	(De Beer et al., 1998)
Cement		8-15 ³²	13	17	Western Europe, technical potential (Price & Worrell, 2006)
Glass		15-25	13		
CHP in industry		10-20			

Table 5-3 – Global and European final energy saving potentials (%) for various industrial sectors

A related study carried out by AEA Technology (2002) examined the first three of the scenarios from the IAG (2002) energy projections, with the objective of identifying the technical possibilities and costs for the abatement of these emissions. Estimates of future energy demand and carbon dioxide emissions were developed using the IEA's MARKAL model, a bottom-up, technology based model that identifies the least cost combinations of technological processes and improvement options that satisfy specified levels of demand for goods and services under given constraints (DTI et al., 2005). The key results for industry were as follows (AEA Technology, 2002):

- A diversity of technology options for reducing CO₂ emissions were identified;

²⁸ From Table 6.4, which is based on a number of different sources, as follows: food and drink (Jochem & Bradke, 1996); iron and steel (ibid., Ameling & et al., 1998); chemicals (Patel, 1999, Brewer & Lopez, 1998); refineries (Anon, 1998); pulp and paper (de Beer, 1998); construction materials (no source given); glass (European Commission, 1997); CHP in industry (European Commission, 1997, European Commission, 1999).

²⁹ Savings in primary energy terms.

³⁰ These percentages are based on the total energy loss identified as a proportion of the total final energy use, and therefore relate to theoretical potential.

³¹ This is the potential to reduce the SEC of heat. The SEC of electricity may stay the same or increase slightly.

³² Actually this figure is for construction materials in general.

- **Energy efficiency** technologies and measures must play a central role in attaining emissions abatement targets.
- **Innovation and technical progress** are seen to be the major drivers behind the transition to a low carbon economy;
- **Large productivity improvements** could be achieved largely through automation;
- **Further structural change** away from heavy industries could lead to a continued reduction in energy intensity; and
- **Natural gas** is considered to be attractive as a fuel of the future, both economically and in terms of its associated low CO₂ emissions.

Finally, five specific technologies were highlighted by the Carbon Trust (2002) as having high technology and low carbon impact potential for decarbonising and increasing the energy efficiency of the industrial sector, namely: combustion technologies, especially in the high temperature industries; improved applications for and new materials; better process control and automation; process intensification; and membrane separation technologies. Another study undertaken in support of the Energy Efficiency Innovation Review (EEIR) analysed the potential of 23 specific technology applications, out of an original 125 possibilities, to offer significant carbon savings and value to the UK economy by 2050 (Future Energy Solutions, 2005). Of four cross-cutting themes concluded to have measurable potential with the assistance of government intervention, two are particularly relevant to industry, namely *boilers and steam systems* and *dematerialisation/lightweighting* of products. The former includes an array of six measures, namely:

- **Radical boiler redesign to exploit advanced burner designs** (ibid. p.22);
- **Low-cost adaptive and robust model-based boiler monitoring and control systems** (ibid. p.50);
- **Novel approaches to steam boiler system design** (ibid. p.77);
- **Low-cost intelligent modelling of steam systems** (ibid. p.84);
- **Second stage waste heat recovery from high temperature processes** (ibid. p.162); and
- **Innovative approaches to enhance recovery and use of waste heat from steam condensate and hot boiler flue gases** (ibid, p.179).

Together, these six measures offer potential annual carbon savings of the order of 3MtC/yr by 2050; likewise the dematerialisation and lightweighting of products is estimated to be capable of saving 1MtC/yr. However, there are significant barriers to adapting the current boiler stock within the UK, which include the lack of performance-related legislation for industrial boilers, and the large installed base of industrial boilers, which, combined with the low rate of installation of new plant, means that the penetration rate is relatively low. Again, these estimates should be treated with some care, as they could only be realised with the elimination of market barriers.

A similar technology-based model was developed of UK industrial energy-saving potential, in order to inform climate change policy debate, in particular as part of a consultation package on

the 2nd phase of the EU ETS (Future Energy Solutions & The Carbon Consortium, 2005). The bottom up technology model ENUSIM was employed in order to generate CO₂ cost abatement curves for 2005, 2008 and 2010, based on information on energy consumption and available energy efficient technologies. The headline results from the study are shown in Table 5-4. The limitations of the study mean that technology penetration and hidden costs are not accounted for, so these results should similarly be treated with care. Nevertheless, the results suggest significant economical potential energy savings in the paper, glass, brick and chemicals sectors, and much more if barriers could be reduced or eliminated.

Industrial Sector	Technology (all fuel use if blank)	Total 2010 Emissions excl. savings (ktCO ₂)	Cost Effective Savings (%)	Technically Possible Savings (%)
Cement	-	6,284	0.7	0.9
Lime	-	540	0.3	0.3
Paper	-	5,799	3.0	7.0
Glass	-	1,716	7.0	10.0
Brick Making	-	1,300	2.0	3.0
Ceramics	-	200	5.0	8.0
Chemicals ³³	-	11,241	11.0	17.0
Chemicals	CHP	11,241	1.0	1.0
Paper and board	-	3,210	3.0	5.0
Paper and board	Biomass boilers	3,210	2.0	35.0
Paper and board	CHP	3,210	2.0	2.0
Vehicles manufacturing	-	628	0.0	12.0

Table 5-4 – Potential emissions savings for energy-intensive industry by 2010 (Future Energy Solutions & The Carbon Consortium, 2005)

5.7 Energy demand projections for the industrial sector

Having discussed the potential for energy efficiency improvement by sector and technology, this section presents a brief summary of published energy demand projections for the industrial sector. Figure 5-11 shows the historical energy demand along with projections from various studies for the industrial sector. Especially noteworthy is the large deviation from the Lewis (1979) projections, which failed to anticipate the massive restructuring, rationalisation and energy efficiency improvements in the sector, leading to an energy demand in 2005 which is approximately half of the projected value. This illustrates the weakness with long-term econometric models, which are rarely if ever able to account for the possibility of low-probability, high impact exogenous shocks to the system and the associated consequences.

³³ The technology for this sector was not updated, only the overall energy balance, hence this is a liberal estimate of remaining potential (Future Energy Solutions & The Carbon Consortium, 2005)

There are a range of projections in the long term out to 2050. Over this period industrial energy demand is expected to remain of the same order of magnitude, and certainly not undergo the large changes as have occurred over the past four decades (although this might be due to the inherent oversight of such models noted above). The shorter term forecasts are less conservative, predicting a significant increase in industrial energy demand over the period to 2030. However, comparison to the historical trend shows that they have not been accurate over the last few years for which data is available – especially the DTI (1995). The central scenario of the latest government energy projections (DTI, 2006c) suggests an industrial energy demand in 2050 that is only slightly higher than today.

The extreme case involves a projected industrial energy demand of about 2000PJ in 2030, but this data is from the European Commission’s (2003d, 2006c) study covering all – then – current EU Member States. The results are therefore not highly accurate on a national basis, and even less so on a sub-national (i.e. industrial) scale. The energy demand projections from these two studies do not correspond as closely as other results to the historical data. This is partly as a result of the study’s highly aggregated nature, and also a question of classification, i.e. how the national energy demand is broken down into sectors – on a national scale these projections are in line with historical trends.

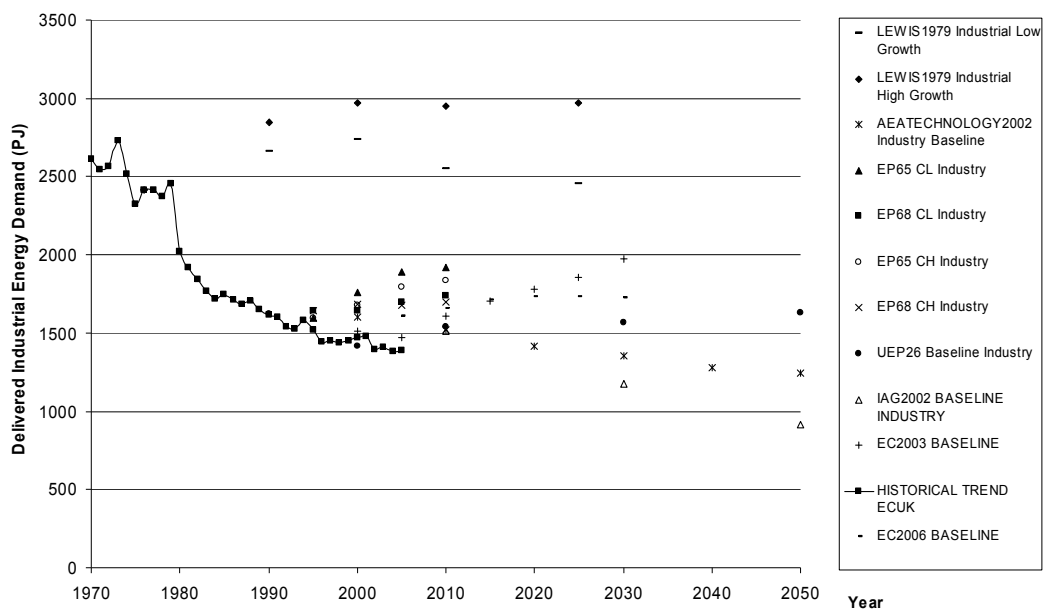


Figure 5-11 – Delivered industrial energy demand projections from various studies

Source: DTI (2007a), AEA Technology (2002), DTI (1995), DTI (2002a), DTI (2006c), IAG (2002), European Commission (2003d; 2006c), LEWIS (1979)

5.8 Summary and conclusions

The manufacturing sector has played an important role in the British economy ever since the first Industrial Revolution, by producing materials and products with domestic and overseas applications, hence providing valuable goods with which to undertake international trade. In

the latter half of the twentieth century in general, and the last quarter in particular, the British economy has shifted its focus away from manufacturing activities towards services. This shift has been observed in many industrialised nations, with empirical evidence from various developed countries (Perkins et al., 2006, pp.686-687), although it is by no means a necessary and sufficient stage of development. Furthermore, this trend is occurring within the manufacturing sector itself, as many manufacturing companies adapt into service providers.

The proportion of manufacturing GVA output recorded in national statistics therefore overlooks these service-related activities as they are not classified within the manufacturing sector. Nevertheless, the sector accounts for higher proportions of energy demand and carbon emissions than output. The sector has reduced its energy demand over the past few decades, mainly due to improvements in energy efficiency after the oil price hikes in the 1970s. The main source of carbon emissions in industry is energy use; less than 10% of total emissions are process related. Large reductions in employment have resulted in improved labour productivity and technological innovation has enabled overall growth in TFP in most sectors, because it has more than offset the labour shedding.

The industrial sector is very diverse in terms of manufacturing processes, ranging from highly energy-intensive steel production and petrochemicals processing to low energy-intensity electronics fabrication. Attempts to characterise sectors have been made based on energy end uses, energy productivities, and overall energy demand. Whilst relatively few energy intensive industrial sectors account for a large proportion of the sector's total energy use, these sectors are characterised by a great degree of diversity. Hence a classification based upon the degree of process homogeneity has been proposed, within which the food and drink and chemicals sectors are the most heterogeneous sectors.

International trade is very important for the manufacturing sector, which in general exports high value goods and imports lower value ones. The UK has a large trade deficit in goods, due largely to the relative decline of the industrial sector in the past few decades, but the distinction between goods and services has become blurred as noted above. Consistently higher levels of trade are undertaken with countries inside rather than outside the EU: approximately 60% of imports and exports come from or are destined for countries within the EU. Since the early 1990s the export share of manufacturing as a whole has remained steady at about 45%, whilst the import penetration has risen from 50% to 60%. The highest levels of trade occur within the automotive, electronics, chemicals (especially pharmaceuticals) and basic metals sectors, which are all high value added sectors. Lower levels of international trade occur within lower value added sectors such as non-metallic minerals because it is not economical to transport these products and they are usually manufactured close to demand (IPTS et al., 1998).

The European cement sector was not strongly affected by the EU ETS in Phase I, but there are concerns that a higher carbon price in Phases II and III will lead to carbon leakage, whereby production capacity is relocated outside Europe. This would directly contradict the intention of the EU ETS by increasing overall carbon emissions due to the additional transport required.

The solution to this threat seems to be a multi-lateral international emissions trading scheme or carbon taxes and/or import quotas on imported cement (or clinker) from regions outside Europe. The methods being employed by the sector to reduce specific emissions, namely material and fuel substitution, have limited potential to improve energy efficiency in the long term. Instead, new technological developments will be required to achieve drastic reductions in carbon emissions by the sector, including Carbon Capture and Storage (CCS) and higher-power cements.

There is evidence of diverse barriers to energy efficiency in industry. The most significant market barriers seem to be hidden costs and access to capital. Imperfect information seems to be the strongest market failure. There is significant systemic potential for increasing industrial energy efficiency if specific barriers can be eliminated. The potential is highest in ubiquitous energy systems such as steam, motors and CHP, as well as in key sectors such as, for example, iron and steel, chemicals, pulp and paper, and food and drink.

6 Spatial modelling of industrial heat loads and technical recovery potentials

This chapter presents a spatial analysis of industrial heat loads and technical recovery potentials in the UK, which also incorporates qualitative exergy considerations. The main data source is the EU ETS NAP, supplemented by capacity/output and SEC data for some sectors. The chapter begins with an introduction, which places the work in context and reviews previous studies. The aims and objectives are then defined, before presenting the general methodology as well as that for specific sectors. The results are then presented and discussed and the suggestions for future work are given. Finally, the chapter closes with conclusions and recommendations.

6.1 Introduction

The market for heat in the UK is currently not well understood, which represents a specific case of ignorance about end uses of energy at the microeconomic level. Whilst energy markets for primary fuels and electricity are well developed and regulated, those associated with heat appear nascent and disorganized. This is largely due to only a small proportion of the economy actually trading heat as a commodity – specifically the process industries. Another reason for this fragmented approach to energy supply is the privatised nature of the electricity and fuel markets, which are currently oriented towards delivering products (i.e. electricity, gas) rather than providing a service (such as lighting, heating).

Against the framework laid out in the Energy White Paper (DTI, 2007c), The Heat Call for Evidence (BERR, 2008f) set out to analyse the current market for heat use in the UK and better understand the policy options for reducing the carbon footprint of heat use. The generation of heat, mainly from gas and electricity, accounts for just under half of the UK's CO₂ emissions (BERR, 2008f, p.12). The domestic sector represents the largest heat demand in the UK, with about 54% of the final energy demand for heat, followed by industry, which accounts for 30% (ibid., p.13). However, the CO₂ emissions associated with these two sectors are of the order of 40% each of the total for the UK (ibid.). This is largely because industry uses more carbon-intensive fuels and electricity for process heating, and emits process emissions, whereas the main fuel for heat generation in homes is natural gas (Shorrocks & Utley, 2003).

The Heat Call for Evidence incorporated two specific studies which attempted to quantify the industrial market for heat. The Carbon Trust established Connective Energy as a subsidiary in July 2006, in order to concentrate on delivering heat-related solutions. Their estimated market potential for surplus heat from industrial processes in the UK is some 144PJ (40TWh), but this could not be substantiated because of commercial confidentiality (Albrow, K., Connective Energy, pers. corr., June 2008). Secondly, the government's Office of Climate Change (OCC), whilst acknowledging the scarcity of available data relating to heat use, employed an estimate of 65PJ (18TWh) in its determination of a marginal carbon abatement cost curve (BERR, 2008f,

p.62 and Appendix 2). This figure is clearly more conservative, but is also subject to a degree of uncertainty. In the absence of a better estimate at the time of writing, a reasonable indication for the actual market potential would be somewhere between these two extremes, perhaps at around 108PJ (30TWh).

Euroheat and Power, the international organisation for district heating, cooling and CHP, undertook an extensive study of the European market for heating and cooling, called EUROHEATCOOL (Work Package 1 deals with heating: Werner, 2006; Euroheat and Power, 2005b). The main data source for OECD countries was the IEA's database of international energy balances. Heat use in industrial processes was modelled across the target area of 32 countries, using experience from the German industry as a framework for apportioning heat use between different processes and sectors. Whilst this overlooks the complexity and country-specific nature of the industrial sector, a study of this scope is only intended to be indicative. Three different temperature bands have been used to classify industrial processes, namely low temperature (below 100°C), medium temperature (100°C to 400°C) and high temperature (above 400°C). The effective power to heat ratio for the industrial sector in the UK³⁴ was found to be around 6% overall, which compares well with other countries for which data was available, such as Spain and Finland with values of 12% and 13% respectively (Werner, 2006, p.21). Another conclusion for the industrial sector was that high temperature heat demands dominate with a 43% share, whilst medium and low temperature demands accounted for 27% and 30% respectively (*ibid.*, p.47).

The problem of quantifying heat demand and waste or surplus heat is exacerbated by the fact that the latter is not recorded in international energy statistics such as the IEA Energy Balances. Work Package 4 of the EcoHeatCool project found that surplus heat from industrial processes is used for district heating in Sweden above all, and to some extent in other Scandinavian countries (Werner, 2006, p.29). Elsewhere there appears to be negligible use of surplus industrial heat in district heating schemes, but this might reflect a lack of data rather than the true situation. Major barriers for the exploitation of the available surplus heat include the inflexibility in being contractually bound to supply heat and the large distances between supply and demand (*ibid.*). Nevertheless, it is technically possible to transport heat over distances up to around 40km, whereby the economics depends on, *inter alia*, the power and length of the network (Werner, Professor S., Energy Technology, Halmstad University, pers. corr., November 2008).

The present study attempts to model industrial heat demands throughout the UK, based largely on the site-specific data contained in the EU ETS NAP. Emphasis is placed on developing a methodology for modelling industrial heat loads through recourse to detailed assumptions and specific knowledge about individual subsectors, and the results are therefore intended to be

³⁴ That is, the ratio between the industrial CHP electricity generated and the net heat generated from fuels. This is indicative of the overall power-to-heat ratio for the industrial sector and reflects the penetration of CHP. If all heat and power within the sector was generated from CHP, this ratio could in theory approach values in excess of 100% as currently achieved by gas-fired combined cycles, but in practice this is constrained by the ability of CHP to supply high temperature processes.

indicative. Whilst other studies of this nature have already been done, they have largely been carried out by private companies and are therefore constrained by concerns about commercial confidentiality. AEA Energy and Environment also produced an industrial heat map for BERR in the context of the Heat Call for Evidence, but the methodology is not well documented (DTI, 2006, p.10, Annex A) and this map did not consider temperature of recovery potential (AEA Energy and Environment, 2009).

6.2 Aims, objectives and scope

The overall aim of this study was to better understand industrial energy, especially heat, usage on a site level. As discussed above, there has been little work carried out in this area, and much of what has been done is subject to commercial confidentiality. Top-down analysis of the industrial sector has led the author to the conclusion that this approach is limited in terms of resolution and accuracy, and that a site-specific approach is favoured for identifying the improvement potential on the ground. One of the largest constraints to adopting an holistic bottom-up approach to modelling heat loads is the paucity of data on this highly disaggregated level. Hence the focus here is on providing an initial picture of the current status, and also on developing a methodology that can be used with the data available. As well as investigating the use of heat for industrial processes at individual sites, two other aims of this work are to consider both the temperature (distribution) of heat use and losses, and the spatial distribution of these loads.

The general objective is therefore to provide an overview of heat demand and losses within the industrial sector in the UK. With this in mind, the specific objectives of this work are to:

- *Categorise* low, medium and high grade industrial heat users;
- *Quantify* heat use and wastage at different temperatures;
- *Quantify* opportunities for heat recovery based on commercial technology (the technical potential), both on and offsite;

In general this study is intended to be indicative of the trends in heat use across industry, rather than a precise representation of individual processes. The model is constrained to the site level; apart from sectors for which the capacity-based methodology has been employed, sites are considered to be black boxes, in which processing activities occur according to the sector specifications (Table 6-3, and Table A3 in Appendix A3.1). This means that, for example, the kinetics involved in chemical reactions is not considered. The focus is on the technical potential for heat recovery from the industrial sector, according to the definition given in section 4.4. The scope is as defined in section 1.4, with the exception of mineral oil refineries because these are considered to be too complex for inclusion within this study. The scope has also been limited by the data sources employed to the energy-intensive sectors, as detailed below.

6.3 *Methodology*

6.3.1 **General assumptions**

Diurnal or annual temporal variations in heat load have been neglected. The heat loads are instead assumed to be in steady state over the year, corresponding to the load factor and efficiency employed for the sector. The emissions allocation from the NAP that has been employed is the site's "relevant emissions" field, which is the average emissions over the period 2000-2003 minus the lowest year. Where a site's emissions changed significantly over this period Allocation Methodology Rules are applied, more details of which can be found in the Phase II NAP (DEFRA, 2007d, ch.3). Five sites in the pulp and paper sector have been excluded from this study because there is a lack of data on emissions for this reason.

This study assumes that there is a use on or off site for the recovered heat, which has not been explicitly specified for individual sites but is instead assumed to exist in the immediate vicinity. The basis for this assumption is that it is technically possible to transport heat over significant distances, as stated in the Introduction, the constraint being largely economic. The lack of a use for recovered heat is therefore taken to be a largely economic phenomenon, which could be alleviated or mitigated with market-based policy. Finally, the sectors as referred to in this study are actually a subset of the whole sectors in reality. Although reference is made to whole sectors, the meaning here is intended to be that proportion of the sector covered by this analysis. The difference between this coverage and the whole sector will be examined later.

6.3.2 **General methodology**

In order to determine the energy use for each site based on the CO₂ emissions, a stepwise procedure has been employed as follows. Information and assumptions about individual subsectors allowed parameters such as the fuel split, load factor, and combustion efficiencies to be estimated, which were then used as key input parameters in determining site-level heat loads. Generally speaking, the approach was the same for all sectors, except for aluminium, iron and steel, chemicals, and lime, for which a specific methodology was adopted due either to their heterogeneous nature and/or because parts thereof are not included in the NAP. For these four sectors the method employed involved using data relating to production capacities for individual sites and products, in conjunction with specific energy consumptions (SECs) for these processes. SEC data was mostly obtained from the relevant sector BREFs and EU ETS Benchmarking studies (details below). By employing appropriate load factors the energy and heat load for each site could then be estimated. This methodology is detailed more specifically in sections 6.3.4, 6.3.7, 6.3.10 and 6.3.11 respectively. Details of the classification on sectors within this framework are shown in Table 6-1, along with a qualitative indication of the accuracy of representation for that sector. The general procedure for homogenous sectors is shown in Figure 6-1. With the exception of the chemicals sector, all process industries have been modelled in sufficient detail to enable a high degree of confidence about the results. The lower accuracy levels in Table 6-1 are generally correlated with the heterogeneous sectors. The remainder of this section outlines the general methodology employed.

	Fair	Good	Excellent
Homogeneous	Other sectors ³⁵	Ceramics (bricks) Pulp and paper	Aluminium Cement CHP Glass Lime
Heterogeneous		Chemicals Food and drink	Iron and steel

Table 6-1 – Classification of sectors as homogeneous or heterogeneous and qualitative indication of the accuracy of representation

Sectors within the EU ETS were broken down into more detailed, homogeneous ones as far as possible. The actual sector categories were determined based on the size of the sector as a whole and the degree to which the sites within it could confidently be grouped together. The sector was then defined based on background knowledge and relevant sources. The first step was to estimate the split between process emissions and combustion emissions for the sector (only in the case where the process emissions are actually covered by the EU ETS). This enabled the purely combustion-related emissions to be determined. The next step was to calculate an overall emissions factor, K_T , for the subsector based on Equation 6-1.

$$K_T = \frac{\sum_{x=1}^N C_x K_x}{\sum_{x=1}^N C_x} \quad 6-1$$

C_x is the fraction of fuel x used in the sector, K_x is its emission factor, and there are N different fuels excluding electricity. Emissions factors were taken from the UK Greenhouse Gas Inventory (Choudrie et al., 2008). For grid-electricity, the emissions factor is assumed to be zero because the emissions associated with electricity generation are accounted for in the power station under the Large Electricity Providers (LEPs) sector. The exception to this is autogenerated electricity, which is produced onsite through a generator or CHP unit. The detailed methodology for the treatment of CHP is presented in section 6.3.3. The emissions factors used for various primary fuels and electricity are shown in Table 6-2. Neither biomass nor waste fuels are accounted for in this analysis. The use of the former is not allocated any emissions within the NAP (DEFRA, 2007d), and hence that part of the heat load met by biomass is neglected. Emissions from waste fuels are included in the NAP, however (European Commission, 2003c), but specific emissions factors for waste have not been included here. Instead, that fraction of heat load that is met by waste materials is allocated to other fuels in the sector fuel splits. This is justified because the emissions factors for waste materials are close to

³⁵ Strictly speaking other sectors are heterogeneous, but they have been lumped together and treated as boilers and steam systems in this case, and hence are considered to be homogeneous. These sectors count for a very small proportion of the overall energy demand, as shown in the Results section.

those for the fuels that they displace (Choudrie et al., 2008), and also because wastes account for less than 1% of the overall industrial fuel split (BERR, 2008b).

Natural gas	Gas oil	Fuel oil	Coal (iron and steel)	Coal (cement)	Coal (other)	Coke	Coke oven gas	Other	Grid electricity
13.99	19.08	20.21	22.76	27.28	22.11	27.15	11.07	22.00	0.00

Table 6-2 – Emissions factors in tC/TJ for primary fuels used in the model

Source: Choudrie et al. (2008)

Fuel splits have been obtained from trade associations and the literature, where appropriate. In the case that this has not been possible, the fuel splits have been taken from DUKES or ECUK tables. The precise source of this information for each sector is given in Table A3 in Appendix A3.1. Based on these emissions factors and fuel splits for each sector, the total site fuel consumption E_{Tf} is determined through

$$E_{Tf} = \frac{C_T \times f_c}{K_T} \quad 6-2$$

where C_T is the total emissions allocated to the site and f_c is the combustion emissions fraction. Equation 8-2 therefore determines the total energy consumption due to fuels, E_{Tf} , at a particular site. In order to include the electricity use, it is then necessary to manipulate this total according to

$$E_T = \frac{E_{Tf}}{1 - f_{el}} \quad 6-3$$

where f_{el} is the fraction of electricity use within the subsector. E_T , which is the total site energy use including electricity, can then be multiplied by the respective fuel split factors for the subsector in order to yield approximate fuel uses for the site. The combustion efficiency reflects the fact that not all of the primary fuel use is converted to heat. Load factors have been taken from the benchmarking studies carried out for Phase II of the EU ETS (Entec UK Ltd. & NERA Economic Consulting, 2005). Otherwise, the default values for the boiler combustion efficiency and load factor are estimated as 80% and 80% respectively. In general furnaces and kilns are assumed to have a combustion efficiency of 90% because they tend to be more effective at direct heat transfer applications. These factors are used to determine the heat load, \dot{Q} , in MW_{th} from the total site fuel use according to

$$\dot{Q} = \frac{E_{Tf} \cdot \eta_c}{t \cdot LF}, \quad 6-4$$

where t is the number of seconds in a year, and η_c and LF are the efficiency of conversion from fuel to heat and the load factor respectively. For some sectors the latter two parameters have the same value, and therefore cancel each other out, in which case the heat load is simply the rate of fuel use over the year. The exceptions to the methodology are aluminium and secondary iron and steel produced through EAFs, for which the site electricity use also contributes to the heat load.

In order to estimate the amount of waste heat for each site, and therefore obtain an indication of potential for heat recovery, the best available estimates for the fraction of the total input energy that is contained in the exhaust gases have been used. In general a conservative approach has been adopted, whereby this fraction is set somewhat below published values. This is in order to reflect the constraints on heat recovery, including the impossibility of recovering all waste heat. In addition, two values for this fraction have been employed, to reflect the uncertainty in making these estimations and thus to provide a range of estimates for the heat recovery potential. Typically half of the sensible heat in an exhaust stream might be technically recoverable. The range of heat recovery fractions employed for each sector has attempted to reflect this by having its median value at 50% of the heat content in the exhaust. For example, if the exhaust fraction is known to be 30% of the total heat input, half of this or 15% should be technically recoverable, so the range of heat recovery fractions is set at 10-20%.

Where published data is not readily available for the exhaust fraction or it is not clear what process is occurring at a particular site, the range for the exhaust fraction has been estimated to be 5%-10%. This is intended to be representative of the exhaust fraction of even the most efficient boiler systems, and therefore reflects the marginal improvements widely considered to be possible with boilers and steam systems across the board in industry (IEA, 2007). Strictly speaking this range does not correspond to heat recovery per se, but instead relates to a more general improvement potential for the whole system. The assumed temperature demand profiles, exhaust temperatures and sources for this data are presented in Table 6-3.

The temperature demand profile is based on an estimation of the fraction of the heat that used for each sector within five temperature bands, namely below 100°C, 100-500°C, 500-1000°C, 1000-1500°C and above 1500°C. The basis for these estimates is background studies of industries and relevant literature such as the BREFs (EC JRC IPTS, 2008). A weighted thermodynamic quality or Carnot factor, Θ , was derived for each of these temperature bands based on Equation A20 of Appendix A2.2.3, where T_a and T_p are the ambient and process temperature respectively (Bejan et al., 1996). T_p was assumed to be the mid-point of each temperature band and T_a was taken as 0°C. Finally, multiplying the Carnot factor for each temperature demand by the proportion of heat use in each band yields the weighted overall Carnot factors shown in Table 6-3.

In general the feedstock energy that becomes embodied in products has not been considered as part of the energy consumption or heat load of a specific site. The fact that this embodied energy might be recovered later in – or at the end of – a material's or product's life is clearly

significant, but feedstock energy use cannot be reduced through energy-efficiency measures (IEA, 2007). Hence the focus here is on the process energy or specific energy consumption, SEC, as opposed to the gross energy requirement, GER (Boustead & Hancock, 1979). In some cases, such as the production of ethylene and ammonia, the feedstock energy is large, and accounts for over half of the GER of the process, in which case it would be inaccurate to include this energy as part of the heat load.

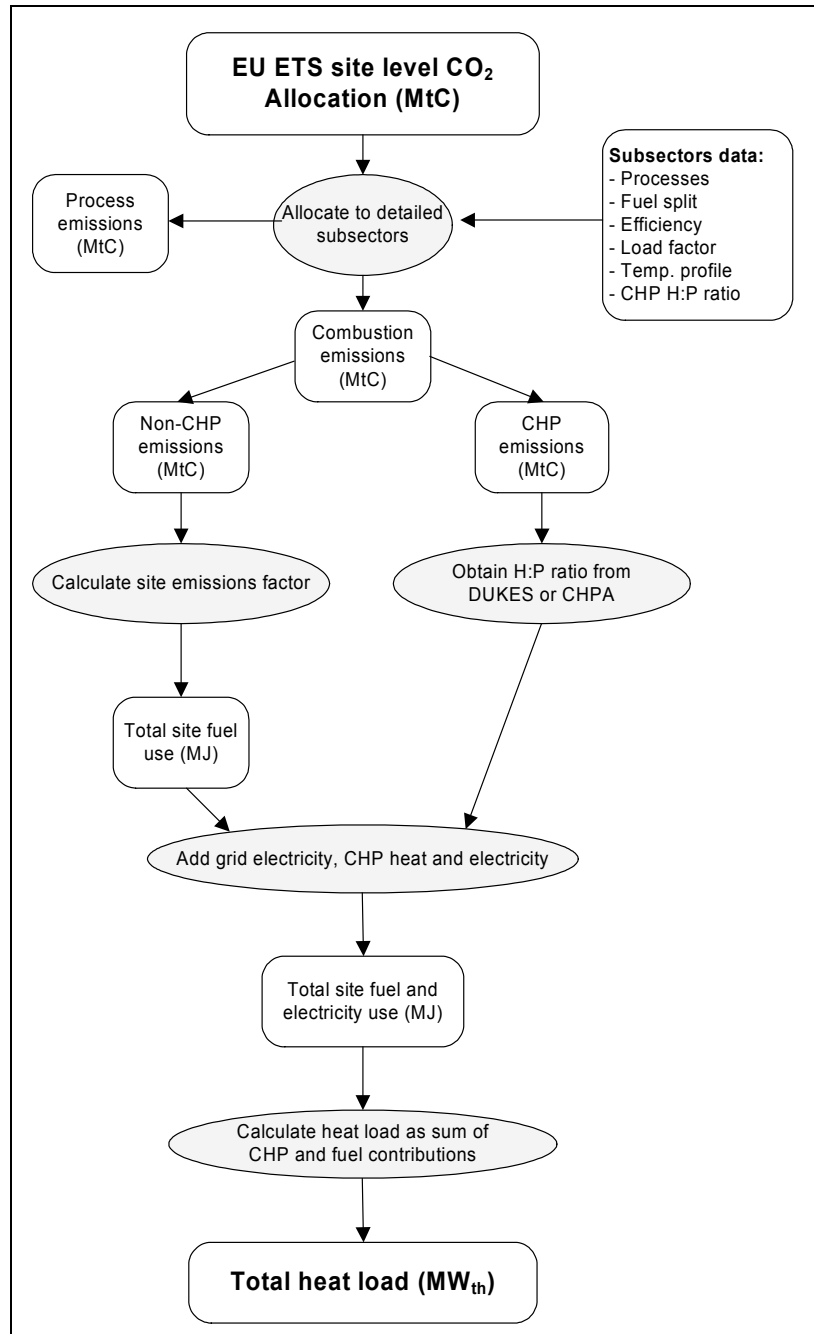


Figure 6-1 – Schematic of NAP-based methodology

Furthermore, the heat obtained from exothermic reactions (i.e. other than the combustion of fuels) has not been considered in this analysis. Examples include the production of nitric and sulphuric acids (European Commission, 2004c) and most polymerisation reactions (European

Commission, 2005d). In such cases there may even be a net heat yield from the reaction, whereby the heat is typically used elsewhere in the plant, which will be characterised by a high degree of energy integration. The justification for excluding exothermic reactions is that the net heat yield is small in comparison to the heat demand of energy-intensive processes considered here. Order of magnitude calculations suggest that the total energy yield from nitric and sulphuric acid production in the UK is of the order of 3PJ/yr, which is an order of magnitude smaller than the energy use consumption due to ethylene production for example³⁶.

6.3.3 CHP

The treatment and coverage of CHP within the NAP is not trivial, especially where installations have emissions relating to CHP plant as well as to other onsite activities. In considering CHP, some general procedural rules were therefore followed in order to ensure consistency and to facilitate the straightforward classification of installations. In brief, these were as follows:

1. If the vast majority (i.e. above 80%) of emissions allocated to a site are for the CHP unit, then the site is classified as wholly CHP.
2. If a smaller fraction of the site's emissions are allocated to the CHP unit, but the unit is classed as "partially qualified" then it is assumed that the rest of the emissions correspond to the non-qualified portion of the CHP, and the site is classified as wholly CHP.
3. If the site has CHP *and* Host Sector emission allocations, and the CHP unit is "fully qualified", then the site is classified within the host sector with the CHP augmenting heat and electricity supply onsite. This enables other onsite activities to be accounted for.

In all three cases the CHP unit's power rating and/or heat to power ratio has been obtained from Smith (2006), National Grid (2008) and DUKES (BERR, 2008c). In the latter two cases above the heat from the CHP unit augments the heat supplied onsite by other means, i.e. process heat and/or boiler systems. The electricity generated onsite displaces grid electricity. In the case that the amount of generated electricity exceeds the demand for electricity the excess is assumed to be exported to the grid. In practice this may then be used at another site, but this has not been accounted for in the model because of the way in which grid electricity has an emissions factor of zero.

Where the heat generated (from both CHP and other sources) is greater than the demand, heat exports to nearby users are not considered. Similarly for CHP units in isolation (according to the first point above), the location of the heat demand is assumed to be the same as that of the supply, so transport over small distances in the vicinity is neglected. Hence the heat use on any one site may be overestimated by the amount that would in practice be exported, but overall the heat use would be the same. Furthermore, because there are no regional or national heat

³⁶ This figure is based on production capacities of 850kt/yr and 800kt/yr and net total energy production of 1.6GJ/t and 2.5GJ/t (based on double absorption plant) for nitric and sulphuric acid respectively (European Commission, 2004c).

networks in the UK heat is not transported large distances (Sustainable Development Commission, 2008), the geographical location at which this heat is actually used will not be significantly different to where it is generated, and the error association with this assumption will be small. The sector total heat loads will not be affected by this assumption.

Sector	Weighted Carnot factor, Θ	Exhaust temp. (°C)	Low exhaust fraction	High exhaust fraction	Source
CHP	0.39	150	0.00	0.00	Reilly, E., UPM Caledonian paper mill, pers. comm., Feb-Dec 2008;
Boilers and steam systems	0.33	150	0.05	0.10	Bowers, J., E.On Engineering, pers. comm., December 2008
Aluminium	0.69	100	0.05	0.10	European Commission, 2001c; NineSigma, 2007
Cement	0.80	150	0.10	0.20	Rushworth, J., Lafarge, pers. comm., March 2008
Ceramics_bricks	0.80	150	0.05	0.10	Beardsworth, D., Ceramfed, pers. comm., June 2008
Chemicals_ ammonia	0.69	350	0.05	0.10	Energetics & E3M, 2004; Rafiqul et al., 2005
Chemicals_ carbon black	0.78	125	0.05	0.10	USEPA, 1995
Chemicals_ general	0.47	150	0.05	0.10	As boilers and steam systems
Chemicals_ steam cracker	0.69	100-500	0.05	0.10	Enviros Consulting, 2006b
Food and drink_breweries	0.27	150	0.05	0.10	Brown et al., 1985
Food and drink_distilleries	0.33	80	0.05	0.10	Brown et al., 1985
Food and drink_maltings	0.27	40	0.05	0.10	US DOE ITP, 2006
Food and drink_sugar beet	0.27	200	0.05	0.10	Brown et al., 1985
Food and drink_sugar cane	0.27	150	0.05	0.10	Brown et al., 1985
Glass_flat	0.74	550	0.10	0.20	Hartley, A, British Glass, pers. comm.; Quirk et al., 1994
Glass_container	0.75	550	0.10	0.20	Ibid.
Glass_other	0.73	550	0.10	0.20	Ibid.
Lime	0.78	150	0.10	0.15	Assumed same as cement
Gypsum	0.39	100-500	0.05	0.10	Brown et al., 1985
Mineral/rock wool	0.73	550	0.10	0.20	Assumed same as glass

Table 6-3 – Carnot factors, exhaust temperatures and heat recovery potentials for different sectors

In terms of heat recovery, CHP is already an efficient means of meeting heat and electricity demands, which generally has overall efficiencies in excess of 80% (Hammond, 2004). Hence for heat demands met by CHP units the assumption is that there is no technically feasible potential for heat recovery, or in other words that the exhaust fraction is zero.

6.3.4 Aluminium

The aluminium subsector within the Phase II NAP only covers electricity generation activities. This includes the 420MW coal-fired power station at Lynemouth, which is owned and operated by Alcan, providing electricity to its Lynemouth smelter. Hence the three aluminium smelters in the UK have been included as additional sites to those in the NAP. These are the two Alcan smelters at Lynemouth and Lochaber, and the Anglesey Aluminium smelter at Holyhead. The operational data for these sites has been gathered from relevant company publications, the BREF document for the sector (European Commission, 2001c), and the trade association ALFED (Siddle, T., ALFED, pers. corr., July-December 2008). These details are presented in Table 6-4 below.

The focus in this work has been on primary aluminium smelters. Although other manufacturing activities associated with aluminium do occur in the UK, e.g. packaging in Bristol and engineering metals in Slough (ALCAN, 2007), the smelting is by far the most energy intensive process. Hence secondary aluminium production, with an approximate capacity of 260kt/yr (European Commission, 2008, p.14), is neglected in this analysis. This is justified because of the much smaller energy requirement for secondary aluminium (less than 5% of that required for primary production, *ibid.*). Aluminium smelting within the UK only uses the pre-baked anodes route rather than the Soderberg route which uses anode paste. Out of approximately 170kt of carbon products produced in the UK in 1998, approximately 148kt were carbon anodes, which was mostly if not all coming from three manufacturers (European Commission, 2001c, p.57). Although only the process of smelting itself has been considered here, the energy used to manufacture the anodes is considered in the total energy intensity figure in Table 6-4. The electrical intensity figure of 14.6MWh/t is the electrical energy required for electrolysis, whereas the total energy figure of 21MWh/t includes the energy required to bake the anodes.

Aluminium manufacture involves the electrolysis of alumina (aluminium oxide), obtained from bauxite, whilst dissolved in a bath of sodium aluminium fluoride (cryolite) at a temperature of around 1000°C (European Commission, 2001c). The main energy use on site is in the form of electricity for the electrolysis, but there are also other significant on-site energy demands for ancillary activities such as casting (*ibid.*). The exhaust gases from the process are drawn off the reduction cells, filtered to conform to environmental legislation and then released to the atmosphere at a temperature of around 100°C (NineSigma, 2007). Overall around half of the input energy is lost as heat, and 30% of this is in the enthalpy of the off-gas (*ibid.*). The main

technical constraint on the recovery of the sensible heat in these gases is the fouling of heat transfer surfaces.

The estimated heat recovery potential for the sector has been determined based on this assumption that 15% of the final energy input is lost in the exhaust gas at 100°C. It has been confirmed by the trade association, Alfed, that this off-gas is indeed released to the atmosphere at this temperature after being filtered (Siddle, T., Alfed, pers. corr., January 2009). Hence the exhaust fraction range has been set at 5-10%.

Plant	Capacity (kt/yr)	Effective capacity 95% utilisation (kt/yr)	Electrical intensity (MWh/t)	Total energy intensity (MWh/t)
Lynemouth	178	169	14.9	21
Lochaber	43	41	14.9	21
Holyhead	140	133	14.9	21
Total	361	343	-	-

Table 6-4 – Aluminium smelters in the UK and salient operational information

6.3.5 Cement

The cement subsector is fully included within the EU ETS; the stipulation for inclusion in the scheme is a kiln production capacity of 500t/day of clinker or above. For Phase II this coverage includes 15 sites. Combustion emissions typically account for 40% of the total CO₂ emissions from cement manufacture (Herson & Mckenna, 2007, section 5.4), although it can be as low as 33% (European Commission, 2007). The latter figure has been employed here to avoid overestimating the heat loads.

