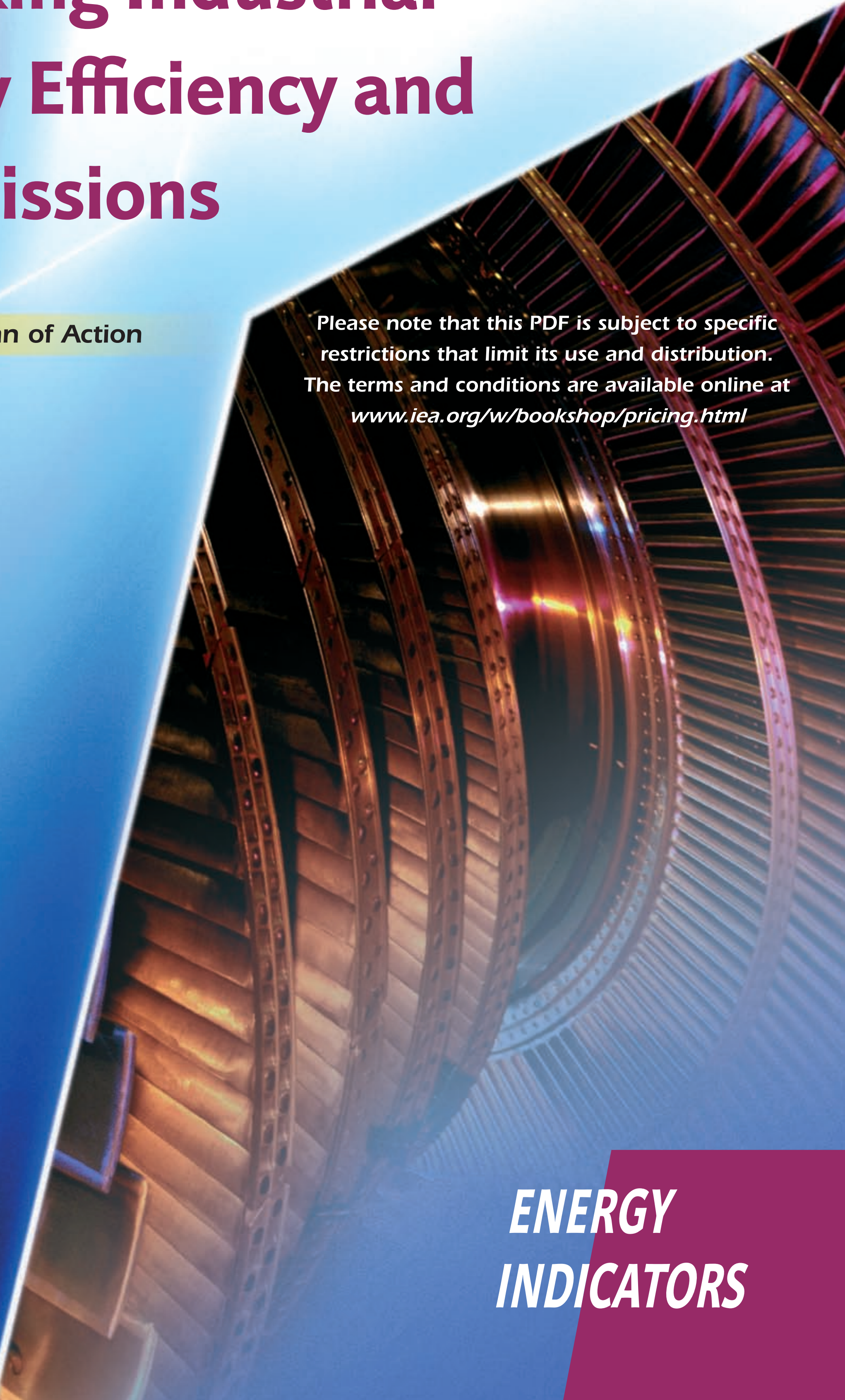
INTERNATIONAL ENERGY AGENCY

Tracking Industrial Energy Efficiency and CO_2 Emissions

In support of the G8 Plan of Action



ENERGY INDICATORS

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

It carries out a comprehensive programme of energy co-operation among twenty-six of the OECD thirty member countries. The basic aims of the IEA are:

- To maintain and improve systems for coping with oil supply disruptions.
- To promote rational energy policies in a global context through co-operative relations with non-member countries, industry and international organisations.
- To operate a permanent information system on the international oil market.
- To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use.
- To assist in the integration of environmental and energy policies.

The IEA member countries are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Republic of Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. The Slovak Republic and Poland are likely to become member countries in 2007/2008. The European Commission also participates in the work of the IEA.

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The OECD is a unique forum where the governments of thirty democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Republic of Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.
The European Commission takes part in the work of the OECD.

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FOREWORD

Improving energy efficiency is the single most important first step toward achieving the three goals of energy policy: security of supply, environmental protection and economic growth.

Nearly a third of global energy demand and CO_2 emissions are attributable to manufacturing, especially the big primary materials industries such as chemicals and petrochemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, is crucial.

This book shows that, while impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced by a further quarter to a third, if best available technology were to be applied worldwide. Some of these additional reductions may not be economic in the short- and medium-term, but the sheer extent of the potential suggests that striving for significant improvements is a worthwhile and realistic effort. A systems approach is needed that transcends process or sector boundaries and that offers significant potential to save energy and cut CO_2 emissions.

The growth of industrial energy use in China has recently dwarfed the combined growth of all other countries. This structural change has had notable consequences for industrial energy use worldwide. It illustrates the importance of more international co-operation.

The IEA has undertaken an extensive programme to assess industrial energy efficiencies worldwide. This study of industrial energy use represents important methodological progress. It pioneers powerful new statistical tools, or "indicators" that will provide the basis for future analysis at the IEA. At the same time it contains a wealth of recent data that provide a good overview of energy use for manufacturing worldwide. It also identifies areas where further analysis of industrial energy efficiency is warranted.

Industry has provided significant input and support for this analysis and its publication is intended as a basis for further discussion. I am encouraged by the strong commitment that industry is demonstrating to address energy challenges and welcome the valuable contributions from the Industrial Energy-Related Technologies and Systems Implementing Agreement of the IEA collaborative network.

This book is part of the IEA work in support of the G8 Gleneagles Plan of Action that mandated the Agency in 2005 to chart the path to a "clean, clever and competitive energy future". It is my hope that this study will provide another step toward the realisation of a sustainable energy future.

This study is published under my authority as Executive Director of the IEA and does not necessarily reflect the views of the IEA Member countries.

Claude Mandil

Executive Director

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Table of Contents

LIST OF FIGURES

Chapter 2 ▶ MANUFACTURING INDUSTRY ENERGY USE AND CO_2 EMISSIONS

Chapter 3 ▶ GENERAL INDUSTRY INDICATORS ISSUES

Chapter 4 ▶ CHEMICAL AND PETROCHEMICAL INDUSTRY

Chapter 5 ▶ IRON AND STEEL INDUSTRY

Chapter 6 ▶ NON-METALLIC MINERALS

Chapter 7 ▶ **PULP, PAPER AND PRINTING INDUSTRY**

Chapter 8 ▶ **NON-FERROUS METALS**

Chapter 9 ▶ **SYSTEMS OPTIMISATION**

Chapter 10 ▶ **LIFE CYCLE IMPROVEMENT OPTIONS**

Annexes ▶ **Annex A • Process Integration**

LIST OF TABLES

Chapter 1 ▶ **INTRODUCTION**

Chapter 2 ▶ **MANUFACTURING INDUSTRY ENERGY USE AND CO_2 EMISSIONS**

Chapter 3 ▶ **GENERAL INDUSTRY INDICATORS ISSUES**

Chapter 4 ▶ **CHEMICAL AND PETROCHEMICAL INDUSTRY**

Chapter 7 ▶ PULP, PAPER AND PRINTING INDUSTRY

Chapter 8 ▶ NON-FERROUS METALS

Chapter 9 ▶ SYSTEMS OPTIMISATION

Chapter 10 ▶ LIFE CYCLE IMPROVEMENT OPTIONS

EXECUTIVE SUMMARY

Introduction

At their 2005 Gleneagles Summit the Group of Eight (G8) leaders asked the IEA to provide advice on a clean, clever and competitive energy future, including a transformation of how we use energy in the industrial sector. This study was prepared in response to that request and a complementary request from the Energy Ministers of IEA countries. The primary objective of this analysis is to develop ways to assess the state of worldwide industrial energy efficiency today and estimate additional technical savings potential.

Nearly a third of the world's energy consumption and 36% of carbon dioxide (CO_2) emissions are attributable to manufacturing industries. The large primary materials industries – chemical, petrochemicals, iron and steel, cement, paper and pulp, and other minerals and metals – account for more than two-thirds of this amount. Overall, industry's use of energy has grown by 61% between 1971 and 2004, albeit with rapidly growing energy demand in developing countries and stagnating energy demand in OECD countries. However, this analysis shows that substantial opportunities to improve worldwide energy efficiency and reduce CO_2 emissions remain. Where, how and by how much? These are some of the questions this analysis tries to answer.

This is a pioneering global analysis of the efficiency with which energy is used in the manufacturing industry. It reveals how the adoption of advanced technologies already in commercial use could improve the performance of energy-intensive industries. It also shows how manufacturing industry as a whole could be made more efficient through systematic improvements to motor systems, including adjustable speed drives; and steam systems, including combined heat and power (CHP); and by recycling materials. The findings demonstrate that potential technical energy savings of 25 to 37 exajoules[1] per year are available based on proven technologies and best practices. This is equivalent to 600 to 900 million tonnes (Mt) of oil equivalent per year or one to one and a half times Japan's current energy consumption. These substantial savings potentials can also bring financial savings. Improved energy efficiency contributes positively to energy security and environmental protection and helps to achieve more sustainable economic development. The industrial CO_2 emissions reduction potential amounts to 1.9 to 3.2 gigatonnes per year, about 7 to 12% of today's global CO_2 emissions.

The estimates employ powerful statistical tools, called "indicators", which measure energy use based on physical production. This study sets out a new set of indicators that balance methodological rigour with data availability. These indicators provide a basis for documenting current energy use, analysing past trends, identifying technical improvement potentials, setting targets and better forecasting of future trends. The advantages of this approach include that these indicators:

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[1] One exajoule (EJ) equals 10^{18} joules or 23.9 Mtoe.

▷ are not influenced by price fluctuations, which facilitates trend analysis. In detail, these indicators provide a closer measure of energy efficiency.

▷ can be directly related to process operations and technology choice.

▷ allow a well-founded analysis of efficiency improvement potentials.

This study builds on other IEA work on energy indicators, a series of workshops and dialogue with experts from key industries, a comprehensive analysis of available data and an extensive review process. The IEA Implementing Agreement on Industrial Energy-Related Technologies and Systems and individual experts from around the world provided valuable input.

One important conclusion is that more work needs to be done to improve the quality of data and refine the analysis. Much better data is needed, particularly for iron and steel, chemicals and petrochemicals, and pulp and paper. This study is presented for discussion and as a prelude to future work by the IEA.

Key Trends

Overall, ***industrial energy use has been growing strongly*** in recent decades. The rate of growth varies significantly between sub-sectors. For example, chemicals and petrochemicals, which are the heaviest industrial energy users, doubled their energy and feedstock demand between 1971 and 2004, whereas energy consumption for iron and steel has been relatively stable.

Much of the ***growth in industrial energy demand has been in emerging economies.*** China alone accounts for about 80% of the growth in the last twenty-five years. Today, China is the world's largest producer of iron and steel, ammonia and cement.

Efficiency has improved substantially in all the energy-intensive manufacturing industries over the last twenty-five years in every region. This is not surprising. It reflects the adoption of cutting-edge technology in enterprises where energy is a major cost component. Generally, new manufacturing plants are more efficient than old ones. The observed trend towards larger plants is also usually positive for energy efficiency.

The concentration of industrial energy demand growth in emerging economies, where industrial energy efficiency is lower on average than in OECD countries means, however, that ***global average levels of energy efficiency in certain industries, e.g. cement, have declined less than the country averages*** over the past twenty-five years.

Broadly, it is the ***Asian OECD countries***, Japan and Korea, that ***have the highest levels of manufacturing industry energy efficiency***, followed by Europe and North America. This reflects differences in natural resource endowments, national circumstances, energy prices, average age of plant, and energy and environmental policy measures.

The ***energy and CO_2 intensities of emerging and transition economies show a mixed picture***. Where production has expanded, industry may be using new plant with the latest technology. For example, the most efficient aluminium smelters are in Africa and some of the most efficient cement kilns are in India. However, in some industries and regions where production levels have stalled, manufacturers have failed to upgrade to most efficient technology. For example, older equipment remains dominant in parts of the Russian Federation and Ukraine. The widespread use of coal in China reduces its energy efficiency, as coal is often a less efficient energy source than other fuels due to factors such as ash content and the need for gasification. In China and India, small-scale operations with relatively low efficiency continue to flourish, driven by transport constraints and local resource characteristics, *e.g.* poor coal and ore quality. The direct use of low grade coal with poor preparation is a major source of inefficiency in industrial processes in these countries.

Tracking Energy Efficiency

Basic industrial processes and products are more or less the same across the world. This enables the use of universal indicators. However, as usual, the devil is in the detail. Comparing the relative energy performance of industries around the world needs to consider that individual technologies, qualities of feed stocks and products are often different in various countries even for the same industry. In order to make proper comparisons, system boundaries and definitions need to be uniform. Indicators complement benchmarking, but they should not be used as a substitute. Industrial energy use indicators can serve as the basis for identifying promising areas by sub-sector, region and technology to improve efficiency. This is, for example, the case for the cement industry in China and industrial motor and steam systems worldwide, which this study shows to have significant potential for energy and/or CO_2 savings.

Reliable indicators require good data. Currently the data quality is often not clear, even those from official sources. As indicators may become the basis for policy decisions with far-reaching consequences, data gaps need to be filled and the quality of data needs to be regularly validated and continually improved.

In all countries, government and industry partnerships, incentives, and awareness programmes should be pursued to harvest the widespread opportunities for efficiency improvements. New plants and the retrofit and refurbishment of existing industrial facilities should be encouraged.

Small-scale manufacturing plants using outdated processes, low quality fuel and feedstock, and weaknesses in transport infrastructure contribute to industrial inefficiency in some emerging economies. Policies for ameliorating these problems should be strongly supported by international financial institutions, development assistance programmes and international CO_2 reduction incentives.

Energy and CO_2 Saving Potentials

This analysis estimates the technical energy and CO_2 savings available in energy-intensive industries worldwide. The ranges of potential savings on a primary energy basis are shown in Table 1 in two categories, either as "sectoral improvements", *e.g.* cement, or "systems/life cycle improvements", *e.g.* motors and more recycling. Improvement options in these two categories overlap somewhat. As well, system/life cycle options are more uncertain. Therefore, with the exception of motor systems,

Table 1 ▶ ***Savings from Adoption of Best Practice Commercial Technologies in Manufacturing Industries***

(Primary Energy Equivalents)

	Low – High Estimates of Technical Savings Potential			Total Energy & Feedstock Savings Potentials
	EJ/yr	*Mtoe/yr*	*Mt CO_2/yr*	*%*
Sectoral Improvements				
Chemicals/petrochemicals	5.0 – 6.5	120 – 155	370 – 470	13 – 16
Iron and steel	2.3 – 4.5	55 – 108	220 – 360	9 – 18
Cement	2.5 – 3.0	60 – 72	480 – 520	28 – 33
Pulp and paper	1.3 – 1.5	31 – 36	52 – 105	15 – 18
Aluminium	0.3 – 0.4	7 – 10	20 – 30	6 – 8
Other non-metallic metals minerals and non-ferrous	0.5 – 1.0	12 – 24	40 – 70	13 – 25
System/life cycle Improvements				
Motor systems	6 – 8	143 – 191	340 – 750	
Combined heat and power	2 – 3	48 – 72	110 – 170	
Steam systems	1.5 – 2.5	36 – 60	110 – 180	
Process integration	1 – 2.5	24 – 60	70 – 180	
Increased recycling	1.5 – 2.5	36 – 60	80 – 210	
Energy recovery	1.5 – 2.3	36 – 55	80 – 190	
Total	**25 – 37**	**600 – 900**	**1 900 – 3 200**	
Global improvement potential – share of industrial energy use and CO_2 emissions	**18 – 26%**	**18 – 26%**	**19 – 32%**	
Global improvement potential – share of total energy use and CO_2 emissions	**5.4 – 8.0%**	**5.4 – 8.0%**	**7.4 – 12.4%**	

Note: Data are compared to reference year 2004. Only 50% of the estimated potential system/life cycle improvements have been credited except for motor systems. The global improvement potential includes only energy and process CO_2 emissions; deforestation is excluded from total CO_2 emissions. Sectoral savings exclude recycling, energy recovery and CHP.

only 50% of the potential system/life cycle improvements have been credited for the total industrial sector improvement potential shown in Table 1. The conclusion is that manufacturing industry can improve its energy efficiency by an impressive 18 to 26%, while reducing the sector's CO_2 emissions by 19 to 32%, based on proven technology. Identified improvement options can contribute 7 to 12% reduction in global energy and process-related CO_2 emissions.

The single most important category is motor systems, followed by chemicals/petrochemicals on an energy savings basis. The highest range of potential sectoral savings for CO_2 emissions is in cement manufacturing. The savings potential under the heading "system/life cycle improvements" is larger than the individual sub-sectors in part because those options apply to all industries. Another reason is that these options have so far received less attention than the process improvements in the energy-intensive industries. Generally, these are profitable opportunities, though they are often overlooked, particularly in the parts of manufacturing where energy is not a main operating cost.

The estimated savings based on a comparison of best country averages with world averages, or best practice and world averages. They do not consider new technologies that are not yet widely applied. Also they do not consider options such as CO_2 capture and storage and large-scale fuel switching. Therefore, these should be considered lower range estimates of the technical potential for energy savings and CO_2 emissions reductions in the manufacturing industry sector. These estimates do not consider the age profile of the capital stock, nor regional differences in energy prices and regulations that may limit the short- and medium-term improvement options. The economic potentials are substantially lower than the technical estimates. Moreover, technology transfer to developing countries is a major challenge. Yet the sheer magnitude of the savings opportunties indicates that more effort is warranted.

Some of these savings will occur outside the manufacturing industry sector. For example, CHP will increase the efficiency in power generation. Energy recovery from waste will reduce the need to use fossil energy for power or heat generation. Increased recycling of paper leaves more wood that can be used for various bioenergy applications. Therefore, these savings estimates are not suited to set targets for sectoral energy use due to the dynamic interaction between sectors.

About 10% of the direct and indirect industrial CO_2 emissions are process-related emissions that are not due to fossil energy use. These CO_2 emissions would not be affected by energy efficiency measures. Another distinguishing feature of the manufacturing sector is that carbon and energy are stored in materials and products, *e.g.* plastics. Recycling and energy recovery make good use of stored energy and reduce CO_2 emissions, if done properly. Currently, these practices are not applied to their full extent.

Sectoral Results

Chemical and Petrochemical

- ▷ The chemical and petrochemical industry accounts for 30% of global industrial energy use and 16% of direct CO_2 emissions. More than half of the energy demand is for feedstock use, which can not be reduced through energy efficiency measures. Significant amounts of carbon are stored in the manufactured products.

- An indicator methodology that compares theoretical energy consumption using best available technology with actual energy use suggests a 13 to 16% improved energy efficiency potential for energy and feedstock use (excluding electricity). The potential is somewhat higher in countries where older capital stock predominates. The indicator results suggest problems with the energy and feedstock data for certain countries.
- The regional averages for steam crackers suggest a 30% difference in energy use between the best (East Asia) and worst (North America). Feedstock use dominates energy use in steam crackers, which can not be reduced through energy efficiency measures.
- Benchmarking studies suggest that potential energy efficiency improvements for olefins and aromatics range from 10% for polyvinyl chloride to 40% for various types of polypropylene.
- About 1 exajoule (EJ) per year (20%) would be saved if best available technology were applied in ammonia production. Coal-based production in China requires considerably more energy than gas-based production elsewhere.
- In final energy terms, the savings potential ranges from 5 to 11 EJ per year, including process energy efficiency, electric systems, recycling, energy recovery from waste and CHP.

Iron and Steel

- The iron and steel industry accounts for about 19% of final energy use and about a quarter of direct CO_2 emissions from the industry sector. The CO_2 relevance is high due to a large share of coal in the energy mix.
- The iron and steel industry has achieved significant efficiency improvements in the past twenty-five years. Increased recycling and higher efficiency of energy and materials use have played an important role in this positive development.
- Iron and steel has a complex industrial structure, but only a limited number of processes are applied worldwide. A large share of the differences in energy intensities and CO_2 emissions on a plant and country level are explained by variations in the quality of the resources that are used and the cost of energy.
- The efficiency of a plant in the iron and steel industry is closely linked to several elements including technology, plant size and quality of raw materials. This partly explains why the average efficiency of the iron and steel industries in China, India, Ukraine and the Russian Federation are lower than those in OECD countries. These four countries account for nearly half of global iron production and more than half of global CO_2 emissions from iron and steel production. Outdated technologies such as open hearth furnaces are still in use in Ukraine and Russia. In India, new, but energy inefficient, technologies such as coal-based direct reduced iron production play an important role. These technologies can take advantage of the local low-quality resources and can be developed on a small scale, but they carry a heavy environmental burden. In China, low energy efficiency is mainly due to a high share of small-scale blast furnaces, limited or inefficient use of residual gases and low quality ore.

▷ Waste energy recovery in the iron and steel industry tends to be more prevalent in countries with high energy prices, where the waste heat is used for power generation. This includes technology options such as coke dry quenching (CDQ) and top-pressure turbines. CDQ also improves the coke quality, compared to conventional wet quenching technology.