Four routes are currently employed in the UK for the manufacture of cement, namely wet, semi-wet, semi-dry and dry. The recent tendency has been towards the dry process because it is less energy intensive, but the process employed depends largely on the nature of the raw materials. The process employed in a specific region depends on the nature of the locally available raw materials, as the relatively low value of these materials makes it uneconomical to transport them over large distances. About 55% of industry capacity is based on the dry process, with another 30% from the wet process. The remainder is either semi-dry or semi-wet.

The common process of cement manufacture involves calcining of calcium carbonate (from limestone) at a temperature of around 1000°C to produce calcium oxide. The clinkering process then occurs at around 1500°C, when the calcium oxide reacts with silica, alumina and iron oxide to form the silicates, aluminates and ferrites of calcium which comprise clinker (European Commission, 2007). The clinker is then ground and blended with gypsum and other additives to produce saleable cement. In principle the wet and dry processes are the same, but the degree of moisture content in the wet materials can necessitate additional technology such as chains within the kiln to break up lumps, as well as additional energy input.

Most cement plants have some kind of preheater and/or calciner for the raw materials, which use heat from the back end of the kiln. A preheater simply raises the temperature of the raw materials prior to them entering the kiln, whereas a precalciner actually starts and carries out the majority of the calcination process before the kiln. As a rule of thumb, the energy demand split between the preheater and the kiln is about 60% to 40% (Rushworth, J., Lafarge, pers. corr., March 2008). State of the art precalciners, which use multi-stage cyclones to transfer heat to the raw meal, result in an energy demand split of 80% to 20%. This is the most efficient technology, and can result in fuel SECs as low as 3GJ/t, compared to around 4GJ/t for the dry process with preheater and up to 6GJ/t for the wet process (European Commission, 2007).

From the kiln the clinker passes into a cooler, which serves to cool the clinker and stop the chemical reactions, and to recover as much sensible heat as possible. All coolers operate by passing cooler air over the clinker, which is then recirculated into the process (Environment Agency, 2001). Hence there are usually two exhausts from a cement plant: from the precalciner or preheater at a temperature of around 200-300°C and from the cooler at around 300-400°C (Khurana et al., 2002; Engin & Ari, 2005). These two exhaust streams together account for 25-35% of the total heat input, with the majority lost through the preheater/precalciner stack (ibid.). In some cases the useful heat in either or both of these streams may already be utilised, but it is not clear precisely to what extent. Based on evidence which suggests final exhaust temperatures in an efficient plant can be as low as 150°C but can be up to 300°C in older plants (Rushworth, J., Lafarge, pers. comm., March 2008), this lower figure was employed as the exhaust temperature in the model. Given that the exhausts represent around 35% of the total energy input overall (Khurana et al., 2002), the range for the exhaust heat as a fraction of the total heat input was taken as 10% to 20%.

6.3.6 Ceramics

The ceramics subsector is covered by the EU ETS, including installations producing ceramic articles with a production capacity of over 75t/d and/or with a kiln capacity exceeding 4m² and with a setting density per kiln exceeding 300kg/m³. The energy requirement and emissions from brick manufacture are heavily dependent upon the raw material, brick type and kiln configuration employed (clearly the three are interrelated because of the technological requirements of different materials). The lack of data relating to the type of output being produced at each site, which the trade association is not willing to disclose, has necessitated a generic approach to this sector.

The vast majority of ceramics installations covered by the scheme, which total 77 in Phase II, are brick manufacturers (Beardsworth, D., Ceramfed, pers. comm., June 2008). All ceramics installations included in the Scheme are therefore treated as brick manufacturing sites, which are assumed to be using tunnel kilns, the state of the art for large scale brick manufacture. The energy content of certain raw materials (Oxford Clays) used in the manufacture of fletton bricks has been neglected in this analysis. This is justified because, of 112 ceramics installations

included in Phase I of the EU ETS, only 2 were producing fletton bricks. The fletton-producing sites therefore accounted for 0.26MtCO₂ out of a total for the sector of 1.79MtCO₂ (i.e. 15%) in Phase I (Enviros Consulting, 2006c). This does not affect the overall accuracy of the estimated heat loads for the ceramics sector (the same heat is required to cure these bricks), but instead means the determined fuel splits overlook the contribution of organic materials from Oxford Clays in meeting this demand.

The tunnel kiln has three main zones along its length with a corresponding temperature profile: the preheat, firing and cooling zones (European Commission, 2006e). The temperature within the firing zone typically reaches around 1000°C, although this can be higher for roof tiles and facing bricks, and a uniform temperature profile is required across the wares. As the bricks are drawn through the kiln on cars, air is drawn through the kiln in the opposite direction. Most manufacturers take waste heat from the kiln and pass it to the dryer, but around 35-40% of the total heat input is exhausted up the chimney at a temperature of around 150°C (Beardsworth, D., op. cit.). For this work, in order to reflect the technical constraints on heat recovery as well as the fact that not all sensible heat can be recovered, limits of 10% and 20% have been selected for the fraction of waste heat. An approximate combustion emissions fraction for brick manufacture given is around 50% (Entec UK Ltd. & NERA Economic Consulting, 2005) and this is the value is employed here.

6.3.7 Chemicals

The chemicals sector is only covered by the EU ETS in terms of its thermal operations, and then only for installations rated at 20MW_{th} and over. The sector is highly diverse, with 19 separate subsectors having very different market drivers and priorities (CIGT, 2002). In total, there are around 3500 companies, represented by some 20 trade associations. This diversity means that it has not been possible to model the sector's activities accurately. Instead the approach for the chemicals sector was dipartite: energy-intensive processes have been modelled based on rated capacities/outputs and process-specific SECs, with the remainder of the sites being included as a generic sector, in which fuel use is assumed to be mainly in boilers for raising process steam. It is not necessary to discuss the latter in detail here, other than to mention that it is modelled according to the general approach described in section 6.3.13. The sites covered within the NAP which are discussed as production sites for the key chemicals in this section have been removed from the NAP in order to avoid double counting of energy use.

The remainder of this section describes the key processes involved in the manufacture of several key chemicals, and the methodology employed to estimate heat loads and recovery potentials. As outlined above this work attempts to identify the technical potential for process improvement. Some studies have attempted to estimate the *theoretical* potential for improving these processes and thus reducing the SEC, but care needs to be taken in interpreting their results (as the authors themselves acknowledge) because of the practical constraints associated with realising this. In particular, Neelis et al. (2005, 2006) have analysed several key processes within the chemicals and refining industries, with a focus on the excess energy use due to non-

selectivity (i.e. the efficiency with which the raw materials combine/react) and due to excess energy (heat). For many processes the excess final energy use identified is very large (i.e. over 50GJ/t), and for the processes described below it is also significant. The same is true for the energy saving potential identified by JVP International (2004), who carried out an exergy analysis on key chemical processes in the US industry to identify the theoretical improvement potential. Such studies have been useful in identifying where the most potential lies in theory, and therefore where further work should focus, but their estimated savings have not been employed here because they do not relate to the technical potential.

6.3.7.1 Ammonia

Ammonia is the source of nearly all synthetic nitrogen fertilisers produced in the world. It is manufactured by combining nitrogen and hydrogen in the Haber (or Haber-Bosch) process. Globally over 80% of ammonia is produced through the steam reforming of hydrocarbon feedstocks (natural gas, naphtha, LPG, refinery gas). Roughly the same proportion of ammonia is used to manufacture nitrogen-based synthetic fertilisers (European Commission, 2004c, p.3). This is therefore the focus of attention here. Production of ammonia in the UK was around 1.0Mt in 2005 (UNSD, 2005), with nameplate capacities of individual companies and sites as detailed in Table 6-5.

The production route in the UK is exclusively through the steam reforming of hydrocarbon feedstocks, as opposed to through partial oxidation or water electrolysis. The synthesis of ammonia, in which nitrogen and hydrogen are reacted over an iron catalyst, is actually exothermic. The energy-intensive part of ammonia production is in the manufacture of hydrogen, which typically occurs in a two-stage reforming process at temperatures up to around 1000°C.

Company/site	Postcode	Feedstock	Capacity (kt/yr)
Kemira/growthow, Billingham	TS23 1XT	Natural gas	550
Kemira/growthow, Ince	CH2 4LB	Natural gas	350
Terra Nitrogen, Severnside	BS10 7SJ	Natural gas	300
Kemira/growthow, Hull	HU12 8DS	H ₂ -rich feedstock	270
TOTAL			1470

Table 6-5 – UK ammonia production capacity by site

Source: European Commission (2004c) and Chemical Week (2006a)

There is a large degree of energy integration in modern ammonia plants, and much of the exhaust heat from the reformers and ammonia synthesis plants is recovered (European Commission, 2004c). The SEC range for ammonia production through steam reforming of hydrogen excluding feedstock is around 8-9GJ/t, and including feedstock this figure is 35-38GJ/t (ibid., IEA, 2007), although Worrell et al. (2000) give a range of 28-40GJ/t for the US industry. Notwithstanding this high degree of energy integration, it is estimated that 10% of waste heat from the reformers is recoverable (Energetics & E3M, 2004). Using a scenario approach Rafiqul

et al. (2005) conclude that a SEC reductions of around 10% on 1995 figures are achievable across the board in the EU, with uncertainties relating to, *inter alia*, the carbon price, investment plans, and future developments in policy. Furthermore, autothermal reforming is an integrated process route for the synthesis of ammonia, which has the potential for primary energy savings of around 20% in the chemicals sector with a payback period of less than four years (Martin et al., 2000, pp.80-82). A value of 10% is therefore employed as an upper limit for the technical potential, with the lower estimate at 5%. The temperature of the exhaust from the secondary reformer after heat has been recovered in a waste heat boiler is around 350°C (European Commission, 2004c).

6.3.7.2 Chlorine

Chlorine and sodium hydroxide are both used extensively within the chemicals industry, chlorine mainly to produce chlorinated compounds (e.g. vinyl chloride) and sodium hydroxide to produce various organic and inorganic chemical compounds with a variety of applications (including soaps and detergents). The two are manufactured through the electrolysis of brine (sodium chloride solution), which is carried out in three types of cell: mercury, membrane and diaphragm. Only the first two of these technologies are employed in the UK, with the vast majority of UK capacity employing the most efficient of the three, membrane technology³⁷. The adjusted total energy use for mercury and membrane cells is around 12-13GJ/t (European Commission, 2001f). The membrane process is more efficient because it uses less electricity, some of which is substituted for steam. Hence the mercury process consumes around 12GJ/t of electricity, whereas the membrane process uses around 10GJ/t of electricity and 2GJ/t steam (IEA, 2007, pp.76-77). The technologies are not directly comparable, however, because they produce sodium hydroxide in different concentrations. The mercury cell produces sodium hydroxide at 50% concentration, but the diaphragm and membrane cells produce concentrations of 12% and 30% respectively, which then needs to be concentrated (*ibid.*).

Although energy (electricity) intensive, the electrolysis does not take place at high temperatures. The temperature within the cells is around 70°C and 85°C for the mercury and membrane processes respectively (Brown et al., 1985). Hence the scope for heat recovery per se is limited or non-existent, but improvements in overall efficiency can be made by optimising the way in which heat and electricity are generated and supplied to this and adjacent processes. The large Ineos Chlor manufacturing site at Runcorn already has a CHP unit, which is rated at 57MW_e (National Grid, 2008). With the sector average heat to power ratio of 2.07 (BERR, 2008c), this corresponds to a rated heat output of around 120MW_{th}. In fact the heat output might be significantly lower than this because the unit is probably power- rather than heat-led given that the main load is electrical. Based on the capacity rating for this site in Table 6-6, along with an adjusted total SEC of 10.7GJ/t (European Commission, 2001f) the total energy consumption is around 7.8PJ per year, the majority of which is electricity. Assuming that the CHP unit produces its rated electrical output on average, it produces around 2PJ of electricity per year.

³⁷ The Ineos Chlor site at Runcorn is currently switching over from the mercury to the membrane process, which is due to be complete by the end of the decade (European Commission, 2003f).

Depending upon how and where the heat from this unit is used, there may be scope to increase the capacity of CHP on this site. However, because of the uncertainty surrounding the heat use for chlorine production and associated process at the sites in the vicinity, it was decided to model chlorine production based on this CHP unit alone, which is included in the NAP. Hence there are system-level savings possible for chlorine production of around 10% (Energetics & E3M, 2004), which have not been considered here because they do not rate directly to heat use.

Process	Company/site	Postcode	Capacity (kt/yr)
Membrane	Ineos Chlor, Runcorn	WA7 4JE	767
Mercury	Albion chemicals, Sandbach	CW11 3PZ	90
Mercury	Rhodia, Staveley	S43 2PB	29
TOTAL			886

Table 6-6 – UK chlorine and sodium hydroxide production capacity

Source: European Commission (2001f)

6.3.7.3 Ethylene

Ethylene is the main raw material for the petrochemicals industry. It is manufactured through thermal or catalytic cracking of hydrocarbon feedstocks. Ethylene manufacture in the UK is carried out at four sites, where hydrocarbon feedstocks are thermally cracked (Table 6-7). There is no ethylene production in the UK by catalytic cracking. The basic process involves preheating the hydrocarbon feedstocks to around 650°C in the preheater section before mixing with steam and cracking at around 850°C (Worrell et al., 2000). The gas mixture is then rapidly quenched to 400°C to stop the reaction, producing high pressure steam, before water is injected to further lower the temperature. The liquid is then extracted as the gaseous fraction is fed to a fractional distillation column.

Process	Company/site	Postcode	Capacity (kt/yr ethylene)
Steam cracker - ethane feedstock	ExxonMobil, Mossmoran	KY4 8EP	830
Steam cracker - naptha feedstock	ExxonMobil, Fawley	SO45 3NP	126
Steam cracker - naptha feedstock	Ineos, Grangemouth	FK3 9XH	1020
Steam cracker - naptha feedstock	Huntsman, Wilton	TS10 4YA	865
TOTAL			2841

Table 6-7 – UK ethylene production capacity through steam crackers

Source: European Commission (2003e) EnviroS Consulting (2006b) and APPE (2006)

The SEC for steam cracking of ethane feedstocks is around 15-25GJ/t excluding feedstock energy and for naptha feedstocks it is about 25-40GJ/t (IEA, 2007, p.66). Steam crackers require large amounts of energy at a high temperature to promote disassociation of the chemical feedstock, but also employ cryogenic separation processes to purify and separate the products (European Commission, 2003e). Hence crackers have a large degree of energy integration, which is typically achieved by recovering as much as possible of the heat from the front end to use as work for separation. The complexity of steam crackers and the proprietary nature of the

technology means that one temperature for the exhaust was not obtainable. It was therefore assumed that the exhaust temperature lies in the range 100-500°C. The estimated heat recovery from steam crackers is around 10% (Energetics & E3M, 2004, IEA, 2007). Hence this is employed as an upper limit to the technical potential with 5% as the lower bound.

6.3.7.4 Other major chemicals

The three chemicals ammonia, chlorine and ethylene together account for 60-90PJ/yr of energy consumption if the SEC ranges and capacities along with appropriate load factors described above are employed. This amounts to around 23-34% of total chemicals sector energy consumption in 2006 (BERR, 2007). These are the most energy intensive processes within the chemicals sector. Other processes have been included in the model, however, which are less energy intensive but nevertheless significant. Specifically, these are titanium dioxide and soda ash production, for which the salient data on production capacities is summarised in Table 6-8. Together the five chemicals covered within this section account for about 80-110PJ of final energy consumption, or 31-42% of the chemical sector's total energy consumption in 2006 (op. cit.). In addition, methanol is also an energy-intensive chemical to produce (IEA, 2007), but it is not made anywhere in the UK (Choudrie et al., 2008).

Product/ Chemical	Process	Company	Postcode	Cap. (kt/yr)	Proc. temp. (°C)	Exhaust temp. (°C)
Soda Ash	Solvay	Brunner Mond, Northwich	CW8 4EE	1100	300	150
Total soda ash				1100		
Titanium dioxide	Sulphate	Huntsman, Grimsby	DN31 2SW	40	800	200
Titanium dioxide	Chloride	Huntsman, Hartlepool	TS25 2DD	150	1200	250
Titanium dioxide	Chloride	Millenium Chemicals, Stallingborough	DN40 2PR	150	1200	250
Total titanium dioxide				340		

Table 6-8 – UK soda ash and titanium dioxide production capacity

Source: Chemical Week (2006b, 2007), European Commission (2005c), Brown et al. (1985)

The total energy SEC for titanium dioxide production is 17-29GJ/t for the chloride process and 24-45GJ/t for the sulphate method (European Commission, 2005c). For soda ash production through the Solvay process the total energy SEC is around 7.5-10.8GJ/t (ibid.). The potential for heat recovery from these processes is thought to be 5-10% (Energetics & E3M, 2004). Given the limited information available about the production processes for titanium dioxide and soda ash (the Solvay process), however, they have been included in the model based on the respective sites in the NAP. Three of the sites are CHP units and the other one (Huntsman, Grimsby in Table 6-8) is included within the general chemicals sector. Hence only the latter includes a potential heat recovery, which overlooks the potential at the three other sites. Substantial data was collated relating to polymer production, but because this is incomplete and difficulties

were encountered in determining process routes, polymer production is modelled based on the NAP allocations. Production data for polymers is summarised in Table A2 in Appendix A3.1.

6.3.8 Food and drink

The food and drink sector is only covered by the EU ETS in terms of thermal energy activities. Process emissions within the sector do result from the fermentation process in bread manufacture as well as alcoholic drinks manufacture, but these are excluded from the Scheme. In addition, CO₂ is released from carbonated drinks. As this CO₂ is often sourced as a waste product from other industrial processes such as methanol production, it is not included in the Scheme (even though there is no methanol production in the UK, see above).

The food and drink sector has been broken down into homogeneous subsectors as far as possible, including breweries, maltings, distilleries, and sugar manufacturing plants – through both the beet and cane routes. Nevertheless, along with the chemicals sector, food and drink is one of the most heterogeneous sectors in terms of energy activities. A precise breakdown into independent sectors has therefore not been possible and the results are therefore expected to be less robust than for other sectors.

British Sugar also operates six onsite lime kilns, but the CO₂ emission from these kilns are reabsorbed during the sugar-making process, so they are not given an emissions allocation (Entec UK Ltd., 2006d). These six lime kilns are all shaft kilns, so are included in the Lime_MFSK sector in Table A3 in Appendix A3.1. Details of the lime sector process and assumptions can be found in section 6.3.11

Specification of the remaining food and drink sectors can be found in Table A3 in Appendix A3.1. The temperature demand profile and assumed heat recovery potentials, along with sources for this data, are shown in Table 6-3. Where it has not been possible to determine the specific activities, or where a large variety of activities occur, the installations have been allocated to the generic boiler and steam systems sector. Within this sector, the main energy activities are assumed to be boilers for raising steam, with the fuel split and temperature profiles taken as the average for the whole food and drink sector.

6.3.9 Glass

All large scale glass manufacturing plants with a capacity over 20t/day are included within the EU ETS. This generally covers all large-scale producers of glass but excludes artisans and manufacturers of speciality glass products. In Phase II there are 26 installations, which includes three separate CHP units serving flat glass plants (hence 23 glass furnaces). For the present model, the sector has been further subdivided into four subsectors for flat glass, container glass, other glass and CHP. The main difference between these subsectors is in the specification of the furnace efficiencies and fuel splits (Table 6-3 and Table A3 in Appendix A3.1).

Details of the production process, SECs, and temperatures involved in glass manufacture are presented in chapter 7. The exhaust gases in the stack are at a temperature of around 550°C and this represents around 30% of the total heat input. Hence a range for the fraction of heat lost in the exhaust of 10-20% has been adopted. The process emissions fraction is quite accurately known to be 30% for a cullet fraction of 30%, which is typical for the UK industry at present (WRAP, 2008b).

6.3.10 Iron and steel

Iron and steel plants producing primary or secondary steel at a rate of more than 2.5 tonnes per hour are included in the EU ETS. Proprietary coke ovens within the iron and steel industry are included within the iron and steel sector allocation in the Phase II NAP. This coverage includes 14 sites in Phase II, three of which are large integrated steelworks, seven are electric arc furnaces (EAFs) producing secondary steel, and four are other processing (coating, tin plating and strip mills) facilities owned and operated by Corus.

As for some of the chemicals sector and other sectors with activities not covered by the NAP (e.g. British Sugar's lime kilns), the iron and steel sector has been modelled based on the production capacities and SECs for individual process units. Data on production capacities has been gathered from a variety of public and private sources, including publicly available Corus documents relating to their business activities (e.g. Dryden, 2004). This has been cross-checked with confidential sources (e.g. AEA Technology, 2004) and confirmed by the trade association (Stace, G., UKSteel, pers. comm., January 2009) and Corus (Lewis, B., Corus, pers. comm., January 2009). Capacity data for integrated iron and steel works is difficult to define because capacities are often "constrained by market constraints and the product mix" (ibid.), as well as being interdependent between all units at the works. Hence the results for this sector need to be considered in light of this. SEC data has been mostly obtained from the sector's BREF and benchmarking documents (European Commission, 2001e, 2008c; Entec UK Ltd., 2006b, 2006c) as well as other relevant studies (e.g. Energetics, 2000). The adopted values for these SEC parameters are shown in Table 6-10 below. The potential for heat recovery is based on commercial technologies according to data in the literature (e.g. Worrell et al., 2001, de Beer et al., 1996, IEA, 2007). The remainder of this section gives a detailed overview of the iron and steel sector's activities and the methodology used to model them and estimate heat recovery potential.

Steel production in the UK is concentrated in the blast furnace/basic oxygen furnace route (for primary steel) and electric arc furnace route (for secondary steel). Although there are other methods of steel production, such as that based on direct-reduction iron (DRI), these do not occur in the UK and are therefore not considered here (IISI, 2007). There are three integrated iron and steel works currently in operation in the UK, at Teeside, Scunthorpe and Port Talbot respectively. Details of these sites along with the production capacities used in this study are presented in Table 6-9. From these capacities the heat loads are estimated from the primary fuel use (i.e. electricity is not used for heating except in the EAF). The load factor for integrated

works was taken as 90%, by relating stated capacity to output in 2006 (EEF, 2007). For EAFs, this figure was 80% based on published utilisation rates (Entec UK Ltd., 2006c). The use of 2006 figures for this sector is justified by the fact that output in this year was very close to the average over the period 2000-2003 minus the lowest year (EEF, 2007). The production of primary steel through integrated steelworks involves several key processes, but the crux of any integrated plant is the blast furnace, which is by far the largest energy consumer (European Commission, 2008c). The roles of the individual units in the plant are described below. The SECs and fuel splits for these operations are given in Table 6-10.

Coke ovens produce coke from coal, for use in the blast furnace as a reducing agent and fuel. Within the oven coal is heated for several hours or days to produce coke through pyrolysis. The coal is loaded into the oven and heated by burning gas through flues in the walls. The vast majority of coke production is in slot ovens, which evolved to collect the by-products and manufacture coke oven gas (IEA, 2007). Due to the large amount of feedstock energy input to coke ovens as coal, the net SEC is relatively low at around 3-5GJ/t. The temperature required within the coke ovens is around 1100°C. Aside from the structural (radiant and convective) losses, there are three main enthalpy releases from coke ovens (Bisio & Rubatto, 2000, Ertem & Ízdabak, 2005):

- The incandescent coke at 1100°C accounting for 43-60% of the thermal energy output;
- The coke oven gas (COG) at 650-800°C accounting for 20-30%; and
- The waste combustion gas at around 200°C after some heat has already been recovered, representing 10-18% of the thermal energy output.

The incandescent coke is quenched in order to prevent burn-off and achieve high mechanical stability. Wet-quenching with water is the most ubiquitous process, in which water is sprayed onto the coke under quenching towers which recover some of the steam generated. Coke Dry Quenching (CDQ) is more efficient because much of the sensible heat of the coke is recovered by a counter-flowing inert gas, which is used to raise steam and/or electricity (European Commission, 2008c, p.193). Dry quenching is practiced very little within the EU (i.e. less than 5% share of works), and it is not in use within the UK because of the very high economic cost and associated long payback period (Lewis, B., op. cit.).

The high enthalpy content of the COG is also barely used today (Bisio & Rubatto, 2000). In practice the exhaust temperature must remain above 400-450°C to prevent tar formation on heat transfer surfaces, but this still presents the potential to recover about 30% of the enthalpy from the COG. The primary use for this recovered heat is to preheat the fuel gas mixture. This is not considered in the present analysis because it is a relatively small fraction of the wasted heat, and it is not clear precisely what heat is already being recovered from the COG at the three integrated plants in the UK.

It seems that the sensible heat of the waste gas has only been recovered in a small number of cases, but it is not clear what the potential for this is. Given the low temperature and small

proportion of the overall energy balance that this gas represents, it is also neglected in the present case. The main potential for heat recovery in coke ovens is therefore assumed to be by employing CDQ technology, as detailed in Table 6-12 below.

Site	No. of BFs	Total BF capacity (Mt/yr)	Total sinter capacity (Mt/yr)	Total coke capacity (Mt/yr)	Total liquid steel capacity (Mt/yr)	Capacity as cast (Mt/yr)
Port Talbot	2	4.37	4.75	0.97	4.90	4.70
Scunthorpe	4	4.10	5.10	1.46	4.70	4.46
Teeside	1	3.25	4.20	1.88	3.70	3.77
TOTALS	7	11.72	14.05	4.31	13.30	12.93

Table 6-9 – Production capacities for Corus’s three UK integrated steelworks

Source: Various public and confidential sources, including Lewis (2009, op. cit.)

Operation	SEC (GJ/t)	Fuel split (fraction of total)				
		COG/ BFG/ natural gas	Solid fuel	Electricity	Steam	Other
Coke ovens	2.95	0.93		0.02	0.05	
Sinter strands	1.64	0.08	0.85	0.07		
Blast furnace	14.70		0.75#	0.01	0.24*	
Basic oxygen furnace	1.44	0.19		0.39	0.42	
Continuous casting	0.31			1.00		
Slab mill	2.87			0.36		0.64
Hot rolling	2.43			0.35		0.65
Cold rolling	1.69			0.56		0.44
Pickling	1.27			0.67		0.33
EAF furnace	2.50			0.75		0.25

Table 6-10 – SECs and approximate fuel splits for unit operations in the iron and steel sector

Source: European Commission (2008c), Energetics (2000), Entec UK Ltd., (2006b)

*Actually blasts of hot air; #66% coke and 9% coal

Sinter plants produce the fine powder of iron ore for injection into the blast furnace. Pelletisation is another method of preparing the iron ore, but this is not employed in the UK (AEA Technology, 2004). The technology employed throughout Western Europe is down-draft sintering on continuous travelling grates (European Commission, 2008c). The process involves heating the blended raw materials (including fine ores, additives, recycled materials from downstream operations, etc.) on a travelling grate to temperatures in the region of 1400°C. Cooling occurs at the end of the grate and may be integrated or, more common, separate to the strand (ibid.). Separate coolers layer the calcined sinter up to about 1m thickness in a large rotating structure and cool with large volumes of air, which are forced upwards through the layer. Some heat content of the air may then be recovered in a waste heat boiler, or used to preheat the raw materials. The assumption for this study is that the heat from the sinter cooler is not presently recovered, and that this presents a technical opportunity for heat recovery. This assumption has been confirmed by the trade association (Lewis, B., op. cit.).

The **blast furnace (BF)** is the vessel within which iron ore is reduced by coke at high temperatures to yield pig iron. The furnace is a tall structure with a temperature profile along its vertical height. It is charged from the top with burden, including sinter, coke, flux agents (lime), and blast furnace gas (BFG) is drawn off for use as an on-site fuel. A hot air blast (enriched with reducing agents) is blown in through tubes known as tuyères lower down in the belly of the furnace (European Commission, 2008c). This reacts with the reducing agents to form mainly carbon monoxide, which in turn reacts with the iron oxide to form iron. Molten iron and slag are tapped off from the hearth at the base of the furnace.

The temperature within the blast furnace ranges from 1500°C at the top to in excess of 2000°C in the belly, and the molten iron leaves the furnace at around 1500° (ibid.). Overall, blast furnaces are very efficient with losses representing less than 10% of the energy input (IEA, 2007, p.116). Areas for potential heat recovery include the BFG, the molten iron and the slag. The latter is ruled out here because the technology is only at the prototype stage and development has been halted since the 1980s (Bisio, 1997). The sensible heat of the molten iron cannot feasibly be utilised as the molten metal is transferred directly to the basic oxygen furnace. Any heat recovered from this stream would have to be transferred back into the metal before the BOF. Hence the only technical heat recovery potential for blast furnace streams is assumed to be the BFG. It is estimated that, using a top pressure recovery turbine, primary energy savings of 0.3GJ/tcs can be achieved (Worrell et al., 2001). This value has been confirmed by Corus, albeit with the caveat that the low temperature of the BFG, at 150°C, means that less than fifty percent of the sensible heat content could feasibly be recovered (Lewis, B., op. cit.).

The **basic oxygen furnace (BOF)** converts pig iron into steel by adding oxygen to remove the carbon, as well as small amounts of silicon, manganese and phosphorous (European Commission, 2008c). Molten iron and steel scrap are charged into the furnace and pure oxygen is blown in through a liquid-cooled lance. The most common technology is the Linz-Donowitz (LD) converter, which is a pear-shaped vessel into which the lance is lowered (ibid.). The temperature inside the furnace is around 1700°C, and after secondary metallurgical processes (such as homogenising), the molten steel is transferred to a casting ladle at around 1600-1800°C. The gases produced during oxygen blowing (BOS gas) exit the furnace at the same temperature as the molten steel, and are therefore a suitable target for heat recovery. A potential method for doing this is by using a heat recovery boiler to raise steam (Worrell et al., 2001), as shown in Table 6-12.

Continuous casting is the state of the art method for casting steel. It is a continuous process that replaced its predecessor, batch-wise casting in moulds before reheating for rolling. The molten steel falls from the casting ladle or tundish at first under gravity and then supported by rollers from the casting ladle, gradually reaching the horizontal (European Commission, 2008c). Thus a continuous strand of material is formed, which is then cut with a torch cutter. The main potential for heat recovery at this stage is from the solidified steel when it is at a temperature of around 800°C, with a radiant heat recovery boiler.

The final stages in integrated steelworks are collectively referred to as finishing operations. The first of these is invariably **milling**, whereby the steel is formed into blooms, bars or billets, depending on the final form of the steel required. Relatively speaking the milling process (and other finishing operations) are less energy-intensive than previous ones detailed above. However, the steel still needs to be reheated up to around 900°C in order to be malleable enough to roll. Near net shape casting eliminates this preheating stage by rolling the steel directly, but this technology is not yet widely employed, partly due to concerns about effects on product quality (Worrell et al., 2004). Hence the heat recovery opportunity from this operation is to capture some of the sensible heat contained in the steel after rolling. The technology for doing this is water spraying (de Beer et al., 1998), but in some cases this is not feasible due to product quality requirements. This has been accounted for by reducing the enthalpy that can be realistically recovered from this stream. The assumption here is that this is possible in the majority of cases, and that the potential heat recovery is around 0.3-0.6GJ/tcs (Table 6-12).

Secondary steel is produced through electric arc furnaces (EAFs) in the UK, which are also included in the model for this sector. Details of the furnaces and the capacities used are given in Table 6-11. Within the furnace, which is charged with scrap before being electrically heated in a batch-wise process, the temperatures reach around 1600°C. The off-gas is typically used to preheat the scrap before melting. Recent improvements in SECs for EAFs mean that on average this value is already close to its theoretical minimum (Stubbles, 2000). Further opportunities for savings involve substituting primary fuel for electricity in order to achieve primary energy savings. There is also the possibility of recovering some of the sensible heat from the molten steel as it is tapped off from the furnace. Hence the exhaust gases from EAFs are not considered a likely candidate for heat recovery, and the only potential for this study is assumed to be through utilise some of the heat in the steel in the continuous casting and rolling stages, as described above.

Operator	Location	Capacity (kt/yr)
Celsa UK	Cardiff	1200
Thamesteel	Sheerness	720
Outokumpu	Sheffield	540
Corus UK Ltd	Rotherham	1250
Forgemasters	Sheffield	130
Total EAF route		3840

Table 6-11 – EAF steel capacity in the UK

Source: Entec UK Ltd. (2006c) and Stace, G. (2009, op. cit.)

The heat recovery potentials for each of the above production units have been estimated from data on the sensible heat of various solid and gaseous streams, based on a typical integrated iron and steel plant which is used as a reference case (de Beer et al., 1998). The sensible heat values in these streams are presented in Table 6-12, whereby these values have been used as the upper estimate for heat recovery potential, with a lower estimate at half of these values.

Exceptions to this are where evidence from Corus suggests reasons why this is not technically feasible (Lewis, B., op cit.). Although obviously not exactly the same configuration as UK plants, the reference plant has similar production capacities. The fact that sensible heat content data is normalised per tonne of rolled steel should make its application reasonable in this case.

Process/unit	Process Temp. (°C)	Exhaust temp. (°C)	Recoverable heat in exhaust (GJ/trs)		Exhaust stream (gas/solid)	Technology for heat recovery
			LOW	HIGH		
Coke ovens	1100	1100	0.12	0.24	Hot coke (s)	Dry quenching
Sintering	1350	350	0.49	0.97	Cooler and exhaust gas (g)	Advanced sintering
Blast furnace	1500	150	0.16	0.31	BF gas (g)	Top-pressure recovery turbine w/ dry cleaning
Basic oxygen furnace	1600	1600	0.10	0.20	BOF gas (g)	Gas recovery/ boiler
Continuous casting	980	800	0.25	0.5	Cast slabs (s)	Radiant heat boilers
Hot rolling	900	900	0.31	0.62	Steel (s)	Water spraying; heat pumps
TOTAL			1.43	2.84		

Table 6-12 – Recoverable heat in exhausts of various steelmaking processes

Source: de Beer (1998) and Lewis, B. (2009, op. cit.)

6.3.11 Lime

The lime sector is covered by the EU ETS insofar as kilns with a production capacity above 50 tonnes per day are eligible. In the NAP for Phase II nine installations are included in the Lime sector. Due to the onsite lime kilns owned and operated by British sugar, but not included in their allocations, this sector has been modelled based on the NAP allocations along with supplemented data on these kilns (Entec UK Ltd., 2006d). Details for these kilns are presented in Table 6-13.

The lime sector has been further broken down according to the particular type of technology employed at a given site. This includes long rotary kilns (LRKs), parallel flow regenerative kilns (PFRKs) and mixed feed shaft kilns (MFSKs). All British Sugar's kilns fall within the latter category. Although the type of technology employed has implications for the SEC, the process is essentially the same. Lime production involves calcining calcium and/or magnesium carbonates in the temperature range of 900-1500°C but sometimes higher (European Commission, 2007). The reaction forms the respective oxide (i.e. CaO or MgO) and liberates carbon dioxide. Given the similarity of the process to that of cement manufacture, the assumptions are the same as for the cement sector, as described above.

Site	Postcode	Operational kilns	Operational capacity* (kt/yr)	Energy consumption# (PJ/yr)
Allscott	TF6 5EH	1	30	0.14
Bury St Edmunds	IP32 7BB	2	105	0.50
Cantley	NR13 3ST	1	38	0.18
Newark	NG24 1DL	1	241	1.13
Wissington	PE33 9QG	1	159	0.75
York	YO26 6XF	2	90	0.42
TOTAL		8	663	3.12

Table 6-13 – British Sugar’s lime kiln capacities and estimated energy consumption

***Based on 85% load factor; #Assuming an SEC of 4.7GJ/t**

Source: Entec UK Ltd. (2006d) and Environment Agency (2001)

6.3.12 Pulp and paper

The EU ETS coverage for pulp and paper covers all pulping of timber or other fibrous materials and the production facilities for paper and board with capacities exceeding 20 tonnes per day. In total 64 installations are included in the Phase II NAP, with 19 of these being mainly or wholly CHP units. The remainder of the sites produce paper and tissues of various qualities, with the energy intensity of production being roughly proportional to the paper quality.

For the present study the pulp and paper sector has been divided in two, by separating the solely CHP installations. For non-CHP related installations the heat load is assumed to be derived from boilers and steam systems, and the generic methodology defined above is therefore applied. There are no process emissions from pulp and paper production, therefore the combustion emissions fraction is taken as unity. The scope for improvements in energy efficiency within this sector is estimated to be significant with future technologies, and with new drying methods the net specific heat consumption of paper production could be reduced almost to zero (De Beer et al., 1998). With current technology, however, the scope for improvement through heat recovery is estimated at around 10%, through improvements in drum and Yankee dryers (Energetics & E3M, 2004). There are several suggested measures for improving overall efficiency and recovering wasted heat that, considering their applicability to the industry as a whole and the savings they each stand to achieve, could together achieve around 10%. Hence, as for several other sectors, then potential range for heat recovery is set at 5-10% for pulp and paper.

6.3.13 Other sectors

Other sectors are grouped within the NAP according to Table 6-14. These sectors have been further broken down and grouped into the relevant sectors. Further details are given about the assumed fuel splits and data sources in Table A3 in Appendix A3.1. Otherwise the methodology has been the same as for other (homogenous) sectors as described above.

NAP Sector	Included Sectors
Others A	Gypsum, mineral wool, rock wool
Others B	Aerospace, vehicles, semi-conductors, woodboard
Others C	Munitions, textiles, tyres tobacco, other non-metallic minerals

Table 6-14 – Classification of other sectors in the NAP

6.4 Results

This section provides an overview of the pertinent results of this study. Discussion of the implication of the results and relating them to the initial objectives is contained in the following section. The high and low estimates for recovery potential relate to the ranges detailed in the methodology section. Where the mid-point of this range has been used as an indication it is referred to as the average heat recovery potential.

6.4.1 Heat loads and estimated recovery potentials

The annual energy use for heat by individual sectors, alongside the lower and higher estimated heat recovery potentials, is shown in Figure 6-2. The largest heat user is the iron and steel sector with a demand around 213PJ, with the chemicals sector being the second-largest at 167PJ. Other significant users of heat include the food and drink, pulp and paper, cement, glass and aluminium sectors.

The total estimated heat recovery potential for the industrial sector lies in the region of 36-71PJ (10-20TWh). The largest heat recovery potential is estimated to be in the iron and steel, chemicals, cement and glass sectors. Together these sectors account for about 80% of the estimated savings through heat recovery, with the iron and steel sector accounting for almost half of the total.

6.4.2 Qualitative and spatial considerations

The energy demand for heat is plotted for different industrial sectors against the temperature at which this heat is used in Figure 6-3. This chart is a histogram with bins of unequal width corresponding to the temperature bands detailed in the methodology section. Clearly the iron and steel sector accounts for the vast majority of the heat demand above 1500°C, with a very small proportion being taken by the chemicals sector's carbon black manufacturing. It is also noteworthy that the highest temperature band has the highest total heat demand – around 175PJ are used within this bin.

For the temperature band from 1000°C to 1500°C the split of users is more balanced. The iron and steel sector still has a significant heat demand at these temperatures, alongside the non-metallic minerals sector, which includes cement, lime, glass and ceramics. The medium temperature band, from 500°C to 1000°C, is dominated by the chemicals sector, with smaller demands from the iron and steel and aluminium sectors. Whereas the iron and steel sector has

its heat demand spread over the three highest temperature bands, that for the chemicals sector broaches the three lower temperature bands. The two temperature ranges below 100°C are therefore dominated by heat use in the chemicals, food and drink, and pulp and paper sectors, with smaller demands within other sectors.

Broadly speaking there are two peaks of heat demand, within the low temperature 100°C to 500°C band and within the highest temperature band above 1500°C. These peaks are emphasised if the heat demand by sector is plotted against the Carnot factor, as shown in Figure 6-4. Due to the non-linear nature of the quality function, which is proportional to the *difference* between the process and ambient temperatures, the heat demand at lower temperatures has been stretched along the x-axis. For the same reason the peak at much higher temperatures has been compressed in the same direction.

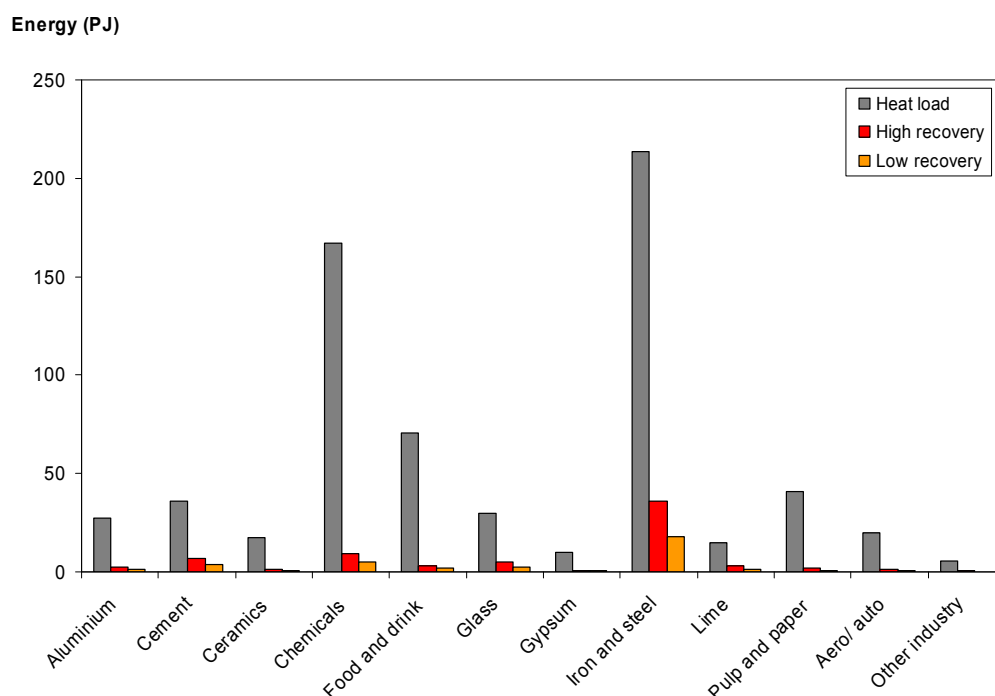


Figure 6-2 – Energy use for heat (heat load) and estimated recovery potentials for industrial sectors

Electricity is shown as the peak with a thermodynamic quality of unity in Figure 6-4 because of its versatility in meeting heat and power demands. In theory much (or all) of the energy used at higher qualities can be reused at lower qualities, or cascaded down the quality scale. Hence the heat used almost exclusively in the iron and steel sector with a thermodynamic quality above 0.85 could be used to supply some of those demands at lower temperatures. The same can also be said of the peak from 0.27 to 0.65. However, in practice the feasibility of heat cascading is limited by the temporal and spatial coincidence of the heat source(s) and sink(s). The temporal demand profile of industrial heat loads is not considered here because it lies beyond the objectives outlined in section 6.2. The spatial distribution of these heat loads is of interest, though, because this was one of the objectives. Hence the spatial distribution of heat loads and

estimated (average) recovery potential is shown plotted against the weighted thermodynamic quality factor in Figure 6-6.