▷ The identified primary energy savings potential is about 2.3 to 2.9 EJ per year through energy efficiency improvements, *e.g.* in blast furnace systems and use of best available technology. Other options, for which only qualitative data are available, and the complete recovery of used steel can raise the potential to about 5 EJ per year. The full range of CO_2 emissions reductions is estimated to be 220 to 360 Mt CO_2 per year.

Cement

▷ The non-metallic mineral sub-sector accounts for about 9% of global industrial energy use, of which 70 to 80% is used in cement production.

▷ The average primary energy intensity for cement production ranges from 3.4 to 5.3 gigajoules per tonne (GJ/t) across countries with a weighted average of 4.4 GJ/t. Averages at a country level have improved everywhere, with the weighted average primary energy intensity declining from 4.8 GJ/t in 1994 to 4.4 GJ/t in 2003. Much of this decline has been driven by improvements in China, which produces about 47% of the world's cement.

▷ The efficiency of cement production is relatively low in countries with old capital stock based on wet kilns and in countries with a significant share of small-scale vertical kilns.

▷ In primary energy terms, the savings potential ranges from 2.5 to 3 EJ per year, which equals 28 to 33% of total energy use in this industry sector.

▷ Cement production is an important source of CO_2 emissions, accounting for 1.8 Gt CO_2 in 2005. Half of cement process CO_2 emissions are due to the chemical reaction in cement clinker production. These process emissions are not affected by energy efficiency measures. Yet it might be possible to reduce clinker production by 300 Mt with more extensive use of clinker substitutes which could reduce CO_2 emissions by about 240 Mt CO_2 per year. Therefore the CO_2 reduction potential could be higher than the energy saving potential.

▷ The average CO_2 intensity ranges from 0.65 to 0.92 tonne of CO_2 per tonne of cement across countries with a weighted average 0.83 t CO_2/t. The global average CO_2 intensity in cement production declined by 1% per year between 1994 and 2003.

Pulp, Paper and Printing

▷ The pulp, paper and printing industry accounts for about 5.7% of global industrial final energy use, of which printing is a very small share. Pulp and paper production generates about half of its own energy needs from biomass residues and makes extensive use of CHP.

▷ Among the key producing countries examined, the heat consumption efficiency in the pulp and paper sub-sector has improved by 9 percentage points from

1990 to 2003. This is a notable improvement, while an additional 14% improvement potential exists when a comparison with best available technology is made.

- This analysis shows relatively little change in the overall energy efficiency of electricity consumption in pulp and paper manufacturing. The weighted average efficiency of electricity use has improved by three percentage points from 1990 to 2003. There is an additional 16% improvement potential based on a comparison with best available technology.
- Increased recycled paper use in many countries could help reduce energy consumption. While Western Europe appears to be close to its practical limit for paper recycling, other parts of the world, *e.g.* North America and parts of Asia, could benefit from more effective policies on waste disposal to encourage higher rates of recycling.
- CO_2 reduction potentials in the pulp and paper industry are limited due to the high use of biomass. However, the more efficient use of biomass still makes sense from an energy systems perspective, as it frees up scarce wood resources which could provide savings elsewhere.
- In primary energy terms, the savings potential ranges from 1.3 to 1.5 EJ per year, which equals 15 to 18% of total energy use in this sub-sector.

Aluminium

- Aluminium production is electricity intensive. Global average electricity use for primary aluminium production is 15 300 kWh per tonne (kWh/t). This average has declined about 0.4% per year over the last twenty-five years. On a regional basis, the averages range from 14 300 kWh/t in Africa to 15 600 kWh/t in North America. Africa is the most efficient region due to new production facilities. New smelters tend to be based on the latest technology and energy efficiency is a key consideration in smelter development.
- The regional average energy use for alumina production ranges from 10 to 12.6 GJ/t.
- With existing technology, energy use in the key steps of aluminium production can be reduced by 6 to 8% compared with current best practice, which equals 0.3 to 0.4 EJ per year in primary energy equivalents.

Other Non-Metallic Minerals and Other Non-Ferrous Metals

- This category includes a wide range of products such as copper, lime, bricks, tiles and glass.
- The resource quality and the product quality is very diverse. This complicates a cross-country comparison. However, the available data suggests that important efficiency potentials remain based on options such as waste heat recovery.
- In primary energy terms, the savings potential ranges from 0.5 to 1 EJ per year. This equals approximately 13 to 25% of total energy use in these sub-sectors.

Systems Optimisation

- Based on hundreds of case studies across many countries, it is estimated that the improved efficiency potential for motor systems is 20 to 25% and 10 to 15% for steam systems. This is 6 to 8 EJ savings in primary energy per year in motor systems and 3 to 5 EJ in steam systems. Process integration could save an additional 2 to 5 EJ.
- Combined heat and power (CHP) is a proven industrial energy efficiency measure. Globally, CHP generates about 10% of all electricity today, resulting in estimated energy savings of more than 5 EJ annually. Up to 5 EJ of primary energy savings potential remain for CHP in manufacturing, equal to 3 to 4% of global industrial energy use.
- These systems options overlap and compete with the other sectoral options and the life cycle options. This interaction must be considered if the total industry potential is to be accurately estimated.

Life Cycle Optimisation

- Industrial energy use is different from other end-use sectors, because important quantities of energy and carbon are stored in the products. Therefore, it is particularly important to consider efficiency improvement options on a life-cycle basis including recycling, energy recovery and the efficiency of materials use.
- Countries differ vastly in their levels of recycling and energy recovery from waste materials. Substantial amounts of waste materials are land filled. Untapped global recycling potential and energy recovery potential are each in the range of 3 to 5 EJ per year. Better materials/product efficiency and waste management could cut some 0.3 to 0.8 gigatonne of CO_2 emissions per year.
- Life cycle optimisation competes with the other options and this reduces the potential for the total industry sector.

Next Steps

This study is a first attempt to provide a reliable and meaningful set of global indicators of energy efficiency and CO_2 emissions in the manufacturing industrial sector. They will be useful for industries, governments and others to improve forecasting of industrial energy use; to provide a realistic basis for target setting and effective regulation; and to identify sectors and regions for more focused analysis of improvement potentials.

This study needs to be followed by more work, as further improvements are possible. Future studies could be more meaningful for the benefit of all parties, including industry itself, if sensitivity and confidentiality issues could be overcome to allow a more detailed, complete, timely, reliable and open database to be developed. Policy makers, industry, analysts and others are calling for more reliable estimates of energy savings and CO_2 emission reductions potentials. This can only be achieved if accurate and complete energy use and efficiency data are available for the analysis of future potential based on best practices to pave the way for adoption of state-of-the-art technologies.

The methodology used here, which is often constrained by data limitations, can be improved. Feedback will be an important component of making future analysis more effective. However, an improved methodology will be more beneficial only if companies and countries make a concerted parallel effort to improve the quality and availability of the manufacturing industry energy data.

Apart from the improvement of the indicators analysis, future work will focus on assessing the potential of new technologies and analysing the integrated reduction potential by running scenarios that assess the economic potential of different technologies given current energy efficiencies and technology use. This work is expected in the first half of 2008.

Indicator and Data Issues

In most energy-intensive industrial sub-sectors, ten to twenty countries account for 80 to 90% of global production and CO_2 emissions from manufacturing. These are the countries where further analysis should focus initially.

There is not a single "true" indicator of energy and CO_2 intensity for an industry. In general, a number of indicators should be used to give an adequate picture of both energy and CO_2 intensity levels of a particular industry in a country. System boundary and allocation issues are very important in the design of indicators and other performance measures for comparative purposes. For example, the allocation of upstream emissions, particularly for power generation, and downstream energy recovery benefits is an element that can affect performance significantly. If indicators are used for policy purposes, the boundaries and allocations may affect industry operating practices. Some choices may favour behaviour that reduce plant-specific CO_2 emissions but increase emissions elsewhere. Examples include if energy intensive parts of the production are outsourced, or higher quality resources are used such as a switch from iron ore to steel scrap in steel production. Indicator development for all industry sectors should be co-ordinated in order to avoid double counting and omissions or perverse incentives.

Product categories are of key importance. Various products in a single category may require considerably different amounts of energy for their production, *e.g.* a coarse versus highly-refined paper. If the product mix within a category varies within or across countries, it will affect the indicator performance measurement in comparisons.

In this study, indicators are developed on a country level. They do not account for variations in plant performance within a country. Therefore, benchmarking and/or auditing activities are needed to complement the indicators approach to better understand energy use in industry.

Some governments have successfully used international benchmarking approaches for industrial energy efficiency targets, *e.g.* Belgium and the Netherlands. Detailed energy benchmarking studies are done on a regular basis in some industries, based on data provided by companies that operate plants. These studies are usually done on a global basis and individual plants are not identified for antitrust reasons.

Usually, these studies are confidential and the benchmarking activities are often limited to the main producers in industrialised countries. This can create a bias in favour of the more efficient plants, which overestimates the industry's average energy efficiency. Benchmarking generally focuses on plants based on the same industrial process and similar product quality. Benchmarking is therefore not suited to evaluate some improvement options such as process integration, feedstock substitution, recycling or energy recovery from waste materials. The same caveats apply for benchmarking and for indicators: the results are influenced by methodological choices. Important efforts are continuing in many industries to expand and improve international benchmarking.

Energy data availability poses a major constraint for developing meaningful indicators. The industrial sub-sector data that countries report to the IEA are not sufficiently detailed to allow country comparisons of physical indicators at a level of relevant comparable physical products. Therefore, other data sources must be used.

The study therefore builds on various sources of data collected through a network of contacts in countries and industries. However, one of the clear outcomes of the study is that more work needs to be done to improve the quality of the data and refine the analysis. In many cases, data are either not available due to a lack of structure or interest and commitment in collecting the data or for confidentiality reasons.

New government and industry co-operation schemes are evolving. For example, the Asia-Pacific Partnership plans to collect additional data on a plant level for iron and steel, cement and aluminium for its six participating countries. Confidentiality rules will apply. It is recommended that such efforts be co-ordinated.

Data on the level of on-site process integration and combined heat and power are lacking, and energy efficiency performance data for actual motor and steam systems are almost non-existent. It is recommended to strengthen the data collection system for such key energy saving options and develop suitable indicators, since a large body of case studies suggests important improvement potentials based on these existing technologies.

In cases where energy use data are lacking, technology data can serve to estimate energy efficiency. Unfortunately, such data are usually not available from government statistics. Capital stock vintage data also can help to determine efficiencies and potential improvements, but such data are scarce and incomplete. In some cases, engineering companies and consultancies that serve the sector have such data, but access is restricted. It should be noted that technology use data can be misleading, for example in situations where operational practices and process integration can have an important impact on the overall industry performance.

Care should be taken when data of different quality are mixed for country comparisons. The quality of data is not always evident. If data are to be used for international agreements, a monitoring and verification system will be needed.

INTRODUCTION

The leaders of the Group of Eight (G8) countries and the governments of International Energy Agency (IEA) Member countries have asked the IEA to contribute to the Dialogue on Climate Change, Clean Energy and Sustainable Development.[1] The aims of the G8 Dialogue and Plan of Action are to:

Promote innovation, energy efficiency, conservation, improve policy, regulatory and financing frameworks, and accelerate deployment of cleaner technologies, particularly lower-emitting technologies.

Work with developing countries to enhance private investment and transfer of technologies, taking into account their own energy needs and priorities.

Raise awareness of climate change and our other multiple challenges, and the means of dealing with them; and make available the information which business and consumers need to make better use of energy and reduce emissions (G8, 2005).

As part of the G8 Plan of Action in the industry sector, the IEA was asked to:

... develop its work to assess efficiency performance and seek to identify areas where further analysis of energy efficiency measures by the industry sector could add value, across developed and interested developing countries.

After consultation with IEA delegations and incorporating views expressed by its Member countries, the IEA Secretariat has extended the scope of its G8 work from energy efficiency to also include CO_2 emissions reduction (IEA, 2005).

The IEA's work on industry is organised into three parts:

1) An analysis of current energy efficiencies and related CO_2 emissions worldwide.

2) An analysis of CO_2 emission reduction potentials from technology options.

3) Identification of policies that can result in an uptake of these options.

Scope of Indicator Analysis

This analysis focuses on indicators for industrial energy efficiency and CO_2 emissions and is a contribution to part one. Historic trends and current efficiencies are considered. It does not consider the impacts of emerging technologies or future energy use and CO_2 emissions. Estimates of improvement potentials are assessed based on indicators for energy efficiency at a country level in key manufacturing industry sub-sectors.

The present study has benefited from the input of a large number of experts from industry, research institutes and academia. Their contributions have been documented in workshop presentations and proceedings. These include Ammonia (IFA, 2007),

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[1] Canada, Germany, France, Italy, Japan, Russia, United Kingdom and United States.

Cement (IEA/WBCSD, 2006a), Chemicals and Petrochemicals (IEA/CEFIC, 2007), Iron and Steel, Pulp and Paper (IEA/WBCSD, 2006b) and Motor Systems (IEA, 2006b). While the comments and suggestions of the workshop participants provided valuable insights and have resulted in revisions of the proposed indicators, the approach proposed in this publication is the responsibility of the IEA Secretariat. Feedback is welcome as we proceed to refine the approach.

In order to develop useful indicators for industrial energy use and CO_2 emissions, a sound understanding of how energy is used by industry is needed. This study provides an overview of global industry energy use; a discussion of indicator methodology issues; energy use and CO_2 emissions in the chemical and petrochemical, iron and steel, non-metallic minerals, pulp and paper and non ferrous metals industries and assesses key systems such as motors and recycling. (Industrial process integration is presented in Annex A.) Key energy consuming industries are concentrated in a few countries. Current and future data collection should be concentrated in these countries.

Apart from increased data collection for energy use in industry, this study aims to establish relevant and valid indicators that permit analysis of the main trends on a country level by looking at the technology mix within an industry and also allow a credible comparison of efficiency data on a sub-sector level between countries. Indicators refer to the average efficiency of a sub-sector or process operation on a country level. Benchmarking implies the comparison of the energy efficiency and CO_2 emissions of individual installations based on a point reference, often “best available technology” (BAT).[2] (Benchmarking is discussed in Annex B) However, data for individual facilities are often confidential because of anti–trust regulations or other concerns. Moreover, data collection is resource and time consuming.

Prior IEA analysis focused on industrial energy use per unit of value added (IEA, 2004). This work is being updated and a publication is planned for September 2007. The analysis here takes a different approach to examine energy use per unit of physical production, *e.g.* energy use per tonne of product. As a next step, the physical indicators analysis will be merged into the general set of IEA indicators.

Work on physical energy intensity indicators is not new. A significant body of literature exists and this analysis builds on it. This study uses data from open literature, industry sources and analyses based on IEA statistics.

Significant work has been done in the United States, for example by the Energy Information Administration (1995 a,b), Freeman *et al.* (1996) and Martin *et al.* (1994). A large body of knowledge also exists in Canada (Canadian Industrial Energy End-Use Data and Analysis Centre (2002), Nanduri *et al.* (2002), Natural Resources Canada (2000). In Europe, considerable work has been done by Utrecht University and by the European Commission research programmes, for example Farla *et al.* (2000), Phylipsen and Blok (1997), Phylipsen (2000), Worrell (1997). Also the Asia Pacific Research Centre has worked on issues of industrial energy use (APERC, 2000).

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[2] The term “best available technology” is taken to mean the latest stage of development (state-of-the-art) of processes, facilities or methods of operation which include considerations regarding the practical suitability of a particular measure to enhance energy efficiency.

The analysis of manufacturing industry sub-sector energy intensities is complemented by studies focusing on CO_2 emission reduction life cycle analysis, material flow analysis, process analysis, benchmarking and technology assessment studies. It is beyond the scope of this overview to discuss all the contributing studies, but a comprehensive set of references by chapter is provided.

An important finding is that energy use in industry is different from other sectors since industrial processes and technologies are not very dependent on the climate, geography, consumer behaviour and income levels. This facilitates a comparison across countries. At the same time, certain factors such as resource availability, resource quality, production scale and age of the capital equipment stock can explain differences in energy efficiency. Such factors are usually not governed by economics and should therefore be taken into account when the improvement potential is assessed.

This study sets out a new set of indicators for country level efficiency analysis that balance methodological rigour with data availability. Discussions with industry experts regarding the best approach are underway, and therefore the indicators should be considered as a "work in progress". The indicators need to be validated and their utility needs to be assessed.

Given the preliminary character of these energy indicators, the country comparisons may be of secondary importance. More refined analysis may lead to different country rankings in the future. An important finding in this study is that the need for data detail and the availability of data should be balanced with the new indicators developed. The authors of this study take the view that the methodology should complement available data. If more data were available, different indicators might have been employed. A second important finding is that there is no single "true" indicator for energy efficiency and CO_2 emissions intensity. Different indicators for the same industry may result in a different ranking, but they may provide different insights regarding improvement potentials. Therefore, policy makers should not focus on the country ranking, but rather on the various improvement options that have been identified.

Energy and CO_2 Saving Potentials

The range of potential savings on a primary energy basis are shown in Table 1.1 as "sectoral improvements", *e.g.* cement, and as "systems/life cycle improvements", *e.g.* motors and more recycling. Improvement options in these two categories overlap somewhat. Also system/life cycle options are more uncertain. Therefore, with the exception of motor systems, only 50% of the potential system/life cycle improvements have been credited for the total industrial sector improvement estimates shown in Table 1.1. The conclusion is that manufacturing industry can improve its energy efficiency by an impressive 18 – 26%, while reducing the sector's CO_2 emissions by 19 – 32%, based on proven technology. Identified improvement options can contribute 7 – 12% reduction in global energy and process-related CO_2 emissions.

A two-step approach was applied to develop the estimates. First, energy saving potentials were estimated for final energy in industrial sub-sectors and for systems.

Next the final energy savings were translated into primary energy equivalents, accounting for losses in power generation and steam generation. In addition, corrections were applied for chemicals and petrochemicals and for pulp and paper as both industries already have a high share of combined heat and power (CHP). Moreover in both industries, CHP competes with steam saving technologies. Conservatively, CHP was excluded for both industry estimates in the primary savings potential (while CHP is included in the final energy estimates). Recycling and energy recovery potentials have also been excluded for all industries. This accounts for the fact that the analysis shows that the efficiency of energy recovery from waste varies widely, and recycling energy benefits decrease as the recycling share increases. Also, electricity savings were excluded for chemicals and petrochemicals because they overlap with motor system savings. These corrections result in a conservative estimate of the technical savings potential. A proper detailed analysis that accounts for the interactions of various options will require a model that covers the full energy system (IEA, 2006a).

Some of these savings will occur outside the manufacturing industry sector. For example, CHP will increase the efficiency in power generation. Energy recovery from waste will reduce the need to use fossil energy for power or heat generation. Increased recycling of pulp and paper leaves more wood that can be used for various bioenergy applications. So these figures are not suited to set targets for sectoral energy use.

The CO_2 estimates show a wider range than the energy saving potentials because in many cases it is not clear which type of energy carrier would be saved. Particularly in situations where the savings are in electricity, the assessment is complicated. To deal with this uncertainty, natural gas and coal have been assumed as extremes, which give almost a factor two difference in the carbon intensity of energy. In other cases, an expert estimate of average carbon intensity has been applied that varies by industry, depending on the global average fuel mix. For cement manufacturing, it is assumed that 300 Mt cement clinker (about 15%) can be substituted by slag, fly ash and pozzolans. This contributes to the energy savings and it increases the CO_2 saving potential substantially. For pulp and paper, an option such as increased recycling results in reduced total energy use; but the savings in these cases are in bioenergy while additional fossil fuels might be needed. Depending on the alternative use of the saved wood, there may or may not be a carbon saving effect. Similar contentious system boundary issues exist for energy recovery. The CO_2 figures are therefore only indicative.

The single most important category is motor systems, followed by chemicals and petrochemicals on an energy savings basis. The highest range of potential savings for CO_2 emissions is in cement manufacturing. The savings estimate under the heading system/life cycle improvements is larger than the individual sub-sectors in part because those options apply to all industries. Another reason is that these options have so far received less attention than the process improvements in the energy-intensive industries.

These estimated savings are based on a comparison of best country averages with world averages, or best practice and world averages. They do not consider new technologies that are not yet widely applied. Also they do not consider options such as CO_2 capture and storage and large-scale fuel switching. Therefore, these should be considered lower range estimates of the technical potential for energy savings and CO_2 emissions reductions in the manufacturing industry sector.

Table 1.1 ▶ ***Savings from Adoption of Best Practice Commercial Technologies in Manufacturing Industries***

(Primary Energy Equivalents)

	Low – High Estimates (Final energy, includes overlap)	Low – High Estimates of Technical Savings Potential (Primary energy, excludes overlap)			Total Energy & Feedstock Savings Potentials
	EJ/yr	*EJ/yr*	*Mtoe/yr*	*Mt CO_2/yr*	*%*
Sectoral Improvements					
Chemicals/petrochemicals	4.0 – 11.0	5.0 – 6.5	120 – 155	370 – 470	13 – 16
Iron and steel	2.0 – 4.0	2.3 – 4.5	55 – 108	220 – 360	9 – 18
Cement	2.2 – 2.7	2.5 – 3.0	60 – 72	480 – 520	28 – 33
Pulp and paper	1.0 – 2.4	1.3 – 1.5	31 – 36	52 – 105	15 – 18
Aluminium	0.1 – 0.6	0.3 – 0.4	7 – 10	20 – 30	6 – 8
Other non-metallic minerals and non-ferrous metals	0.4 – 0.8	0.5 – 1.0	12 – 24	40 – 70	13 – 25
System/life cycle Improvements					
Motor systems	2.6	6 – 8	143 – 191	340 – 750	
Combined heat and power	4.5	2 – 3	48 – 72	110 – 170	
Steam systems	3.3	1.5 – 2.5	36 – 60	110 – 180	
Process integration	2 – 5	1 – 2.5	24 – 60	70 – 180	
Increased recycling	3 – 4.5	1.5 – 2.5	36 – 60	80 – 210	
Energy recovery	3 – 4.5	1.5 – 2.3	36 – 55	80 – 190	
Total		**25 — 37**	**600 — 900**	**1 900 — 3 200**	
Global improvement potential – share of industrial energy use and CO_2 emissions		**18 – 26%**	**18 – 26%**	**19 – 32%**	
Global improvement potential – share of total energy use and CO_2 emissions		**5.4 – 8.0%**	**5.4 – 8.0%**	**7.4 – 12.4%**	

Note: Data are compared to reference year 2004. Only 50% of the estimated potential system/life cycle improvements have been credited except for motor systems. The global improvement potential includes only energy and process CO_2 emissions; deforestation is excluded from total CO_2 emissions. Sectoral final savings high estimates include recycling. Sectoral primary savings exclude recycling and energy recovery. Primary energy columns exclude CHP and electricity savings for chemicals and petrochemicals. Primary energy columns exclude CHP for pulp and paper.