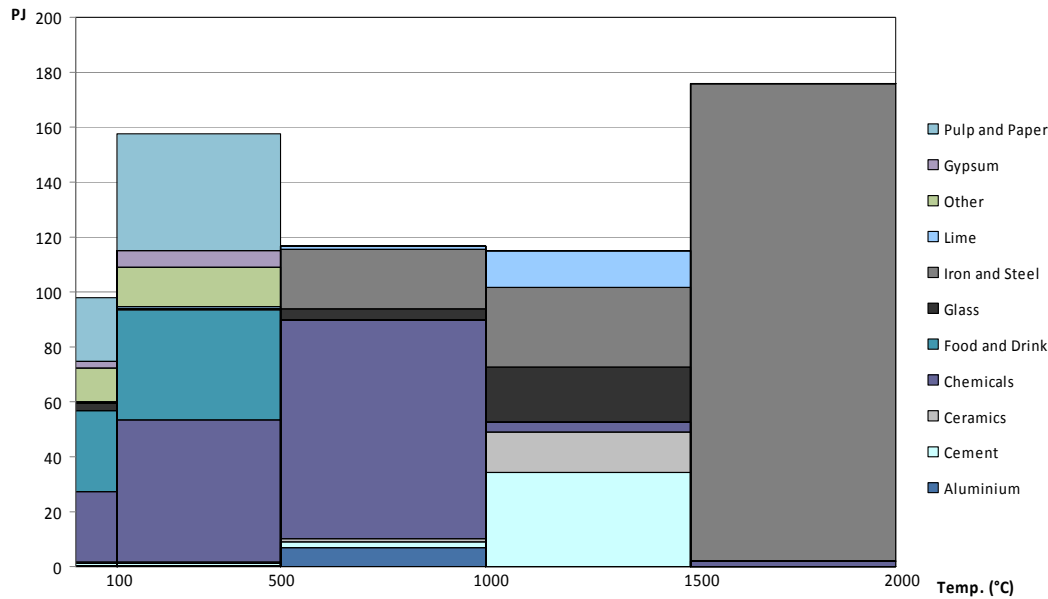


Figure 6-3 – Heat demand against temperature for industrial sectors

It is clear from Figure 6-6 that the majority of the high temperature recovery potential is at the three integrated iron and steelworks. Although there are other industrial heat demands in the vicinity of these works, the number and variety of these heat loads is smaller than in other areas of the UK. There seems to be a significant concentration of industrial heat loads within the area enclosed by a triangle with corners approximately located at Birmingham, Manchester and Leeds. The density of heat loads is particularly high in the region around Chester, and the large variation in colour in this area suggests that there might be technical potential for heat recovery and/or sharing between sites.

Another general trend in Figure 6-6 seems to be that the total heat load, and indeed the recovery potential, is concentrated in a small number of sites. Comparison with Figure 6-2 verifies that this is indeed the case, with iron and steel and chemicals being the key sectors. Hence there is a “background” of relatively small heat loads, with only marginal recovery potential, upon which the larger ones are superimposed. This can be seen more clearly in Figure A7 in Appendix A3.1, which shows all heat loads above 100MW along with the range of estimated heat recovery estimates. It is clear from this chart that the heat recovery potential is not just proportional to the heat load, as shown by the many sites with smaller heat loads and a substantial potential. The sites with no recovery potential are CHP units (cf. section 6.3.3). The highest heat loads are at the three integrated iron and steel works, followed by three steam crackers, two aluminium smelters and then mainly chemicals, food and drink, pulp and paper, cement and glass sites. These 26 sites account for 60% of the total estimated heat load.

Although around half of the heat recovery potential is estimated to be in the iron and steel sector, not all of this is at high temperatures. In fact the majority of heat recovery is estimated to be within the temperature band from 100°C to 500°C, as shown in Figure 6-5.

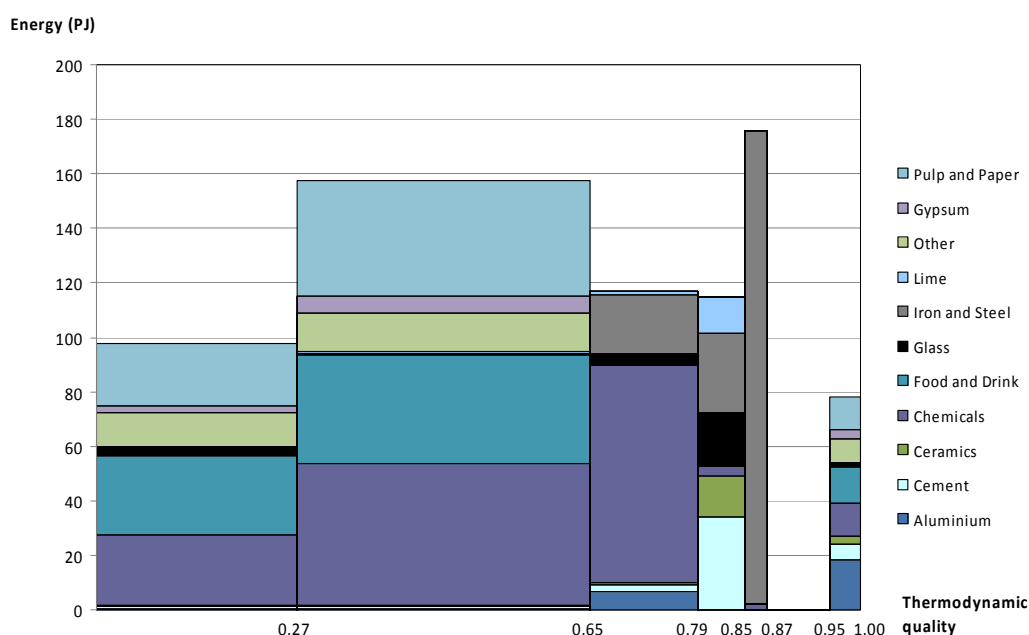


Figure 6-4 – Heat demand against thermodynamic quality for industrial sectors

6.4.3 Contextualisation of results

In order to appreciate how well this model corresponds to national statistics, the results have been compared to the ECUK dataset (DTI, 2007b), the most highly disaggregated data available on industrial energy use in the UK. Although offering higher resolution than DUKES, ECUK suffers from lower accuracy (section 3.1). The estimated total energy use for each industrial sector is shown alongside the respective ECUK totals in Table 6-15. These totals are the average values from 2000 to 2003 minus the lowest year (cf. section 6.3.1), except for iron and steel where the ECUK figure corresponds to 2005 because more recent production capacities were used.

Also shown in Table 6-15 are the sector totals in primary energy terms from the model against the second period (Target Period 2, TP2) results of the Climate Change Agreements (CCAs), which ran from 2002-2004. The conversion to primary equivalents within the model has been carried out by multiplying electricity use by 2.6, which is the reciprocal of the overall grid efficiency of 38% used by DEFRA (2007c) in converting electricity into primary energy terms. The CCA results could not be summed for “other industry” sectors because of differences in coverage and problems with allocation of activities.

Most sectors show a good agreement with the ECUK data. This is especially the case with energy-intensive sectors because the primary dataset, the EU ETS NAP, is focussed on energy intensive activities. Hence the coverage of other industry, which includes *inter alia* the non

energy-intensive sectors textiles and wood products, is very poor. In a few specific cases the correspondence with ECUK is weaker. The primary energy results, however, show a very good correspondence with the CCA results from TP2. These comparisons, and reasons for these discrepancies will be discussed in more detail in section 6.5.

6.5 Discussion

The fact that the majority of industrial heat demand is accounted for by a small number of sectors is not surprising, for the same sectors are widely understood to be the most energy-intensive ones. By definition, excluding feedstock energy which is not considered here, fuels are used to generate heat, hence there is a direct correlation between fuel consumption and heat use in these sectors. Hence the sectors with the highest heat loads are those carrying out primary (material) processing operations. Perhaps more surprising is that the heat recovery potential is not in all cases directly proportional to the total heat load for the sector. Although the largest heat loads present the largest potentials for recovery, some of the sectors with relatively low total heat loads seem to have a significant potential for improvement. Overall the heat recovery potential for individual sectors seems very small in comparison to their total heat load. But close inspection of Figure 6-2 reveals that the recovery potential within the iron and steel sector is roughly equal to the total heat demand in some other sectors.

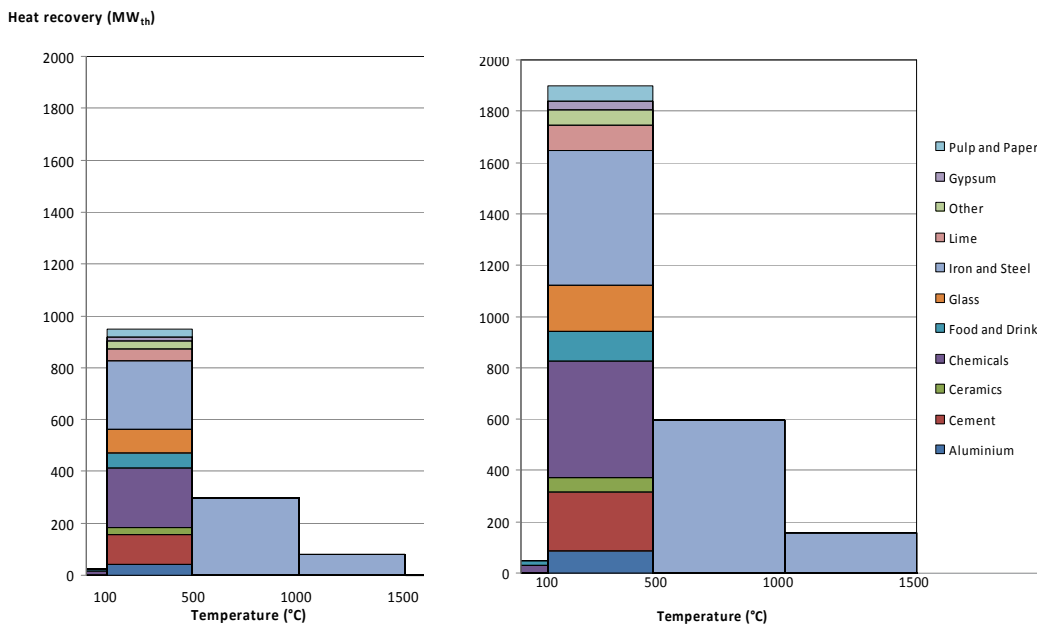


Figure 6-5 – Low (left) and high (right) heat recovery potential by sector against temperature

The number of installations covered in each sector is worthy of attention because this greatly affects the scope for realising the heat recovery potential identified in this study. Clearly the largest potential, in the iron and steel sector, is focussed at the three large integrated works and to a lesser extent at the seven EAFs. This sector has the highest geographical concentration of both heat loads and estimated savings of all the sectors studied (Figure 6-6). For other sectors, though this “density” of the heat use and savings is less obvious, hence these figures are

detailed in Figure 6-7, which omits the iron and steel sector as it has very large potentials per site – in the range 1.8-3.6PJ/yr. The total industry bars in Figure 6-7 include the iron and steel sector.

Sector	Final energy use (PJ)		% share	Primary energy use (PJ)		% share
	This model	ECUK average 2000 to 2003 minus lowest		This model	CCA TP2 2004	
Aluminium	26	29	89	56	63	89
Cement	44	17	258	53	56	95
Ceramics	19	12	160	24	23	104
Chemicals	203	271	75	230	279	82
Food and drink	83	163*	51	104	127	82
Glass (incl. rockwool)	29	26	110	31	38	82
Iron and steel	251	222 ^Δ	113	294	308	95
Lime	16	2 [‡]	703	17	10 [§]	170
Pulp and paper	78	106 [^]	74	98	98	100
Other industry	39	450	12	49	N/A	-
TOTAL INDUSTRY (SIC 15-37 excl. 23.2)	788	1300	61	944	~1200	79

Table 6-15 – Industrial sectors' total energy use – comparison of results with ECUK and CCA

***Includes tobacco; [‡]11PJ from 1996-1999; [§]Excludes in-house production; [^]Includes publishing; ^Δ2005 data to reflect recent production capacities used;**

Compared to the industry average, that is for all sites included within this study, the aluminium, cement, lime and glass sectors all present above average concentrations of estimated recovery potential at a small number of sites. The concentration for the chemicals sector is in fact biased by the non-homogeneity of the sector, which resulted in many sites being lumped together as boilers and steam systems (section 6.3.7). Certainly the two sectors to concentrate on primarily, apart from iron and steel, would be aluminium and cement.

Comparison of the sector level results with those published in ECUK has been carried out by way of comparison, and the correspondence is good for most sectors (Table 6-15). There are a few sectors for which the estimated total energy use from this model exceeds that in ECUK. In general the reason for this is probably the inaccuracy of the ECUK data, which is based on survey data from the Annual Business Inquiry (ONS, 2008a), which is then scaled up to roughly correspond with DUKES. A similar procedure has been employed to compare the model's results with CCA TP2 results for the sectors, which in most cases shows good agreement. The CCA for the iron and steel sector includes some downstream processing activities that are not covered by the model. In general such activities only account for a small fraction of the total energy consumption because it is the primary steel production itself that is very energy intensive (European Commission, 2008c). Hence the comparison of the results for this sector with the CCA is a reasonable one in this case.

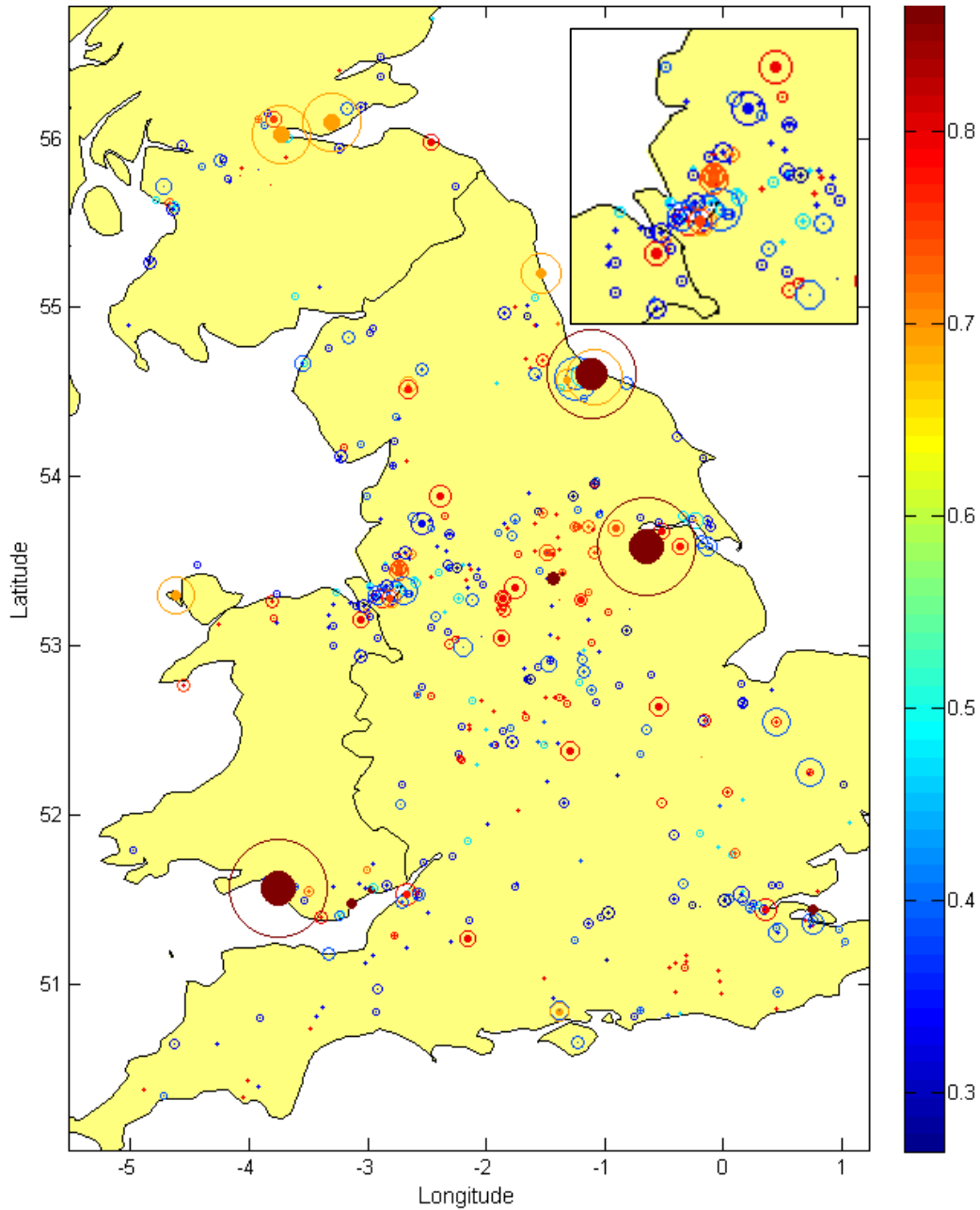


Figure 6-6 – Distribution of industrial heat loads (empty circle) and recovery potentials (solid circle) against thermodynamic quality parameter (colour), for the UK and the area around Chester (inset)

The sectors with the largest differences to ECUK in Table 6-15 are the non-metallic minerals sectors, which are also the only sectors modelled based purely on the NAP with process emissions. Whilst too much emphasis should not be placed on the ECUK data, this does raise some uncertainty relating to the combustion emissions fractions underpinning the results from these sectors. The factors employed for the cement, lime and glass sectors are considered to be reasonably accurate because they are based on previous detailed studies of these sectors (section 5.4 and Appendix A3.1). In addition, the primary energy results for these three sectors are all in close agreement with the CCA results from TP2. The reason for the discrepancy for the lime sector is that the CCA only covers merchant facilities and some in-house facilities,

whereas the model has included all lime production. Most notably, the lime sector CCA does not cover in-house lime production for British Sugar and Corus (DEFRA, 2001b).

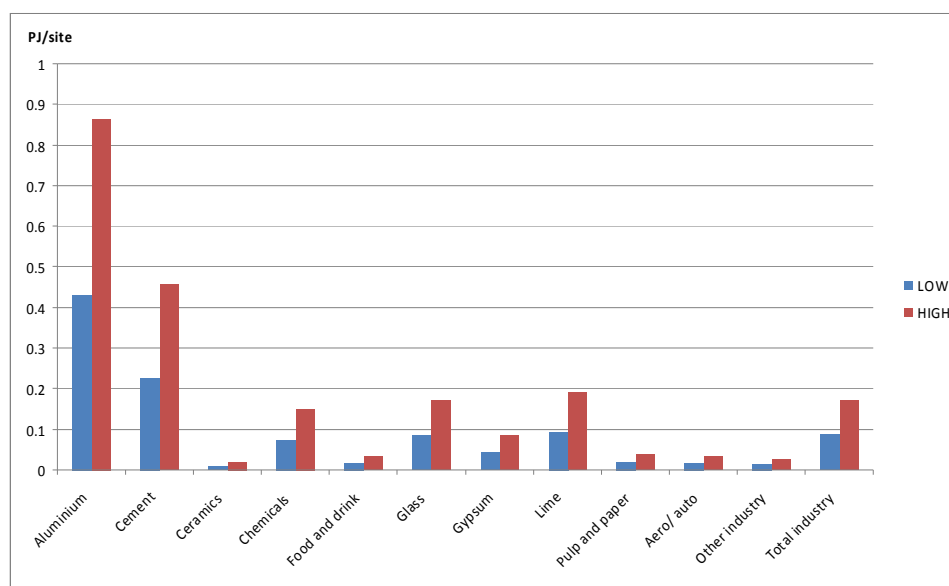


Figure 6-7 – Average estimated heat recovery potentials per site for all sectors except iron and steel

The combustion emissions factor employed for the ceramics sector, however, has a higher degree of uncertainty associated with it. This can be seen from the fact that the model overestimates the sector's energy consumption in both delivered and primary terms relative to ECUK and CCA results respectively. This uncertainty is mainly due to ignorance about the types of bricks being manufactured at a particular site. As outlined in section 6.3.6, the process emissions from brick manufacture are heavily dependent on the raw material, type of brick, and kiln type etc. Whilst the latter is known to be quite consistent across the industry (Beardsworth, D., op. cit.), the other variables are not. The benchmarking study for the ceramics sector (Enviros Consulting, 2006c) suggested a combustion emissions fraction of around 60-73%, depending on the type of brick being produced. This is significantly higher than the 50% employed here, and would have resulted in a total final energy consumption for the sector of up to 27PJ. The implication is that the 19PJ end-use energy figure from this model for the ceramics sector could in fact be an underestimate. It is more likely, in fact, that the model has slightly overestimated the total energy consumption of this sector, because the CCA data corresponds to five sectors in total, only two of which are covered by the model (i.e. fletton and non-fletton bricks).

The discrepancies with the ECUK data, along with the fact that it is not a highly accurate source, mean that it does not provide a fair basis against which to assess the outputs from the current model. Instead it serves as an indication of the order of magnitude check on the results, to check whether they are roughly similar. Certain sectors are also covered by DUKES, so can be compared directly. These include food and drink, chemicals, pulp and paper (and publishing), as well as iron and steel, but the latter excludes activities associated with coke production and use in the blast furnace. On a more disaggregated level DUKES cannot serve as

a cross-check, especially for the non-metallic minerals sectors, which are all grouped into “other industries”.

The only sectors about which there is a significant, unexplained discrepancy according to the comparison with the CCA data are the other industry sectors – in other words the non energy-intensive sectors. The poor coverage of these sectors is due to the non-energy intensive nature of their activities, which means they are not covered (or only to a limited extent) by the EU ETS. Some of them do have CCAs, including the automotive, aerospace, metal forming, textiles, leather and wood products sectors, which could be used to determine company locations and production information. However, extrapolating the correlation above, that the energy-intensive sectors have the largest overall heat loads, these small non energy-intensive sectors probably do not have significant heat demands.

The total estimated potential for heat recovery from industrial processes, of 36-71PJ (10-20TWh), is in good agreement with the only other studies of this potential known to exist (see section 6.1). The estimated potential in this study is at the lower end of the range between these figures, which was from 65PJ (18TWh) to 144PJ (40TWh). This is probably due to the conservative approach employed in estimating the technical potential in this study, and also because of its restricted coverage of certain sectors. Details are not available relating to the breakdown of potential savings by sector for these two studies, mainly because of their commercially sensitive nature, such that a detailed comparison of the results is not possible.

The temperature demand profile for the sectors studied suggests that there is significant scope for heat cascading of energy down to lower qualities. This appears especially to be the case at high temperatures for the iron and steel sector, and at medium temperatures (100-500°C) from various sectors. In theory this recovered energy could be used to meet heat demands at lower temperatures, but in practice this is limited by temporal and spatial constraints. The former have not been considered in this study, but the latter have. Indeed, the high temperature heat is used almost exclusively in the three integrated iron and steel works, so the heat would have to be used at or in the vicinity of these plants. The heat used at medium temperatures is more evenly distributed throughout the UK, along with the loads at lower temperatures which might be partly met by it (Figure 6-6).

It might be the case that the best use for recovered heat is onsite, in which case these spatial considerations are less significant. There are clearly other heat loads that have not been included in Figure 6-6. Perhaps most significant of these are the heat loads associated with buildings for space heating, which are often met in the Scandinavian countries by district heating schemes using heat recovered from industrial processes (Werner, 2006). Where a demand does not exist onsite for recovered industrial waste heat, there are currently barriers in place to it being used elsewhere, including other industrial sites and non-industrial buildings. The most significant of these is the lack of infrastructure for transporting heat (i.e. heat networks). If these were extant then industrial heat users would not necessarily have to find a use or user for recovered heat; instead it could be fed into district or regional heat networks for

use, as appropriate, for space heating. However, this sort of arrangement relies on companies being bound by contracts for supplying heat, which is not always an attractive option for firms focussed on maintaining production. There would also be some degree of variation in the quantity and quality of heat that it is possible to supply to the network. As this variation would not necessarily match the demand profile, some kind of correction would be necessary.

6.6 *Critique of methodology*

Having discussed the results in general and compared them to other sources, this section assesses the methodology employed with a particular focus on the weakest and/or most sensitive aspects. The outputs from the model are very sensitive to a few input variables, in particular the total emissions allocation, the combustion emissions fraction, the fuel split, the SEC and the capacity/output employed. Other parameters such as the load factors and efficiencies do have an effect on the results, but this is marginal in comparison to these other variables. As mentioned above, these two variables cancel out in Equation 6-4 for some sectors; even where they do not, their overall effect is small.

Clearly the total emissions allocation is beyond the scope of this work; any errors resulting from this parameter must be due to errors in the allocation procedure. The assumption on employing the NAP is that the data is accurate. Due to the allocation being based on an average of three years, it potentially overlooks changes in production that have occurred since then. The advantage of using an average value is that it reduces the chance of employing anomalous data from one year in particular.

The combustion emissions fraction is an important variable in the model, but it only has values other than unity for sectors producing non-metallic minerals, as discussed above. The site/sector's total energy use is linearly proportional to this parameter according to Equation 8-2. It will therefore not be further discussed here. Another parameter in Equation 8-2 is the sector's overall emissions factor, to which the site total energy use is inversely proportional. The emissions factors vary from 11tC/TJ for coke oven gas to around 27tC/TJ for coal use in the cement sector (Table 6-2). The overall emissions factor is dependent upon the fuel split employed for the sectors, which in turn are taken from a variety of sources (Table A3 in Appendix A3.1). Where alternative data was not available these fuel splits have been taken from ECUK, which in light of the preceding discussion is an unreliable source. In most cases these figures have been checked with the trade association, but for the few sectors where they have not there is an uncertainty introduced by using this data.

The SEC-based methodology applied mainly for the chemicals, iron and steel, lime and aluminium sectors is also sensitive to a few key variables. In this case it is the particular SEC and capacity employed. In many cases the BREF documents contain many separate process routes for the same product. If it is not clear exactly which route is being employed at a particular site, uncertainties are introduced by assuming one particular route or taking an

averaged SEC value. The capacity employed is less variable; when used in conjunction with an appropriate load factor it should give a good indication of the actual output from a given site.

Another crucial element of the methodology, which affects both the NAP-based and SEC-based approaches, is the way in which the thermodynamic considerations were integrated into the model. Firstly, where the SEC-based approach was used to estimate heat loads and savings there was inevitably some ambiguity about the fraction of the SEC that was required as heat. In general, therefore, it was assumed that the fuel use for a given process accounts for the heat fraction, and in most cases it is possible to obtain purely fuel-based SEC values. The problem with this approach is that it overlooks the use of electricity for heating. It is not that this energy use is excluded from the model; it is accounted for, but the heat demand is assumed to be met by combusting fuels rather than with electricity. The distinction between electricity used for heat and power is therefore ambiguous within the model although the total final energy is the same as it would be otherwise. As mentioned above, there is very little data on the split between electricity use for heat and power in industry, which was reflected in the development of this model.

Another salient aspect of the thermodynamic methodology is the way in which the temperature demand profiles for sectors were determined. Data on industrial energy use by temperature is also very scarce and the only public source is the ECUK end-use breakdown. As well as being unreliable, as discussed above, this source only distinguishes between low temperature and high temperature processes, whereby the boundary between the two is around 250-300°C (Knight, J, Energy Markets Units, BERR, pers. corr., May 2007). The approach in this study was therefore to estimate the fraction of energy (heat) used in each of five temperature bands, as detailed in Table 6-3. This estimation was based on background knowledge of the processes occurring within individual sectors, obtained from previous work in the area and supporting literature such as the BREF documents. It is not intended to be highly accurate, but instead reflects the approximate distribution of energy use by temperature in these sectors. In the absence of any available data this was considered to be the most suitable means of incorporating thermodynamic quality aspects into the model. Furthermore, the Carnot factors have only been used qualitatively and do not quantitatively affect absolute heat loads or recovery potentials. Instead they are intended to offer an insight into the quality of the heat demands determined.

Finally, there are a few other areas that deserve attention here, because the results have provoked questions surrounding the underpinning methodology. The potential for heat recovery at low temperatures has probably been underestimated. This is because the exhaust temperatures from boilers and steam systems were lumped together at 150°C (Table 6-3), which represents an average over the range 50-300°C, say. The fact that the lower temperature band employed was 0-100°C means that the lower end of this averaged range is included in the higher temperature band at 100-500°C. Hence some of the heat recovery potential identified within the latter band is probably in the lower (former) band. This does not affect the total potential identified, however.

Similarly the estimated heat recovery potential (but not the total heat load) has probably been underestimated for some sectors, especially, food and drink, pulp and paper, and chemicals. This is due to the fact that a large proportion of these sectors are modelled simply as boilers and steam systems, with only marginal potential for improvement. In actual fact the savings for the pulp and paper sector through systems level integration have been estimated to be around 30% (IEA, 2007), and in the long term the heat savings are up to 90% (De Beer et al., 1998). For chemicals the systemic potential is estimated at greater than 10% (Jochem, 2000). This could only be more suitably reflected in the model if the sectors were further broken down, the SEC based methodology was improved (e.g. for chlorine) and the savings were determined on a site (as opposed to sector) level.

6.7 Suggested improvements and areas for future work

The preceding section has identified some limitations with the methodology employed. These are clearly areas where the modelling technique could be improved, but it lies beyond the scope of this study to do this. This section therefore provides some suggestions for where attention could be focussed to improve the robustness of the existing methodology. There are ways in which the existing model could be improved and potential avenues of enquiry which the results have shown might be worthwhile exploring.

In terms of improving the existing methodology, clearly the points highlighted in the preceding section could be addressed. Firstly, the combustion emissions factors, in particular for the non-metallic minerals sectors, could be improved based on more detailed calculations. Especially for the ceramics sector, more accurate data relating to split between process and combustion emissions should be sought. In order to do this the brick sector should ideally be broken down into further sectors, each manufacturing different types of bricks, and each site allocated to the relevant sector. The crucial problem here is determining what type of bricks are manufactured at each site. High-level data on output by brick type and material is available in BERR's (2008h) Monthly Statistics of Building Materials, but one category of material (sand-lime) is suppressed and lumped with clay, ostensibly for commercial confidentiality reasons. It also breaks down output of these materials by region, which might be used in conjunction with site level data to determine a regional average output split, which would probably be more accurate than the present industry average that is employed. Some site-level data can be gleaned from company websites and annual reports relating to the type of bricks produced at each site, but this is by no means comprehensive.

Several other improvements to the methodology could be made. Many of these are aimed at improving the accuracy and resolution of the results. Given that the initial objective was to gain an overview of heat use in industry, they are beyond the scope of this work, but in adopting the methodology for other similar applications they should be considered:

- **Update the dataset** upon which it is based, perhaps by using the Phase III NAP when it is published in the next few years. The same applies to the SEC-based approach, whereby the individual product capacities should be checked with the trade associated and updated as appropriate.
- **Seek clarification of the temperature-demand profile** for individual sectors, which would involve cross checking with other sources.
- **Clarify the specification of exhaust temperatures**, especially from boilers and steam systems. Particular focus should be placed on exhausts below 100°C, which might have been lumped together in the average exhaust temperature used of 150°C.
- **Consider the temporal aspect** of heat loads and this might affect the estimated potential for recovery. The most important considerations are probably the diurnal and annual variations in load, as well as any downtime for maintenance.
- **Improve the coverage of non energy-intensive sectors**, which due to the nature of the primary data source have been largely excluded from this work.
- **Clarify the fuel split for specific sectors** where this is based on ECUK data.
- **Consider the economic constraints** on heat recovery, and therefore the fraction of the identified technical potential that is currently economic. Another question is what carbon price would be necessary in order to incentivise some of the heat recovery that is currently uneconomical.
- **Select specific technologies** for specific sites/sectors and thereby identify exactly how these savings would be realised in practice.
- **Clarify the distinction between electricity use for power and heating**, which is necessary if the use of heat in industry is to be understood from a thermodynamic perspective, in the context of an evolving energy supply system.
- **Improve the capacity-based methodology**, to better account for specific process routes (where this is ambiguous) and to reflect more accurately the integration of several process on any one site (e.g. for the chlorine sector).

In terms of developing and/or applying this methodology elsewhere, it might be instructive to use a similar approach to model industrial sectors in other countries based on the same data source (i.e. the NAP for that country). Alternatively, a similar approach could be applied to other sectors in the UK, in order to fill in some of the gaps in understanding the spatial distribution of heat loads in Figure 6-6. It would be particularly relevant to consider the heat demand for space heating of buildings, in the domestic, commercial and public sectors as these together account for the largest (although most disperse) proportion of overall heat use (BERR, 2008d). Certainly for the industrial sector, the distinction between energy (or heat) use for processes and space heating is somewhat of a grey one (Brown, 2005; BRE, 2002), which could perhaps be clarified by such an extension to this work.

6.8 *Conclusions and recommendations*

The heat demand and technical recovery potential based on commercial technology has been estimated for the industrial sector, with an emphasis on energy-intensive industries. Around

60% of industry has been covered in terms of energy use, and 90% of energy-intensive sectors. The total annual heat use for these sectors was estimated at 650PJ, with technically feasible annual savings in the region of 36-71PJ (10-20TWh). This is in agreement with the only extant estimates for heat recovery from industrial processes, which are 65PJ (18TWh) and 144PJ (40TWh) respectively.

The largest heat loads are in the iron and steel, chemicals and food and drink sectors. The greatest potential for heat recovery is in the iron and steel, chemicals, aluminium and non-metallic minerals sectors, and lies mainly in the 100°C to 500°C temperature range. Heat recovery at higher temperatures is feasible only in the iron and steel sector. Although the largest proportion (around 50%) of the estimated recovery potential is in the iron and steel sector, the potential in other sectors is typically not proportional to the total heat load. The density of the heat loads (i.e. normalised by the number of sites) also differs greatly between sectors. The consequence is that there are several sectors apart from iron and steel with only moderate total heat loads, where savings could be realised by targeting a small number of sites. Most notable are the aluminium and cement sectors, where average savings of 0.6PJ/site and 0.3PJ/site are technically possible (the figure for iron and steel is 2.7PJ/site).

The iron and steel sector is by far the greatest user of high temperature heat at over 500°C. At medium and lower temperatures the demand for heat exists in many sectors, with the greatest diversity in the temperature band 100-500°C. There is technical potential to reuse some of the high temperature heat at lower temperatures, but in practice this will be constrained by the extent of heat sinks in the vicinity and the temporal variation in loads. The latter has not been considered in this study.

The coverage of sector activities shows a very good correlation with published data on overall energy use from the Climate Change Agreements. There remains some uncertainty surrounding the specification of the combustion emissions fraction for the ceramics sector, however, which has resulted in a slight over-estimated of the sector's total energy use. The estimated heat recovery potential for some sectors has probably been underestimated, especially for the pulp and paper, food and drink, and chemicals sectors. This is due to the approach used to estimate savings from boilers and steam systems, whereby the savings through heat recovery and system optimisation were set in the range 5-10%. In fact the systemic potential for these sectors in the medium to long term is much higher than this. There is also some remaining uncertainty surrounding the potential for heat recovery at temperatures below 100°C, due to the way in which boiler exhaust temperatures were averaged to 150°C, which meant that exhausts at lower temperatures were lumped into the higher temperature band at 100-500°C. Suggestions have been made for where future work should focus, such as obtaining better data for the ceramics sector and considering heterogeneous sectors in greater detail.

This study provides some answers to questions raised in the Heat Call for Evidence (BERR, 2008f), in particular those concerning the amount of surplus heat exhausted to the environment

by industry, and reasons why this is necessary (Q.19). It also helps to suggest areas where the government should collate data on industrial heat use and waste (Q.24). By modelling sectors based on emissions allocations and capacities/outputs this study has highlighted the weaknesses of the ECUK dataset relating to industrial energy use. It has thereby shown that reliable industrial energy statistics at high levels of disaggregation can be developed in this way. Notwithstanding the limitations of its methodology, this study has provided a good indication of industrial heat use and technical recovery potential in the UK.

7 Energy and exergy analysis of a glass furnace³⁸

This chapter presents an energy and exergy analysis of a cross-fired regenerative glass furnace, based on a model developed to reflect the state of the art in the industry. The analysis is intended to give an insight into the exergy flows through a typical British furnace and to enable CO₂ emissions to be accurately estimated in different operating regimes. The chapter begins with a short introduction to the sector and glass manufacture, before reviewing the literature on thermodynamic analyses of glass furnaces. The methodology is then presented in detail followed by results and discussion sections. The chapter closes with conclusions and recommendations.

7.1 Introduction

7.1.1 Background to the glass sector and glass manufacture

Glass manufacture is a very energy-intensive activity that requires significant fossil fuel inputs at a high capital cost, and produces significant quantities of combustion and process related CO₂ emissions. The combustion and process emissions of CO₂ for the sector were around 1.9MtC in 2003 (DEFRA, 2007e) and in the region of 2.3MtC in 2007 respectively (DEFRA, 2007d). In 2005 the UK glass sector accounted for some 22PJ (1.5%) of total industrial delivered energy use (DTI, 2007b), although the heat modelling reported in chapter 6 suggests a figure substantially higher than this. This energy is mainly used in the production of container and flat glass, which account for approximately 61% and 27% of total production by mass in 2004 (British Glass, 2004). The fuel split for the sector as a whole is around 80% natural gas, 14% electricity, 4% heavy fuel oil, and 2% gas oil (Entec UK Ltd. & NERA Economic Consulting, 2005).

Container glass is mainly used for packaging in the food and drink sector, whereas flat glass has its main applications as glazing in the construction and automotive industries. These three sectors together account for around 90% of demand for glass manufactured in the UK (British Glass, 2004). In 2002, domestic output of container and flat glass was 1.70Mt and 0.70Mt respectively (ibid.). These values stood at 2.3Mt and 1.0Mt respectively in 2007 (Hartley, 2007b). The estimated total capacity for the sector is shown in Table 7-1. The level of international trade within the sector is relatively low because of the low cost of the raw materials, which means glass is manufactured close to the demand for it. Hence the import penetration of all glass products in the UK remained steady at around 20% over the period 1992 to 2004, and their export share has similarly been quite constant at 14% during this time (ONS, 2006c)³⁹.

³⁸ This study was presented by the author at the 4th European Conference on the Economics and Management of Energy in Industry, in Porto, Portugal, November 2007. The presented paper is attached in Appendix A1.3.

³⁹ These two terms were defined in section 5.3: import penetration refers to the fraction of total demand which is met by imports, and export share is defined as the percentage of total supply that comes from exports.

The industry is generally concentrated in and around Yorkshire, mainly because of the abundance of sandstone and limestone deposits in the vicinity (BGS, 2006), and also because coal was conventionally used as the main fuel and is profuse in the region. Approximately 1.9Mt of the UK's 3.8Mt of total annual production capacity is situated in this region (Table 7-1). Soda-lime glass is the most common type of industrially manufactured glass (European Commission, 2008b). The main raw materials in this type of glass are Silica (SiO₂, from sand) and calcium oxide (CaO, from limestone, which contains calcium carbonate, CaCO₃), accounting for 72% and 11% respectively by mass (British Glass, 2004, p.10). The remainder is 13% sodium oxide (Na₂O, from soda ash) alongside 4% other minor ingredients, which depend on the specific application for the glass.

Company	Location	Furnaces	Average furnace capacity (t/day)	Total annual capacity (kt/yr) ⁴⁰
Rockware	Knottingley, Leeds	3	220	240
Rockware	Wheatley, Doncaster	3	350	380
Rockware	Portland, Irvine	2	300	220
Rockware	Barnsley	3	270	300
Allied Glass	Leeds (2 sites)	3	240	260
O-I Manufacturing	Alloa, Sterling	4	250	370
O-I Manufacturing	Harlow, Essex	2	250	180
Beatson Clark	Rotherham	2	160	120
Quinn Glass	Elton, Cheshire	2	380	280
Quinn Glass	Derrylin, Co. Fermanagh	2	550	400
Stolze	Knottingley, Leeds	1	120	40
Total Container		28	3100	2800
Pilkington	St Helens	3	680	500
Guardian	Goole, East Riding	1	620	230
Saint Gobain	Selby	1	600	220
Total Flat		5	1900	950
Total		33	5000	3800

Table 7-1 – UK glass sector production capacity (Hartley, A., British Glass, pers. corr., March 2009)

The furnace typically accounts for 75% of the energy used in a glass manufacturing plant (European Commission, 2001b) and all of the process-related, as well as 90% of the combustion-related, CO₂ emissions (Enviros Consulting, 2006d). It has therefore been, and continues to be, the focus of many efforts to increase the energy efficiency of manufacture. The state of the art for both types of glass manufacture is cross-fired or end-fired regenerative furnaces, with roughly 50% of UK capacity met by each type (Hartley, 2007b). Hot combustion and batch gases pass through a regenerator, where much of their heat content is recovered when the direction of the flow is reversed periodically (typically every twenty minutes) as the pre-

⁴⁰ That is, at 100% utilisation. A more practical utilisation factor of 85% makes the total capacity around 3200kt/yr.

combustion air is then preheated (Figure 7-1). Furnaces operate continuously in campaigns of ten to twelve years for container glass and up to fifteen for flat glass.