3. One exajoule (EJ) equals 10^{18} joules.

These estimates do not consider the age profile of the capital stock, nor regional differences in energy prices and regulations that may limit the short- and medium-term improvement options. Further, this study does not consider process economics explicitly in the assessment of improvement potentials. So the economic potential will be substantially lower than the technical estimates. However, changing market conditions and values for CO_2 can affect the process economics significantly. Therefore, the technical potential is an important indicator. The fact that a certain process is economic in parts of the world is taken as an indication that the process can be economic in real world conditions. However, this does not mean that a major energy efficiency improvement of a certain industry sector is economic worldwide in the near or long term. Such analysis would require assumptions regarding future energy prices and CO_2 policy regimes, which are beyond the scope of this analysis.

Furthermore, the analysis acknowledges the role of technology and resource quality as key explanatory factors. The technology mix often provides important insights regarding industrial energy use, as a certain technology implies a certain level of energy efficiency. Therefore, it is proposed to use the technology mix as an additional indicator for the energy efficiency level in cases where the actual energy use data are not available. Moreover, efficiency estimates based on technology can serve as a valuable cross-check for indicators based on energy statistics. In a number of cases this cross-check has resulted in the discovery of discrepancies in the energy statistics.

This study does not consider the introduction of new technologies that are still in the research and development (R&D) or demonstration stage. As these options have been excluded, the results underestimate the long-term efficiency potentials. The analysis allows the identification of best practice on a technical level and the gap between country averages and best practice. Note that best practice reflects not only the level of technology, but also the energy economics of a country. In a country where energy is expensive, energy efficiency will generally be higher. This study does not discuss the economics and past sector developments that may explain the observed differences in energy efficiency. International competitiveness issues are not considered in this analysis.

In certain areas this study found that the data that countries submit to the IEA do not correspond to those contained in national statistics, or they do not correspond with industry statistics. In some cases the energy intensity per unit of physical product data are evidently in error, *e.g.* below the theoretical minimum. The fact that such statistical problems have been identified shows the usefulness of physical indicators compared with value-added based indicators.

Next Steps

Modelling and scenario development plays an important role in the industry analysis, especially in the second part of the IEA's programme of work. As a first response to the G8 request, the IEA has developed new scenarios that analyse impacts of technology–related policies in the period to 2050. These scenarios were presented in *Energy Technology Perspectives: Scenarios & Strategies to 2050* (IEA, 2006a). It concluded that substantial global energy efficiency potentials remain based on current technology and different operational techniques. The next edition of *Energy Technology Perspectives* in 2008 will contain a special chapter with industry scenario analysis that covers the potential of existing and emerging technologies.

The new sets of indicators presented in this study are to provide a basis for discussion for development of meaningful indicators of energy efficiency and CO_2 emissions in the industrial sector. They can be useful for industries, governments and others to improve forecasting of industrial energy use; provide a realistic basis for target setting and effective regulation and to identify sectors and regions for more focused analysis of improvement potentials. This study shows that the methodology can be improved and that better data is needed. Suggested next steps in this direction are:

- IEA energy data should be validated for industrial sub-sectors and countries. In particular, data for developing countries and transition economies need to be improved.
- The IEA statistics category "other industries" needs to be refined for meaningful indicators in co-operation with the national statistical bureaus and industry.
- The treatment of combined heat and power (CHP) in IEA statistics needs to be complemented with better data on current CHP capacity, use and generation, as well as through improved presentation of CHP in energy balances and statistics.
- Currently the IEA collects only data of economic activity in monetary terms. Industrial physical production data should be collected by the IEA on a regular basis, notably for energy-intensive commodities. Physical production data already are collected on an annual basis by other government and industry bodies. Therefore, it is a matter of improving and institutionalising the existing co-operation and exchanges.
- More detailed data for industry are needed than those available from IEA statistics. A comprehensive framework should be developed including indicators, benchmarking, capital stock age data at a plant level and in certain cases on a process level. Part of these data need to be treated confidentially, but country level data should be public.
- Various international data collection and analysis activities should be closely co-ordinated and be further developed into a system that allows periodic data collection.
- An independent non-commercial trusted party should be appointed to oversee the data collection and analysis. This could be done on a sub-sector basis.
- Data regarding the technical characteristics of the industrial capital stock should be collected on a regular basis.
- This work should be done in close collaboration with industry federations.

MANUFACTURING INDUSTRY ENERGY USE AND CO_2 EMISSIONS

Total global primary energy supply was about 469 exajoules (EJ) (11 213 Mtoe) in 2004.[1] Industry accounts for nearly one-third of this energy use at more than 147 EJ (3 510 Mtoe) including conversion losses from electricity and heat supply.

Total final energy use by industry was 113 EJ in 2004 (Table 2.1).2 The data include oil feedstocks for the production of synthetic organic products. Industry also uses substantial amounts of wood as feedstock for the production of pulp and structural wood products. Approximately 1 000 million tonnes (Mt) of wood feedstock used by industry, equivalent to 16 – 18 EJ of biomass, is not accounted for in these figures. The use of about 10 Mt of natural rubber is also not included, this is equivalent to 0.3 EJ per year. If these quantities were considered, the total energy demand in the industry sector would increase further. The totals in Table 2.1 exclude energy use for the transportation of raw materials and finished industrial products, which is important.

Most industrial energy use is for raw materials production. The sub-sectors covered in this study are the main manufacturing industries: chemical and petrochemicals, iron and steel, non-metallic minerals, paper and pulp, and non-ferrous metals. Together, these industries consumed 76 EJ of final energy in 2004 (67% of total final industrial energy use). The chemical and petrochemical industry alone accounts for 30% of industrial energy use, followed by the iron and steel industry with 19%. The food, tobacco and machinery industries, along with a large category of non-specified industrial uses, account for the remaining 33% of total final industrial energy. However, some of the energy that is reported under non-specified industrial users is in fact used for raw materials production, which increases its share above two-thirds of total industrial final energy use.

Industrial energy intensity (energy use per unit of industrial output) has declined substantially over the last three decades across all manufacturing sub-sectors and all regions. In absolute terms, however, energy use and CO_2 emissions have increased worldwide. Industrial final energy use increased 61% between 1971 and 2004, an average annual growth of 2% (Figure 2.1). But the growth rates are not uniform. For example, in the chemical and petrochemical sub-sector, which is the largest industrial energy consumer, energy and feedstock use has doubled while energy use for iron and steel production has been relatively flat, despite strong growth in global production.

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1. One exajoule equals 10^{18} joules or 23.9 Mtoe.
2. Final energy is the sum of all energy carriers that are used without accounting for energy conversion losses.

Table 2.1 ▶ ***Industrial Final Energy Use, 2004***

(EJ/yr)

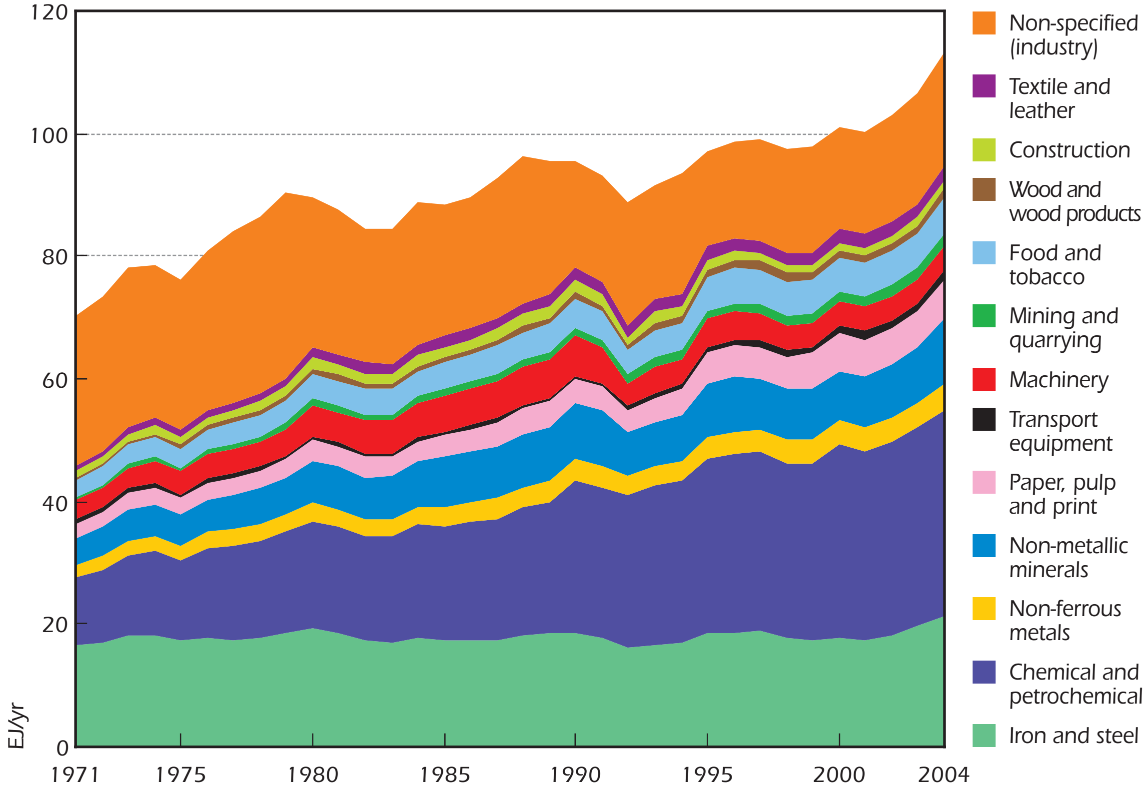
	AFR	AUS	CAN	CEU	CHI	CSA	FSU	IND	JPN	KOR	MEA	MEX	ODA	US	WEU	World
Chemical and petrochemical	0.47	0.21	0.85	0.64	**4.53**	**1.43**	**2.42**	**1.09**	**2.35**	**1.50**	**2.50**	0.48	**2.06**	**7.65**	**5.45**	33.62
Iron and steel	0.39	0.19	0.23	0.62	**7.11**	**1.24**	**3.11**	**1.04**	**1.89**	0.72	0.06	0.23	0.42	**1.46**	**2.74**	21.44
Non-metallic minerals	0.08	0.09	0.04	0.23	**4.53**	0.40	0.62	0.42	0.31	0.24	0.02	0.06	0.80	**1.07**	**1.70**	10.61
Paper, pulp and print	0.01	0.06	0.72	0.11	0.66	0.40	0.03	0.11	0.37	0.09	0.00	0.04	0.09	**2.24**	**1.52**	6.45
Food and tobacco	0.02	-	-	0.17	0.77	0.86	0.43	0.34	0.18	0.07	0.01	0.10	0.36	**1.24**	**1.30**	5.98
Non-ferrous metals	0.11	0.35	0.24	0.09	0.93	0.38	0.86	0.03	0.08	0.01	0.03	0.00	0.00	0.52	0.57	4.21
Machinery	0.00	-	-	0.08	**1.11**	0.01	0.66	0.02	0.36	0.15	0.00	0.00	0.17	0.85	0.82	4.25
Textile and leather	0.01	-	-	0.04	0.91	0.07	0.08	-	-	0.15	0.00	0.00	0.19	0.26	0.40	2.17
Mining and quarrying	0.20	0.12	0.43	0.03	0.35	0.12	0.12	0.04	0.03	0.01	0.01	0.07	0.06	0.09	0.13	1.81
Construction	0.08	0.03	0.06	0.04	0.39	0.01	-	-	0.15	0.02	0.00	0.01	0.03	0.08	0.35	1.41
Wood and wood products	0.00	0.05	0.02	0.05	0.13	0.00	-	-	-	0.01	-	-	0.01	0.48	0.23	1.36
Transport equipment	0.00	-	-	0.03	0.34	0.00	-	-	-	0.10	0.00	0.01	0.01	0.40	0.37	1.28
Non-specified	**2.35**	0.05	0.47	0.19	0.72	**1.62**	**1.34**	**1.94**	0.95	0.12	**2.43**	0.48	**3.27**	**1.09**	**1.62**	18.65
Total	**3.72**	**1.33**	**3.06**	**2.31**	**22.48**	**6.56**	**10.22**	**5.08**	**6.66**	**3.18**	**5.06**	**1.48**	**7.48**	**17.43**	**17.20**	**113.25**

Note: Includes coke ovens and blast furnaces. Sub-sector values in excess of 1 EJ/yr are marked in bold. CSA – Central and South America; CEU – Central and Eastern Europe; FSU – Former Soviet Union; MEA – Middle East; ODA – other developing Asia; WEU – Western Europe.

Source: IEA data.

Figure 2.1 ▶ *Industrial Final Energy Use, 1971-2004*

Key point: Industrial final energy use increased by 61% between 1971 and 2004, an average annual growth of 2%.



Note: The discontinuity around 1990 is caused by developments in Eastern Europe and the FSU that resulted in a rapid decline of industrial production.

Source: IEA data.

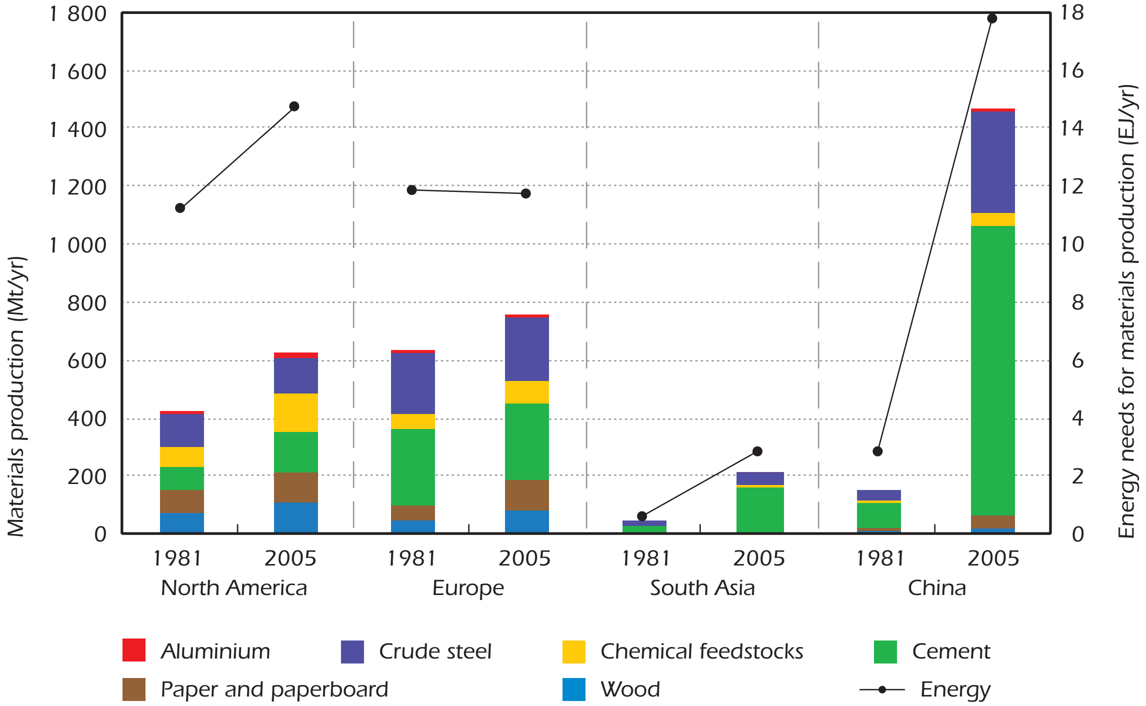
China accounts for about 80% of the growth in industrial production during the past twenty-five years, and for a similar share in industrial energy demand growth for materials production, about 16 EJ (Figure 2.2). Today, China is the largest producer of commodities such as ammonia, cement, iron and steel and others. The energy efficiency of production in China is generally lower than in OECD countries and it is largely coal-based.

The United States, Western Europe and China together account for half of total global industrial energy use, followed by the Former Soviet Union and Japan. An analysis of current energy use therefore must concentrate on these regions.

No detailed statistics are available that allocate industrial energy use for the various steps in manufacturing. Rough estimates suggest that 15% of total energy demand in industry is for feedstock, 20% for process energy at temperatures above 400°C, 15% for motor drive systems, 15% for steam at 100 – 400°C, 15% for low-temperature heat and 20% for other uses, such as lighting and transport.

Figure 2.2 ▶ *Materials Production Energy Needs, 1981 – 2005*

Key point: China accounts for the bulk of energy demand growth for manufacturing in the past twenty-five years.



Note: North America includes Canada, Mexico and US. Europe includes EU27 excluding three Baltic States, and including Albania, Bosnia, Croatia, Iceland, Former Yugoslav Republic of Macedonia, Norway, Serbia, Switzerland and Turkey.

Source: IEA data.

Detailed information on energy and materials flows and on process activities are not readily available. In many cases these data are regarded as confidential. Better data are needed on the spread in energy efficiencies and on the age and size of production equipment in all regions. The IEA Secretariat plans to commence new data collection activities in the framework of the G8 Dialogue on Climate Change, Clean Energy and Sustainable Development. This study uses data from open literature, industry sources and analyses based on IEA energy statistics.

The share of industrial energy used for basic materials production has been quite stable for the last thirty years, but the shares of sub-sectors have changed significantly. The share of crude steel production, for example, has declined from 24 – 19% since 1971, while the share of ammonia, ethylene, propylene and aromatics has increased from 6 – 15% (IEA, 2006).

Table 2.2 shows a global breakdown of industrial energy use by fuel and energy carrier. The amounts of coal, gas, oil and electricity used are similar. Combustible renewables and waste is lower and is largely biomass use in the pulp and paper industry.

Table 2.2 ▶ *Final Energy Use by Energy Carrier, 2004*

	EJ/yr	Gt CO_2/yr
Coal & coal products	28.9	2.72
Natural gas	23.6	1.32
Oil & oil products	28.0	0.73
Combustible renewables & waste	7.0	
Electricity	21.5	3.59
Heat	4.2	0.29
Other	0.0	
Process emissions		1.08
Total	**113.3**	**9.73**

Source: IEA statistics.

In many sectors of the economy, CO_2 emissions are closely related to energy use. However, in the industry sector the distribution of CO_2 emissions is very different from the distribution of energy demand. The main reasons are:

- ▷ Large amounts of fossil carbon are stored in petrochemical products.
- ▷ Process CO_2 emissions unrelated to energy use are large in some sectors, especially in cement production.
- ▷ CO_2 emissions differ by fuel, and the use of fuels is not evenly distributed across industrial sub-sectors.

Total CO_2 emissions from industry were 9.7 gigatonnes (Gt) in 2004 and accounted for 36% of total global CO_2 emissions.[3] Three sub-sectors were responsible for 70% of the direct industrial CO_2 emissions: iron and steel, non-metallic minerals, and chemicals and petrochemicals (Figure 2.3). These data exclude upstream CO_2 emissions from the production of electricity and downstream emissions from the waste treatment of synthetic organic products.

It should be noted that energy use and CO_2 emissions related to power generation are allocated to the electricity sector in IEA statistics. In the case of industrial combined heat and power (CHP) plants, all fuel use and CO_2 emissions are allocated to the transformation sector, except for fuel use and emissions related to heat generation that is not sold, which are allocated to industrial energy use. As a consequence, sub-sector energy use and emission data based on company emission data may differ from the figures in the IEA statistics.

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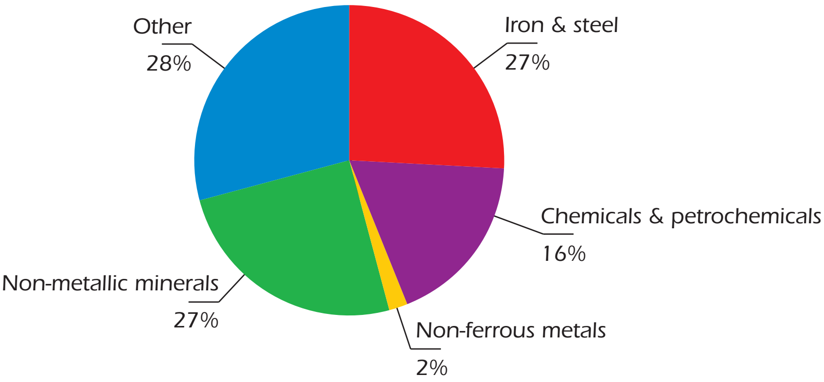
[3] This includes coke ovens and blast furnaces that are reported as part of the transformation sector in IEA statistics. It also includes CO_2 emissions from power generation and process emissions.