7.1.2 Theoretical and actual energy requirements

Analytical thermodynamic approaches have enabled the theoretical minimum energy requirements for glass melting to be determined, which is known to consist of three main components (Kröger, 1953; Beerkens et al., 2004). These are the enthalpy of the glass at a high temperature, the enthalpy of the exhaust (batch) gases and the heat of reaction required to drive the chemical reaction. Typical values for these three components are depicted in Table 7-2, the values of which are based on using only raw materials. There is an energy and carbon saving resulting from using cullet (recycled glass), because the heat of reaction is not required and no batch gases are produced. The theoretical energy requirement for a batch consisting of 100% cullet is therefore 0.6-1.2GJ/t less than that for wholly raw materials (Table 7-2).

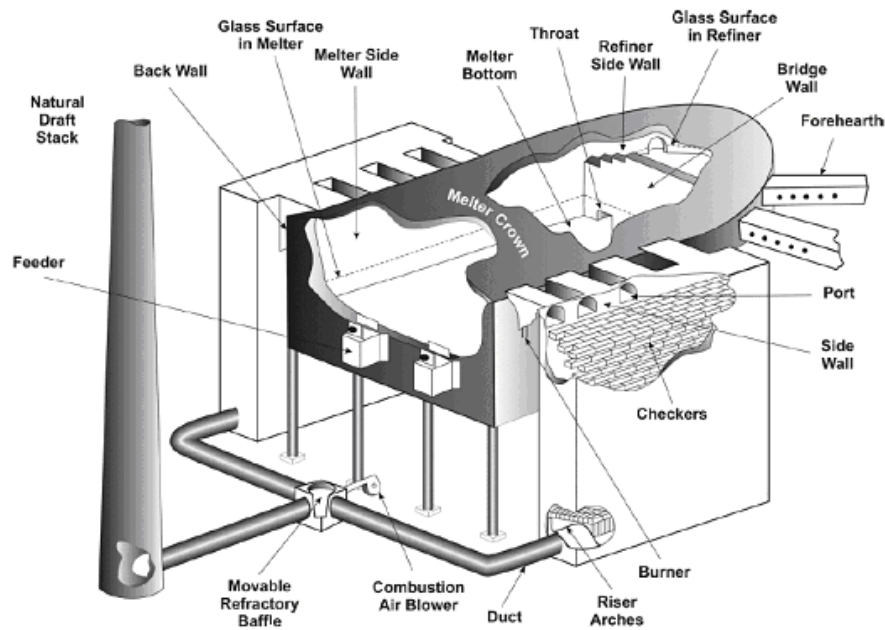


Figure 7-1 – Cross-fired regenerative furnace (Office of Industrial Technologies, 2002)

Source	Hartley (2004)	Beerkens et al. (2004)	European Commission (2001b, p.73)
Temperature of glass (°C)	1300	1400	1500
Theoretical SEC (GJ/t)			
1. Enthalpy of glass	1.58	1.75	1.89
2. Heat of reaction	0.56	0.52	0.49
3. Enthalpy of batch gases	0.61	0.10	0.30
Total	2.75	2.37	2.68

Table 7-2 – Theoretical energy requirements for glass melting (0% cullet)

In practice the specific energy consumption of glass furnaces depends on a number of factors, including:

- **Furnace type** – end-fired furnaces are more efficient than cross-fired ones; container furnaces have a higher thermal efficiency than flat ones; typical SECs for container and flat furnaces are 5.4GJ/t and 7.2GJ/t respectively (Hartley, 2007a);
- **Furnace size** – an economy of scale is associated with larger furnaces mainly due to the $3/2$ power relationship between contained volume and surface area;
- **Specific pull rate** - Beerkens et al. (2004) have shown that above specific pull rates of approximately $3\text{t/m}^2\text{d}$ there are only very small gains in energy efficiency. With a 50% cullet fraction, based on an international survey of 131 furnaces, the optimum SEC corresponding to this specific pull rate was found to be around 4GJ/t;
- **Furnace age** – Trier (1987) suggests that the energy consumption of regenerative furnaces may increase by 1.5 to 4% per year, as well as a seasonal variation;
- **Electric boost** – creates convection currents which stir the molten glass and can be used to increase furnace capacity, but is inefficient in thermodynamic terms as well as economically expensive;
- **Oxygen firing** – reduces direct pollution and direct energy consumption, but proves to be no more efficient in primary energy terms (Ross & Tincher, 2004, p.15);
- **Combustion conditions** – non-stoichiometric fuel to air ratios can result in incomplete combustion, meaning less energy is released by the reaction;
- **Residence time** – along with the required production rate this determines the furnace volume, which largely dictates energy requirements (Beerkens, 2004);
- **Moisture content** – water in the batch adds to the energy requirements of the furnace, as it has to be evaporated before melting can occur;
- **Cullet fraction** – melting cullet does not require reaction energy nor does it produce batch gases (see above). At constant load, a cullet increase of 10% reduces energy consumption by approximately 2% (Beerkens et al., 2004).
- **Pack or yield ratio of the product** – the lower this ratio the less of the glass from the furnace ends up in the product and thus the more energy is wasted. A typical yield ratio for the UK industry is about 85% (AEA Technology, 2004, p.18).

As well as the factors listed above there are several others that the furnace operator has to adjust in order to maintain the integrity of the product and the effective operation of the furnace. Furnaces are required to operate within a range of pull rates due to fluctuations in demand for glass. Higher pull rates than the design condition can theoretically be achieved with a greater heat input, but with a compromise of sub-optimal efficiency. The practical consequence is a limit of economically reasonable operation beyond which the marginal increase in quality glass yield for an additional energy input is negligible. There is a tripartite compromise between the production efficiency (in terms of the pull rate), environmental sustainability (in terms of energy efficiency) and glass quality (Conradt, 2007).

Glass manufacture is also largely governed by kinetics, of which heat transfer is only the first process, so residence times must facilitate the complete dissolution of the batch materials, as well as the refining and homogenizing of the melt (Martlew, 2002, Anon, 2007). A compromise is inevitably reached between the high temperatures required for these processes and the lower temperatures at which the glass can be worked once it has passed through the refiner and forehearth (Figure 7-1). This temperature difference often results in a large heat loss, particularly in flat glass furnaces, which have longer refining ends because of the higher quality requirement (Hartley, 2007c). In addition, a temperature difference is required for heat transfer to occur and heat is lost through walls and openings. These mechanisms all require extra energy, which leaves the system in the flue gases and as structural heat losses (Beerrens 2004).

Hence there is a significant difference between the theoretical minimum energy requirements and those achieved in practice. Typical SECs for glass furnaces are around double the theoretical minimum, with a large variation across the industry (Ercole, 2004, The Carbon Trust, 2005a, cf. Table 7-2). The sector's CCA target for 2010 in primary energy terms is 12.6GJ per tonne of packed ware (DEFRA, 2001a). Assuming the fuel split quoted above and the conversion factor of 0.38 for primary energy from electricity (ibid.), this corresponds to around 10.5GJ/t in final energy terms. Even if this is multiplied by 0.75 to consider just the furnace, the figure of 7.9GJ/t is still much higher than the SECs quoted above for the reasons discussed. The desire to quantify these losses in thermodynamic terms, and to understand the economic potential to reduce them, is the motivation behind this study. Hence attention is now drawn to applications of relevant methodologies in the literature.

7.2 *Contextual background*

7.2.1 **Thermodynamic analysis of glass furnaces**

Several analytical attempts have been made to understand the relationships between various furnace operational parameters and energy consumption (e.g. Kröger, 1953; Cooper, 1980; Conradt, 2000b). These have involved constructing heat or power balances across the furnace in order to develop theoretical governing equations that can be tested with empirical data. Conradt (2000b, 2000a) has done this by reference to three crucial temperature levels within the furnace: the adiabatic temperature of combustion, and the exit temperatures of the melt and the exhaust gases. He yields a relationship between the pull rate and overall energy demand, and shows that there is an optimal pull rate in terms of energy efficiency for a given furnace. At lower pull rates than this the wall losses from the furnace dominate, and at higher ones efficiency is lower because the heat transfer between the combustion space and the glass bath is limited.

Significant resources have been devoted to benchmarking furnaces. Glass furnaces cannot directly be compared from a thermodynamic perspective because of differences in the key operating parameters. Adjustments therefore need to be made for, *inter alia*, the cullet fraction and the age of the furnace (Beerrens et al., 2004). In the USA several extensive benchmarking

studies have been carried out in recent years, including a detailed industry profile (Office of Industrial Technologies, 2002), and a comprehensive techno-economic assessment of the current state of the art within the field (Gas Technology Institute, 2006). The Carbon Trust (2005a) has recently taken the lead in the UK, with a detailed survey of the container glass sector, covering 29 of the sector's 31 operational furnaces in 2003. It concluded that the container glass industry has halved its SEC over the last twenty years, as well as reducing container weight significantly, which together have reduced the energy consumption per product by around 60-70%. A relationship between the furnace pull rate based on this survey was developed, whereby the total furnace energy demand is linearly proportional to the pull rate, plus a constant known as the furnace holding heat (see section 7.3.3.1).

Sardeshpande et al. (2007) developed a parametric model of an end-fired regenerative furnace (with a reference pull rate of 100t/d), validated against actual furnace data from the Indian industry. Energy and mass conservation equations were applied across control volumes within the furnace, namely the combustion space, the molten glass bath, and both sides of the regenerator. Heat losses have been estimated based on empirical coefficients and relations, as appropriate, from various sources. A user-friendly Graphical User Interface (GUI) has been created to facilitate model configuration and data entry. The model demonstrates that, in accordance with operational furnaces, the largest heat losses are in the flues gases (23% of the heat input) and through the walls and openings (15%). It is proposed that the model be used for estimating the energy performance of a given furnace at the design stage, thereby optimising the design for energy efficiency and applied to existing plant in order to identify opportunities for energy saving.

Most if not all of these benchmarking studies highlight the importance of reliable and accurate data, and how the availability of such data ultimately determines the degree of success of the study. In particular, proprietary reasons often inhibit the disclosure of commercially sensitive information to third parties, which is especially the case in the UK, where a small number of firms dominate the industry. These studies also show that there is no absolute consensus on the relationship between the pull rate and the overall energy consumption of furnaces. Whilst it appears to be linear in some cases (The Carbon Trust, 2005a), in others this is not clear, which has led to much debate in the past on the dependency of these variables (Anon, 2007).

7.2.2 Exergy analysis of glass furnaces

The application of exergy analysis to glass furnaces seems to be somewhat esoteric. Wall's (1992) comprehensive – albeit now somewhat dated – bibliography of exergy analysis cites only two studies specific to the glass sector. Additional literature searches have revealed only one other pertinent study (Kozlov et al., 1985). A summary of the findings from the relevant literature is presented in Table 7-3.

De Lucia et al. (1990) presented an exergy balance of a small end-fired glass furnace producing high-quality, artisanal glass. They investigated the effects on this exergy balance of varying the

levels of oxygen enrichment in the furnace in the region of 20-30%. The combustion process was found to account for approximately 25% of the total exergy destruction in the furnace, and was also rather insensitive to the level of oxygen enrichment employed. The overall conclusion is that oxygen enrichment (or so called oxy-firing) can be used to increase the overall exergetic efficiency of the furnace. Heat transfer to the glass batch is proportional to the level of oxygen enrichment, because this increases the adiabatic flame temperature. In addition, the exergy loss to the stack decreases with oxygen enrichment because of the lower mass flow rates through the system (less air, if any, is required for combustion).

Source	Furnace type	Pull rate (t/d)	Melting area (m ²)	Fuel	Energy Efficiency	Exergy Efficiency
De Lucia et al. (1990) ¹	End-fired regenerative	3.5	-	Natural gas	-	10.5
Sun and Xie (1991)	End-fired regenerative	290	22	Heavy fuel oil	35.6	21.5
Kozlov et al. (1985)	Regenerative ²	120	148	Furnace oil	19.0	16.2

Table 7-3 – Exergy studies of glass furnaces

(¹23.5% oxygen enrichment, producing high quality glass; ²furnace type not reported)

Similarly, Sun and Xie's (1991) study concludes that the majority of the exergy is lost through irreversible processes – especially combustion. They suggest that the reduction of these internal irreversible processes is the key to energy conservation. Whereas external losses such as leakage and heat dissipation that can be ameliorated through corrective measures, the true thermodynamic losses are more difficult to address – especially because they are due to the destruction of chemical exergy. The large combustion exergy destruction can be reduced by increasing the adiabatic combustion temperature, reducing excess air, preheating (fuel and combustion air), and using pressurised burners. The energy balance suggests a large energy loss to the atmosphere up the flue, but the exergy analysis suggests that this energy is of a relatively low quality.

Kozlov et al. (1985) analysed two industrial glass furnaces, one producing containers of “semi-white glass” at a rate of 120t/d and running on furnace oil, with a melting area of 148m² excluding the conditioning end (Table 7-3). The precise furnace configuration in this case is not clear, but is ostensibly an end-fired or cross-fired regenerative furnace. The results highlight large differences between the energy and exergy contents of the determined losses, in particular the exhaust stream and the losses through the furnace lining. The largest exergy destruction, as for the other two studies mentioned above, results from the combustion process itself (which accounts for around 21% of the total exergy input). Other significant losses occur due to the heat exchange process itself and through the furnace walls, whereby the latter is much larger in energy than in exergy terms (i.e. 15% and 7% of the total input respectively). The authors also conclude that the use of energy balances alone can lead to serious errors when attempting to reduce the specific fuel consumption of glass furnaces (ibid.).

There only seem to have been a few applications of exergy analysis to glass furnaces in past, one of which was to a very small furnace producing very high quality gas (De Lucia & Manfrida, 1990). This is not representative of the sector in the UK. The other two studies in Table 7-3 do provide some general insights, but are also based on furnaces which are non-typical of UK plant and are now somewhat dated. The present study is therefore aimed at providing an analysis based on typical UK plant and to consider developments in the industry since previous studies. This study is also intended to present a useful tool for calculating emissions and benchmarking furnaces in the context of the EU ETS.

7.3 Furnace model and data sources

7.3.1 Introduction

A simplified thermodynamic model of a cross-fired regenerative container furnace has been set up, which is normalised to the production of one tonne of glass. A necessary simplification for the case of the present study was to consider a two-dimensional slice through the furnace, as shown in Figure 7-2. The implication of this is that the third dimension is still included in the analysis but the temperature profile in this direction is assumed to be constant. It was not feasible to develop a three dimensional model which also considers the temperature profile and heat/mass transfer along the length of the furnace, because of the inherent complexities associated in modelling such phenomena (Sardeshpande et al., 2007). Whilst this is clearly a significant simplification, it is a necessary one to make this analysis feasible according to the scope in section 1.4. It should thereby be possible to gain an approximate insight into the energy and exergy demands without the large resource requirements associated with sophisticated computational modelling. The temperatures employed are therefore indicative of averaged values across certain regions rather than precise measurements.

7.3.2 Model specification and assumptions

Based on this cross-section through the furnace (Figure 7-2), the model has been developed as depicted in Figure 7-3. This schematic shows the control volumes across which principles of mass and energy conservation are applied, namely the combustion space, the glass bath, the two regenerators, the exhaust to stack, and the stack itself. One important difference between this model and the cross-section through the furnace is that there is a large ingress of air below the regenerators (at point five). This is accounted for in the model based on the change in mass flow rates between points five and six. In addition, the model considers the operation of the furnace in the steady state, such that the periodical reversal of the flow control valve is neglected. In this way the regenerators are treated as simple heat exchangers in which the hot exhaust side gases transfer heat directly to the cold pre-combustion air. The system boundary is taken to be sufficiently close to the furnace superstructure such that the ambient temperature outside the boundary is 25°C, and the glass is assumed to cross the boundary in the molten state, at or very near its temperature in the furnace itself. This overlooks the thermodynamic and mass flows occurring as the glass is cooled and formed outside the furnace, but has been

necessary in order to keep the scope of analysis feasible and has been successfully employed elsewhere (Sardeshpande et al., 2007).

Temperatures, pressures and mass flow rates are known (or have been estimated) at the salient points shown in Figure 7-3 and are detailed in Table 7-4. These temperatures have been empirically obtained and are documented in a patent for NO_x reduction in a flat glass furnace (Quirk et al., 1994). For the sake of the present analysis there is little difference between the temperature distribution around the two-dimensional slice through a float furnace and a container furnace – the main differences between the two are the longer residence times required and the open working end in the flat glass furnace. Hence this model could equally apply or be applied to a container or flat glass furnace. The pressure around the system is assumed to be atmospheric pressure, except at the base of the stack where natural convection creates a negative pressure of about 7.5kPa relative to the atmosphere (Hartley, 2007c). Apart from this, the pressure within the furnace is maintained slightly positive in order to prevent (or reduce) air ingress. This pressure difference is very small though, at around 10Pa, so is considered negligible in the present case.

Position	Description	Temperature (°C)	Pressure (kPa)	Approximate velocity (m/s)
0	Ambient environmental state	25	101.3	~ 0.0
1	Preheated air before combustion	1250	101.3	2.4
2	Combustion products	1650	101.3	2.0
3	Molten glass (at flux line)	1400	101.3	0.0
4	Exhaust gases above regenerator	1350	101.3	3.8
5	Exhaust gases below regenerator	650	101.3	17.2
6	Exhaust gases at base of stack	550	93.8	15.2

Table 7-4 – Environmental conditions at salient points within the furnace (reference case)

7.3.3 Model structure and procedure

The model consists of one main Excel spreadsheet, which has separate tabs for each of the main modules. The relevant temperature and pressure data have already been described above. The other key input variables are the furnace operating parameters, through which the specific furnace configuration is specified. These include the pull rate and cullet fraction being employed for a given setup – 300t/d and 0.5 respectively in the reference case, which is representative of the UK sector (Hartley, 2007c) – as well as the moisture content of the batch (4% by mass), and the degree of batch preheating (none in the reference case). Based on these inputs, the SEC and batch composition for this configuration is calculated in the relevant modules. The remainder of this section describes the operation of the individual modules in detail.

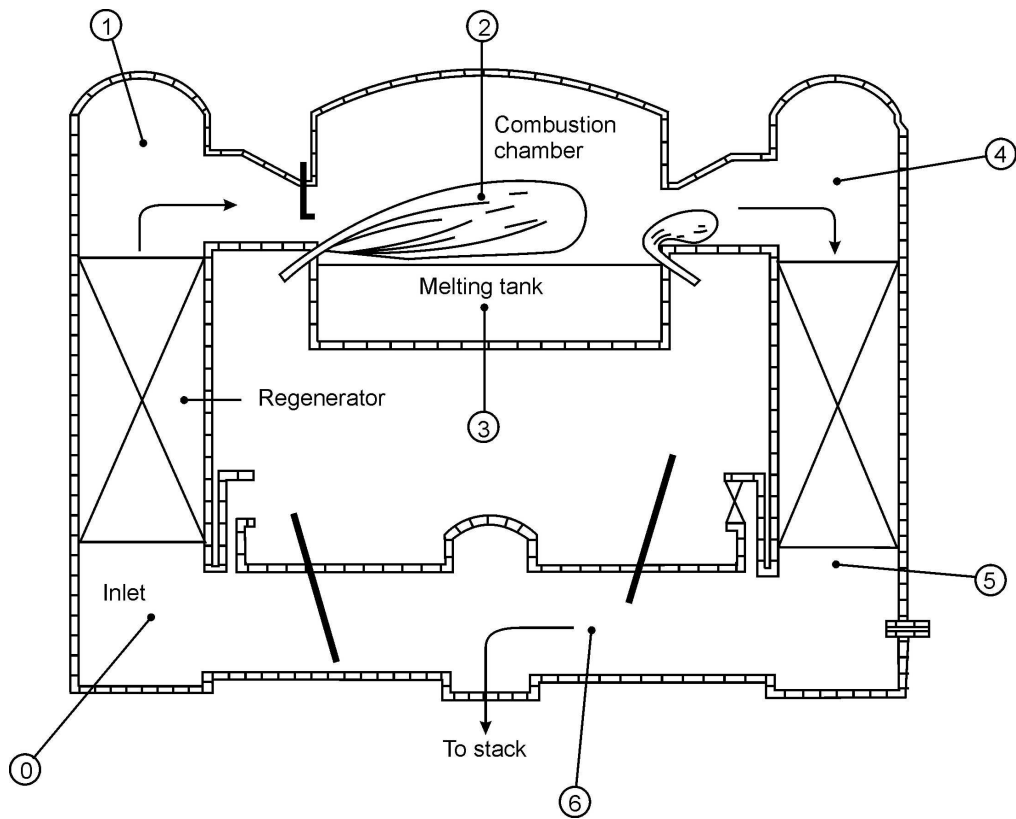


Figure 7-2 – Cross-section through a cross-fired regenerative furnace
 Source: Adapted from Quirk et al. (1994)

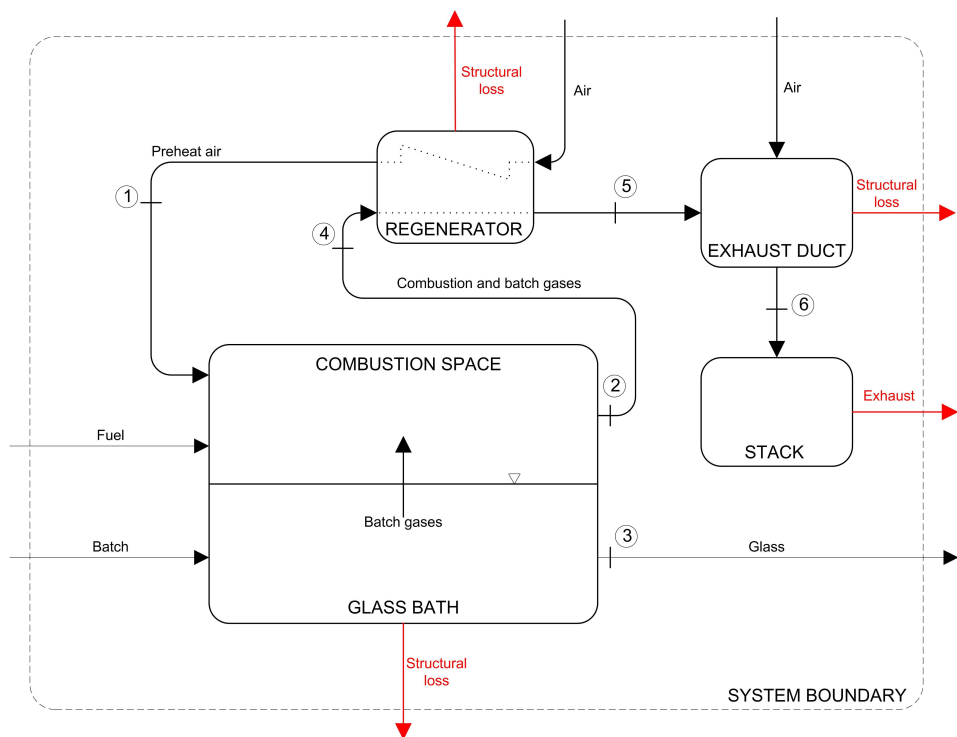


Figure 7-3 – Schematic of furnace model showing salient points and flows

7.3.3.1 SEC module

There is certainly a strong dependency between the SEC and the pull rate, but it is not clear whether this takes a linear, logarithmic, power law or other form. The Carbon Trust (2005a) found that a linear relationship provided a good fit to the 29 furnaces surveyed in 2003, and as these container furnaces were solely within the UK industry, this relation has also been employed here along with some modifications. The SEC also exhibits a weak dependence on other parameters such as the cullet fraction, the moisture content, and the degree of batch preheat (i.e. the temperature of the batch), because of the energy penalties associated with these variables. Hence in the present case the SEC function takes the form

$$SEC = \left(\frac{F}{L} + k \right) (1 - 0.2c) + B - P \quad 7-1$$

where F and L are the furnace holding heat and load, respectively, and k is an empirical constant. In addition, c is the cullet fraction, B is the batch moisture correction, and P is the batch preheat correction. The empirical constants F and k are taken from the Carbon Trust's (2005a, p.6) survey of the container glass industry, with values of 352.8GJ/d and 4.4GJ/t respectively. Hence the cullet fraction effects a linear reduction in the SEC, based on the assumption that an additional 1% of cullet addition to the batch results in a reduction in the furnace SEC of 0.2% (Beerrens et al., 2004, p.49). Additional batch moisture (i.e., over and above the 4% in the reference case) requires 3.6GJ/t of energy to raise it to an exit temperature of around 550°C (Hartley, 2004, p.3). The batch preheat correction simply subtracts the enthalpy of the batch materials (over and above their enthalpy at ambient conditions) from the SEC function, because this heat is not required from the fuel.

7.3.3.2 Batch module

The batch composition is representative of a typical batch currently used to manufacture soda-lime container glass in the UK (Noble, B., British Glass, pers. corr., July 2007). The composition in the reference case is shown in Table 7-5, whereby the moisture content in these raw materials is assumed to be 4% by mass overall.

The cullet fraction is one of the key variables in the model. Based on this value, the other raw material inputs are adjusted in order to manufacture exactly one tonne of glass. Cullet is assumed to have the same composition as the finished glass, and also has a moisture content in the reference case of 4%. As well as the energy requirement, the cullet content also affects the total batch weight, because the decarbonisation reactions only occur with primary raw materials. In other words, with the batch composition according to Table 7-5 and no cullet, 1.2t of raw material is required to produce 1t of glass; but 1t of cullet produces 1t of glass⁴¹. The variation in batch mass with cullet fraction has been taken to be linear.

⁴¹ Strictly speaking, cullet contains slight impurities such as organic matter, but the assumption is that the vast majority of these will be removed prior to entering the furnace. Even if this is not the case, the proportion by mass of impurities in the cullet can reasonably be assumed to be much less than 20% (i.e. the additional mass required if no cullet is used).

Raw material	Sand	Soda Ash	Limestone	Saltcake	Nepheline Syenite	Calumite	TOTAL (t)
Batch %	0.60	0.19	0.14	0.01	0.02	0.04	1.00
Formula	SiO ₂	Na ₂ CO ₃	CaCO ₃	Na ₂ SO ₄	-	-	
SiO ₂	0.3329		0.0002		0.0082	0.0079	0.3492
Al ₂ O ₃	0.0059				0.0035	0.0028	0.0122
CaO	0.0001		0.0480		0.0002	0.0087	0.0570
MgO	0.0002		0.0001			0.0019	0.0022
K ₂ O	0.0042				0.0013	0.0001	0.0056
Na ₂ O	0.0005	0.0680		0.0016	0.0011	0.0001	0.0713
Fe ₂ O ₃	0.0008					0.0001	0.0008
Other						0.0004	0.0004
CO ₂		0.0483	0.0378				0.0862
SO ₂				0.0016		0.0003	0.0020
H ₂ O	0.0189						0.0189
TOTAL (t)	0.3636	0.1164	0.0861	0.0036	0.0145	0.0218	0.6061

Table 7-5 – Batch composition by mass in the reference case (t)⁴²

Name	Formula	Mass (t)	Fraction, %
Silicon Dioxide (Silica)	SiO ₂	0.349	69.78
Sodium Oxide	Na ₂ O	0.071	14.25
Potassium Oxide	K ₂ O	0.005	1.11
Calcium Oxide	CaO	0.057	11.39
Magnesium Oxide	MgO	0.002	0.43
Aluminium Oxide	Al ₂ O ₃	0.012	2.44
Iron (iii) Oxide	Fe ₂ O ₃	0.000	0.16
Sulphur Trioxide	SO ₃	0.001	0.32
Other	-	0.000	0.07
	TOTAL	0.500	100.00

Table 7-6 – Basic glass and cullet composition (inconsistencies due to rounding)

7.3.3.3 Geometry module

The majority of the geometric data has been taken from Trier & Lowenstein (1987), whereby the exact furnace geometry is determined based on the input parameters for the specific case – in particular the type of furnace. The type of furnace being modelled (container or flat glass) dictates the specific pull rate, which is defined as the mass of glass produced per square metre of melting area per day (t/m²d). The current state of the art for specific pull rates in container and flat furnaces is for 2.6t/m²d and 2.0t/m²d respectively (Scully, P., Eurofusion, personal communication, September 2007, cf. Trier & Loewenstein, 1987). For container furnaces electric boosting and oxy-firing can increase this value to around 3.5t/m²d, but these practices are not

⁴² Four significant figures are shown in this table because of the trace amounts of some of the compounds, which could not be quantified at lower levels of precision. This is not representative of the overall precision of this study.

typically employed in float furnaces because the quality requirements on the glass are much higher, and the pull rate therefore tends to be constrained by this. The melting area is therefore determined based on the furnace load and specific pull rate possible by this kind of furnace. The length to width ratio for container and flat glass furnaces is selected as two and three respectively, whilst the number of pairs of firing ports is four or six respectively. From these parameters, and modelling the furnace itself as a cuboidal space with an arch (melter crown, cf. Figure 7-1) radius equal to the melter width, it is possible to calculate the necessary geometry in order to estimate structural losses (Table 7-7). The regenerator geometry is estimated in a similar manner.

Width (m)	7.6	Average wall thickness (m)	0.5
Length (m)	15.2	Regenerator width (m)	1.5
Height to base of arch (m)	2.7	Regenerator length (m)	15.2
Height to arch top (m)	2.9	Regenerator height (m)	4.4
Depth of glass (m)	1.2	Regenerator wall thickness (m)	0.3
No. of pairs of firing ports	4	Checker packing ratio	0.5
Port diameter (m)	0.8	Doghouse exposed area (m ²)	0.5

Table 7-7 – Furnace geometry (reference case)

Structural heat losses are estimated as follows. Conductive losses are calculated with Fourier's law in one dimension,

$$\frac{dQ}{dt} = -\lambda A \frac{dt}{dx} \quad 7-2$$

where dQ/dt is the rate of heat flow through the wall, λ is the thermal conductivity, t is the temperature and x is the perpendicular distance through the wall (Eastop & McConkey, 1993, ch. 16). The thermal conductivity of the refractory materials is based on published empirical rates of heat transfer through well-insulated refractory walls, as shown in Table 7-8.

Radiant losses are estimated from the Stefan-Boltzmann law for a non-black body,

$$\frac{dE}{dt} = \epsilon \sigma T^4 \quad 7-3$$

where E is the energy emitted, ϵ is the emissivity of the body, and σ is the Stefan-Boltzmann constant, with a value of $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ (ibid.) All external furnace surfaces were assumed to be grey bodies with surface emissivities of 0.8, except the feeder, where the value taken was 1.0 because this is open to the surroundings (Gray & Müller, 1974).

Convection losses from the cold side of the superstructure are estimated through the empirical relationship used by Sardeshpande (2007, p.9):

$$\frac{dQ}{dt} = A_{c,wall} \times S_{conv} \times (\Delta T)^{5/4} \quad 7-4$$

where $A_{c,wall}$ is the area of the surface, S_{conv} is an empirical constant that depends on the type and orientation of the surface, and ΔT is the temperature difference between the cold-side wall temperature and the ambient air (Table 7-8). The ambient air velocity over the furnace is relatively small (Table 7-4) so that natural (buoyancy-driven) convection is assumed to be the dominant mechanism. Forced convection is therefore neglected.

Structural element	Heat transfer coefficient, U (W/m ² K)	ΔT across wall (K)	Wall thickness (m)	Thermal conductivity, λ (W/mK)	S_{conv} (W/m ² K ^{5/4})
Bottom of tank	1.0	1250	0.5	0.52	1.29
Walls of tank – glass	2.3	1250	0.4	0.93	1.99
Walls of tank – combustion	2.1	1380	0.4	0.83	1.99
Crown	1.7	1380	0.6	1.04	2.49
Regenerators	2.3	1250	0.4	0.93	1.99
Source	Trier and Loewenstein (1987)	Estimated from Quirk (1994)	Trier and Loewenstein (1987)	Calculated from Equation 7-2	Sardeshpande (2007)

Table 7-8 – Heat transfer and convective coefficients used for the furnace structure

7.3.3.4 Thermodynamic module

The thermodynamic module carries out the heat and mass balance across the control volumes and generates the relevant outputs. The SEC delivered from the SEC module determines the amount of fuel (natural gas and/or electricity) required to produce one tonne of glass. Natural gas is assumed to wholly consist of methane, which although not the case at extraction is almost entirely the case upon delivery (BERR, 2007, p.208). The net calorific value of methane employed is 50.0GJ/t on a mass basis (BSI, 2007).

The enthalpy of batch, fuel and ambient air is then calculated using their specific heats. For standard substances in the environment, specific heats have been determined from published thermodynamic tables (Rogers & Mayhew, 2000); for the constituents of the batch, the relationships developed by Sharp and Ginther (1951, refined by Moore & Sharp, 1958) have been used at moderate temperatures, and those determined more recently by Richet et al. (1997) across the glass transition temperature and up to around 1400°C. In the former case, for some of the minor constituents, together accounting for less than 0.1% of the total batch mass (i.e. “other” in Table 7-6), the empirical constants were assumed to be the same as for silicon dioxide, the main batch constituent by mass.

Exergy is calculated based on Equation A17 in Appendix A2.2.3, in which the first two terms together constitute the physical exergy components. The summation term in this equation corresponds to the chemical exergy component, and the final two terms are (gravitational) potential and kinetic exergy, respectively. The physical exergy can be calculated for common substances based on their enthalpy and entropy at various temperatures, the empirical data for which is tabulated (Rogers & Mayhew, 2000). For the constituents of the glass batch, however, data concerning entropy variation with temperature is not widely available. Hence the entropy of the raw materials (and cullet) is estimated based on a method proposed by Kotas (1985, pp.173-174), which assumes a linear temperature change up to the glass transition temperature and above it. In this way, the entropy is inferred from the enthalpy change divided by the average temperature, as shown schematically in Figure 7-4. At the glass transition temperature, T_g , the entropy change is equal to the enthalpy of reaction divided by the glass transition temperature. Hence

$$\begin{aligned}
 T < T_g : S_{t1} - S_t &= 2(H_{t1} - H_1) / (T_g + T_1) \\
 T = T_g : S_{t2} - S_{t1} &= H_r / T_g \\
 T > T_g : S_2 - S_{t2} &= 2(H_2 - H_{t2}) / (T_g + T_2)
 \end{aligned}
 \tag{7-5}$$

where the subscripts 1 and 2 denote the lower and upper temperatures of the glass during heating respectively. Subscripts “t1” and “t2” refer to the entropy states of the glass in the glass and liquid phases respectively at the glass transition temperature T_g , which is assumed to be 850K (Richet et al., 1997).

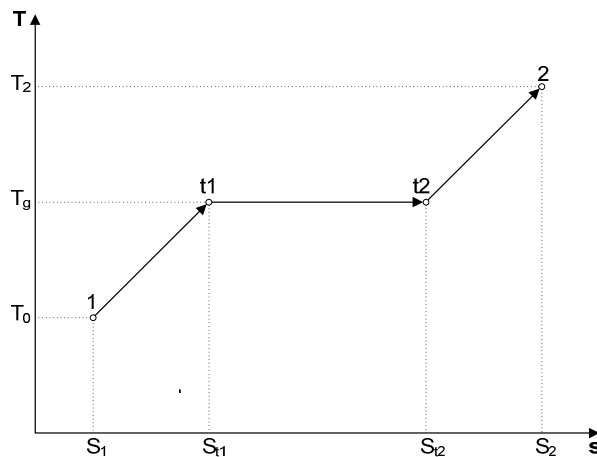


Figure 7-4 – Schematic of T-s diagram for glass melting (after Kotas, 1985, p.173)

The chemical exergies of the fuel and raw material have been calculated based on the environmental model of Szargut (1988, cited in Bejan et al., 1996), in which $T_0 = 298.15\text{K}$ and $p_0 = 1 \text{ atm}$. This reference temperature might seem rather high for the UK, where the winter design temperature is typically -1°C (Hammond, 2007a), but the system boundary is drawn close to the furnace as stated above and the ambient temperature is therefore around 25°C . Finally,

variations in gravitational potential are neglected within the furnace. The kinetic energy and exergy is estimated based on the required mass flow rates of fuel, air and raw materials, and of the resulting products, which includes a consideration of the large air ingress below the regenerators (Figure 7-3).

7.3.3.5 Calculation of mass, energy and exergy flows

Based on the above modules the model calculates the mass, energy and exergy flows into and out of the control volumes. Firstly, the SEC is determined based on equation 7-1 for the current input parameters. Based on this SEC, the correct mass of natural gas along with the stoichiometric ratio of oxygen (as contained in air at STP) is calculated, whilst taking into account the amount of electric boost being used. The raw material inputs are simultaneously determined based on the cullet fraction and batch composition calculated in a separate sheet. The fuel is then assumed to completely and adiabatically combust, reaching an average localised temperature of 1650°C (Table 7-4), and transferring this heat to the molten glass at a lower temperature. In this combustion process all of the chemical exergy is assumed to be converted into thermo-mechanical exergy. Exergy efficiencies, losses and destruction are calculated according to Equations A16 to A21 in Appendix A2.2.3.

In the melting process the batch gases liberated cross the system boundary of the glass bath and mix with the post-combustion gases. The temperature at the top of the regenerators determines the amount of heat transfer to the glass bath from the post-combustion gases, whilst the total enthalpy of the molten glass and post-combustion gases must sum to the total enthalpy of the combusted fuel and the raw materials at STP. That is, that fraction of the enthalpy contained in the hot gases that is not transferred to the glass bath remains in the exhaust gases and enters the regenerators. This methodology of balancing the flows across each control volume is similarly applied to the other spaces shown in Table 7-4, in order to build up the balance for the whole furnace. Total inputs and outputs are then compared by way of cross-checking the overall balance.

7.4 Results and discussion

7.4.1 Reference case

The reference case for the furnace operates at a pull rate of 300t/d and with 50% cullet in the batch. The batch moisture content is 4% and no batch preheating is employed. The energy and exergy balances across the key control volumes and for the whole system are shown in Table 7-9, in which positive and negative values represent flows into and out of the system respectively. Some of this data is graphically represented in Figure 7-5, which shows Sankey and Grassmann diagrams for the reference case. They depict the energy (enthalpy) and exergy respectively, of the flow streams through the furnace.

	Energy (MJ)	Exergy (MJ)
Furnace		
Fuel	5107	5180
Batch materials	252	584
Preheated air	2710	1259
Glass	-2393	-1237
Combustion/heat transfer destruction	0	-2800
Structural loss	-1018	-637
Exhaust	-4658	-2349
Furnace efficiency	0.30	0.18
Regenerator		
Hot gases	4658	2349
Recovered (preheating)	2710	1259
Structural loss	-169	-138
Exhaust	-1779	-952
Regenerator efficiency	0.58	0.54
Exhaust		
Inlet gases	1779	952
Structural loss	-306	-11
Exhaust	-1473	-941
Overall balance		
Total in	5359	5763
Glass out	-2393	-1237
Recovered (preheat)	2710	1259
Total set free	8069	7023
All losses	-1492	-3586
Exhaust	-1473	-941
Overall efficiency	0.45	0.22

Table 7-9 – Energy and exergy balances for one tonne of glass (reference case)

Overall, the whole furnace including regenerators has energy and exergy efficiencies of 45% and 22% respectively, which compares well with other studies. To avoid double-counting, these efficiencies do not include the energy or exergy content of the batch and exhaust gases liberated during the decarbonisation and combustion processes respectively, as this is accounted for in the heat recovered by the regenerators. The main reason for the large difference in these efficiencies is the large exergy destruction which occurs when the fuel is combusted and the chemical exergy is converted into thermo-mechanical exergy. These combustion and heat transfer processes are thermodynamically irreversible and together represent around 54% of the total exergy input. This fraction is in agreement with de Lucia (1990) and Kozlov (1985), who both found it to be in the region of 50%. These exergy destructions are necessary in order for the energy in the fuel to be made available as heat. The scope for improvements to the combustion process is limited by the theoretical minimum exergy destruction required for such a combustion process. In most cases the majority of the exergy destruction associated with combustion and heat transfer is unavoidable (Bejan et al., 1996, p.160). Although the detailed mechanisms involved in combustion are not well

understood, the majority of the exergy destruction is thought to be due to internal heat conduction, so future research should be focussed in this area (Hammond, 2007a, Som & Datta, 2008).

Apart from the large difference in efficiencies due to combustion, there are also variations between the energy and exergy content of most other flows within the system. The main exergy losses, aside from the combustion process, are structural in nature. High temperature energy is inevitably lost through the walls of, and openings in, the superstructure. In exergy terms these losses account for around 14% of the total input to the system, yet in energetic terms they amount to double this figure, 28%. Although the losses are significant in both respects, the quality – and usefulness – of this leaked energy is lower than suggested by the energy analysis alone. The greatest proportion of the structural losses occurs through the walls of the furnace and regenerators, and through the crown, as shown in Table 7-10.

The second main energy and exergy loss is the exhaust from the system. The exhaust stream accounts for 27% of the energy and 16% of the exergy input to the system. These gases are at temperatures in excess of 500°C and therefore represent a more concentrated exergy stream than the structural ones, which occur throughout the superstructure. The gases have a velocity of around 15m/s in the stack itself (Table 7-4). Their energy content is thus around 1.5GJ per tonne of glass produced, which in the reference case amounts to 450GJ per day. The cost of wasting this heat, assuming £5/GJ for natural gas (BERR, 2008i) and perfect stoichiometric combustion and heat transfer, is therefore in the region of £2250 per day or £800,000 per annum. The nature of the assumptions makes this a conservative estimate.