Another special factor is blast furnace gas that is delivered by the iron and steel industry to power generators or that is used on-site in CHP plants. The specific CO_2 emission factor for blast furnace gas is very high, as this gas already contains substantial amounts of CO_2 originating from coal gasification and coal gas use in the blast furnace. Typically, 4.8 gigajoules (GJ) of blast furnace gas is generated per tonne of hot metal. The carbon content of this gas is equivalent to 0.8 Gt CO_2 emissions worldwide. About 25% of the energy content of this gas was used for power generation in 2004, the remainder was used within the iron and steel industry. Depending on the allocation approach, between 0 – 0.2 Gt of CO_2 should be allocated to power generation. Figure 2.3 allocates 60% of the CO_2 emissions from blast furnace gas use to the iron and steel industry.

Figure 2.3 ▶ ***Industrial Direct CO_2 Emissions by Sector, 2004***

Key point: Three sectors: iron and steel, non-metallic minerals, and chemicals and petrochemicals account for 70% of industrial CO_2 emissions.



Note: Includes coke ovens, blast furnaces and process CO_2 emissions. Excludes emissions in power supply; assumes 75% carbon storage for all petrochemical feedstocks.

Source: IEA statistics.

GENERAL INDUSTRY INDICATORS ISSUES

Energy Indicators Based on Economic and Physical Ratios

The IEA has analysed and reported indicators of industrial energy use and CO_2 emissions for some time (IEA, 1997; IEA, 2004). These indicators have been based on economic ratios as they analyse energy use or CO_2 emissions per unit of value-added output. In addition, trends in energy use and emissions have been decomposed into those changes that are due to structural effects and those related to energy efficiency effects, based on an analysis of developments in the industrial sub-sectors. While such indicators may be adequate to capture aggregate energy and CO_2 trends, they are less suited to a detailed analysis of industrial energy efficiency developments over time or across countries, or for an examination of improvement potentials. This is because they do not take full account of product quality and composition, or the processing and feedstock mix, which can vary widely within a sub-sector. Furthermore, indicators based on economic ratios cannot be validated by technological data.

This study presents new indicators for industrial energy use and CO_2 emissions that are based on physical ratios, *e.g.* energy use per tonne of product. These indicators are often called the specific or unit energy consumption. They can account for structural differences in industries between countries and so enable a fair and consistent comparison of energy efficiency and CO_2 emissions performance. The analysis also uses explanatory indicators to examine some of the driving factors behind the patterns of energy use and emissions, such as technology differences and resource qualities. This again allows for a more robust comparison across countries. Other advantages of the approach are:

- ▷ Indicators based on physical ratios are closer to a measure of the "technical efficiency" of an industry and hence can be linked more directly to technology performance. They can therefore be used to identify the potential for efficiency improvements through new technologies.
- ▷ They are not affected by cyclical variations in the price of industrial commodities, as is the case with indicators that use value added and so tend to be subject to less "noise" from economic fluctuations.
- ▷ The energy and emissions performance of specific process steps in an industry can be separately analysed and differences in product mix between countries and over time are more easily taken into account. The impacts of changing product mix need to be considered separately from technical efficiency gains, because the driving factors may change over time.

The following sections discuss the issues that need to be considered when developing physical indicators of industrial energy use and CO_2 emissions: the availability and quality of energy and activity data; and the approach followed in this study. It also briefly describes other international activities that are developing indicator-based approaches.

Methodological Issues

Energy use in many industrial sub-sectors is complex. Even when necessary data are available, it is often not straightforward to calculate consistent and comparable indicators that are useful for policy analysis. Three areas in particular, require careful consideration: aggregation levels, boundaries and allocation.

Aggregation Levels

Energy use and CO_2 indicators can be developed at different levels of aggregation depending on the purpose for which they are to be used and the level of information available. The aggregation level is very important as it determines the extent to which structural differences affect the results observed. Structural differences can include:

- **Availability and quality of input resources.** The energy needs for some industrial processes will depend on the quality of the natural or other resources available, *e.g.* ore quality. The indicators need to account for the resource quality variations in cross country comparisons. For example, countries with a more mature economy may have ample scrap resources available, while emerging economies may not have such scrap. Scrap availability can have an important impact on the apparent energy performance of an industry. The energy and feedstock mix also matters. Coal-fired energy conversion processes are often inherently less efficient than processes that use natural gas or electricity. However, in certain cases coal is the preferred fuel for chemical conversion, for example in iron production.
- **Definition of products.** Definitions require care. For example, in the case of the iron and steel industry, the choice for tonnes of iron, tonnes of crude steel or tonnes of finished steel can make a big difference. The production ratio of these three categories is not the same for all countries.
- **Diversity of products.** Industrial products are not uniform. Indicators must be designed in a way that the product categorisation makes sense.

To address these issues, the industry chapters present a range of indicators at different levels of aggregation. In cement, for example, an indicator of total primary energy consumption per tonne of cement is shown, as well as more detailed indicators such as electricity use per tonne of clinker and the clinker to cement ratio.

Boundary Issues

For a consistent analysis across countries, it is necessary to use common boundary definitions for each sub-sector. Such boundary limits relate to:

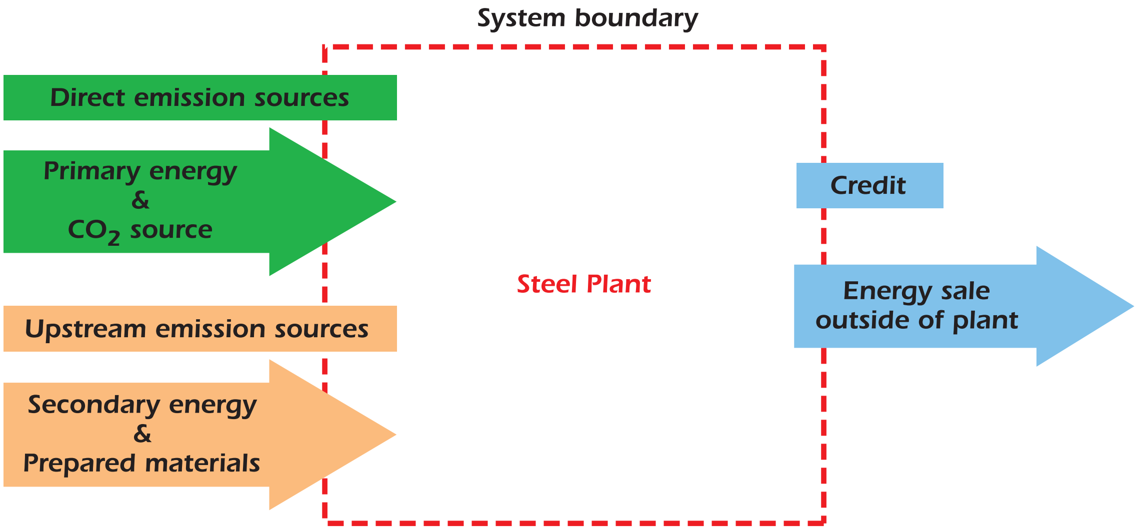
- **Production steps.** Industrial production processes often consist of several steps. The processes/production steps that are included or excluded from an indicator can make a difference in cross country comparisons and need to be fully described. The treatment of combined heat and power (CHP) is particularly important for some sub-sectors (discussed under allocation). Indicators need to take into account the differences in the comprehensiveness of the process chain.

- ▷ **Embodied energy and carbon.** Both energy and carbon can be stored in materials. While energy can be recovered when materials are recycled or incinerated, any carbon stored in the products is released when they are incinerated. These factors and potentials should be assessed on a materials/product life cycle basis, as they are not apparent from an industry sub-sector analysis. Furthermore, a lot of fossil carbon is locked into synthetic organic products and therefore energy relevance is not equivalent to CO_2 emissions relevance.
- ▷ **Process emissions.** A significant share of industrial CO_2 emissions are process emissions, not related to the use of fossil fuels. Where important, these process emissions should be included along with those from fuel combustion.

In this analysis the following general principles have been used in setting the boundaries:

- ▷ Included in the indicators:
  - Energy use and CO_2 emissions directly associated with the sub-sector.
  - Upstream (primary) energy use and CO_2 emissions associated with electricity production, but excluding mining and transportation of fuels to the electricity industry.
- ▷ Excluded from the indicators:
  - Electricity, heat and other fuels, *e.g.* blast furnace gas, sold to a third party.

Figure 3.1 ▶ *Possible Approach to Boundary Issues for the Steel Industry*



Source: Ono, 2006.

Allocation Issues

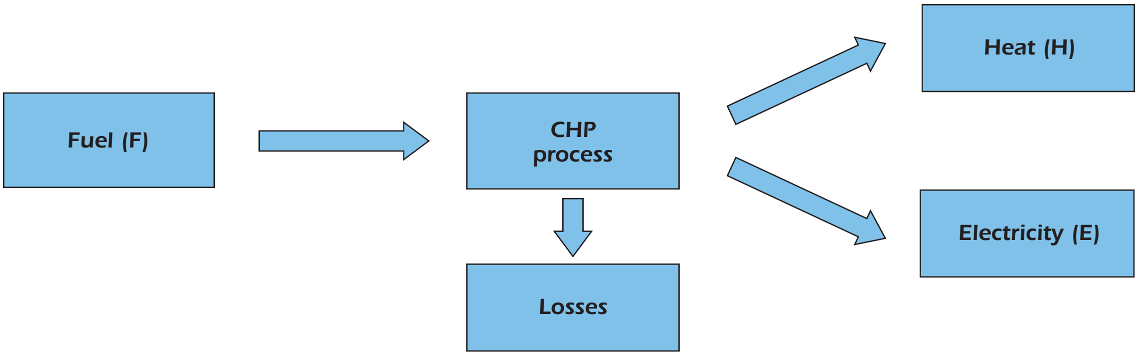
In addition to setting consistent boundaries, a number of important allocation issues arise in constructing energy use and CO_2 emissions indicators analysis.

- ▷ **Combined heat and power.** The treatment of CHP needs special consideration in those sub-sectors where it plays an important role to ensure that CO_2

emissions and efficiency gains from CHP are correctly reflected. There are a number of elements. First is the allocation of input fuels between those used for electricity production and those used for heat production. Second, fuel use and electricity and heat production by CHP plants may be recorded in statistical balances as part of final consumption in the industry sector or as part of the transformation sector, or a mixture of the two. As well, electricity and/or heat may be sold to a third party and so not actually used in industry where the plant is located.

Figure 3.2 illustrates the approach taken in IEA energy statistics. Fuel input to CHP is allocated between heat (Fh) and electricity (Fe) based on their shares of heat and electricity in total output. The fuel used for heat generation is then allocated to the industrial sub-sector where the CHP plant is located (net of any fuel used to generate heat that is sold, which is accounted for in the transformation sector), while the fuel used for electricity production is assigned to the transformation sector. This approach could lead to the potentially misleading result that most of the efficiency gains for increased CHP use are credited to the transformation sector, rather than to the industry sector.

Figure 3.2 ▶ *Allocation Issues for Combined Heat and Power*



$$F_h = F \times \left(\frac{H}{E+H}\right) \qquad F_e = F \times \left(\frac{E}{E+H}\right)$$

Source: IEA, 2005.