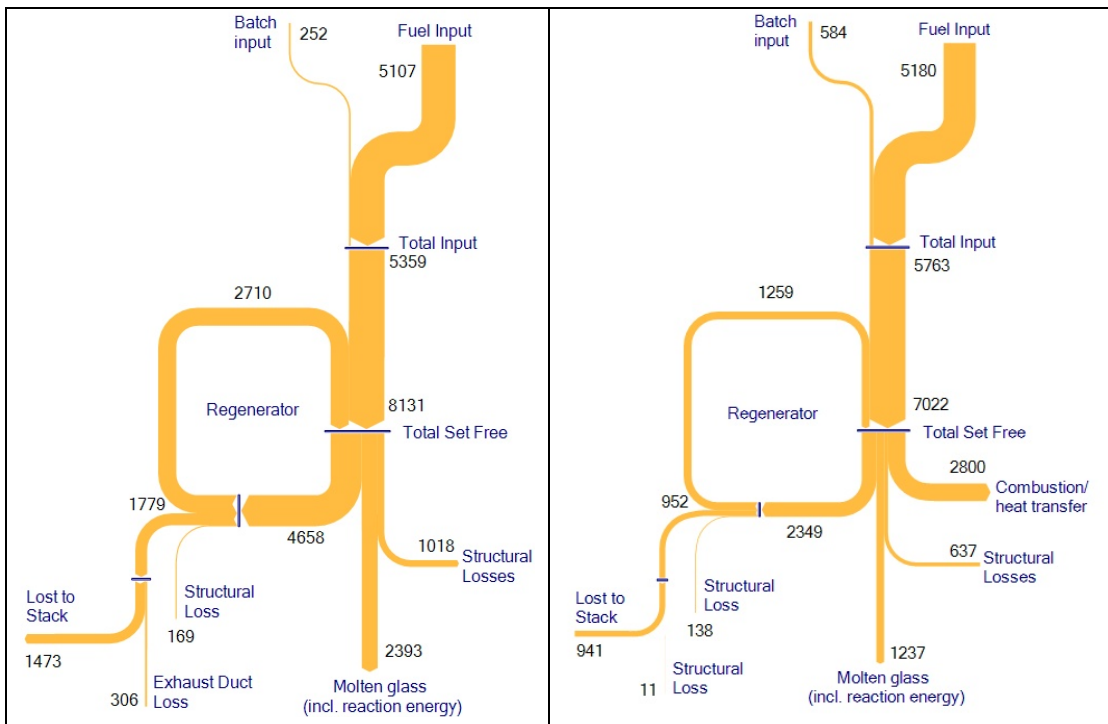


Figure 7-5 – Sankey (l) and Grassmann (r) diagrams of the reference case in MJ (300t/d, 50% cullet)

	Conductive		Radiative		Convective		TOTAL	
	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
Bottom of tank	43.2	42.4	36.4	10.8	17.9	5.3	97.5	58.5
Walls of tank	45.7	44.9	17.3	5.1	13.1	3.9	76.0	53.8
Walls combustion	61.4	60.4	77.3	34.9	41.5	18.8	180.2	114.0
Crown	83.5	82.3	124.9	56.3	84.0	37.9	292.4	176.5
Regenerators	168.8	137.9	49.8	10.0	42.0	8.4	260.7	156.3
Doghouse leaks			96.4	81.5			96.4	81.5
Leakage - holes			89.3	75.5			89.3	75.5
Leakage - surface	30.5	30.1	37.8	17.1	25.4	11.5	93.8	58.6
TOTAL	433.1	397.9	529.2	291.1	224.0	85.7	1186.4	774.7

Table 7-10 – Structural energy and exergy losses from the furnace, excluding exhaust duct (MJ/t)

7.4.2 Parametric modelling and comparisons with other studies

The input parameters for the reference case have been varied in order to test the sensitivity of the model and to investigate the ways in which changes in these variables can improve the overall efficiencies. This also enables a fair comparison with the results of other studies, which analyse furnaces operating under different regimes.

Exergy related parameters tend to be sensitive to changes in the dead state, because the concept of exergy is itself based on the potential with reference to this state (Appendix A2.2.3 and section 3.2). If the dead state temperature is varied from the 25°C specified in the baseline case, the exergy related parameters are affected but those relating to energy are not. With a dead state temperature of 15°C, for example, the exergy efficiency increases by around 3%, but the energy efficiency stays the same. This is as would be expected for such an analysis, and should be borne in mind when comparing different studies.

The temperatures at all points around the system have been systematically varied above and below the baseline values in Table 7-4 by several hundred degrees. This was in order to test the sensitivity of the model to these changes, to ensure that the responses are of the type expected (in magnitude and sign) and to investigate the ways in which the overall energy and exergy efficiencies might be increased. In general the responses were as expected, for example increasing the temperature of the combustion products leads to higher efficiencies overall and also reduces the combustion-related exergy destruction. An increase of 150°C results in firing efficiencies in energy and exergy terms of 50% and 32% respectively. Similarly, reducing the temperature of the exhaust upon exiting the system tends to improve the overall efficiencies.

The variation in the furnace CO₂ (process and combustion) emissions and SEC with the cullet fraction is shown in Figure 7-6. Both of these parameters are inversely proportional to the cullet fraction in the batch, because the decarbonisation reaction is not necessary when manufacturing

glass from cullet (i.e. recycling). For this reason, the impact of the cullet fraction is strongest on the process-related emissions rather than those resulting from the combustion of the fossil fuel. Similarly, the SEC exhibits a weaker dependency on the cullet fraction because the majority of its value is accounted for by the enthalpy of the glass (cf. Table 7-2), which is independent of cullet content.

Significant reductions in the SEC and CO₂ emissions are possible if the cullet fraction is increased to a value approaching unity. However, there are barriers in the UK to increasing the overall cullet fraction used in glass manufacture, which have limited the industry average in the past (further discussed in section 7.4.4). In theory, if 100% cullet is used the energy and exergy efficiencies of the furnace become 50% and 24% respectively (compared to 45% and 22% in the reference case). This corresponds to an SEC of 4.5GJ/t and CO₂ emissions of 0.25tCO₂/t glass.

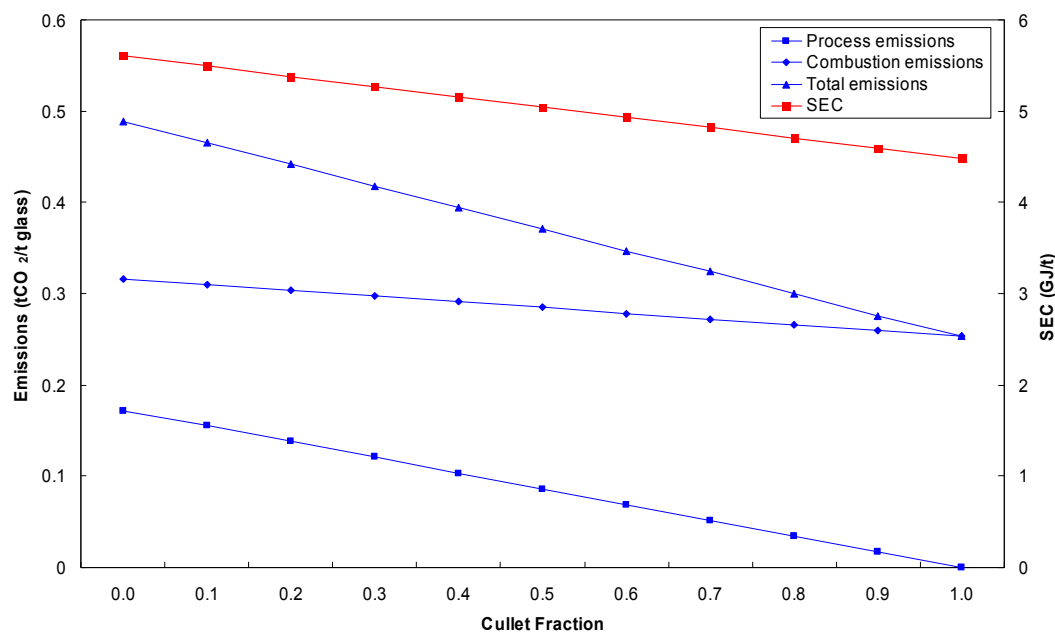


Figure 7-6 – CO₂ emissions and SEC variation with cullet fraction

The variation of the SEC and CO₂ emissions with the pull rate is shown in Figure 7-7. Both parameters exhibit a similar, asymptotically reducing trend with increasing pull rates. Hence furnace loads in excess of, say, 700t/d, do not economically yield further efficiency or emissions gains because of decreasing returns to scale and the physical limit on furnace size and specific pull rate. The SEC curves with different cullet fractions are offset by a constant amount, so that optimising the efficiency of the furnace involves moving towards the origin of Figure 7-7.

The efficiencies of the overall system and the furnace also exhibit a similar, but reversed, asymptotic relationship (Figure A8 in Appendix A3.2). The energy and exergy efficiencies increase up to a pull rate of 700t/d, at which point these values are around 50% and 24% respectively. However, the regenerator efficiencies decrease slightly at higher furnace loads, which is probably due to the fact that their rate of heat transfer is necessarily less at higher rates of throughput. Much of the heat from the exhaust and batch gases is recovered in the

regenerators and transferred to the inlet air, which is preheated to 1250°C in the reference case. The regenerators operate optimally at lower pull rates because of the lower velocities of the gases at these regimes, which allow more time for heat transfer to, and from, the checkers in the regenerators.

With an output of 120t/d of glass, and the same (i.e. 50%) cullet fraction as in the reference case, the current model has energy and exergy efficiencies of 32% and 16% respectively. The exergy efficiency corresponds almost exactly with the study of Kozlov et al. (1985), although the energy efficiency is significantly higher. The latter is because of the large difference in specific pull rates between the two studies. The present study has a melting area of 46m² under this regime, whereas Kozlov et al.'s (1985) furnace has one of 148m² (i.e. specific pull rates of 2.6t/m²d and 0.8t/m²d respectively). The exergy efficiency of the model exhibits only a weak variation due to fluctuations in underlying parameters, because the large combustion-related exergy destruction is always incurred.

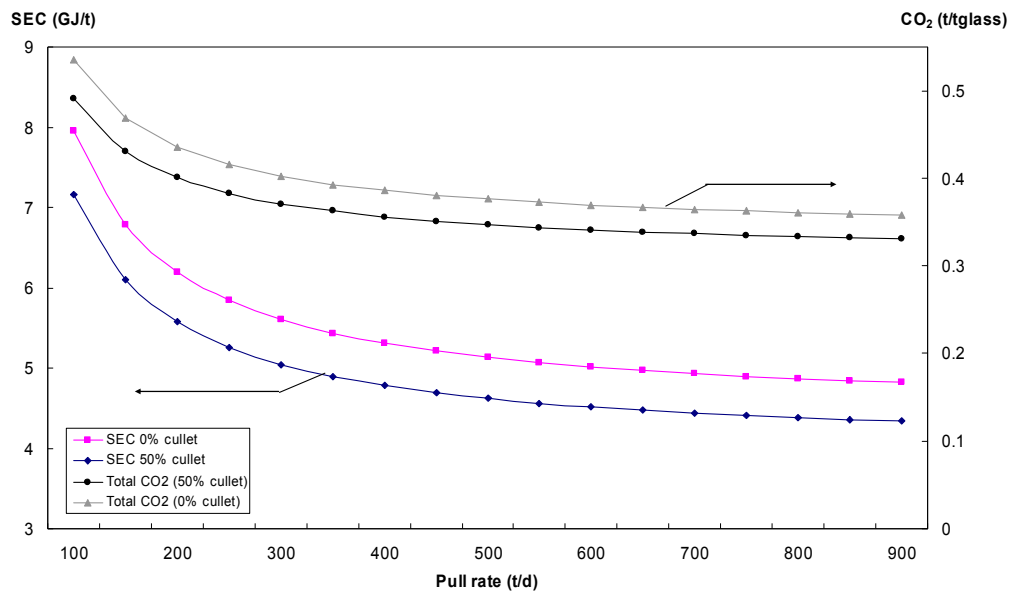


Figure 7-7 – SEC and CO₂ emissions against pull rate

The case is similar when comparing the present model to the analysis of Sun and Xie (1991). With a pull rate of 290t/d this model has overall energy and exergy efficiencies of 43% and 21% respectively. The reason for the difference in the energy efficiency is again due to the difference in melting areas (i.e., specific pull rates). Sun and Xie (1991) quote 22m² as their melting area, which seems to be erroneous because it implies a specific pull rate of 13.2t/m²d when the current state of the art is a maximum of 3.6t/m²d with electric boost and/or oxy-firing (see section 7.3.3.3).

A fair comparison with the work of de Lucia et al. (1990) is not feasible with the current model because of the very small furnace which they have studied, producing just 3.5 tonnes of glass per day. When configured to produce 50t/d of glass this model has energy and exergy efficiencies of 22% and 11% respectively, which is again very close to that of 10.5% quoted in

Table 7-3. However, because of the small furnace size and the oxygen-enrichment employed, care should be taken when comparing these figures.

7.4.3 Investment appraisal of a waste heat recovery boiler

The magnitude of the energy and exergy losses suggests that the areas where attention should be focussed are the combustion itself, and then the structural losses and those due to the high temperature exhaust gases. Although the exergy destruction associated with combustion cannot be avoided, the efficiency of the heat transfer process itself could be improved and thereby reduce this destruction. A precise quantification of the minimum theoretical exergy destruction in this particular combustion process is beyond the scope of this work, so the focus here is on qualitative methods to improve this. More efficient heat transfer could be achieved with a more uniform flame distribution within the furnace, a higher temperature difference between the flame and batch and a higher preheat temperature for the pre-combustion air, all of which are possible with HiTAC technology (section 4.3.2.1). However, such technology, as well as being limited by the high capital cost, is constrained because it can only be installed during furnace downtime, such as when the furnace is being rebuilt, every 10-15 years. The same applies to the second significant area of interest, namely the structural energy and exergy losses from the furnace, as well as there being a structural limit to the thickness of the insulation that can be used (Hartley, 2007c). However, this is not to disregard potential savings through improved furnace insulation; spray-on insulation has previously been successfully applied to a depth of 50mm, resulting in a reduction in the outer surface temperature of 40°C (Lax and Shaw, 1998). Measures such as increased furnace insulation and control are proven methods of improving energy efficiency, which both result in payback periods of less than two years (Enviros March & Glass Technology Services, 2000).

The savings through these measures are relatively small in comparison to longer term opportunities such as building furnaces to best practice guidelines and recovering some of the waste heat (ibid.). Indeed, the exhaust gases at around 550°C represent a significant energetic, exergetic and economic loss in this energy system, amounting to a power of around 5.5MW in the reference case. At present this medium temperature mixture of gases is exhausted into the environment at an estimated cost to the furnace operator of over £2000 per day. According to the present analysis, the composition of these exhaust gases is mainly carbon dioxide, nitrogen and water, but this is based on the assumption of complete combustion. In practice this is not the case as the exhaust gases also contain NO_x and possibly smaller quantities of SO_x. In addition, there may be organic matter in the exhaust from the cullet and/or raw materials. The consequence of this is that the unclean nature of these gases is likely to result in fouling and corrosion of any equipment which is used to recover their energy content, which is a major consideration in terms of evaluating the alternatives.

Korobitsyn (2002) suggests that an air bottoming cycle (ABC) is a suitable means of recovering some of the waste heat from glass furnaces, resulting in payback periods of 3-4 years. His analysis neglects to account for fouling of heat transfer surfaces though, so should probably be

treated with caution. Enviros March & Glass Technology Services (2000) also highlight the successful application of steam and power generation from exhaust gases. Rozendaal (2007) reports that the problem of fouling has been overcome in a flat glass plant in Holland, where a heat recovery boiler with an inline cleaning system has been installed. This system obviates the need to stop and manually clean the boiler, meaning that the integrity and therefore heat transfer coefficient of the heat transfer surfaces can be maintained. Automatic pipe cleaners are moved into position and inserted into the boiler tubes at regular intervals, as determined by the detection system. The recovered steam can be used for heating purposes, preheating feed streams and generating electrical power. Indirect preheating in this manner is especially favourable compared to direct methods, because it does not involve dust emissions. The case study plant where the system was installed had an exhaust gas temperature in the range 600-650°C with a flow rate of 65,000Nm³/h, and the boiler has thermal and (potential) electrical capacities of 8.9MW and 2.1MW_e respectively. The potential for heat recovery is largely dictated by the degree to which the recovered heat can be used; without an application for this energy then recovering it is pointless.

An investment appraisal has therefore been carried out of installing such a boiler on the furnace studied. The typical capital cost of this heat recovery system is US\$650,000, which depends on the specific application (ibid.). At the time of writing the \$/£ exchange rate is 1.57, but this figure is declining steadily after peaking at over 2.00 during the summer of 2008 (HMRC, 2008). This yields a capital cost for the heat recovery boiler in the region of £414,000. As Rozendaal (2007) is not explicit about whether this figure is the installed cost, an additional 10% or £41,400 is assumed for installation, along with an annual maintenance cost corresponding to 2.5% of the total capital expenditure or £10,350. The benefits of the project are in the cost savings associated with foregoing natural gas consumption. The power of the exhaust gases is around 5.5MW and the cost of natural gas to large industrial users was 4.81£/GJ in 2007 according to BERR's (2008i) Quarterly Energy Prices publication.

It is also assumed that the heat generated steam in the boiler, which is either used for preheating raw materials or passed through a turbine to generate compressed air or electricity. In the case of using the steam directly, the benefit comes from the offset primary fuel (natural gas), but in the case of generating compressed air or electricity the benefit lies in the offset cost of electricity. The price of electricity, at around three times the price of primary fuels, reflects the efficiency of generation, so that in primary energy terms the cost per unit of energy is approximately the same. Hence this analysis assumes that the recovered heat offsets natural gas, because the cost benefits associated with electricity generation would be similar. The estimated costs and benefits are shown in Table 7-11 based on a discount rate of 5% and assuming a ten year lifetime for the boiler. The results show that the discounted payback period (DPP) is around 14 months, the net present value (NPV) is £2.7 million, and the internal rate of return (IRR) is 88%, which were all determined according to Equation A2 in Appendix A2.1.3. The latter has been determined for completeness, but the problems with employing the IRR as discussed in Appendix A2.1.3 should be borne in mind.

These underlying assumptions were varied in order to test the sensitivity of the NPV and DPP to them. If the discount rate is doubled to 10%, the DPP remains extends to around 16 months and the NPV reduces to £2.0million. Similarly, increasing the capital and maintenance costs of the project result in a smaller NPV at the end of the ten years, but the annual maintenance cost must be increased by a factor of ten before the DPP exceeds three years. Clearly the project is also heavily dependent upon the price of natural gas; increases in this price increase its economic feasibility whereas a fall in the price makes it less attractive. With a gas price of 6£/GJ, *ceterus paribus*, the DPP is reduced to one year; the price has to reduce to around 3£/GJ before the DPP becomes three years. In addition, the pricing of the heat lost based on the natural gas price is not strictly correct, because in fact more gas would be required than the amount corresponding to the heat content of the exhaust, due to incomplete combustion resulting in not all the gas being converted to heat. These two factors, along with the liberal estimates of the installation and maintenance costs, probably conspire to make the economic project criteria presented in Table 7-11 conservative ones. The DDP would probably be shorter and the NPV larger if these factors were taken into account.

COSTS		BENEFITS	
Item	Amount	Item	Amount
Capital cost of equipment (£)	414,000	Power of exhaust gases (MW)	5.52
Installation cost (£)	41,400	Cost of natural gas (£/GJ)	4.81
Maintenance cost (£/yr)	10,350	Cost of exhaust (£/yr)	838,000
Lifetime of boiler (yrs)	10	Efficiency of heat recovery boiler	0.50
		Estimated cost saving (£/yr)	419,000
		NPV at 5% DR (£million)	2.7
		DPP (yrs)	1.2
		IRR (%)	88

Table 7-11 – Investment appraisal of proposed heat recovery boiler, 5% discount rate and 10 year life

7.4.4 Lifecycle/systemic potential

One obvious method for improving the thermodynamic efficiencies of furnaces in general, and hence to reduce energy costs, is to increase the amount of cullet used in the batch. This can be achieved through closed-loop recycling, whereby glass containers are collected and re-melted in the furnace. This route has been shown to be environmentally favourable in comparison to either incineration or landfill (WRAP, 2006b). Such an approach also reduces the amount of raw material used in production and provides valuable public and stakeholder involvement in the industry (British Glass, 2007).

The benefits of open-loop recycling, in which the glass undergoes a change in properties or use before being reused, are less clear-cut. Two examples are using glass to replace aggregates in roads and as filtration media. In some cases the energy required to collect and recycle the glass exceeds that required to manufacture the raw materials which they replace (Enviros Consulting, 2003). In general, though, open-loop recycling is preferable “if both raw material extraction is

avoided and some kind of process improvement is achieved by using cullet, whereas landfilling is more favourable if the cullet only replaced the raw material” (WRAP, 2006b, p.111).

The EU’s Packaging and Packaging Waste Directive (European Commission, 2005b) requires the UK to recycle 60% of all glass packaging by 2008, but the current closed-loop rate for the container industry is around 33%, and the open-loop rate is some 51% (Hartley, 2007c). The closed-loop recycling rate for the flat glass industry is lower than for containers, due to the stricter quality requirements, and currently lies in the range 20-30% (WRAP, 2008b). In order to reach the target, recycling infrastructure would need to expand by around 160,000 tonnes per year – equivalent to doubling annual household collections from around 27kg in 2003/2004 to 50kg in 2008 (David Davis Associates, 2005). The whole glass sector would need to recycle 1.63Mt by 2008, of which the container glass sector could probably accept around 0.8Mt, with the remainder being used in other markets (op. cit.).

The recycling rate has grown significantly in the past, but this trend has slowed recently, so there is now doubt that the above target will be met (British Glass, 2007). The actual mass of cullet recycled through container furnaces dropped from around 750kt in 2006 to less than 700kt in 2008, hence DEFRA’s recent announcement that this target will be pushed back to 2010, when total recovered glass might need to reach 1.8Mt (WRAP, 2008b). Furthermore, recent increases in the open-loop recycling rate have only resulted from moderate additions to re-melting in furnaces – much of the improvement has been due to growth in the aggregates market for cullet (ibid.).

The three main barriers in the UK to increasing glass recycling rates are (British Glass, 2007):

1. **Supply** – the UK is a net importer of glass packaging, mainly in the form of full wine bottles, whilst other European countries are mainly exporters;
2. **Demand** – the UK produces mainly clear glass whereas other EU countries produce mainly green glass;
3. **Collection infrastructure** – this is significantly different to other EU countries, relying heavily on kerbside collections.

Many councils currently base their targets for glass recycling solely on tonnages without differentiating by colour, because it is less complex and more economical to do this. In addition, the waste stream is often contaminated – for example with organic matter. Container furnaces can accept a certain amount of this contamination but often there is too much present (Hartley, 2007c); there is a shortage of high quality, colour-separated cullet, which is crucial for flat glass production and favourable for containers.

Improved collection infrastructure could certainly increase the amount of useful cullet available for recycling in the container sector. For drastic improvements in the recycling rate, however, some international trade in cullet might be necessary, which would obviously have environmental implications associated with the transport. Furthermore, there is very little

incentive, from an economical perspective, for the manufacturers themselves to invest in improving the recycling infrastructure whilst the raw materials for production remain relatively inexpensive. Recent upward increases in the prices of raw materials and natural gas, however, along with a peak in the price of soda ash, have all conspired to make cullet a more economically attractive alternative and has put pressure manufacturers to address the bottlenecked supply chain (WRAP, 2008b).

Given this mismatch between supply and demand in the glass recycling stream, a recent study (WRAP, 2006a) set out to investigate the potential for using coloured glass in the manufacture of clear containers. The study approached this problem from opposite perspectives, by attempting to determine how clear a glass can be made through the use of decolourants, and how clear it actually needs to be for the customer. The findings were encouraging: considerable quantities of amber cullet can be incorporated into the batch for flint glass to produce a satisfactory product through the addition of decolourising agents. It seems that the constraints placed on colour integrity by the manufacturers are not reflected by customers, such that a certain degree of colour is acceptable, whilst still retaining the “perceived purity” so valued by manufacturers. A failsafe method for quickly and effectively testing the degree of colour contamination of a cullet batch was also developed and applied, and a user-friendly Excel programme was developed in order to calculate the required amounts of decolourising agents.

Whilst the present study has focussed solely on the furnace, the weight of a single container obviously has an indirect effect upon the energy consumption of the furnace. By using less glass to manufacture the same component one can effect downstream, demand-side energy savings, because the energy requirement of an one functional unit is reduced. Energy savings associated with this so-called lightweighting have been made in the glass industry since 1980, during which time the technology associated with it has continued to develop (The Carbon Trust, 2005a). Over the period 1996 to 2002 the average weight of a glass container produced by the sector has reduced from 292g to 273g (op. cit.) The recent Container Lite project demonstrated the scope for weight changes, and also found that consumers are less sensitive to weight changes than expected (WRAP, 2007c). A case study carried out with the Co-op identified the potential to save 46kt of glass waste just by lightweighting the supermarket’s own brand whiskey bottles (WRAP, 2007b). In addition, Grolsch reduced the unit weight of its 300ml beer bottles by over 20%, resulting in glass savings of 4kt per year, demonstrating that lighter packaging can be cost-effective, practical and commercially appealing (WRAP, 2007a).

7.4.5 Critique of methodology

This section discusses the limitations of the methodology. The main limitation of the methodology lies in the consideration of just two dimensions. Whilst there is clearly not a uniform temperature profile along the third dimension, this assumption enabled an analysis to be carried out with only a fraction of the resources that are needed for a much more detailed 3D study. The results obtained are still similar to those obtained by more detailed studies in three dimensions (Sardeshpande et al., 2007). The overall objective of this study was to gain an

insight into the energy and exergy flows within a typical furnace in the UK glass sector, and this has been satisfactorily met based on the applied methodology. Other related limitations include the assumptions of steady state operation, which overlooked the time evolution of the glass and the changing flow around the furnace. The assumption of perfect adiabatic heat transfer between the combustion products and the glass bath is not a true representation of reality, but is a reasonable simplification in the present case. The same also applies to the assumption of complete combustion and stoichiometric fuel-to-air ratios in the furnace. The investment appraisal is based on just one source for economic data relating to the waste-heat recovery boiler, but such data is notoriously difficult to obtain as mentioned throughout this thesis. The investment appraisal is clearly sensitive to the input values employed, many of which were varied and discussed above. The exchange rate is a crucial parameter in these calculations; the analysis should be repeated following significant fluctuations in the exchange rate (say above 10%). The results are only intended to be indicative, however, and should not be used as the basis for an investment. A more detailed, site-specific investment appraisal would be recommended if this project is being considered.

The usefulness of the exergy method could also be questioned in this case, because it leads to the same conclusions as the energy analysis. However, the low exergy efficiency resulting from the large combustion-related exergy destruction is both advantageous and disadvantageous. It shows where attention should and should not be focussed, but could also suggest a large scope for improvement which in reality is constrained by this exergy destruction. The smaller but still significant exergy content of the exhaust stream led to a focus on this area over the structural losses because it represents a higher energy flux.

Finally, this study has not considered heat recovery from the molten glass once it leaves the system. Some unsuccessful attempts have been made to extract heat from the glass in the forehearth (Figure 7-1) using heat exchangers (Hartley, A., British Glass, pers. corr., March 2009). It would also be theoretically possible to extract some of the heat during container forming, but this is complicated by the high rate of heat extraction required to ensure structural integrity and the necessity for constant access to the machinery (ibid.). This study has also overlooked the potential for technologies which are not yet commercial. For example, Bauer et al. (2003) have analysed the potential for thermophotovoltaics to generate electricity by being installed in the furnace superstructure. Although the author's identify substantial potential, most of this involves substantial disruption to the existing process and therefore requires medium to long term R&D to become viable. Such novel applications are therefore also considered to be beyond the present scope.

7.5 Conclusions and recommendations

A general model of an industrial glass furnace has been developed, which enables energy and exergy balances to be performed over a range of furnace loads, batch recipes, cullet contents and temperature regimes. The model shows a good correspondence with published data and a sensitivity study has shown that its behaviour is within the expected theoretical limits. Whilst

the energy analysis suggests a large energy loss in the waste gases, the exergy analysis indicates a large exergy destruction due to combustion but highlights the structural and exhaust losses as other significant areas where attention should be focussed. The model can also be used to accurately predict the CO₂ emissions from the furnace under different operating regimes and batch compositions, which could be especially valuable in the context of benchmarking furnaces for the EU ETS.

Based on these results an investment appraisal has been performed to assess the economic feasibility of installing a waste heat recovery boiler, which would utilise some of the heat content in the exhaust to preheat the batch or fuels, or could generate electricity to meet ancillary needs on or off site. The investment appraisal is predicated on the assumption that one of these uses for the recovered heat exists; it does not apply if this is not the case. If one of these uses does exist, heat recovery is a highly attractive opportunity with a discounted payback period of fourteen months and a net present value of £2.7million (IRR of 88%). These figures are somewhat sensitive to the underlying assumptions, such that higher or lower gas prices would make the project more or less attractive, respectively. Nevertheless, the recommendation that follows from this analysis is that such a heat recovery boiler is a very suitable economic means through which to increase the energy efficiency of the sector. The energy saving for this particular furnace running at 300t/d is 239GJ/d (i.e. 0.80GJ/t glass produced), which is based on a boiler efficiency of 50%. If such heat recovery boilers were rolled out across the sector as a whole, and every furnace has a use for the recovered heat, then the total saving potential might be ten times this figure, based on the total operational capacity of the sector and a utilisation factor of 85% (Table 7-1 and footnote 40).

In theory there is much scope for improving the systemic energy efficiency of the glass sector in the UK by increasing the recycling rate, but this is limited in practice by barriers such as the colour and quality mismatch between the domestic supply of and demand for cullet. Whether these barriers can be overcome will depend on many factors, including the price of the raw materials (especially sand and soda ash) and fuels (mainly natural gas), as well as the development of the carbon price within the EU ETS and the changing market environment. Lightweighting of containers also stands to offer further energy efficiency improvements.

8 Process integration in a pulp and paper mill⁴³

This chapter presents a process integration study, involving pinch analysis and economic optimisation, of an integrated mechanical pulp and paper mill. The chapter begins with an introduction to the sector and its activities and a short review of relevant literature. An overview of the mill's operations is then presented, followed by mass and energy balances of the energy systems. The results of this section are then used to carry out the pinch analysis and economic optimisation. The chapter closes with conclusions and recommendations.

8.1 Introduction

The pulp and paper sector produces various grades of paper, tissue and board products. The sector's production capacity is concentrated in a small number of companies and mills, which produce high volume, low value output. A small number of manufacturers therefore account for most of the bulk grade⁴⁴ production capacity and high quality products such as tissues are produced in relatively small quantities (Bateman, B., CPI, pers. corr., July 2007). Energy costs are the third highest cost for the sector, accounting for approximately 8% of the turnover (European Commission, 2001d). The sector used around 75PJ of energy in 2005 (DTI, 2007b) and the sector's emissions allocation under the EU ETS was around 1MtCO₂ during Phase II of the Scheme (DEFRA, 2007d). Key statistics for the sector are presented in Table 8-1.

Papermaking companies	49
Paper and board mills*	68
Papermaking employees (1000)	12.6
Paper making turnover (£billion)	3.5
Consumption of paper and board (Mt)	12.3
Production of paper and board (Mt)	5.6
Imports of paper and board (Mt)	7.8
Exports of paper and board (Mt)	1.0
Recovered paper usage (Mt)	4.2

Table 8-1 – Key indicators for the pulp and paper sector in 2006

Source: CPI (2007); *7 mills ceased operation during this year

The pulp and paper sector is one of the only industries that actually generates energy as a by-product – i.e. black liquor from chemical pulping is used as a fuel – and could therefore drastically reduce its SEC (De Beer et al., 1998) and even become a net exporter of energy in the long term (Gielen & Tam, 2006). As is the case for most other industrial sectors, large improvements in overall energy intensity have been achieved through energy efficiency measures over the past few decades. On average, the UK sector has reduced its primary SEC by

⁴³ This chapter is based on the Masters Thesis "Process Integration at a Pulp and Paper Mill: A Case Study of Caledonian Paper Mill" carried out by Morten Styrng of the Technical University of Denmark between February and July 2008. The project was undertaken in the Department of Mechanical Engineering at the University of Bath under the supervision of the present author.

⁴⁴ Bulk grade is the term given to the lower quality paper products produced in large volumes, such as for newspapers.

1.6% per year over the period 1973-1991 (Farla et al., 1997). This annual change may be an underestimate because it does not account for indirect efficiency improvements through new CHP plants.

The fundamentals of pinch analysis are presented in Appendix A2.2.2.3. Pinch analysis has previously been used to identify significant potential for efficiency improvements in the hot and warm water system in paper mills (Nordman, 2005; Bengtsson et al., 2002; Nordman & Berntsson, 2006, 2009a, 2009b; Natural Resources Canada, 2002). These systems have therefore been the focus of attention for optimisation and heat recovery. Nordman and Berntsson developed (2009a) and applied (2009b) an advanced pinch analysis methodology for retrofit situations. It employs four different composite curves above and below the pinch point, which relate more detailed information about the actual and theoretical temperature and enthalpy difference of the respective streams. Due to the fact that the advanced curves only give a qualitative indication of the cost-effective heat recovery potential, however, they are best used as a screening tool to identify targets and show the order in which they should be addressed. Bengtsson et al. (2002) employed another method of advanced pinch analysis, including new composite curves and the so-called matrix method. The latter represents an attempt to improve the optimisation procedure by accounting for other parameters in addition to the area of the heat exchanger network (HEN). These include the physical distance between streams, types of heat exchangers, heat transfer coefficients and fouling. The matrix method seems more suited to complex problems, however, so was not fully exploited in this case (ibid.).

Wising et al. (2005) applied pinch analysis to a pulp and paper mill, concluding that reducing the overall water consumption in the mill increases the quantity and temperature of excess heat. This excess heat can also be used for evaporation in the process, thus reducing live steam demand by up to 1.5GJ/t. Furthermore, the authors found that by removing pinch rule violations in the mill, water consumption becomes less of an important factor. The economically best solution is probably a combination of reducing water consumption, removing pinch violations and using some of the excess heat for evaporation (ibid.). Clearly pinch analysis in general is a useful method in identifying the potential for efficiency improvements in pulp and paper mills.

UPM's Caledonian Paper Mill (hereafter the mill) in Irvine, Scotland, is one of the largest mills in the UK. It is the only producer of Light Weight Coated (LWC) paper in the UK, with a capacity of 280kt/yr, and one of two large scale integrated mechanical pulp and paper mills in the UK, the other being Iggesund at Workington (Morgan, D., CPI, pers. corr., August 2008). Pulp is produced in electrically-driven mechanical grinders, where fibres are extracted from logs and heat is dissipated due to friction, much of which is removed by water. Heat recovery from the shower water and humid air exhaust from the paper machine is used to supply the process heat demand and reduce the overall steam consumption. The pulping temperature and bleaching process have recently been modified in the mill, and there is a desire to understand the effect(s) of these changes on the HEN and losses in the effluent system. The focus of this study is in the hot and warm water systems at the mill, which are already integrated to a large

degree. An Opportunities Assessment was carried out at the mill in 2007 (NIFES Consulting Group, 2007), which concluded that one key area to focus attention should be the grinders (i.e. the Pressurised Ground Wood pulping machines, PGW, section 8.4.1). It also identified the already high efficiency of the steam system, which had a condensate return efficiency of 83%.

8.2 *Aim and objectives*

The overall aim of this case study was to determine the potential for thermodynamic efficiency improvements at Caledonian Paper Mill based on process integration techniques and to carry out an economic assessment of any proposed changes. With this general aim in mind, the specific objectives required to meet this aim are to:

- Provide an overview of the process in the mill, and specify how production constraints affect the energy consumption (section 8.4);
- Estimate energy and mass balance in the system with a focus on the utility, hot and warm water, and heat recovery systems in the paper machine (section 8.5);
- Estimate the overall potential for heat recovery through a pinch analysis, and suggest possible ways to utilise this excess heat (section 8.6);
- Calculate the cost-effectiveness of modifying the HEN to balance the heat demand and recovery for the process and thus reduce overall heat demand (section 8.7);
- Determine the sensitivity of the results to key variables and suggest improvements to the methodology (sections 8.7.3 and 8.7.4).

8.3 *Applied software*

The energy system simulator Dynamic Network Analysis (DNA, Elmegaard, 1999) was used to model the heat recovery system. The basic idea is to structure an energy system network based on components that are connected through branches by nodes. The software contains a catalogue of pre-defined components such as heat exchangers, pumps, boilers, turbines, and valves. DNA solves the energy and mass balances by applying the First and Second Law of Thermodynamics to a control volume around the components and using the nodes as boundary conditions. The interrelationship between components will determine the total number of additional conditions that are required from user input. DNA also requires initial estimates for output variables that are independent of the initial conditions and are not given by the component constraints. The most common fluid and solid properties are defined in DNA; it is possible to create new fluids and solids by defining the composition from a number of available compounds. The system is solved via a numerical iteration method, whereby the value of the additional and initial conditions determines whether the system converges. When a physically meaningful solution is obtained, the mass flow, temperature, pressure, enthalpy, entropy and specific volume are calculated for each node. A complete description of DNA is given by Elmegaard (1999). The economic optimisation was performed via algebraic equations that describe the technical and economic behaviour of the suggested HEN. The free parameters in the models are used to optimise the payback period and the equations were solved

simultaneously in Engineering Equation Solver (EES). EES was also used to find the relative humidity of air based on the results from DNA.

8.4 Overview of the mill's operations

Although chemical pulping is the most common method globally and in Europe, the UK is an exception with only one chemical pulping mill at Ahlstrom Chirnside in Radcliffe, near Manchester (Morgan, D., *ibid.*). At Caledonian the pulp from mechanical pulping (83%) is used together with imported chemical pulp (17%) to produce paper. The mechanical pulp is produced from virgin fibres, i.e. no recycled paper is used. Light Weight Coated (LWC) paper has a weight of 51-70g/m² and is used in magazines, catalogues and newspaper supplements. The production capacity is 280kt/yr of paper, which corresponds to approximately 5% of the total UK production in 2006 according to Table 8-1. An overview of the pulp and paper process is presented in Appendix A3.3.1. A new biomass fired CHP plant is currently under construction and is expected to be in operation in 2009.

8.4.1 Mechanical pulping and temperature considerations

Wood fibres are extracted from softwood logs in a mechanical pulping process. The logs are debarked and cut to a length of around 1.5m before being pressed against a rotating stone in the grinders (Figure 8-1), which causes local vibration and heating of the timber. Extraction of fibres is enhanced due to overpressure of approximately 2.3bar in the grinders (four in total). The process is called Pressurized Ground Wood (PGW) pulping, and results in a higher production rate than normal mechanical pulping (Reilly, 2003). Hot shower water is added to process the fibres and clean the grinding stones, which acts as a cooling medium, but must be warm enough to prevent thermal shock to the stone. The electricity used to drive the grinding stone is transformed into heat through friction, and mostly removed by the shower water. The pulp is then lead through different screening and refining stages, before being bleached and stored.

The choice of grinding temperature is a trade-off between pulp quality, energy consumption and chemical consumption. Due to the grinding overpressure, water and grinder pit temperatures up to 95°C and 125°C respectively are possible. However, these two temperatures have previously been changed to 75°C and 100°C respectively. The lower grinding temperature reduces the long fibre content and thus the pulp strength, which is important to prevent paper breaks in the paper machine and to improve final product quality. A reduction in strength means a higher freeness value⁴⁵ and better draining ability, which leads to a lower SEC for the refining process (European Commission, 2001d). The optical properties are also improved at lower temperature because the pulp is lighter, which reduces the demand for chemical bleaching. A higher temperature could increase the production rate (as fibres loosen faster), but

⁴⁵ Freeness relates to the ability of the pulp to drain and lose water, and is measured in millilitres Canadian Standard Freeness, mlCSF (European Commission, 2001d, p.182).

this is more sensitive to the condition of the grinding stone, timber quality and grinding pressure (Reilly, 2003).

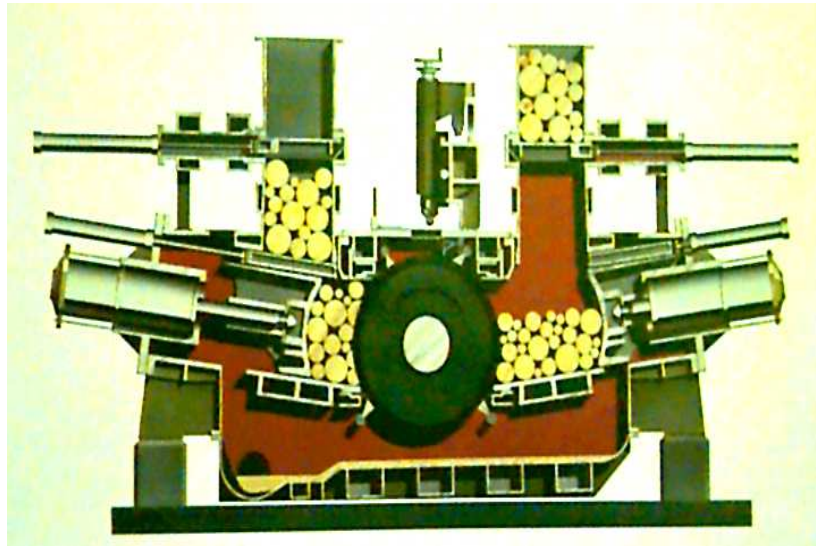


Figure 8-1 – Mechanical grinder (UPM, 2004)

When the pressure is released after the grinding process it causes water to evaporate, which increases the moisture content in the grinding exhaust air. Heat was previously recovered from the humid air in a condenser and used to heat water. After the pulping temperature was reduced, UPM decided to refrain from heat recovery of the evaporated vapour due to the commensurate reduction in the exhaust air temperature. According to the European Commission (2001d), around 20% of the energy demand is recoverable as steam from PGW pulping. The determination of a suitable grinding temperature is thus very complex, involving trade-offs between, *inter alia*, pulp quality, energy consumption and chemical consumption. The volume and temperature of the effluent is also affected by the grinding temperature.

8.4.2 Paper production

The stock is prepared in up to five cleaning stages, before it approaches the machine screening and paper machine itself. The machine can be broken down into roughly five sections, as shown in Figure 8-2. The head box introduces a suspension of fibres to the wire and distributes the fibres uniformly across the wire belt. The wire section drains the paper web to 18% consistency, and the press section increases the strength of the web and removes even more water by pressing to a consistency of 50%. The dryer section evaporates the water in the web to a consistency of approximately 91%, and is usually one of the largest energy consumers within a paper machine (Sivill et al., 2005). The paper is then coated to attain a smooth surface for printing and treated with chemicals to achieve the required brightness. The coated paper is then dried with hot air to a final consistency of approximately 95%. The paper is passed through a series of hard and soft rolls, known as supercalendering, which make the surface of the coated paper smooth and glossy, before it is finally reeled up and stored until being cut down to specific customer sizes and wrapped. The paper machine is 8m wide and runs at

1400m/min, which determines the production rate as well as the length of the drying section due to limitations in heat transfer and thus evaporation rate.

In the dryer section the web is pressed against hot drying cylinders, which allow heat conduction to occur. The contact time and pressure determine the heat transfer rate. The inside of the cylinder drum is simultaneously heated with steam, and the heat transfer is affected by the temperature and mass flow of steam, as well as the effectiveness of steam condensate removal. The paper is simultaneously cooled due to evaporation of water and heated due to convective heat transfer from the surrounding air. The air needs to be circulated and externally heated to avoid vapour saturation (US DOE ITP, 2005).

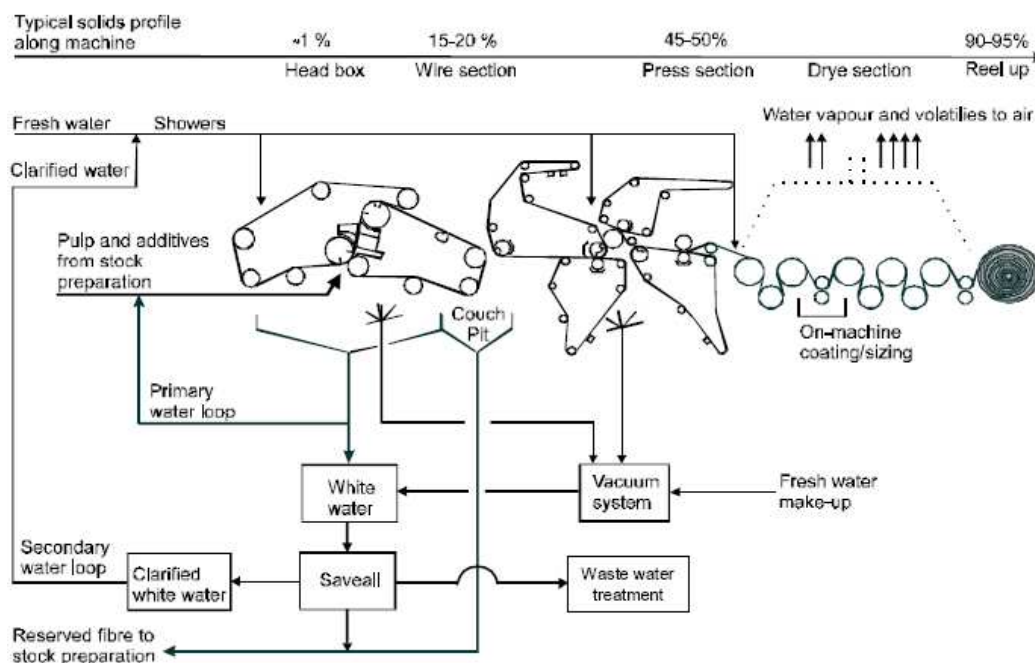


Figure 8-2 – Schematic overview of a paper machine (European Commission, 2001d)

When paper is lost during the papermaking process – known as broke – it is reintegrated into the process to conserve fibres within the system. The broke needs to be treated before it is mixed with virgin fibres. Broke is generated during normal operation due to winding of the paper sheet, but also because of paper breaks. The amount of broke differs but 29% is reported in the mill with 40% and 60% of wet and coated broke, respectively (Luumi, R., Process Development Engineer, UPM, pers. corr., March 2008). The energy wastage due to broke is significant because the same mass flow is passing through the process more than once. Generation of coated broke in particular should therefore be minimized since drying of the web is the most energy demanding process. Increased paper strength will reduce the frequency of paper breaks, which is possible by improving the press section (or increasing grinding temperature as previously mentioned). A rule of thumb is that a 1% improvement in press consistency corresponds to a 4% improvement in drying efficiency (European Commission, 2001d).

8.5 Energy and mass balance of the mill

In this section an energy and mass balance is presented for three systems, namely the utility system, the warm and hot water system, and the heat recovery system in the paper machine. It is necessary to carry out an energy and mass balance in order to provide the data for the pinch analysis.

8.5.1 Utility system

8.5.1.1 Steam

The steam system in the mill is shown in Figure 8-3 and the annual average steam consumption is shown in Table 8-2. The small deviation in mass balance (i.e. 13.07kg/s vs. 12.26kg/s) is probably caused by steam reforming in the thermocompressor.

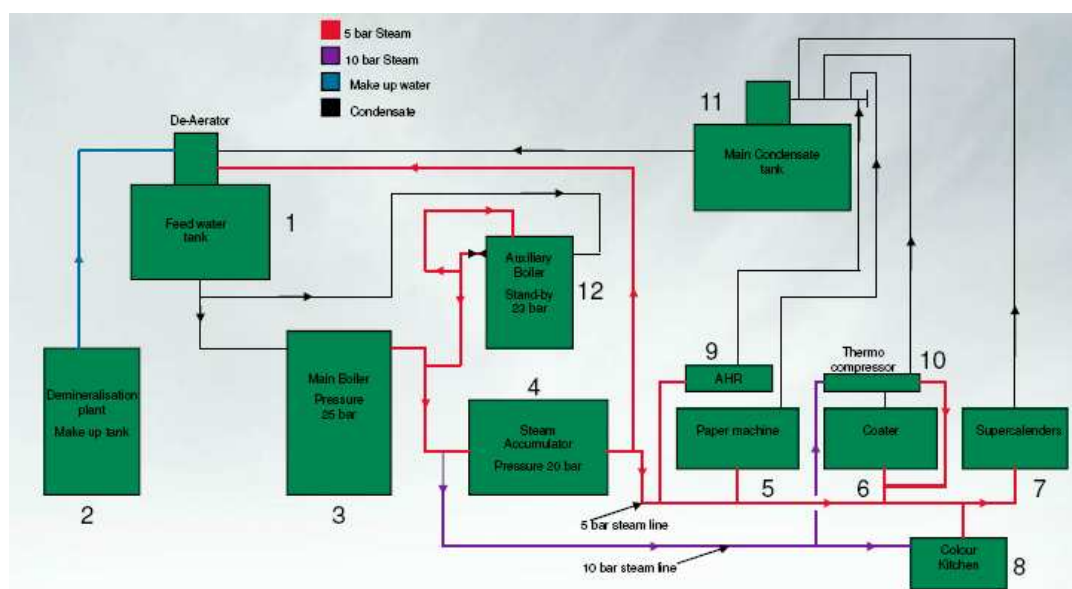


Figure 8-3 – The mill's 5 and 10 bar steam system

The paper machine press section steam box also requires direct steam injection to improve moisture profiling, but it is negligible compared to the heat effect used to dry the paper sheet in the drying section (Reilly, E., Environmental Superintendent, UPM, pers. corr., March 2008). In addition, direct steam injection is possible in the hot filtrate tank to maintain the required temperature, but the consumption is currently not measured. It is assumed to be negligible and therefore disregarded in this analysis. The specific steam consumption over 2007 varied over the range 4-9GJ/t LWC overall and more consistently 4-5GJ/t base⁴⁶ in the drying section of the paper machine (Reilly, E., op cit.).

⁴⁶ Paper prior to coating and rolling is referred to as base.

Steam from main boiler		13.08
• Steam to 10 bar system	0.28	
• Steam to Accumulator	12.80	
Steam to Feed Water Tank		0.54
Steam to mill (5 bar)		12.26
• Steam to paper machine		10.12
○ Steam to drying	8.60	
○ Steam to wire pit	1.15	
○ Steam to wet end hood	0.17	
○ Steam to dry end hood	0.20	
• Steam to coater		0.85
• Steam to supercalanders		0.89
• Steam to Aqua Heat Recovery (AHR)		1.20
○ Steam to mill heating water	0.60	
○ Steam to warm water tank	0.60	
Main Condensation return flow		10.90

Table 8-2 – Annual average steam consumption in the mill (kg/s)

8.5.1.2 Electricity

The annual electricity consumption in 2007 is given in Table 8-3. Assuming a load factor for the whole plant of 90% (Entec UK Ltd., 2006f), this corresponds to an average power demand of 41MW. The grinders account for around 1/3 of the total electricity consumption. The specific electricity consumption of the grinders was consistently 4.0-5.0GJ/t pulp, and the total electrical SEC of the mill was 4.3-6.5GJ/t LWC in 2007.

8.5.1.3 Fuel

The fuel consumption by source is shown in Table 8-4. The current boiler house consists of a coal and biomass fired boiler and a natural gas fired auxiliary boiler (Figure 8-3). The new CHP plant will eliminate approximately 81ktCO₂ from non-renewable energy sources along with 2/3 of the grid electricity consumption and is estimated to use more than 350kt/yr of biomass. The thermal heat to the boiler is 99.5MW.

PGW pulping and refining (grinders ~70 %)	553.3
Kraft pulp refining, stock preparation, paper machine	353.5
Finishing, paper machine	31.0
Utility (compressors ~39%)	65.9
Coating	69.1
Lighting and cranes	77.0
Other	13.0
Total	1,156.0

Table 8-3 – Electricity consumption in 2007 at Caledonian Paper Mill (TJ/yr)

	Coater natural gas	Boiler natural gas	Coal	Bark	Total
TJ	180.2	101.2	803.5	327.6	1,412.5
ktCO ₂	9.3	5.2	75.7	36.0	126.2

Table 8-4 – Energy consumption and CO₂ emissions by source in 2007

8.5.2 Warm and hot water system

An overview of the water and effluent system is given in Appendix A3.3.3. The mill has a number of loops in which water is circulated. If limits in tank capacities are exceeded, or mass flow is required elsewhere in the pulp production, water is cascaded through the system in the following order:

Mill Water Tank >> Clean Filtrate Tank >> Cloudy Filtrate Tank >> Hot Filtrate Tank or Effluent.

Mill water is only added to the cloudy filtrate tank if the process needs cooling (Luumi, R., op. cit.). The volume of effluent is a measure of the losses from the system, but is also necessary due to contamination with wood solubles and bleaching chemicals. Fresh water is added continuously to the mill water tank at a flow rate of approximately 100l/s. The mill water is used as sealing water in the grinders, to cool machinery in the paper mill and is filtered afterwards to remove oil. Approximately 60l/s is heated and used as warm water in the coating and wire section, whilst the remaining water is re-circulated.

Hot filtrate water is drained from the stock at approximately 85-90°C in the pressure thickener after the grinders. The pressure thickener is a large slowly rotating wire mesh drum used to increase the consistency of pulp from approximately 1.5% to 40% (Luumi, R., op. cit.). The hot filtrate water is then lead to the hot filtrate tank, where the average temperature is 75°C (Figure 8-4). The water in the tank is used as shower water in the grinders (approximately 210kg/s) and as hot streams in three heat exchangers, namely the warm water HEX, the wire pit HEX and the white water HEX. The circulation of hot filtrate water takes place within the hot loop, the purpose of which is to recover heat for the process and minimize the use of steam heating.

The mass flow rate through the heat exchangers varies with the operation of the paper machine and grinders. Average measurements of mass flow rates and temperature have therefore been used to estimate the heat transfer in the heat exchangers, as shown in Table 8-5 (average values in bold). The mass flow rate of the hot stream in wire pit HEX is estimated from a measured total flow of 210kg/s in the three heat exchangers. The hot filtrate tank is a heat and mass storage, with the capacity being used to balance variations in consumption and supply of heat and mass flow in the hot loop. The temperature of hot filtrate water from the pressure thickener is estimated from an energy balance by placing a control volume around the hot filtrate tank and assuming steady state conditions. Hence from Table 8-5 the balance is as shown below.

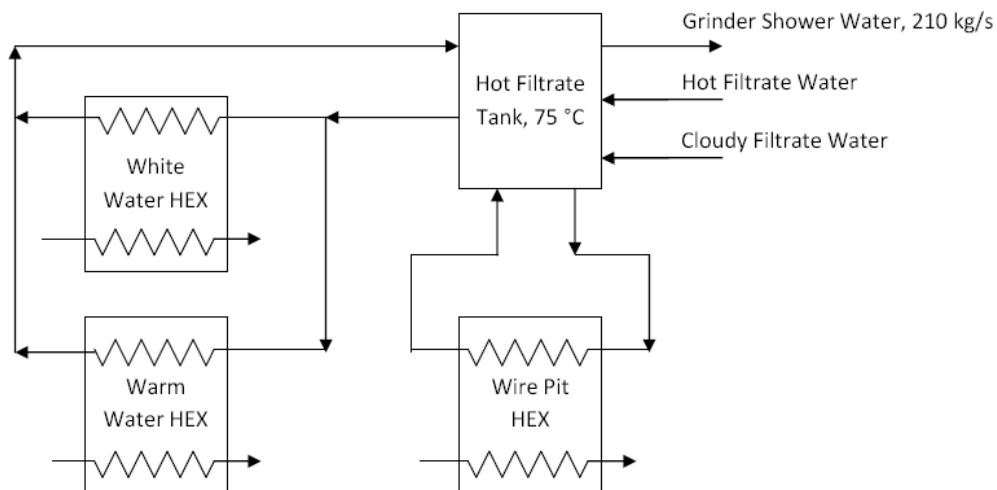


Figure 8-4 – Existing heat exchanger network for hot filtrate water

$$\sum \dot{Q}_{\text{HEX}} = \dot{m}_{\text{ShowerWater}} \cdot c_{p,\text{water}} \cdot (T_{\text{HotFiltrate,in}} - T_{\text{ShowerWater}})$$

$$\Leftrightarrow$$

$$(1.88 + 4.51 + 3.55)\text{MW} = 210 \frac{\text{kg}}{\text{s}} \cdot 4.18 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} \cdot (T_{\text{HotFiltrate,in}} - 75^\circ\text{C})$$

$$\Leftrightarrow$$

$$T_{\text{HotFiltrate,in}} = 86.3^\circ\text{C}$$

It is therefore reasonable to assume 87°C as the inlet temperature of the hot filtrate water when losses in tanks and heat exchangers are taken into account. The overall heat transfer in the hot loop is thus approximately 10.5MW based on the above energy balance, which is confirmed by instantaneous measurements from the grinders (shown in Appendix A3.3.2). The latter shows that the heat transfer to the shower water at a flow rate of 187kg/s is 9.3MW. If the heat transfer increases proportional to the mass flow of shower water (i.e. proportional to pulping rate), which is a reasonable assumption if the specific electricity consumption in the grinders is independent of the mass flow rate of logs, this corresponds to 10.4 MW heat transfer to the shower water at a flow rate of 210kg/s. This is clearly very close to the calculated value of 10.5MW.

The total heat demand of the wire pit is estimated to be 5MW (Horner, G., Utilities Supervisor, UPM, pers. corr., March 2008), and the remaining heat transfer is provided as direct steam injection. The need for extra steam is probably caused by the longer periods of unbalance in supply and demand in the hot and warm system. According to Table 8-2 the average steam consumption in the wire pit is 1.2kg/s, which when added to the value in Table 8-5 gives a total heat transfer of $1.2\text{kg/s} \cdot 2.1\text{MJ/kg} + 3.6\text{MW} \approx 6\text{MW}$ ⁴⁷. This corresponds to an average additional steam requirement of approximately 1MW or 0.47kg/s.

⁴⁷ The heat transfer due to condensation of 5 bar steam is equal to the difference in enthalpy between the vapour and liquid phases, which is approximately $h''-h' = 2.1\text{MJ/kg}$ (Rogers & Mayhew, 2000).

Warm Water HEX	T _{in} (°C)	T _{out} (°C)	\dot{m} (kg/s)	\dot{Q} (MW)
Hot stream	77	65	90	
Cold stream	18	36	60	4.51
White Water HEX				
Hot stream	77	71	70	
Cold stream	50	60	45	1.88
Wire Pit HEX				
Hot stream	77	60	*50	3.55
Cold stream	50	60	85	

Table 8-5 – Heat transferred in the White Water HEX, Warm Water HEX and Wire Pit HEX

*Estimated from measured total flow of 210kg/s through three heat exchangers

The heat supply from all three tanks lasts a maximum of twenty minutes at a flow rate of 210kg/s if the grinding process is shut down. Due to restrictions on the allowable tank level and temperature requirement, the period before steam is injected is much shorter than this. The steam injection to the wire pit is constantly fluctuating along with the changing supply and demand for heat in the process. An increase in tank capacities would reduce the need for direct steam injection, but a calculation of the optimal tank capacity would require duration curves of the heat flow, which are not available. It is therefore assumed that the steam consumption in the wire pit consists of 0.47kg/s from direct steam injection and 0.68kg/s from the wire pit HEX.

Due to the recent increase in heat exchanger area and investment in a new heat exchanger, the original data on heat exchanger area is no longer valid, but the overall heat transfer coefficient is assumed to be unchanged. Based on this and the measurements in Table 8-5, the minimum installed heat transfer area has been calculated as shown in Table 8-6.

	U (kW/m ² K)	ΔT (°C)	A (m ²)
Source	Assumed unchanged	Equation 8-9	Equation 8-10
White Water HEX	1.6	18.7	63
Warm Water HEX	1.6	43.9	64
Wire Pit HEX	3.0	13.2	90

Table 8-6 – Estimation of heat transfer area in hot and warm water system

The effluent caused by the cloudy filtrate overflow is at approximately 85°C, and the volume is estimated at 2000-3000m³/day (23–35kg/s). The effluent caused by clean filtrate overflow in chemical pulp preparation is at approximately 47°C and the volume is estimated to 1700m³/day (20kg/s). The volume flow of effluent is determined by the degree of pulp bleaching. Increased bleaching will cause an increase in cloudy filtrate overflow, but a reduction in clean filtrate overflow since this is used as shower water in the bleaching process. Bleaching of pulp is performed to approximately 80% of the manufactured pulp, which makes it worthwhile to consider heat recovery from the cloudy filtrate overflow. In the following analysis it is assumed that 25kg/s of cloudy filtrate effluent is available at 85°C.

8.5.3 Heat recovery system in paper machine

The purpose of this section is to describe the existing heat recovery system in the mill and estimate the humidity ratio of the air for various operating conditions based on measurements. The humidity ratio is subsequently used to calculate the heat recovery potential as a function of the outlet temperature of this air.

8.5.3.1 Estimation of the average humidity ratio

A common design for a heat recovery system in a paper dryer is presented in Figure 8-5, which is similar to the overall layout found in Caledonian mill. The temperature and flow values based on average measurements for the mill are shown in Figure 8-6, whereby the mass flow of hood supply air is estimated from an investigation at a Finnish paper mill in 2001 (Sivill et al., 2005). In general, the humidity ratio of the exhaust air in the dry end of the drying section is slightly lower than that in the wet end (Reilly, E., pers. corr., op. cit.).

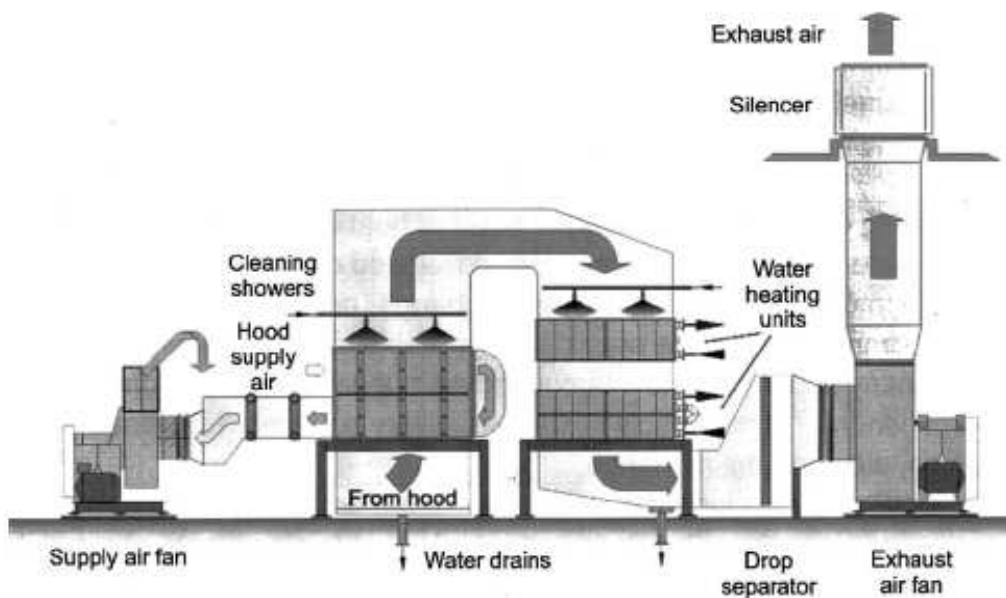


Figure 8-5 – Modern heat recovery system of paper machine dryer section (Sivill et al., 2005)

The evaporated water is transported from the paper sheet to the air in the paper machine drying section and the exhaust air from wet and dry ends of the drying section preheats the inlet air (i.e. mezzanine air from paper machine hall) in two air-to-air plate heat exchangers (Figure 8-6). The inlet air is then heated with indirect steam heating, to reach the required temperature before entering the paper machine. The exhaust air from the wet and dry ends is then mixed and lead into two series of connected cross-flow heat recovery banks, where the mill heating water and warm water to the paper machine is heated in this order. Each heating bank consists of six units connected in parallel, each with four passes. The Aqua Heat Recovery (AHR) unit appears to be completely un-documented, i.e. construction details such as tube

finned area, total heat transfer area, tube diameter and length, are all unknown to UPM. After the heating banks the exhaust air is ejected through the roof ventilation (Figure 8-6).

The mill heating water circulates in a loop as shown in Figure 8-7. It is cooled in several heat sinks located around the mill, and afterwards led back to the AHR unit, where a valve controls the flow through the heating banks and by-pass respectively, depending on the return temperature. The flow through the first heating bank in the AHR unit is therefore not necessarily constant. The two streams are then mixed again and direct steam injection will be used if the temperature is lower than a chosen limit. A pump raises the pressure and restarts the loop.

Temperature and flow data is continuously collected from the heat recovery system in the paper machine via the mill monitoring system. Measurements of humidity in the exhaust air are also available but they do not seem accurate due to a lack of equipment calibration. However, an approximate value for the water content in the exhaust air can be estimated by calculating the evaporation rate of water. The paper grade varies between 51-70g/m², but up to 30% of this weight is added in the coater section. The paper grade after the drying section is therefore in the range 36-62g/m², and the average value is known to be approximately 43g/m² with 9% moisture (Reilly, E., pers. corr., op. cit.). The paper sheet is 8m wide, moving at a speed of 1400m/min (23m/s) in the paper machine, and enters the drying section with a 50% moisture content. Assuming conservation of stock through the drying section gives the average evaporation rate of water according to Equation 8-1.

$$m_{\text{stock}} = 0.043 \frac{\text{kg}_{\text{product}}}{\text{m}^2} \cdot 0.91 \frac{\text{kg}_{\text{stock}}}{\text{kg}_{\text{product}}} = 0.391 \frac{\text{kg}_{\text{stock}}}{\text{m}^2} = m_{\text{water,in}} \quad 8-1$$

$$\dot{m}_{\text{water}} = (0.391 - 0.043 \cdot 0.09) \frac{\text{kg}_{\text{water}}}{\text{m}^2} \cdot 1400 \frac{\text{m}}{\text{min}} \cdot 3600^{-1} \frac{\text{min}}{\text{s}} \cdot 8\text{m} = 6.58 \frac{\text{kg}_{\text{water}}}{\text{s}}$$

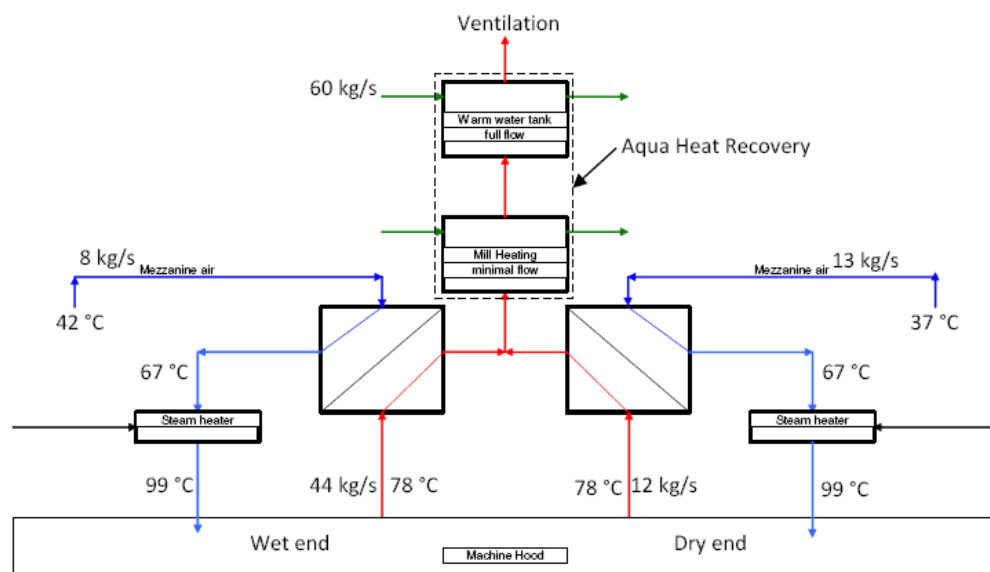


Figure 8-6 – Heat recovery system in the paper machine

The inlet mezzanine air to the dryer is assumed to have a humidity ratio of $w_{air,in} = 0.02$ kg_{water}/kg_{air} (approximately 50% relative humidity), and the total exhaust air flow from the machine is approximately $56kg_{air}/s$ (Figure 8-6), giving a humidity ratio according to Equation 8-2.

$$w_{air,exhaust} = \frac{6.58 \text{ kg}_{water}/s}{56 \text{ kg}_{air}/s} + 0.02 \frac{\text{kg}_{water}}{\text{kg}_{air}} = 0.14 \frac{\text{kg}_{water}}{\text{kg}_{air}} \quad 8-2$$

A similar calculation was carried out for the lightest and heaviest paper grades, of $36g/m^2$ and $62g/m^2$ respectively, to find the evaporation rate of water, humidity ratio, dew point and relative humidity, whilst assuming constant mass flow of humid air at $56kg/s$ and hood exhaust temperature of $78^{\circ}C$ (Figure 8-6). The results are shown in Table 8-7.

The temperature of the hood exhaust air is $78^{\circ}C$, so the dew point and relative humidity are approximately $58^{\circ}C$ and 42%, respectively. It is important not to have an excessively high dew point to avoid condensation in the hood, which will cause formation of droplets that can destroy the paper sheet and cause a paper break. The inlet mass flow of mezzanine air needs to be adjusted depending on the paper grade in order to maintain the same dew point and relative humidity in the drying section. This is done manually at the mill and the humidity ratio is therefore expected to be proportional to the paper grade.

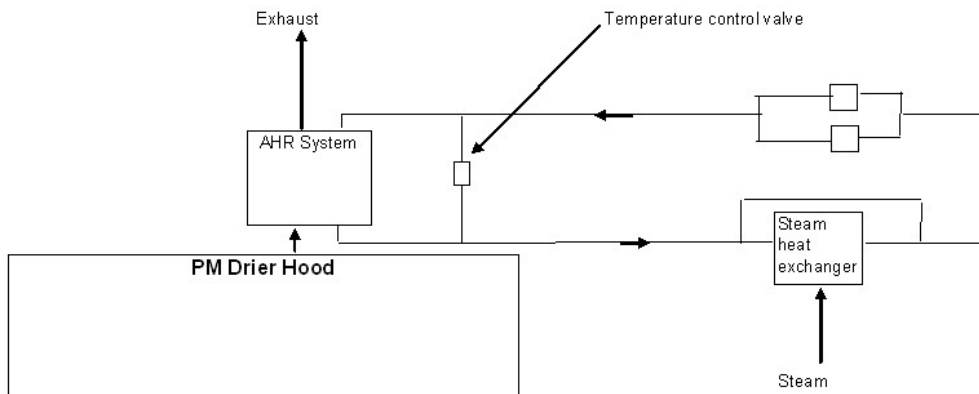


Figure 8-7 – Mill Heating Water loop (Corner, G., Utilities Supervisor, UPM, pers. corr., March 2008)

Paper grade (g/m ²)	\dot{m}_{water} (kg/s)	$w_{air,exhaust}$ (kg _{water} /kg _{air})	Dew point (°C)	Relative humidity (%)
36	5.51	0.12	56	37
43	6.58	0.14	58	42
62	9.49	0.19	64	54

Table 8-7 – Evaporation rate of water, humidity ratio, dew point and relative humidity for light, average and heavy paper grades

The potential heat recovery at a given mass flow and air humidity ratio depends on the outlet temperature of the humid air. When it is used as a hot fluid in a condensing heat exchanger, the heat exchange will occur both as sensible and latent heat transfer (Kakac & Liu, 2002). When the boundary layer of the humid air near the wall becomes fully saturated, condensation will occur and the heat flux will be much higher than for sensible heat transfer alone. When the water content in the humid air decreases due to condensation, the dew point will also be reduced, and condensation will therefore continue as long as the temperature of the heat exchanger wall is below the dew point.

Measurements of the temperatures in the heating banks at discrete intervals over a period of 75 minutes have been recorded and are detailed in Appendix A3.3.4. The heat transfer in the heating bank can be calculated according to Equation 8-3 below, as shown in Table 8-8. The highest outlet temperature of the warm water heating bank is found in the measurements at 15:00, which corresponds to the lowest steam consumption. However, the heat transferred in the AHR unit is lowest at the same time, while the roof ventilation temperature is highest. The same is true for the measurements at 14:45 and 15:15.

$$\dot{Q} = \sum_{i=1}^6 \dot{m}_i \cdot c_p \cdot (T_{i,out} - T_{i,in}) \quad 8-3$$

Time	$\dot{Q}_{\text{Millwater}}$ (MW)	$\dot{Q}_{\text{Warmwater}}$ (MW)	\dot{Q}_{total} (MW)	$T_{\text{roof ventilation}}$ (°C)
14:00	2.11	3.38	5.50	47.7
14:30	2.07	3.01	5.08	47.3
14:45	1.79	4.15	5.94	45.5
15:00	2.07	2.71	4.77	47.8
15:15	1.81	4.18	5.99	45.5

Table 8-8 – Calculated heat transfer to mill heating water and warm water, and measured temperature of roof ventilation

The total heat recovery as a function of outlet temperature for a mass flow of 56kg_{air}/s was calculated using the DNS model for three humidity ratios, which approximately correspond to light, average and heavy paper grades (Table 8-7). The heat transfer to preheat the inlet air is constant at approximately 200kW and 400kW for wet and dry ends respectively. These values must be added to the heat recovery in the AHR to find the total heat recovery from the humid air. Results from the DNA simulation model and the calculated total heat recovery in Table 8-8 are therefore plotted in Figure 8-8.

It can be seen that the total heat recovery potential depends significantly on the humidity ratio and outlet temperature of the air. The more cooling of the humid air occurs, the more latent and sensible heat transfer occurs. This trend is confirmed by the measurements in Appendix A3.3.4. Reducing the inlet temperature of the mill heating water and warm water increases the amount of heat that is transferred. This means that the inlet temperature of the cold fluid

should be as cold as possible to achieve the maximum heat transfer. Minor variations in the hood exhaust temperature only influence the sensible heat transfer and thus have only a small influence on the overall heat recovery potential. The heat demand of the mill heating water is estimated to be less than 5MW in winter conditions (Luumi, R. op. cit.). Measurements indicate that the mill heating water has inlet and outlet temperatures of 30°C and 45°C respectively, along with a mass flow rate of 75kg/s (ibid.). The resulting heat transfer to this water is 4.7MW.

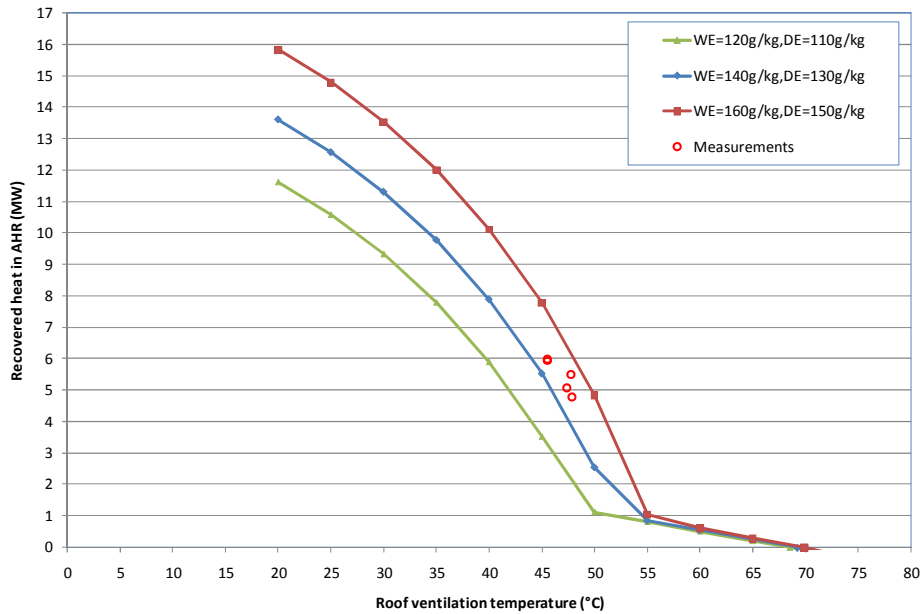


Figure 8-8 – Heat recovery in AHR as a function of outlet air temperature for various humidity ratios

Although the measurements plotted in Figure 8-8 provide some validation of the estimated humidity ratios, they do appear to be slightly higher than what would be expected from the average paper grade (WE = 140g/kg, DE = 130g/kg). The paper grade at which the measurements were taken is unknown, however, but can reasonably be assumed to be constant due to the relatively small time step between measurements.

8.5.3.2 Estimation of the overall heat transfer coefficient

The purpose of this section is to determine how the dimensioning of the existing heat recovery system influences the quantity of heat recovered. Based on the data for the heat recovery potential from the humid air in the hood exhaust shown in Figure 8-8, it is possible to estimate an overall heat transfer coefficient for the condensing heat exchanger as a function of the outlet air temperature. A cross-flow heat exchanger design with water in tubes and humid air outside has therefore been used to determine the total heat transfer area for various logarithmic mean temperature differences. The overall heat transfer coefficient and flow measurements are then used to estimate the existing heat transfer area in the AHR unit.

The overall heat transfer coefficient, U, is determined by the thermal resistance of the pipes, and hot and cold fluid in the heat exchangers. In the case of condensation of humid air, the thermal

resistance of the hot fluid particularly affects the heat transfer. Determination of the heat transfer coefficient of humid air is difficult since moisture content, specific heat value and thermal conductivity vary strongly during condensation of water vapour in the air. However, the following approximation has been suggested (Söderman & Pettersson, 2003),

$$U = \frac{1}{\frac{1}{f_{\text{cond}} \cdot h_h} + \frac{1}{h_c}} \quad 8-4$$

where f_{cond} is the specific condensation factor and h_h and h_c are the heat transfer coefficients of dry air (hot fluid) and water (cold fluid) respectively. The specific condensation factor is unity if no condensation is taking place, and 10-20 near the saturation point. The condensation factor relates the total heat transfer from the moist air, \dot{Q}_{total} , to the sensible heat transfer from the dry air, $\dot{Q}_{\text{d.a.}}$, and is defined according to Equation 8-5 (Söderman & Pettersson, 2003, Söderman & Heikkilä, 2001).

$$f_{\text{cond}} = \frac{\dot{Q}_{\text{total}}}{\dot{Q}_{\text{d.a.}}} = \frac{\dot{Q}_{\text{cond}}}{\dot{Q}_{\text{d.a.}}} + 1 \quad 8-5$$

The instantaneous value of f_{cond} depends on, *inter alia*, the difference in moisture content, temperature and specific heat capacity between the humid air and the surface where condensation occurs. This is a result of condensation occurring in the boundary layer at the wall. It is necessary to use iteration to obtain the instantaneous value of f_{cond} , since the surface temperature and specific condensation factor are dependent variables. This analysis is therefore based on an average value over the heat transfer temperature interval. The heat transfer from the dry air is defined according to Equation 8-6, where w_i is the humidity ratio of the inlet humid air to the AHR, $w_i = 0.14$ after mixing of wet and dry exhaust air has occurred.

$$\dot{Q}_{\text{d.a.}} = \dot{m}_{\text{d.a.}} \cdot c_{p,\text{d.a.}} \cdot (T_i - T_o) = (1 - w_i) \cdot \dot{m}_{\text{total}} \cdot c_{p,\text{d.a.}} \cdot (T_i - T_o) \quad 8-6$$

The specific heat value for dry air is set at $c_{p,\text{d.a.}} = 1.006 \text{ kJ/kgK}$ (Rogers & Mayhew, 2000). \dot{Q}_{total} is plotted in Figure 8-8 for a humidity ratio of $140 \text{ g}_{\text{water}}/\text{kg}_{\text{air}}$ and $130 \text{ g}_{\text{water}}/\text{kg}_{\text{air}}$ for wet and dry ends, respectively, and a mass flow of air of 56 kg/s . The specific condensation factor under these conditions is shown plotted against the outlet temperature of humid air in Figure 8-9. This data can be used to calculate the heat recovery potential from the n th fraction of humid air according to Equation 8-7, where $\dot{Q}_{\text{total}}(T_{n,o})$ is a sixth order polynomial fitted to the results.

$$\dot{Q}_n(T_{n,o}, \dot{m}_n) = \dot{Q}_{\text{total}}(T_{n,o}) \cdot \frac{\dot{m}_n}{\dot{m}_{\text{total}}} \quad 8-7$$

The overall heat transfer coefficient under clean conditions based on the outside radius of tubes can now be estimated. Taking individual heat transfer coefficients into account and neglecting fouling effects, Kakac & Liu (2002, p.41) suggest the following relationship,

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{r_o}{r_i} \frac{1}{h_i} + r_o \frac{\ln(r_o/r_i)}{\lambda}$$

$$U_o = \frac{1}{\frac{1}{f_{cond} \cdot h_h} + \frac{r_o}{r_i} \frac{1}{h_c} + r_o \frac{\ln(r_o/r_i)}{\lambda}}$$
8-8

where λ is thermal conductivity of the tubes. Assuming countercurrent flow conditions gives a logarithmic mean temperature difference $\Delta T_{lm,cf}$ according to Equation 8-9 (ibid., p. 45).

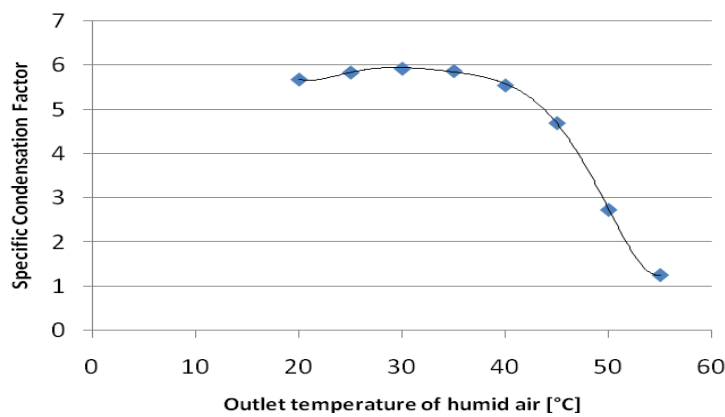


Figure 8-9 – Specific condensation factor for average humidity ratio against the outlet temperature of humid air

$$\Delta T_{lm,cf} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln \frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}}}$$
8-9

8.5.3.3 Estimation of the existing heat transfer area

The total heat transfer area can then be determined from Equation 8-10 (ibid., p.48),

$$A_o = \frac{Q_{total}}{U_o \cdot \Delta T_{lm,cf} \cdot F}$$
8-10

where F is a correction factor for cross-flow heat exchangers, which takes into account the degree to which the flow is not, in fact, countercurrent. The heat transfer coefficient on the cold side is determined as shown in Appendix A3.3.5, but in general the thermal resistance on the cold side and in the tubes is almost negligible ($h \approx 3000$ W/mK) compared to the thermal resistance of the hot side ($h_h \approx 50$ W/mK) (Kakac & Liu, 2002). The resulting overall heat transfer coefficient for the existing heating banks can therefore be determined from Equation 8-11.

$$U_o \approx 48 \frac{W}{m^2 \cdot K} \cdot f_{\text{cond}} \quad 8-11$$

The heat transfer coefficient according to Equation 8-11 can now be used to estimate the existing heat transfer area in the AHR unit based on the measurements shown in Appendix A3.3.4. The first step is to determine a value for the humidity ratio that leads to the same heat recovery as seen in the measurements. Figure A14 in Appendix A3.3.5 shows the heat recovery at different air temperatures for humidity fractions in the wet and dry air that correspond well with the measurements. In this case the humidity ratio is set at 150g_{water}/kg_{air} and 135g_{water}/kg_{air} for wet and dry end exhaust air respectively. Hence the minimum installed heat transfer area can be estimated and the results are presented in Table 8-9.

Variable	Unit	Source	Mill Water				Warm Water			
			14:00	14:30	15:00	15:15	14:00	14:30	15:00	15:15
$\dot{Q}_{\text{MillWater}}$	MW	Table 8-8	2.11	2.07	2.07	1.81	3.38	3.01	2.71	4.18
$\dot{Q}_{\text{d.a.}}$	MW	Equation 8-6	0.70	0.69	0.70	0.69	0.35	0.31	0.29	0.41
f_{cond}	-	Equation 8-5	3.00	2.98	2.96	2.63	9.80	9.71	9.44	10.27
$\Delta T_{\text{lm,cf}}$	°C	Equation 8-9	17.2	17.3	16.7	16.5	10.1	9.3	8.6	14.1
A_o	m ²	Equation 8-10	855	837	873	870	713	694	693	601

Table 8-9 – Calculated minimum installed area in mill heating water HEX based on four measurements for estimated specific condensation factor and logarithmic mean temperature

The heat transfer area should be the same for both measurements, provided the assumption that the two banks have the same area is valid. However, the average difference between the calculated heat transfer areas for the two heating banks is approximately 15%. This suggests that the areas are, in fact, not the same. Although the method used to estimate the heat transfer coefficient during condensation (Equation 8-5) is rather approximate, an error of this size would not be expected. Hence, on the basis of these results it is concluded that the heating banks are of different sizes, around 850m² and 700m² respectively. Nevertheless, the analysis that follows employs a total installed heat transfer area of 1400m², such that resulting estimates are of a conservative nature.

8.6 Pinch Analysis

8.6.1 Thermal data

The thermal data for the pinch analysis is based on the results of the energy and mass balance in the mill. Two of the hot streams do not have predefined target temperatures, namely the humid air and the effluent, as indicated by an asterisk in Table 8-10. The total heat recovery potential is actually dependent on the outlet temperature of these streams, which are therefore called loose streams. The non-linear specific heat capacity of the humid air means that the large

temperature interval of 20-79°C has been broken down into ten smaller intervals of approximately five degrees. The calculation of the specific heat capacity over these small ranges and a diagrammatic representation of the streams in Table 8-10 are shown in Appendix A3.3.6.

8.6.2 Problem Table Algorithm

The result of the Problem Table Algorithm for $\Delta T_{\min}=0$ is shown in Table 8-11. The minimum requirement for external cooling and heating is 12.54MW and 0.25MW respectively, when the outlet temperature of the loose hot streams is 20°C. The pinch point temperature is 87°C and the Composite Curve for $\Delta T_{\min}=0$ is shown in Figure 8-10.

No.	Stream	T _{available} (°C)	T _{target} (°C)	Mass flow (kg/s)	Specific heat capacity (kJ/(kgK))	Heat capacity flowrate (kW/°C)	Heat content, Q (MW)
<i>Hot streams</i>							
1-10	Humid air	78	*20	56	f(w,T)		
11	Hot Filtrate	87	75	210	4.18	877.8	10.5
12	Effluent	85	*20	25	4.18	104.5	
<i>Cold streams</i>							
13	Warm water	18	50	60	4.18	250.8	8.0
14	Mill heating water	30	45	75	4.18	313.5	4.7
15	Air preheat D.E.	37	99	13	1.00	13.0	0.8
16	Air preheat W.E.	42	99	8	1.00	8.0	0.5
17	Wire Pit	50	60	120	4.18	501.6	5.0
18	White Water	50	60	45	4.18	188.1	1.9

Table 8-10 – Thermal data used in pinch analysis (* indicates loose streams)

The pinch point is located almost at the highest core process temperature, which should make it easy not to transfer heat across the pinch point. This is obeyed in the existing HEN, but heaters are placed below the pinch point, which violates the pinch rules. The (steam) heaters are used to heat up water at approximately 50°C, but the pinch analysis shows there should be no need for external heating below the pinch point. The potential reduction in steam demand according to Table 8-2 is therefore 2.58kg/s as shown below.

$$\Delta \dot{m}_{\text{steam}} = \dot{m}_{\text{steam,MHW}} + \dot{m}_{\text{steam,WW}} + \dot{m}_{\text{steam,WP}} + \dot{m}_{\text{steam,WE}} + \dot{m}_{\text{steam,DE}} - \frac{\dot{Q}_{\text{H,min}}}{(h'' - h')_{\text{steam,5bar}}}$$

$$= 0.60 + 0.60 + 1.15 + 0.17 + 0.20 - \frac{252}{2100} = 2.58 \frac{\text{kg}}{\text{s}}$$

The minimum amount of external cooling is significantly influenced by the outlet temperature of the loose streams. In practice it is only the hot filtrate water that needs cooling because it is possible to vent the humid air at high temperature and release the effluent to the surroundings

after mixing with low temperature effluent. The Grand Composite Curves in Figure 8-11 show the cooling demand for various outlet temperatures of the loose streams.

Interval number	Temp. int. (°C)	ΔQ_{cool} (MW)	ΔQ_{heat} (MW)	D_i (MW)	Sequential Balance		Max Table	
					$\dot{Q}_{i-1,i}$ (MW)	$\dot{Q}_{i,i+1}$ (MW)	$\dot{Q}_{i-1,i}$ (MW)	$\dot{Q}_{i,i+1}$ (MW)
1	99-87	0.00	0.25	0.25	0.00	-0.25	0.25	0.00
2	87-85	1.76	0.04	-1.71	-0.25	1.46	0.00	1.71
3	85-78	6.88	0.15	-6.73	1.46	8.19	1.71	8.44
4	78-75	3.16	0.06	-3.09	8.19	11.28	8.44	11.54
5	75-69	1.00	0.12	-0.88	11.28	12.16	11.54	12.41
6	69-60	1.51	0.19	-1.32	12.16	13.48	12.41	13.73
7	60-55	0.82	2.61	1.79	13.48	11.69	13.73	11.94
8	55-50	2.18	2.61	0.43	11.69	11.26	11.94	11.51
9	50-45	3.45	1.36	-2.09	11.26	13.35	11.51	13.60
10	45-42	1.70	1.76	0.05	13.35	13.29	13.60	13.54
11	42-40	1.13	1.16	0.02	13.29	13.27	13.54	13.52
12	40-37	1.43	1.73	0.31	13.27	12.97	13.52	13.22
13	37-35	0.95	1.13	0.18	12.97	12.79	13.22	13.04
14	35-30	2.03	2.82	0.80	12.79	11.99	13.04	12.25
15	30-25	1.76	1.25	-0.50	11.99	12.50	12.25	12.75
16	25-20	1.55	1.25	-0.29	12.50	12.79	12.75	13.04
17	20-18	0	0.50	0.50	12.79	12.29	13.04	12.54

Table 8-11 – Sequential Balance and Max Table for the pinch analysis

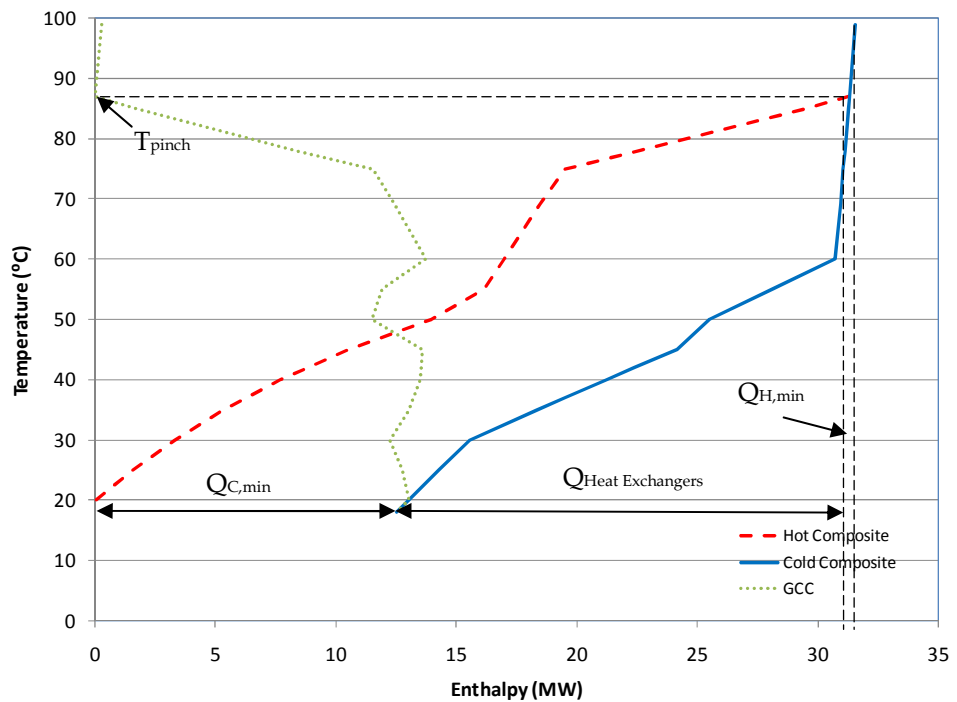


Figure 8-10 – Composite Curves for $\Delta T_{min}=0$ and outlet temperature of loose streams of 20 °C

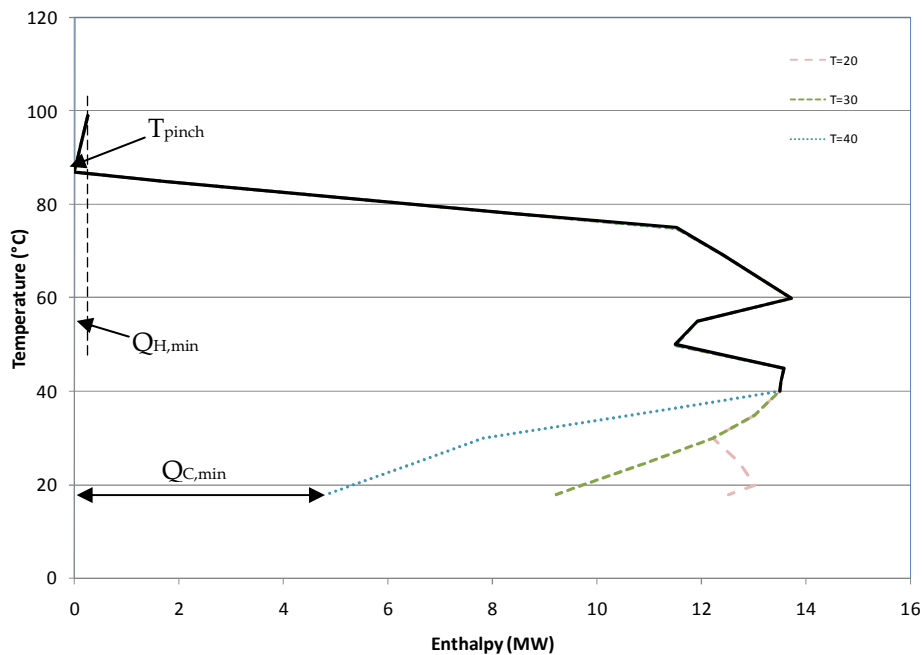


Figure 8-11 – Grand Composite Curves for different outlet temperatures of the loose streams

The overall heat consumption in the process is the sum of the cold streams in Table 8-10, or 20.9MW. Cooling of hot filtrate water supplies 10.5MW and air-preheating and steam heating supplies 1.3MW (Figure 8-6). The remaining heat supply in the process is thus 9.1MW, which has to be supplied by heat recovery from the humid air exhaust and effluent, but the potential heat recovery from the loose streams is much higher than this. The actual heat transfer from the loose streams (especially the humid air) depends on the existence of a demand at lower temperatures, which is indeed the case as the heating demand below 50°C from the warm water and mill heating water is 12.7MW in total (i.e. 60% of the total heating demand). Hence if heat recovery at a low temperature (less than 50°C) is increased, excess heat will be released at a higher temperature, i.e. the cold composite curve is shifted to the left due to a smaller temperature difference. Excess heat at a high temperature (available at 87°C) could have a useful thermodynamic and/or economical value to other processes in the energy system. In other words, cooling demand is treated as excess heat by increasing heat recovery at low temperature (Nordman, 2005).

Heat from the core process should be utilised to fulfil the most economically feasible demand. It might be the most cost-effective solution to meet the heat demand in the core process via heat recovery and thereby decrease or remove the need for live steam heating. The required retrofitting of the HEN might not be worthwhile due to high investment costs. Hence the following section presents an economic analysis of the possible improvements to the HEN.

8.7 *Economic analysis*

This section presents an economic analysis of optimising the installed HEN, in order to recover heat to the core process (and thereby reduce the net steam demand). The objective is to obtain an indication of the feasibility of suggested modifications rather than to obtain precise costs, and costs are based on off-the-shelf rather than custom-built equipment. Broadly speaking there are five categories of cost estimations for projects, ranging from the order of magnitude to the detailed estimate (Kharbanda & Stallworthy, 1988). Whilst the former is associated with a high degree of uncertainty, the latter is able to obtain estimates within about 5% of the actual project cost. However, the cost of implementing these methods is proportional to their associated accuracy, which implies a trade-off between the two. In this section the first two methods have been employed, known as order of magnitude and study estimates respectively (Gerrard, 2000). They are able to estimate the project cost to within about 30%, so the results should be treated as indicative and further studies would be required before any measures should be implemented.

8.7.1 **Technical assumptions**

The economic analysis is based on the results from the preceding pinch analysis of the existing HEN and the thermodynamic analysis of the CHP plant in Appendix A3.3.8. The key assumptions are:

- An average humidity ratio of $0.138 \text{ kg}_{\text{water}}/\text{kg}_{\text{air}}$ (section 8.5.3.1);
- The overall heat transfer coefficient is estimated based on Equation 8-11;
- The specific condensation factor is estimated from Figure 8-9;
- The minimum installed heat transfer area in the hot and warm water systems is calculated in Table 8-9;
- The pinch analysis shows that:
 - the process has a potential of excess heat if heat is recovered at low temperature according to the GCC in Figure 8-11;
 - the theoretical maximum reduction in steam consumption is 2.58 kg/s ;
- The total steam consumption is estimated at 12.80 kg/s according to Table 8-2.
- The electricity from the CHP plant is approximately 26MW, which is less than the electricity demand of approximately 41MW. Reduced steam consumption will therefore increase electricity production and vice versa according to Figure A19 in Appendix A3.3.8.

8.7.2 **Economic assumptions**

The Lang factor for the project is assumed to be three (Brennan, 1998). If an existing heat exchanger can be used but needs extra heat transfer area, the required area is the difference between the two. All costs are estimated in sterling based on the exchange rate of $\text{US}\$2 = \text{€}1.43 = \text{£}1.00$. Correlations of cost as a function of area depend on the type of heat exchanger

employed (Taal et al., 2003). The cost of water-to-water heat exchangers is based on the “six-tenth” method with an exponent of 0.8 (i.e. mid-point of 0.6-1.0) and the capital cost is £62,500 based on a manufacturer’s price for an effluent heat exchanger (NIFES Consulting Group, 2007). The cost of air-to-water heat exchangers is based on the empirical relationship given by Söderman and Pettersson (2003).

To secure a reliable supply of hot filtrate water at 87°C it could be necessary to install a new tank. The volume is chosen to be 100 m³, which is the same as the existing hot filtrate tank at 75°C. The capital cost is estimated based on a relation given by Sinnott (1996, ch.6.6) and the Lang factor is assumed to be two for the tank based on the cost breakdown prepared for the Carbon Trust (NIFES Consulting Group, 2007).

The cost of grid electricity is approximately £50/MWh and biomass for the CHP plant costs around £15/tonne (Reilly, E., op. cit.). Production of electricity from biomass in the UK receives a subsidy from a pool fund created by the main electricity producers, who are obliged by the Renewables Obligation to produce a share of their output by renewable means. Electricity generated from biomass therefore receives a subsidy equal to the current price of Renewable Obligation Certificates (ROCs), which is currently around £34/MWh (OFGEM, 2008). This means that the relative difference (opportunity cost) between consuming or extracting 1MWh steam from the CHP unit is around £80/MWh, which will be referred to as the total electricity price. Onsite electricity generation from CHP units is also eligible for Levy Exemption Certificates (LECs), which mean that the Climate Change Levy does not apply to that electricity, but relative value of these certificates is small at around £5/MWh (OFGEM, 2007). Other relevant economic assumptions are shown in Table 8-12.

Annual projection rate, %	2
Availability of CHP plant, %	95
HEN annual maintenance (% of total project cost)	5
Discount rate, %	5

Table 8-12 – Economic assumptions

8.7.3 Optimisation of the HEN

The design of the existing HEN needs to be taken into consideration when excess heat is released in the process. It is possible to reach the required outlet temperature of both mill heating water and warm water if heating banks in the AHR are connected in parallel. The humid air can in theory supply the entire heat demand of the two streams, which is shown in Figure 8-12 for a mass flow of humid air of 33kg/s in the warm water HEX and 23kg/s in the heating water HEX. The slope of the composite is determined by the heat capacity flow rate. A reduction in the mass flow rate of humid air in the mill heating water HEX will cause the hot composite to cross the cold composite and the maximum heat transfer to reduce. The economic effectiveness of the HEX depends on how much heat is recovered from the humid air, i.e. the outlet temperature, and the cost of the required additional heat transfer area.

The basic approach to optimise the HEN is to balance the heat demand and recovery in the core process. A control volume is placed around each heat exchanger and the energy balance established by simultaneous solution of the equations by Engineering Equation Solver (EES). There are three free parameters in the system: the mass flow rate of the humid air to the warm water HEX, $\dot{m}_{HA,WW,o}$ (whereby the mass flow rate to the heating water HEX is determined by conservation); the mass flow rate of the effluent, $\dot{m}_{effluent}$; and the temperature difference across the wire pit and white water HEXs, ΔT_{HEX} (cf. Figure 8-4). Based on the optimisation procedure these three variables are set at 24kg/s (i.e. 32kg/s in heating water HEX), 25kg/s and 15°C respectively. The proposed HEN resulting from this optimisation is shown below in Figure 8-13. The reduction in steam consumption is 1.88kg/s, corresponding to a 15% reduction due to heat recovery from effluent and a higher outlet temperature of warm water in the AHR. A heat balance of the hot filtrate water system and AHR shows the heat recovery from the humid air is 4.38MW. The outlet temperature of effluent must be 40°C in order to balance the heat demand of the mill heating water.

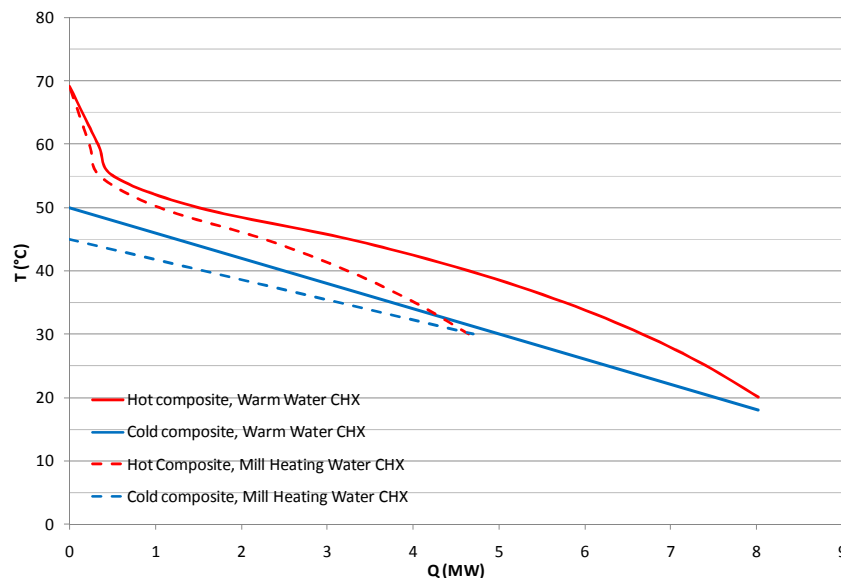


Figure 8-12 – Hot and cold composite curves for the warm water HEX for maximum heat recovery⁴⁸

The discounted payback period is very short, at approximately five months, and the investment cost of the project is small. This shows that it is a very attractive investment to reduce steam consumption, because the equivalent increase in electricity production is economically valuable. The increase in electricity production in the CHP plant is 0.9MW, which corresponds to an increase in the electrical energy efficiency of approximately 3% (summer conditions).

The heat recovery in the warm water HEX requires part of the humid air or warm water to be bypassed in order to ensure the cooling of the hot filtrate water in this HEX. However, the

⁴⁸ The inlet temperature of the hot composite is in reality 69°C but the dew-point temperature at approximately 55°C is used to estimate the required heat transfer area, as this gives a more realistic mean temperature difference for the average heat transfer.

system is less dependent on direct steam injection because the heat recovery in this HEX can be adjusted, according to changes in the supply and demand of heat in the hot and warm water system due to the existing installed heat transfer area in the AHR. The mass flow rate of hot filtrate water in the warm water HEX can be reduced by approximately 35kg/s (1.8MW) before the heat recovery from the humid air is insufficient to meet the heat demand, given the assumed area of 1400m². The change in mass flow of hot filtrate water could be caused by increased heat demand in mill water HEX or wire pit HEX in periods with low tank level.

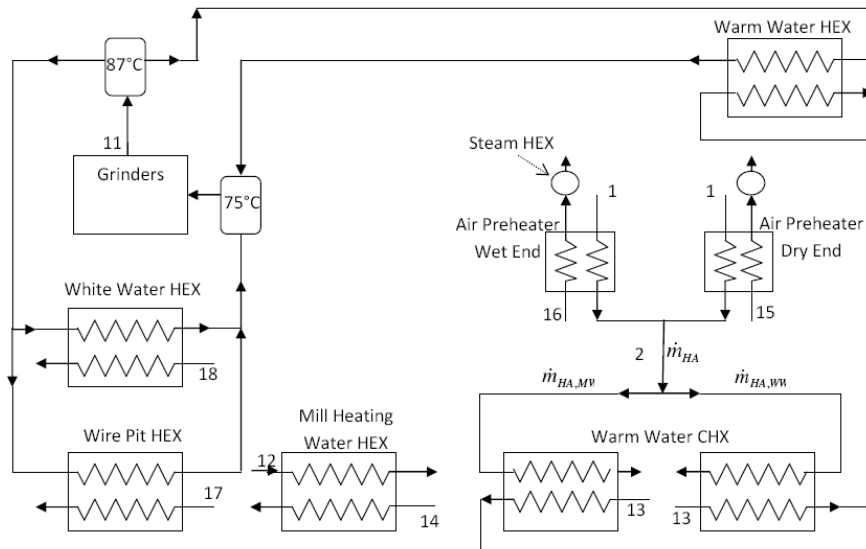


Figure 8-13 – Schematic of modified HEN

Investment costs (£million)	-0.23
Mill heating water HEX	-0.15
Tank project	-0.08
Revenue (£million/yr)	0.59
Reduced electricity cost	0.59
Maintenance of HEX	-0.00
Discounted payback period (years)	0.40
Simple payback period (years)	0.39
Additional required heat transfer area (m ²)	136
Mill heating water HEX	136
Warm water HEX	0 (existing 959)

Table 8-13 – Key economic criteria for proposed HEN

The relative impact of the simulation parameters on the calculated payback period is shown in Figure 8-14. The total electricity cost has the highest negative influence on the payback period, and a 40% reduction in this parameter (approximately equal to a situation without subsidised biomass to produce electricity) leads to a 60% increase in the payback period. The cost per heat

transfer area is more important with regards to the payback period than the cost of a new tank. The discount rate is almost insignificant because the revenue is high relative to the investment cost. Clearly the payback period is very sensitive to the reference cost of the heat exchanger, which in turn is heavily influenced by the exchange rate.

If the assumed average humidity ratio of the humid air ($WE = 140\text{g/kg}$, $DE = 130\text{g/kg}$, dew-point 55°C) is replaced with the lowest humidity ratio ($WE = 120\text{g/kg}$, $DE = 110\text{g/kg}$, dew-point 50°C), the payback period is not noticeably increased. The outlet temperature of the humid air decreases by approximately 3.6°C and the inlet temperature of the humid air (dew-point temperature) decreases by about 5°C . Overall, this requires a heat transfer area of around 1355m^2 , which is still less than the existing heat transfer area.

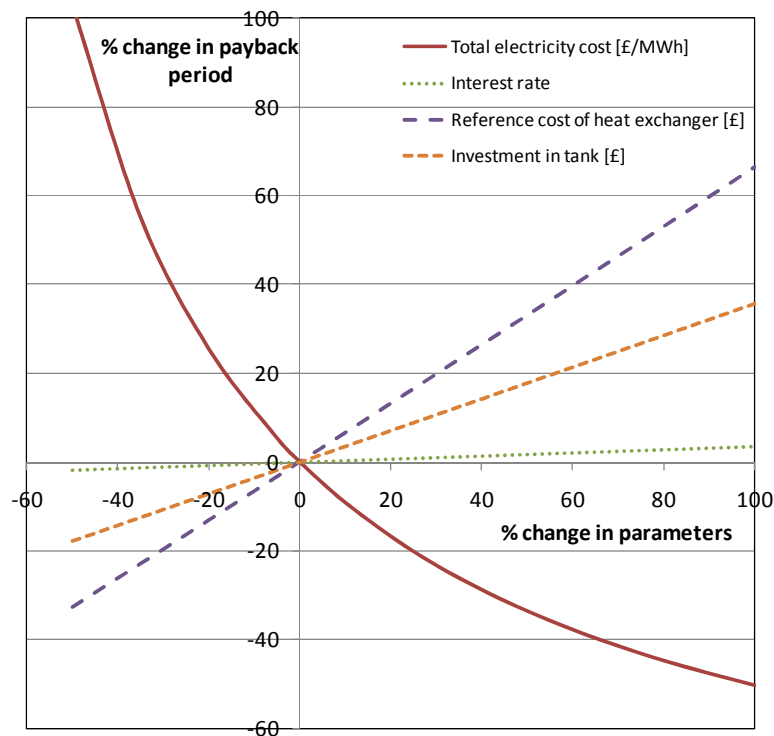


Figure 8-14 – Sensitivity of payback period to key parameters for $\Delta T_{\text{HEX}} = 15^\circ\text{C}$ and $m_{\text{HA,WW}} = 24\text{kg/s}$

In the case that it is not possible to use the effluent at 85°C it is still possible to balance the heat supply and demand in the core process. This requires a modified HEN, which increases the heat recovery from the humid air. The payback period for this HEN is around 1.65 years and the heat recovery from the humid air is approximately 9MW. However, the additional required heat transfer area is significantly increased if the lowest humidity ratio of humid air is used instead of the average humidity ratio. The investment cost in the project more than doubles, and the resulting payback period is 4.2 years. It is therefore important to obtain a good estimate of the average humidity ratio of the humid air if additional heat recovery is required.

8.7.4 Critique of the methodology and suggestion for future work

The main limitation of the methodology is the few measurements upon which the determination of the existing heat transfer area is based. The fact that no data exists for the heating banks meant that estimates had to be made of both the heat transfer area and the overall heat transfer coefficient. These estimates are subject to a degree of uncertainty, which could be reduced by obtaining more accurate data as proposed below. The approximate method used to determine the overall heat transfer coefficient in the condensing heat exchanger is clearly influenced by the approximate determination of the specific condensation factor. However, the estimate is used to determine both the existing heat transfer area and the required heat transfer area, which means that the systematic error is probably the same in both cases and a comparison of the existing and required areas is reasonable. The accuracy of the heat transfer coefficient in the condensing heat exchanger is constrained by the limited data and documentation of AHR, which makes it impossible to make a better estimate without additional data.

The heat recovery from the humid air is dependent on the humidity ratio, and it would be desirable to have more accurate measurements within the heating banks to support this analysis, especially if the heat recovery is increased in AHR. Furthermore, the construction of AHR unit should be investigated to perform a more convincing determination of the overall heat transfer coefficient. The staff at Caledonian Mill have not been able to address these issues yet due to the large workload associated with the new CHP plant. They are keen to develop this study in the future, however, when more accurate data could be sought.

Examples of process constraints were highlighted in section 8.4 that could lead to improved efficiency. The pressing section should be investigated, because reducing the moisture content of the paper after the pressing section would result in steam savings, which have been proven to have a high value due to increased electricity production. Furthermore, the strength of the paper is influenced by the pressing, so reducing the moisture content in this section could lead to less broke production and thus less recirculation of feedstock in the system.

8.8 Conclusions and recommendations

A pinch analysis of the warm and hot water system in Caledonian Paper Mill has been carried out based on measured and estimated data. The average humidity ratio in the dry and wet ends of the dryer section of the paper machine was estimated based on measurements and conservation principles, along with some relatively minor simplifying assumptions. The estimated average humidity ratio determined with a DNA model is in good agreement with the several measurements.

The complete lack of information relating to the heating banks in the Aqua Heat Recovery (AHR) system meant that their overall heat transfer coefficient and heat transfer area had to be estimated using further assumptions. The overall heat transfer coefficient was estimated based on the assumption that the thermal resistance of the cold side of the heat exchanger is negligible

compared to that of the hot side. A condensation factor enables account to be taken of the mechanisms of sensible and latent heat transfer respectively. The overall heat transfer area of the existing heat exchangers was estimated based on two measurements, with a deviation between the two of 15%. The latter is probably due to the assumption that the two heating banks are identical being incorrect.

Based on these results a pinch analysis and economic optimisation of the heat exchanger network (HEN) were carried out, which has shown potential for cost-effective improvements in the overall efficiency. It is economically feasible to increase heat recovery from the pulp and paper process in order to balance the heat demand and thereby reduce the steam consumption by approximately 1.9kg/s or 15%, increasing electricity production by approximately 0.9MW. The recommended changes in the HEN based on the shortest payback period are to heat exchange the effluent from cloudy filtrate overflow with mill heating water and supply the required heat demand of warm water in the condensing heat exchanger. The existing installed heat transfer area in the hot and warm water system and AHR is sufficient for the heat recovery as long as:

- The temperature difference between hot outlet and cold inlet temperature in the white water HEX and wire pit HEX is approximately 15°C or higher;
- The inlet temperature of hot filtrate water to the HEXs is as high as possible (87°C);
- The inlet temperature of the warm water to AHR is as low as possible (18°C).

The pinch analysis has shown that the latter two criteria are currently not fulfilled because warm water is currently heated before the AHR and the valuable heat content of the effluent is not exploited. The proposed changes require a new heat exchanger for heat recovery of effluent, with a heat transfer area of 136m², and a new hot filtrate water tank. The total investment cost is estimated to be approximately £0.23million, and the reduced annual running cost due to increased electricity production is estimated at £0.59million. The discounted payback period is thus approximately five months. The proposed changes are intended to be implemented during scheduled maintenance of the paper machine in order to minimize the production loss.

9 Discussion

The results from the three preceding chapters were discussed therein. This chapter is concerned with drawing out generalisations from these results, as well as discussing and comparing the respective methodology employed in each case.

9.1 Introduction

The overall aim of this thesis has been to determine the extent to which it is possible to improve energy efficiency in industry, by employing techniques and insights from thermodynamics and economics. The scope of this thesis as outlined in section 1.4 includes all manufacturing sectors. Hence the objectives as outlined in section 1.5 were to assess what improvements in energy efficiency are possible across all of these sectors. However, the research process has highlighted obstacles to carrying out such a cross-cutting analysis of industry as a whole (as summarised in section 1.4). One of these obstacles is the lack of willingness – or indeed requirement – of industrial firms to partake in studies of this nature. Energy accounts for up to 50% of operating costs in industry (DTI, 1994, European Commission, 2006d, Eichhammer, 2004), which means that in most cases its use is professionally managed. Combined with the fact that corporate studies relating to energy are subject to commercial confidentiality, this means that the data is not widely available to carry out detailed analyses of all sectors. Another obstacle to a broad analysis covering all of industry is the associated compromise between detail and scope. The data requirement increases at higher levels of disaggregation, whilst the coverage of the study is commensurately reduced (as discussed in chapter 4 and shown in Figure 4-1). This thesis has therefore employed various levels of disaggregation, in order to reach a compromise between coverage and detail. In chapter 5 industry was analysed from a macroeconomic perspective using a variety of indicators from thermodynamics and economics. Chapter 6 subsequently employed thermodynamic (physical) methods to analyse heat use of whole sectors at the site or meso-level. Finally, chapters 7 and 8 related detailed microeconomic case studies of individual industrial plants using thermodynamic and economic techniques.

9.2 Generalisation of the results

Chapter 5 demonstrated that macroeconomic studies are useful in retrospectively identifying the reasons for underlying trends. Such top-down approaches are also able to estimate the systemic or sectoral potential for energy efficiency improvement through technological change in the long term, based on assumptions about future technological developments and market penetration rates. These estimates are inevitably associated with a degree of uncertainty about the future, though, just as energy projections in the 1970s failed to foresee the massive reductions in energy intensity of the manufacturing sector since then (cf. Figure 5-11). Macroeconomic analysis is therefore limited in terms of understanding the mechanisms that actually cause industrial energy demand. Whilst it is possible to decompose changes in demand into contributions from output, intensity and structural effects, the absolute demand at

any time is not very conducive to estimating saving potential. This problem is similar to the one concerning TFP and its measurement discussed in chapter 2: it is possible to measure with reasonable accuracy changes in TFP over a given period, but this measurement does not actually *explain* the phenomena of technological change. Furthermore, macroeconomic analysis of energy demand alone does not reflect the changes in output and product mix that can be understood through decomposition methods. Hence why productivity measures are widely employed and were developed for industrial sectors in section 5.2.3, because they normalise the output onto some form of input. Energy productivity reflects the efficiency of the production process, but in this case is still constrained by the issues surrounding the determination of suitable price indices discussed in section 4.2. The consequence is that the output in GVA terms does not directly correspond to the physical output from these sectors. This is the only way in which output can be aggregated though; if physical measures are used this is often not possible – the problem of “adding apples and pears”. To develop more accurate energy intensity measures the level of disaggregation could be increased and physical measures employed. This would be possible with production databases such as PRODCOM (ONS, 2006b) or the UNSD’s (2005) Industrial Commodities Database, but is constrained by the lack of energy data at the four-digit SIC level and below (the main source being ECUK, which has clear limitations as identified in section 3.1.1 and further discussed in chapter 6). Even if the data were available and accurate at such levels of detail, energy intensity measures are also constrained by boundary conditions that are not always directly comparable between industrial systems (Tanaka, 2008). The importance of boundary conditions will be discussed in section 9.3.

It is perhaps not surprising that the majority of industrial sectors have lower energy productivities than the economy as a whole, but the fact that some industries have much higher energy productivities is less obvious. The sectors to which this applies are electronics, motor vehicles and textiles. These are known to be non energy-intensive sectors, but this is not the sole reason for high energy productivities. Rather, the energy productivity is exaggerated because these sectors have relatively low energy demands *and* high value-added products. This can be seen clearly by comparing these three sectors to the chemicals sector in Figure 5-8, which also produces high value products but has lower energy productivity due to its significantly higher overall energy demand. In general all energy productivities in Figure 5-8 are increasing over time, reflecting the role of technological development (TFP), which has contributed most to the overall productivity growth in the industrial sector over the period 1981 to 2005 (cf. Figure 5-9, p.95) by more than offsetting the large reductions in the labour force.

Globalisation has also played – and is playing – an important role in the manufacturing sector. Although it has been one of the reasons why heavy industries have declined quite rapidly in the past few decades it has presented many opportunities for manufacturing. The fierce competition in the form of cheaper labour markets is especially strong from China in industries where the UK was traditionally strong, including metals, chemicals and electronics (BDO Stoy Hayward, 2007). Whilst a rapidly increasing volume of imports are sourced from China, it is also the destination of many manufacturing exports and has been the destination of many British firms which have seized the opportunity to relocate into cheaper labour markets. The

global effect on industrial energy efficiency of the rapid growth in manufacturing in developing economies such as China is probably negative, though. Industry in developing countries is known to be less efficient and it is here that much of the potential for systemic improvement lies (IEA, 2007, cf. section 5.6). The probable effect on UK industry of relocation overseas is a reduction in energy demand, but this is not necessarily an improvement in energy efficiency because output has been commensurately reduced. If the emissions associated with the manufacture of imports are accounted for, the UK's CO₂ emissions have in fact increased in recent years (Wiedmann et al., 2008), which contradicts national statistics on emissions. It has been beyond the scope of this thesis to further quantify this affect for the manufacturing sector though.

Globalisation also means that many industrial sectors are dominated by foreign ownership. This is now the case for the whole primary iron and steel sector as the Anglo-Dutch Corus is now a subsidiary of the Indian Tata Steel, the vast majority of the automotive industry, and much of the chemicals industry. British defence companies such as BAE Systems and QinetiQ remain strong; in the case of the former this is largely due to a significant proportion of public funding from the government (The Economist, 2009a). Energy efficiency should be easier to achieve in a manufacturing sector dominated by multinationals than one in which national companies prevail, because such large organisations are better able to implement horizontal measures in several countries at once. The right incentives are required, however – in particular a high enough carbon price or fuel taxes – if energy efficiency is to be incentivised. The disadvantage of global operations for energy efficiency is the flexibility it allows in shifting production between countries, which was shown to be one of the threats to the efficacy of the EU ETS in chapter 5. The implication of this globalised manufacturing sector for the results of this thesis will be explored in section 9.4 below.

Another emerging macroeconomic trend is the gap that seems to exist in the innovation chain between early prototype and fully commercial stages. This is particularly relevant to the manufacturing sector because it is one of the sectors most engaged in R&D activities aimed at technological development. FES (2005) identified this gap for energy technologies in UK and concluded that many technologies are not sufficiently developed beyond the R&D stage. The Environmental Innovations Advisory Group (EIAG) was established to address this and other issues relating to the innovation chain for environmental and energy-related technologies (DTI, 2006a). This problem is not just confined to the UK, however. A similar trend across the EU has been referred to as the European Paradox (IPTS et al., 1998). Europe in general has a strong scientific research base in universities and research institutes – which the DTI's (2002c) Manufacturing Strategy also recognised for the UK – but the results of such research are not being turned into technologies. The UK has a relatively low return on scientific investment, as measured by patents divided by business R&D expenditure. Furthermore, there seems to be a lack of qualified graduates in certain areas and a weak link between industry and academia in some cases. The latter problem was encountered in the research supporting this thesis, the focus of which was largely dictated by the willingness of companies and trade associations to engage, and the availability of data. One way of strengthening the link between industry and

academia would be to shift the criteria of success away from outputs such as technical papers onto applied measures such as patents, patent citations and industry-targeted publications (DTI, 2000). Another way would be to ensure applied research involves industrial and academic stakeholders as much as is feasible.

Chapter 5 demonstrated that few industries are fully integrated, gypsum being one of the few (Entec UK Ltd., 2006a). In many cases demand is driven by a small number of other economic sectors, including manufacturing itself. Where these are manufacturing sectors, the goods are classed as intermediate, as they are subsequently processed further. In fact, most of the energy intensive sectors in industry produce intermediate goods. It is debatable whether or not construction is classed as a manufacturing sector; within this thesis it is not. Nevertheless, much of the demand for products such as cement, glass, steel, aluminium and lime comes from the construction sector. Similarly, much demand for steel, glass and aluminium comes from the automotive sector. The exception is perhaps the chemicals sector, because it produces a large number of intermediate products that are mostly processed further within the sector. The consequence of manufacturing output being used and often processed further in other sectors of the economy, is that this output has significant implications for the life-cycle energy and environmental impact of the use that it finally finds. This means that decisions made at the design stage (in the manufacturing sector) have implications throughout the product lifecycle until, and even after, disposal. This will be discussed in section 9.4 below.

The characterisation of sectors discussed in section 5.2.2 is a useful means of understanding their energy-related activities. The categorisation of sectors according to the SIC (ONS, 2003), which is based on the type of products produced, is intended mainly for the organisation of economic production statistics. For this task it is well designed, but for the present purposes a classification by output has several disadvantages. Firstly, and most importantly, such a classification overlooks the type of processes (activities) being carried out by each sector. By grouping similar products (materials) together one fails to distinguish between alternative production routes for the same product, as well as between primary and secondary processing methods (such as integrated iron and steelworks versus EAFs) with vastly different energy requirements. Secondly, this categorisation does not consider the provenance of goods or the way in which they are processed through the economy. For example, there is the well-known problem of double-counting, whereby intermediate goods are accounted for both in the primary processing sector and the intermediate sector which carries out further processing (Boustead & Hancock, 1979; Herendeen, 1973; Slessor, 1978; Spreng, 1988). This is particularly important for secondary products; in the context of input-output tables Bullard and Herendeen (1975) cite the example of an aluminium industry producing castings as its secondary product. The castings are transferred to the secondary products sector as a sale, but the input is not transferred. This effectively means that the cost of the output has been counted twice, but the energy input has only been counted once. It could be argued that industrial classifications are not required to differentiate between process routes because input-output tables serve this purpose adequately, but similar problems also relate to these tables. If an industrial classification is to reflect the types of processes occurring, which is necessary in order to understand the energy demand of

individual sectors, then it needs to consider the stage at which that process occurs in the manufacturing life of the product.

A particularly useful classification of industrial sectors for energy analysis is according to the homogeneity of the processes performed within them. This method was proposed in chapter 5 and used in chapter 6 to dictate the type of modelling approach employed (cf. Table 6-1). In sectors that can be reasonably considered homogeneous the processes are the same or very similar at all sites. Furthermore, the process *within* the site is also homogenous: one main product is produced by each site in the sector. This simplifies analysis because it is possible to model a whole sector based on one site which is then scaled up, whereby a differentiation between technology and/or process types is required as in the case of cement and lime. If the geographical distribution of the production capacity at individual sites is not required, and the national production capacity (or output) is known then reasonable estimates of the energy demand by these processes can be obtained through such an approach. This method would ideally be based on the sector's total production capacity (or output) and energy demand, which could then be used to derive an energy intensity or SEC for the process. In the case where the total energy consumption is unknown at such a level of disaggregation, as was the case in chapter 6 for many sectors, the output/capacity data can be used alongside technology- or process-specific SECs from the literature, to obtain a reasonable estimate of the total energy use of the process.

This SEC-based approach was mainly employed for heterogeneous sectors – that is, those that carry out many different processes. The two main heterogeneous sectors of interest are food and drink and chemicals, but this definition only applies according to the current classification. That is, the processes occurring within three and even four digit SIC codes cannot reasonably be considered as homogeneous. An obvious way around this problem would be to disaggregate these two sectors further, until the processes *can* be considered homogeneous. Even at the four-digit SIC level of disaggregation, however, some of the sectors cannot be considered homogeneous. An example is SIC 15.83, which is sugar manufacture. This sector includes sugar manufacture from sugar beet as carried out by British Sugar at several locations and from sugar cane as carried out by Tate and Lyle at its London Thames refinery. For the purposes of energy analysis the SIC classification clearly has limitations. Several alternative classifications have been proposed as discussed in section 4.2, including a process-based one (Beyene & Moman, 2006). If the chemicals and food and drink sectors are to be disaggregated into homogeneous sub-sectors, then an approach based on individual processes and capacity data similar to that employed in chapter 6 should be made (section 10.3 on future work).

The limitations of macroeconomic analysis discussed above mean that more highly disaggregated approaches are required that take into account the specific processes occurring in each sector at the meso- and micro-economic level. If overall demand is to be reduced, one has to concentrate on the manufacturing processes themselves, which dictate this demand. Chapter 6 showed that the energy intensive sectors are those with the highest heat demands, which is not surprising given that fuels by definition are used to generate heat. The iron and steel sector

is the largest user of heat and also the sector with the highest estimated technical potential for heat recovery. Apart from this sector, though, it is not generally the case that the heat recovery potential is proportional to the heat load. In fact sectors with modest overall heat loads have significant heat recovery potential, which if normalised upon the number of sites suggests that the aluminium and cement sectors should be the primary focus. In these sectors much of the proportion of heat that can technically be recovered by targeting one notional site is higher than in all other sectors apart from iron and steel.

The technical heat recovery potentials identified in chapter 6 will in practice be constrained by economics, which is certainly the case for many of the technologies employed for the iron and steel sector (Lewis, B., Corus, pers. corr., January 2009). If these measures are not cost-effective according to the criteria employed by industry, then they will not be taken unless some policy makes it necessary (or makes them economical). The study was only intended to indicate the technical potential, however, and determination of the economic potential was considered beyond the scope. It is difficult to generalise about the fraction of the technical potential that is currently economically feasible without more detailed studies. As an order of magnitude estimate, it would probably be reasonable to assume that the economic potential is around half of the technical potential.

The detailed case studies in chapters 7 and 8 both identified cost-effective savings for the sectors concerned. The former is based on a typical glass container furnace, and the homogeneous nature of the sector means that the identified savings could reasonably be extrapolated across the whole sector. Assuming there is a use on or off site for the recovered heat, heat recovery boilers could be installed at all similar furnaces, including flat glass ones. Given that the total glass capacity in the UK is around 5,000t/d, and the furnace capacity used in the baseline analysis was 300t/d, the total savings across the sector could be estimated at ten times those resulting from one furnace. Taking the data from Table 7-11, this corresponds to a power saving of around 30MW, which at a load factor of 85% corresponds to around 1PJ per year (around 5% of the sector's total energy use).

The pinch analysis and economic optimisation of the HEN in Caledonian paper mill is more difficult to generalise because of the specific nature of the HEN and the fact that Caledonian is the largest integrated pulp and paper mill in the UK. The cost savings resulting from reduced steam consumption, which in turn leads to a higher electricity output from the CHP unit, are partly due to the Renewable Obligation Certificates (ROCs) received for the electricity and partly because of the offset cost of buying electricity from the grid. Nevertheless, the estimated savings based on the optimisation of the HEN are significant, with a discounted payback period of five months. It is not possible to quantitatively extrapolate such savings out across the industry because of the reasons mentioned above. Considering that Caledonian was already a very efficient mill, however, it seems reasonable to assume that equivalent or greater savings exist elsewhere. This is supported by the very large systemic savings potential identified in Table 5-3 for the sector.

Another interesting finding from the case study at Caledonian paper mill was that the company had a lack of data relating to their energy system. The mill was built in 1989 by UPM, yet a significant amount of data required for the analysis in chapter 8 was not available (and therefore had to be estimated). This is especially the case for the two banks of heat exchangers for the AHR system. Not only was no online data available about actual operation of these heat exchangers, but UPM was not able to provide any data relating to the design and construction of the heating banks. The implication is that energy efficiency was not the important management issue that it is today, and therefore the information relating to the heat exchangers was regarded as superfluous at some stage. This illustrates the way in which energy efficiency is an entrenched management issue that is concerned with all aspects of a company's operations. Again, it is difficult to extrapolate such insights across the whole sector or even other industries, as they are somewhat anecdotal. Nevertheless, evidence does indicate that lack of real-time data about energy systems is a real barrier to energy efficiency, as discussed in section 5.5 and confirmed by some other instances (e.g. Howe, S., Head Brewer, Sharp's Brewery, pers. corr., December 2008).

The two detailed case studies quantified the potential for economic energy efficiency improvement in two specific cases. The meso-level analysis quantifies the technical potential for energy efficiency improvement in the majority of industrial sectors. Hence these three studies together meet the original aim of this thesis, which has been to determine the economic and technical potential energy efficiency improvements across industry. However, uncertainty remains about the degree to which it is technically and economically possible to improve energy efficiency across the whole industrial sector – especially those sectors not analysed in detail here. It has not been possible to quantify this precisely, for the reasons outlined above. In order to quantify the improvement potential for a sector, detailed (i.e. meso- or micro-level) studies are required that consider the processes themselves and economic constraints on potential improvements. It was beyond the feasibility and scope of this thesis to carry out such detailed studies for all industrial sectors. This and related points will be taken up in the following sections that discuss the methodologies and areas for further work.

9.3 *Discussion of the methodologies*

This section discusses the advantages and disadvantages of the respective methodologies employed in this thesis, whilst bearing in mind that the choice of methodology is largely dependent on the energy system. Pinch analysis is specifically intended for optimising heat exchanger networks (HENs) and would therefore not be very useful – or even applicable – in analysing a glass furnace, for example. On the other hand energy and exergy analysis are generic techniques that can be (and have been) widely applied to diverse energy systems.

The meso-level analysis in chapter 6 employed several related methodologies. The level of aggregation and the data sources employed mean that the methodology is effectively a hybrid between process analysis (PA) and statistical energy analysis (SEA) – the unclear distinction between the two is discussed in Appendix A2.2.2. Site level emissions data was employed

alongside process-specific SECs and capacities/outputs to quantitatively determine site level energy use. In addition exergy considerations were used to qualitatively assess the temperature levels at which this energy (heat) is used and wasted. The quantitative methodology based on CO₂ emissions allocations is a robust, reliable method for determining the site-level energy use. Provided the emissions data is initially accurate, then the main inaccuracies in determining the energy use are introduced by the combustion emissions factor. Some uncertainty remains in determining this value for specific sectors, namely non-metallic minerals, but this did not lead to significant errors overall compared to the data from the Climate Change Agreements. Relatively minor uncertainties are also introduced by the use of fuel splits for different sectors and the emissions factors for the fuels.

The SEC-based methodology is clearly less accurate, but this was only employed for a small number of sectors (or parts thereof). Uncertainties surround the choice of a suitable SEC value in some cases, especially where the process route or technology type is unknown. Published output data should be reliable, but rated capacities are obviously less so, especially if used alongside load factors (which in some cases have to be assumed). The errors introduced by these uncertainties might not be insignificant because the sectors (or parts thereof) modelled based on this approach account for approaching half of the total energy use in the model. However, the model's results have been compared to two other data sources (Table 6-15), with a good agreement in one case and an excellent one in the other. It is therefore very unlikely that significant errors have resulted from this approach.

The thermodynamic quality aspects of this methodology are certainly less accurate, but they are only intended to be qualitative and do not affect the absolute value of the quantitative results. In the absence of relevant data on industrial energy use by temperature, the temperature demand profile was estimated across broad temperature bands. Related to this is the way that electricity used for heat was overlooked, meaning that this heat demand was assumed to be met by fuels directly. The heat recovery potential at temperatures below 100°C has probably been underestimated because of the way in which exhaust temperatures from boilers and steam systems were lumped together at 150°C. This does not mean that the total heat recovery potential has been underestimated, rather that its distribution across temperature bands is imprecise. Finally, the estimated heat recovery potential has probably been underestimated in some sectors, especially food and drink, pulp and paper and chemicals.

Ideally the quantitative aspect of the heat modelling in chapter 6 would have been based on one data source, namely emissions allocations or SEC/capacity data. The non-homogenous nature of the chemicals sector in particular meant that it was not feasible to model the whole sector based on a cross-cutting approach. Such an approach was initially attempted, whereby the chemicals sector was broken down into several sub-sectors that could be considered roughly homogenous. The problem encountered was that even these sub-sectors could not reasonably be considered homogenous, because although producing similar products they were not all carrying out the same process. Furthermore, many sites produce more than one product, and therefore employ several distinct processes. The only way in which these sites could be broken

down into homogeneous sub-units would disaggregate below the factory fence, by analysing individual processes. This is effectively what was achieved with the SEC/capacity-based methodology, but it only considered the main products of a given site (in terms of energy demand).

This meso-level analysis demonstrated that it is possible to model industrial energy use at the site level based chiefly on emission allocation data, with especially heterogeneous sectors supplemented based on and SEC/capacity based methodology. In most cases this analysis was more accurate compared to the CCA TP2 results than the national statistics in this area, namely ECUK. Langley (1984a) also found that his data was not in exact agreement with the national statistics on energy use in industry. The implication is that an industrial energy database that is derived from the EU ETS has the potential to improve the accuracy of national statistics on industrial energy use for energy-intensive sectors. The caveat is that the chemicals and food and drink sectors were less well reflected because of the difficulty in accounting for their heterogeneous nature. Development of such a methodology to augment national statistics would therefore have to account for this and take measures to remedy it. This or a similar methodology could be applied relatively easily to any other energy system or nation that has an emissions database relating to the EU ETS or similar emissions trading scheme.

By applying exergy analysis to the glass furnace in chapter 7 it was possible to understand the thermodynamic quality of the energy losses and to differentiate between exergy *losses* and *destructions*. The former occur when exergy crosses the system boundary (defined as a box drawn closely around the furnace superstructure in this case), whereas the latter are associated with irreversible processes occurring within the system. In the case of the glass furnace, the main exergy destructions inside the furnace are due to the combustion of the fuel and heat transfer between the combustion products and the raw materials/molten glass. These two processes could themselves be improved, but quantifying the degree to which this is possible was beyond the scope here. In fact the chemical reaction of combustion is very efficient at around 95%; the majority of exergy destruction in combustion is associated with internal heat conduction within the process (Dunbar & Lior, 1994). There is a trade-off associated with maximising the flame temperature whilst minimising the temperature gradient in the combustor (Som & Datta, 2008). Also, the type of combustion system could itself be addressed, but unfortunately there is no other currently feasible method of meeting the exergy demand of this process (heat at 1500°C) than burning fuels⁴⁹.

The exergy analysis of the glass furnace therefore highlighted the areas where attention should be focussed to improve the existing system, namely the exergy losses through the walls (structural), and in the exhaust and molten glass respectively. According to both the energy and exergy analyses the largest loss from the system is the enthalpy of the molten glass, followed by the enthalpy in the exhaust and finally the structural losses. That is, the energy

⁴⁹ In theory the demand could be met with electricity – in fact electric “boost” is used in some furnaces – but this is also based, indirectly, on combustion. The current low generation and distribution efficiency of the electricity network do not make electrical heating thermodynamically attractive.

analysis led to the same conclusions in this case, and would have done without a consideration of exergy. Hence why the focus was on the exhaust here, although improved insulation has also been shown to result in significant savings (Lax and Shaw, 1998). Heat recovery from the molten glass was not considered feasible due to technical constraints discussed in chapter 7.

Even though it considers the exergy destructions in the process, the exergy analysis leads to the same conclusions as the energy analysis. There are advantages and disadvantages to the consideration of exergy destructions. The advantage is that it enables the identification of the areas on which to focus attention and shows which areas (namely combustion and heat transfer) present little if any potential for improvement. The disadvantage of this is that, wherever the energy system being studied involves combustion of fuels as so many currently do, there is inevitably a large exergy destruction. The exergy destruction is the “penalty” paid for harnessing the exergy content of the fuel (that is, the chemical exergy) and being able to use it. There are avoidable and unavoidable parts of this exergy destruction, so that by reducing the former, the size of this “penalty” can be reduced. An example of an avoidable exergy destruction is the one resulting from non-optimal combustion conditions, such as non-stoichiometric fuel to air ratios. However, the majority of the exergy destructions associated with combustion are unavoidable, and are an inevitable consequence of employing such combustion equipment (Bejan et al., 1996, p.160).

The consideration of these largely unavoidable exergy destructions is an important aspect of exergy analysis because it suggests where attention should be focussed, by excluding from consideration certain aspects of the system. However, it means that the overall exergy efficiencies of a wide range of energy systems involving combustion are very low, especially in comparison to the energy efficiency. This has been demonstrated by a diverse range of applications of exergy analysis as discussed in section 3.2. On face value this low exergy efficiency might seem to suggest a large improvement potential, but in many cases it is a direct and inevitable consequence of combustion. Hence employing lumped energy and exergy efficiencies to indicate the thermodynamic improvement potential should be done with care if misguided interpretations are to be avoided.

According to the analysis in chapter 7, the exergy destruction due to combustion and heat transfer accounts for almost half of the total exergy input to the process. The exergy efficiency could probably not exceed 50% even in a technically optimal case, and could by no means approach the energy efficiency. Even with the suggested heat recovery boiler installed in the glass plant, the exergy efficiency only increases to around 30%. The exergy efficiency of a system should therefore not be interpreted as an indication of the improvement potential. Van Gool’s (1992) concept of the improvement potential (Equation A21 in Appendix A2.2.3) is a useful indication of the thermodynamic potential, but it can never be achieved in practice. The improvement potential for a system with low exergy efficiencies (large relative potentials) and large irreversibilities is large overall. In many cases, however, the main reason for this apparently large overall potential is combustion. The exergy efficiency should therefore be employed alongside the energy efficiency in order to gain an insight into the suitability of the

specific energy system in the meeting the energy service demand. A good example of this being the case is in Bilgen's (2000) study of several CHP systems. He found the energy efficiency to be very sensitive to the heat to power ratio, but the exergy efficiency is only very weakly dependent. Exergy analysis alone would not have revealed the whole picture in this case.

Another issue with exergy analysis is that the exergy parameter itself relates to the potential to perform work and not heat. Although the Carnot factor according to Equation A20 in Appendix A2.2.3 is dependent on the temperature, it actually determines the capacity of a thermal reservoir to perform work. The application of exergy analysis to heating systems therefore results in low exergy efficiencies partly because these systems are generally not efficient at performing work. Reistad (1975) cites the exergy efficiency of a large electric motor as over 90%, which is due to the fact that both exergy inputs (electricity) and outputs (work and heat) have high exergy contents. Combustion systems that do not convert the high quality chemical exergy input into work therefore typically have lower exergy efficiencies, such as around 50% for large steam boilers and around 25% for internal combustion (petrol) engines (ibid.).

Pinch analysis is a very useful method for the optimisation of Heat Exchanger Networks (HENs), as demonstrated in chapter 8. In this particular case the pinch rules were unable to enhance the heat recovery because the pinch point is located at a high temperature and no streams are crossing the pinch point, which reflects the already efficient nature of the paper plant studied (NIFES Consulting Group, 2007). Nevertheless, the economic optimisation of the HEN was able to identify potential savings because heating is employed below the pinch point. The graphical representation of the HEN via hot and cold composite curves and the Grand Composite Curve is a useful tool in order to understand the network, but it is generally not easy to optimise the system based on these diagrams. Exergy analysis could have been used in this instance, but the exergy content of warm water at less than a 100°C is very low. Furthermore this exergy content is virtually useless and the real exergy losses are caused by steam generation and consumption in the process. If steam extraction at two different pressure levels was examined, exergy would be a more useful measure to compare the lost potential to perform work. The main way in which the pinch analysis methodology could be improved would be to obtain more accurate data upon which it is based, as determined in section 8.5.3.

The general applicability of exergy analysis is both a strength and a weakness. It is a strength because the method can be applied to any energy system, but this generality has also been cited as one of the main reasons for its lack of application in recent years (Tsatsaronis, 1999). Pinch analysis, however, is specifically applicable to HENs. It cannot accurately be applied to other systems, including HENs incorporating heat pumps and threshold problems (Wall & Gong, 1996). The latter refers to the limiting case when the external heat input or output disappears, and the energy need is not affected by the horizontal position of the composite curves. In exergy terms the position of the curves is important, though, because heat released at a high temperature is more valuable than that released at a low temperature. Furthermore, pinch analysis can only deal with heat transfer processes – it does not consider pressure or

composition changes that are common in energy systems. Several practitioners have compared the two methods by applying them to a proposed nitric acid plant to be integrated into an existing plant (Gaggioli et al., 1991 and Linnhoff & Alanis, 1991, cited in Wall & Gong, 1996). The energy (and cost) savings identified with the exergy analysis were much larger than with the pinch analysis, which seems to demonstrate that exergy analysis is generally much more powerful, as in this case it identified opportunities that pinch analysis could not. In an attempt to retain the advantages of these two methods yet overcome the disadvantages, others have attempted to combine them. Feng and Zhu (1997) have retained the visually appealing representation of composite curves with a quantitative consideration of exergy, by employing a quality-enthalpy diagram along similar lines as van Gool (1992). The exergy composite curves further distinguish between avoidable and unavoidable losses (destructions), thus enabling a simple visual identification of the areas where attention should be focussed. This method has been further developed by Anantharaman et al. (2006) to analyse process units with multiple inputs and outputs (as opposed to just one of each). This revised approach is useful for giving a general feeling and understanding of the system as a whole, but does not give any explicit recommendations about integrating process units and overlooks the fact that not all process units involving energy level changes can be used for energy integration. Another obvious disadvantage of energy-level composite curves is the additional data requirement; data relating to the chemical exergies of non-standard substances is not universally available.

For all applications of thermodynamic techniques to analyse energy systems, the stipulation of the system boundary is crucial. Particularly for industrial energy systems, very different results are obtained through the adoption of different system boundaries (Tanaka, 2008). This means that the results from different studies are not directly comparable and that there is no common benchmark for comparison. Energy and exergy analyses are likewise sensitive to the system boundary conditions, so these need to be defined with the objectives in mind. For example, by drawing the system boundary closely around the glass furnace, the exhaust stream could be considered as a loss from the system as the molten glass also leave the system with a significant exergy content. Similarly the system boundary meant that the temperature around the furnace could reasonably be considered to be at 25°C, which was used as the reference temperature. A wider system boundary would have meant setting a lower reference temperature and would have resulted in the exergy loss from the molten glass perhaps becoming a destruction when it occurs inside the system. In this case the interest was in the furnace itself though, and a wider system boundary would have complicated matters by having to account for fuel injection and mixing that were considered beyond the scope. Perhaps more pertinent is the fact that the ultimate purpose of the furnace is to produce molten glass; high temperatures are required for the chemical reactions and melting, and the glass is required in the molten phase in order to be worked, after which it must be cooled rapidly. When studying industrial energy systems it is therefore logical to determine the system boundary such that the output from the unit operation is also an output from the system (i.e. in the same form).

In summary, the methodology employed depends very much on the specific energy system. One single methodology does not stand out as being particularly useful for all purposes, rather

the choice of method needs to be made based on the specific characteristics of the energy system. In general pinch analysis is useful for optimising HENs. Energy and exergy analysis are useful for all energy systems if used together, but care needs to be exercised when interpreting low exergy efficiencies. Meso-level analyses based on CO₂ or other emissions allocations are generally robust overall indicators of energy use. For heterogeneous sectors, a SEC/capacity based approach is favoured because of its ability to reflect inter- and intra-site differences in processes.

9.4 *Limitations of the results*

Some of the limitations of the results have already been mentioned. The first of these is the effects that globalisation has had (and is having) on the manufacturing sector. The profusion of foreign ownership by large multinational companies means that in many industries British manufacturing represent only a small proportion of the company's whole portfolio. The consequence for the present work is that, by focussing on the UK, only one part of a much larger picture is considered. Furthermore, by attempting to optimise the smaller system one overlooks changes in the larger one. Companies shift their production capacity around according to global trends such as fluctuations in market forces, e.g. there is evidence that some cement manufacturers will shift production capacity outside of the EU if the carbon price within the EU ETS becomes high enough to make this economical (section 5.4). Another reason why this focus on one nation's activities is a limitation is that these companies are often not based in the UK. Hence many decisions relating to production activities in the UK are made abroad; the arm of the company in the UK is not necessarily in a position to influence decisions that apply to the company as a whole. This limitation does not directly affect the main findings of this thesis, but it does define the broader context in which they should be understood. It also presents an important driver for the direction of future work in this area, which should not necessarily confine its scope to national boundaries.

The second main limitation also relates to the scope of the work, but in time rather space. The importance of the industrial sector in meeting demands in many other economic sectors was highlighted in chapter 5. As well as making the industrial sector a crucial one, this also gives the sector much control over the environmental impact of products over their lifecycle. Decisions made at the design stage affect the energy demand of products in use as well as the ways in which they can be disposed of at the end of life. Indeed, this is what energy labelling schemes and policies concerning the energy demand of products during the use phase are attempting to address (section 4.3.3.5). Hence the limitation in this research is that it only considers the industrial processes that actually create these products, and not the wider context, such as the whole supply chain or lifecycle. In the process of carrying out this research the feasibility of a lifecycle assessment (LCA) was investigated, and the conclusion was reached that it would not be possible to maintain such a broad scope whilst also considering the impacts of specific products over the lifecycle. LCAs tend to be highly specific studies that attempt to answer specific research questions. They therefore have large resource requirements and are associated with a trade-off between scope and level of detail as discussed above. To incorporate

an LCA to the level of detail required would therefore not have been possible given the research constraints of this thesis. For the future, though, it is important that the implications (especially for the use phase) of industrial energy systems are considered, and that the relationship between process or embodied energy and energy in use is better understood.

A further limitation is that energy is only one factor of production. By concentrating on energy one is arguably overlooking other considerations, which might require a system to operate sub-optimally in thermodynamic terms. In the broader context, whilst energy is currently playing a crucial role in making human activities unsustainable, it is only one aspect that needs to be considered in achieving sustainability. As outlined in section 1.1, one of the common themes in the many definitions of sustainable development is the complexity of the interactions that need to be considered, in particular those associated with social, environmental and economic systems. The implication for this thesis is that the industrial sector should be assessed from a sustainability- rather than just an energy-perspective. Once again, the focus of the work was defined in the scope in chapter 1, and it would not have been feasible to carry out such a broad study given the resource constraints.

Notwithstanding these limitations this thesis has met its aim through the application of several detailed cases studies, including macroeconomic analyses of whole industrial sectors, a meso-level analysis of heat use in most sectors, an energy and exergy analysis of a glass furnace, and a process integration study of a pulp and paper mill. These studies have quantified technical and/or economic potential for energy efficiency improvements in these energy systems as well as suggesting where further work should focus. This chapter has generalised some of the results of this thesis, discussed the respective methodologies employed and highlighted the limitations of the results. Attention is now turned to the final chapter of this thesis, which contains conclusions and recommendations for future work.

10 Conclusions and recommendations for future work

This chapter contains the conclusions of this thesis, a statement of the contribution to knowledge and an assessment of the areas in which future work should be focussed.

10.1 *Conclusions*

The conclusions are related back to the original objectives defined in section 1.5 of the Introduction and are presented under subheadings of these objectives below.

10.1.1 **To discuss relevant approaches emanating from the fields of thermodynamics and economics, and to highlight the problems with the neoclassical concept of production.**

The discussion of interdisciplinary approaches in chapter 2 found many instances of techniques and insights being “borrowed” between thermodynamics and economics. In most cases the borrowing has been by the latter from the former. In general, the most successful of such approaches have involved the actual integration of two (or more) disciplines, such as is the case for the transdisciplinary field of ecological economics. The problem with simply borrowing ideas is that they are liable to be taken out of context and therefore misunderstood or misapplied. In many of the cases discussed, whilst there has been no real paradigm shift, it is exactly this application of ideas out of context that has enabled a different understanding of an existing problem. The many problems of the neoclassical paradigm can be better understood from a thermodynamic perspective. Apart from to suggest that the model should better reflect natural and physical constraints, though, these insights do not lead directly to a solution. There appears to be a weak relationship between energy (and exergy) and value that is not strong enough to form the basis of a theory of value, at least not without a formal and quantitative investigation of this relationship.

The discussion of economic growth, technological change and energy efficiency in chapter 2 highlighted the way in which these concepts are closely related, and the ambiguity surrounding the relationship between them. The standard neoclassical production model is inadequate because it fails to account for the essentiality of energy and other inputs, and finite nature of natural resources. If the latter are incorporated into the production function, there is an implied growth drag which can only be ameliorated by technological change – within limits defined by the output elasticities of the respective inputs. It also appears that the output elasticities given to energy and exergy in production functions is generally too low, showing that these inputs make significant contributions to economic growth – but the evidence is limited and contradictory in some cases. Furthermore, technological change remains mostly elusive in models of production; it can be accounted for but not understood. The S-E framework is a promising alternative, but it also suffers from a lack of empirical testing.

10.1.2 To review applications of thermodynamic and economic techniques to industrial energy systems.

The literature review in chapter 3 found a lack of applications of statistical energy analysis (SEA) to industrial sectors in the past few decades. This seems mainly due to the privatisation of ETSU in the 1990s (and the associated reduction in public funding for these activities) and the concomitant decline of heavy industries. An exhaustive review of applications of process analysis (PA) to British industries was not carried out because of the large variation in processes across sectors and the resulting number and diversity of studies. The fact that PA has been so widely applied is a testament to the useful insights it can provide into energy systems. The transferability of PA studies between sectors and countries carrying out the same processes means that they need not necessarily be sector-specific. In addition, the issue of commercial confidentiality was identified as preventing company- and site-specific analyses from being published. In general there seems to be a lack of application of PA to the site level; mostly studies have focussed on the unit operation scale, which can be interpreted partly as an uncertainty in the distinction between PA and SEA. The same trend emerges from applications of exergy analysis: it has been applied to macro and micro systems but not in between, which might be in part due to the availability of data at these two extremes. Exergy analysis has also been widely applied to industrial energy systems, and has provided useful insights, but it should not be used in isolation. Chapter 3 also highlighted the lack of data relating to industrial energy use in four specific areas, namely: highly disaggregated energy use by sector; data relating to end uses of energy; the distinction between electricity used for power and heat; and the temperatures at which energy is used (a so-called temperature demand profile).

10.1.3 To define energy efficiency, discuss its measurement and associated problems, and to identify the means of increasing efficiency.

The wealth of definitions and application-specific nature of the term “energy efficiency” was discussed in section 4.1. The definition adopted for this thesis was the amount of product/output per unit of energy consumption, which is equivalent to economic productivity and is the reciprocal of the specific energy consumption (SEC) or energy intensity. Section 4.2 discussed the interdisciplinary ways in which energy efficiency can be measured. There are essentially two means of measuring output, through economic and physical measures respectively. Physical indicators are generally preferable because they overcome problems associated with price fluctuations. In practice the choice of indicator is constrained by data availability, however, as well as the disadvantage that physical measures cannot always be aggregated. Section 4.3 identified the main ways in which energy efficiency can be increased, namely through behaviour, technology and policy. The former are mainly concerned with energy management – implementing systems to better manage the existing infrastructure. A successful energy management system relies as much on a company’s organisation and culture as on technical measures. There is anecdotal evidence of its application, which suggests that it is not universally employed. Technology is the next stage on the energy hierarchy (section 1.3), and includes widely employed energy systems such as steam, combustion and motors, as well

as process-specific technologies. A wide variety of energy technologies are available; only the ones associated with ubiquitous industrial systems were identified in chapter 4. The third way of achieving energy efficiency is through public policy measures. The policies especially relevant to energy use in industry were reviewed in section 4.3.3, which concluded that the CCL and CCA package are effective, but that other policies are ineffective. In particular, only a small proportion of the savings identified by the Carbon Trust are being realised, the EU ETS does not appear to have achieved emissions reductions within Europe, and the government's 10GWe target for GQCHP by 2010 will almost certainly not be met.

10.1.4 To identify drivers for and barriers to increased energy efficiency, including theoretical frameworks and empirical evidence.

The theoretical framework for drivers and barriers was presented in section 4.4.1 and empirical evidence for these drivers and barriers was discussed in section 5.5. The theoretical framework assists in understanding the complex nature of barriers to energy efficiency uptake in industry. It classifies barriers into economic market barriers, economic market failures, organisational and behavioural barriers, whilst recognising that many barriers fall into multiple categories. The distinction between the first two types of barrier is somewhat ambiguous, however, because real markets are neither perfect nor efficient. The empirical evidence suggests that the most significant market barriers are those of hidden costs and access to capital, which have been often cited in the literature as reasons given (e.g. in energy audits) for not undertaking energy efficiency measures. Of the market failures, imperfect information appears to be by far the strongest barrier, as well as one which might benefit from a public policy intervention. There is significant systemic potential for increasing industrial energy efficiency if these barriers can be eliminated. The potential is highest in ubiquitous energy systems such as steam, motors and CHP, as well as in key sectors such as, for example, iron and steel, chemicals, pulp and paper, and food and drink. There is very little evidence for the rebound effect in industry; the available evidence suggests that the effect is small in this sector.

10.1.5 To analyse the industrial sector from a macroeconomic perspective, using a variety of interdisciplinary tools, in order to determine and understand current and historical energy trends.

The macroeconomic analysis of the industrial sector in chapter 5 determined the baseline against which changes in energy efficiency are measured. The sector's shift towards services activities was highlighted as both a continuation of a broader trend that has occurred since industrialisation began and as reason for the misrepresentation of the sector's performance in national statistics. The sector as a whole has demonstrated drastic reductions in energy demand through energy efficiency in the last few decades, largely motivated by the oil price hikes in the 1970s. Significant improvements in productivity were made at the same time, whereby technological developments have more than offset the large reduction in employment in manufacturing. Analysis of the energy and carbon trends in individual sectors reveals a

large diversity across industry. In general the vast majority of carbon emissions from industry are combustion emissions, but the fraction of process emissions varies by sector. Attempts to characterise sectors were made based on energy end uses, energy productivities, and overall energy demand. A classification of sectors based on the degree of process homogeneity was proposed, within which the food and drink and chemicals sectors are the most diverse.

International trade is very important for the British manufacturing sector, which in general exports high value goods and imports lower value ones. Consistently higher levels of trade are undertaken with countries inside rather than outside the EU. The highest levels of trade occur within the automotive, electronics, chemicals (especially pharmaceuticals) and basic metals sectors, which are all high value added sectors. In the international context, many sectors are dominated by foreign ownership, which is especially the case for the iron and steel and automotive sectors. A case study of the European cement sector suggests that the EU ETS is not functioning as desired and that, ironically, if it becomes more effective, there is a threat of carbon leakage outside Europe. Solutions to this problem include a multilateral international emissions-trading scheme and/or carbon taxes or import quotas on cement imported from outside Europe. The potential for short term energy efficiency improvement in the cement sector is marginal. In the long term new technological developments will be required to achieve drastic reductions in carbon emissions by the sector, including Carbon Capture and Storage (CCS) and higher-power cements.

10.1.6 To estimate the long term potential for energy efficiency improvement through systemic optimisation.

Chapter 5 also estimated the potential for long term improvements in industrial sectors, mainly by focussing on the ubiquitous technological systems discussed in section 4.3.2. Motor and steam systems are estimated to have energy efficiency improvement potentials of 20% and 10% respectively. The scope for improving combustion systems in the long term is unknown, mainly because these systems are so diverse. There is little consensus about the potential for CHP in industry, although DEFRA (2007a) suggested an *additional* economical potential for low to medium temperature industry in 2010 of 5.4GW_e, rising to 6.8GW_e in 2015. There is also an estimated 1.4GW_e potential in high temperatures industries by 2010, especially refineries and LNG terminals (ibid.). The scope for long term, systemic energy efficiency improvements is largest in the basic metals, chemicals, pulp and paper, food and drink, and non-metallic minerals sectors.

10.1.7 To apply relevant methodologies to industrial energy systems in order to determine the short term technical and/or economic energy efficiency improvement potential

Three industrial energy systems were analysed using relevant methodologies in chapters 6, 7 and 8. Chapter 6 relates to a meso-level, spatial analysis of heat demand and technical recovery

potential at industrial sites, which also incorporated a qualitative consideration of the thermodynamic quality of the heat. The technical heat recovery potential based on commercial technology was estimated for the industrial sector, with an emphasis on energy-intensive industries. Around 60% of industry has been covered in terms of energy use, and 90% of energy-intensive sectors. The total annual heat load for these sectors was estimated at 650PJ, with technically feasible annual savings in the region of 36-71PJ (10-20TWh). This is in agreement with the lower of the only two extant estimates for heat recovery from industrial processes, which are 65PJ (18TWh) and 144PJ (40TWh) respectively.

Chapter 7 presents a general model of an industrial glass furnace, which enables energy and exergy balances to be performed over a range of furnace loads, batch recipes, cullet contents and temperature regimes. The model shows a good correspondence with published data and a sensitivity study has shown that its behaviour is within the expected theoretical limits. A waste heat recovery boiler is recommended and an investment appraisal suggests that this is an economically feasible investment with a discounted payback period of fourteen months and a net present value of £2.7million (IRR of 88%). A heat recovery boiler is a very suitable economic means through which to increase the energy efficiency of the sector. The energy saving for this particular furnace running at 300t/d is 239GJ/d (i.e. 0.80GJ/t glass produced), which is based on a boiler efficiency of 50%. If such heat recovery boilers were rolled out across the sector as a whole, and every furnace has a use for the recovered heat, then the total saving potential might be ten times this figure, based on the total operational capacity of the sector and a utilisation factor of 85% (Table 7-1 and footnote 40). In theory large scope for improving the systemic energy and carbon efficiency of the glass sector is possible through increasing the recycling rate, but this is limited in practice by barriers such as the colour and quality mismatch between the domestic supply and demand for cullet. Whether these barriers can be overcome will depend on many factors, including the price of the raw materials (especially sand and soda ash) and fuels (mainly natural gas), as well as the development of the carbon price within the EU ETS and the changing market environment.

Chapter 8 reports a process integration study of a pulp and paper mill. A pinch analysis was carried out in conjunction with an economic optimisation of the heat exchanger network (HEN) in the paper machine. It was concluded that excess heat from the grinders could be recovered and recycled into the process (paper machine), thus replacing direct steam injection. Steam consumption in the process can be reduced by 1.9kg/s or 15%, leading to an increased electricity production from the CHP plant of 0.9MW. The recommended changes in the HEN based on the shortest payback period are to heat exchange the effluent from cloudy filtrate overflow with mill heating water and supply the required heat demand of warm water in the condensing heat exchanger. The proposed changes require a new heat exchanger for heat recovery of effluent and a new hot filtrate water tank. The total investment cost is estimated at approximately £0.23million, and the reduced annual running cost due to increased electricity production is estimated at £0.59million. The discounted payback period is approximately five months. This potential cannot be extrapolated across the pulp and paper sector because the plant studied is one of the few integrated mechanical pulp and paper mills in the UK. However, the fact that

this potential was identified in an already very efficient plant suggests that the same or additional potential probably exists elsewhere in the sector.

10.1.8 To discuss the results of these detailed studies and the suitability of combining their respective methods in the wider context of the preceding chapters.

The discussion in chapter 9 highlighted several ways in which the results from this research can be generalised. The characterisation of industrial sectors leads to the conclusion that, as far as possible, sectors should be disaggregated until they can reasonably be considered homogeneous. This greatly facilitates energy analysis, because the unit of analysis is common in all cases and can be applied to other industrial systems. Furthermore, it was suggested that the SIC is perhaps not the most suitable classification for the purposes of energy analysis, and that a more suitable one could be defined to better facilitate this.

The discussion of the methodologies in section 9.3 found that the methodology employed depends very much on the specific energy system. One single methodology does not stand out as being particularly useful for all purposes; rather the choice of method needs to be made based on the specific characteristics of the energy system. In general pinch analysis is useful for optimising HENs. Energy and exergy analysis are useful if used in conjunction for all energy systems, but care needs to be exercised when interpreting low exergy efficiencies. Meso-level analyses based on CO₂ (or other) emissions allocations are generally robust in determining energy use and could easily be applied to other energy systems, such as sectors or countries. For heterogeneous sectors, a SEC/capacity based approach is favoured because of its ability to reflect inter- and intra-site differences in processes.

10.1.9 To discuss the limitations of this research.

The limitations of this research were discussed in section 9.4. They mainly relate to the scope of the work in space and time. The global nature of the manufacturing sector, where foreign ownership is common, means that national boundaries are not necessarily the best way of defining the limits of the system in space. Also, the large impact of decisions made at the design stage on the environmental performance of products is a strong motivation to consider products over their complete lifecycle. The relationship between embodied or process energy and energy demand during use therefore needs to be better understood. Finally, there is a weakness in focussing on energy as the sole parameter upon which to optimise a system. Although a single definition of sustainable development has not been consensually adopted, one common thread in many definitions is the consideration of multiple facets, in particular social, environmental and economic. In addition, there are often reasons why a system is required to operate in a thermodynamically sub-optimal way. The industrial sector therefore also needs to be assessed from an holistic sustainability perspective rather than just based on energy considerations.

10.2 *Statement of contribution to knowledge*

This section outlines the contribution to knowledge of this thesis, in each case by highlighting the contribution and explaining its original aspect.

- I. The review in chapter 2 merges diverse areas of thermoeconomics by clarifying and summarising the shortcomings of the neoclassical paradigm as well as ways in which they might be overcome.
- II. The review in chapter 3 identifies the areas where industrial energy analysis needs to focus, in particular relating to developing more accurate data;
- III. The interdisciplinary macro-economic analysis of the industrial sector employs various indicators to bring previous studies up to date. Its novel aspects include:
 - i. The determination of energy productivity indicators by sector, which are not available in national statistics and have not previously been published;
 - ii. The estimation of carbon emissions (combustion and process) by sector, which are not available in national statistics;
 - iii. The characterisation of industrial sectors using various metrics and the proposition of a classification based on the degree of process homogeneity;
 - iv. The case study of cement sector in the context of the EU ETS, which provides primary evidence that the EU ETS has been ineffective in emissions reductions;
 - v. The collation of empirical evidence for barriers and drivers to energy efficiency;
 - vi. The development of a meso-level database drawn from various sources, including data on companies, production capacities, and locations for all sectors, which was not previously available;
- IV. The analysis in chapter 6 quantifies the heat use and technical recovery potential for industrial sectors, whilst considering the spatial distribution and thermodynamic quality of the heat, which had not previously been done in such detail;
- V. Chapter 7 quantifies the energy and exergy flows in a British glass furnace and provides a useful benchmarking tool in the context of the EU ETS; such an analysis had not previously been published;
- VI. Chapter 8 applies pinch analysis and economic optimisation to a specific British pulp and paper mill, identifying economical savings and demonstrating the suitability of the method in this application; the scope for improvements in the warm and hot water system at the mill were previously unknown;
- VII. Generalisation of the above three studies to provide an indication of the energy efficiency improvement potential at other sites and/or in other sectors.

10.3 *Recommendations for future work*

Based on the discussion above, several potential areas have been identified, where future work relating to industrial energy efficiency should be focussed.

- Relating to chapter 6:
 - Quantify the economical fraction of the technical heat recovery potential;
 - Refine the temperature profile and clarify the specific exhaust temperatures;
 - Develop the SEC-based methodology to cover all rather than a fraction of heterogeneous sectors; these sectors could also be disaggregated into homogeneous sub-sectors and data collated or production capacities;
 - Include the Environment Agency's Pollution Inventory dataset, which includes all industrial sites (as opposed to those over 20MW_{th} in the EU ETS);
- Those sectors that have not been studied in detail should be analysed and the potential for economic energy efficiency improvements quantified, with a particular focus on the chemicals and food and drink sectors because of their heterogeneous nature;
- Several aspects of the database could be developed, including the relationship between R&D spend and GVA per sector, and more disaggregated energy productivities;
- Investigate the split between electricity used for industrial heat and power applications;
- Investigate the relationships between embodied energy and/or carbon and the position in a product's manufacturing lifecycle (Roberts, 1982), and between process energy and energy in use of products – that is, what effect(s) changes to the manufacturing process have on the energy in use, and vice versa;
- Quantify the effect that the blurring of the distinction between manufacturing and services activities is having on national output statistics; and
- Adopt more holistic approaches, which include a broader geographical scope, a consideration of product lifecycles and multifaceted sustainability criteria.

10.4 *Closing statement*

This thesis has quantified the technical and economic potential for industrial energy efficiency improvement in several sectors, which can be intra- and inter-sectorally generalised to a degree. It has also demonstrated the distinction between long term, systemic improvements through widely employed technologies and short to medium term, sector- or process-specific measures, and the need to employ bottom-up studies to identify the latter. In order to realise either type of potential, public policy is required to overcome market-related barriers. In particular, the EU ETS and the Carbon Trust could be improved, and there is additional scope for mandatory efficiency standards relating to motors and industrial boilers. Organisational and behavioural barriers mean that energy efficiency also has to be an integral part of a company's strategy in order to be effectively achieved, but overcoming these types of barriers rely mainly on firms themselves rather than external policies. Future work should focus on heterogeneous sectors such as chemicals and food and drink, as well as the broader implications of globalisation and the trend towards service activities on British manufacturing.

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