- **Treatment of waste fuels.** Industry uses large amounts of waste fuels. The CO_2 emissions from waste fuel use are not always significantly below those for fossil fuel use, but on an energy system basis the re-direction of waste flows from incinerators to industrial kilns makes sense. Indicators should use an allocation system for waste emissions that is appropriate on a systems level.
- **Auto-production of electricity.** Some industries produce their own electricity. In terms of primary energy and CO_2 emissions allocation, it can make a big difference if the indicator uses country average efficiencies and emissions factors for electricity production or industry specific ones.

Definition of Best Available Technique and Best Practice

One approach to compare energy use and CO_2 performance of an industry across countries and to estimate the improvement potential is to make a comparison between the current level of energy use and what could be achieved through the use of the *best available technique* (BAT).[1] Defining what represents BAT is not straightforward. It requires consideration of both technical and economic factors. In this study BAT designation in relation to energy efficiency in a particular industry has been drawn from a range of sources, including technical documentation produced for the European Union Directive 96/61/EC concerning integrated pollution prevention and control (IPPC) and other technical and peer reviewed literature. These data were discussed with experts as part of this study.

The European Union IPPC Directive defines *best available technique* as "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques...". This is further elaborated as:

- "Techniques" shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.
- "Available techniques" shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages... as long as they are reasonably accessible to the operator.
- "Best" shall mean most effective in achieving a high general level of protection of the environment as a whole.

In the language of the IPPC Directive, BAT associated environmental performance is usually represented with a range, instead of a single value. In general, the best achievable performance is not included in the range, because the BAT range also involves an assessment of costs versus benefits, sustainability, etc. So the term BAT needs to be interpreted within a given context and is not as rigid as, say, a theoretical thermodynamic minimum. Moreover, BAT will change over time as technology improves.

In contrast to BAT, *best practice* is a term that applies to technologies and processes that are currently deployed. Best available technology could, in many cases, be identical with best practice. In other cases, a new technology may have just emerged, but is not yet deployed. If this is the case, the BAT energy efficiency may be better than best practice. However, as best practice often refers to a more "proven" technology than the best available technology, it may be more policy relevant. The terms best practice and BAT are often used interchangeably.

In this study, a third term is employed – *best country average*. This refers to a level of performance that has an even higher level of feasibility, but it will by definition be equally or less efficient than BAT and best practice.

Data Issues

An accurate analysis of energy efficiencies and CO_2 emissions using physical indicators requires good quality disaggregated energy and physical production data. For energy, the data available from IEA energy statistics and national energy

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[1] Industry analysis in this study also uses the term *best available technology*, to examine the concept as it relates to technological performance, rather than the wider interpretation implied by *technique*.

balances are at a relatively high level of aggregation. Furthermore, the data that are submitted by countries to the IEA are the responsibility of the countries. The IEA can not guarantee the quality of these data and performs limited checking, such as looking at the overall balance of supply and demand for individual energy carriers on a country level.

Ideally, analyses of industrial energy efficiencies require more detailed data than are available through such statistical balances. A significant effort was undertaken as part of this study to identify and obtain better sources of energy use data. These sources include information from national energy statistics and industry associations, such as Stahlzentrum in Germany and the Japanese Iron and Steel Federation. Many industries also have detailed energy use data but can not share these because of antitrust regulations. Antitrust laws prohibit anti-competitive behaviour and unfair business practices, which can include sharing information that could be used for price-fixing.

As publicly available energy data are often scarce for a particular industry sub-sector, then data availability itself creates a potential bias in the analysis. The most comprehensive data are often available for those companies that are well managed. These are usually the companies with relatively high energy efficiency. These data overestimate the energy efficiency of the industry on a global scale. This is evident when the data situation on a country level is assessed. There is better data available for OECD countries than for non-OECD countries, while the energy efficiency potential is higher in the latter category.

There is a clear need for the data situation to be improved, if detailed industry indicators were to be reported on an annual basis, assuming adequate resources. For example, this could involve a permanent working group of the IEA Secretariat and certain key industry federations. Also the antitrust issue needs to be resolved.

Production data used in this study were taken from various sources, including the UN commodity statistics, the US Geological Survey, the UN Food and Agriculture Organization, industry federations such as the International Iron and Steel Institute, Cembureau and consultants.

There are also issues related to the coverage and quality of this data. Physical production data are confidential for particular products because of antitrust regulations. Also data on sales and production data are sometimes not clear. For example, in the petrochemical industry significant amounts of intermediate products are processed on-site, so the quantities of products traded are often much lower than the quantities produced. For some products, the product definition is not clear. In the case of cement, data for cement clinker production are sometimes mixed with data for finished cement product. The cement production of stand-alone slag grinding stations may or may not be included. Additions of cement clinker substitutes to concrete or the use of blast furnace slag as replacement of cement binder in road foundations is not reported as cement production. Such accounting problems can have a significant impact on production data.

Care also has to be taken when combining energy and production data from different sources to ensure that they have a consistent coverage of an industry or process. In this analysis, industrial sub-sectors have been identified based on their economic activities as defined by the International Standard Industrial Classification (Rev 3). This classification system is commonly used for both energy statistics and production data, *e.g.* IEA energy statistics and UN commodity statistics.

A number of additional checks also have been carried out to try and eliminate major inconsistencies in the data. First, the energy data for a given sub-sector has been cross-checked using a bottom-up calculation of the expected energy use given the technology mix, typical energy consumption per unit of output by technology and physical production figures. Second, the energy indicators themselves can help identify potential issues. For example, if the energy use per tonne of production is lower than the thermodynamic minimum, it is evident that there is a data problem. But this does not mean that values well above the thermodynamic minimum are correct. As a rule of thumb, any country energy intensity value more than two to three times above the world average has been treated as suspect. Both energy and production data were peer reviewed by experts, including at six industry specific workshops.

During this analysis it was found that the quality of information and the level of co-operation vary by sub-sector. The fertilizer and aluminium industries have international benchmarking efforts and regional average efficiency data that are publicly available. Adequate information was found for the cement industry. For sub-sectors such as the pulp and paper and petrochemicals industries, benchmarking is also an accepted form of energy management effort that compares similar plants across countries. However, these data are confidential. The quality of the energy data is an issue, especially for the pulp and paper industry because of the complexities around accounting for CHP. The iron and steel industry is the only sector for which there is no international benchmarking effort and the quality of the available data from energy statistics poses a challenge.

Practical Application of Energy and CO_2 Emission Indicators

This section explains which indicators have been developed for each industry and how they should be interpreted. It is rarely possible to define a single "true" indicator that satisfactorily captures all the information that needs to be conveyed about energy use and CO_2 emissions in a sub-sector or a process. Selecting only one indicator for cross country comparisons can produce a misleading picture. The key is to aim for transparency in how the indicator is constructed, *e.g.* in relation to boundaries and allocation rules so that differences in methodology are clearly understood and their impact on the results can be assessed.

Given the limitations in the datasets, the analyses presented in the following chapters can only provide a general idea about the order of magnitude of the improvement potentials in manufacturing industries. It is recommended that more detailed analysis on a country-by-country level is done before such indicators could be considered as a basis for target setting.

Pulp, Paper and Printing

Worldwide paper and pulp is a capital intensive, high tech industry, which comprises large multinational players and many small companies. Most energy used in paper production is for pulping and paper drying. Ideally, separate indicators of energy use and CO_2 emissions for this industry should take account of the type of pulp used (mechanical, chemical or recycled), the grade of paper and the level of integrated paper and pulp mills (since these avoid the need for pulp drying and so are more energy efficient). The need for large amounts of steam makes CHP a widely used technology, and so the way in which CHP is accounted for in energy statistics is very important.

Data limitations, particularly related to the energy use for different process steps, make it impossible to construct detailed indicators for country comparisons. So in order to provide some indicative estimates of the relative energy performance among countries, the approach has been to calculate the energy consumption of the pulp and paper industry in a country relative to what it would be if best available technologies were used. Different BAT assumptions were applied to steam and electricity consumption in mechanical pulping, chemical pulping, waste paper pulp and seven different grades of paper production. Heat and electricity are treated separately to allow for CHP analysis.

Iron and Steel

From an indicator perspective, the most important distinction for iron and steel is between the two crude steel production processes, basic oxygen furnace (BOF) and electric arc furnace (EAF). However, ideally a range of other issues need to be taken into account including different types of finished steel products, the variability in feedstock quality and the availability of scrap steel. A further complication arises over the complex set of energy and materials commodity flows associated with the industry. Most of these energy and material flows can be bought from or sold to third parties. As a consequence, the full production chain energy use and CO_2 emissions may be considerably higher or lower than the site or plant footprint would suggest, which if not accounted for in a consistent way, can give misleading results. These flows include the possible purchase of pellets, coke, oxygen, lime, steam and electricity and the sale of coke by-products, blast furnace slag, steel slag, blast furnace gas, electricity and heat.

Given these complexities, the approach taken in this study has been to use a standardised set of comparisons with corrections for energy use and CO_2 emission effects.

Cement

The production of cement clinker from limestone and chalk is the main energy consuming process in this industry. There are two basic types of cement clinker production processes and a number of different kiln types. Clinker production is either “wet” or “dry”, depending on the water content of the raw material feedstock. The dry process avoids the need for water evaporation and is much less energy intensive. In a second step, cement is produced by blending clinker with additives. The most widely used type is Portland cement, which contains 95% cement clinker.

Ideally, indicators should look at the energy used to produce a tonne of clinker and the electricity use (for grinding) per tonne of cement production. The clinker to cement ratio is a key explanatory indicator for the industry. As the cement industry uses a high proportion of alternative (waste) fuels, correctly accounting for these is a key issue (see the Cement Sustainability Initiative in the last section).

Data for the cement industry are available thanks to a number of international initiatives looking at its energy performance. This has enabled the indicators described to be developed for most producing countries. The approach taken is similar to that being used by the Asia Pacific Partnership in their energy and CO_2 emissions indicators work. The IEA has used its own data on country emission factors and CO_2 emissions factors for electricity generation or Intergovernmental Panel on Climate Change (IPCC) defaults in the absence of data. For alternative fuels, direct emissions have been included while an analysis of their net CO_2 profile (whether higher or lower) has not been attempted.

Chemicals and Petrochemicals

The chemicals and petrochemicals industry is highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousands of tonnes. Because of this complexity, reliable data on energy use are not available. In addition, more than half of the total fuel inputs to this sub-sector are accounted for by feedstocks, and so is non-energy use.

While it would be unrealistic to develop separate indicators for all chemical and petrochemical products, it would be, in theory, possible to construct aggregate energy indicators for the sub-sector (excluding feedstock use), together with separate indicators for key products such as ammonia, ethylene, propylene and benzene, toluene and xylene. In addition, for some products different production processes can be used and these need to be taken into account.

However, in reality, data problems are substantial and therefore an approach similar to the paper and pulp industry has been used, with an aggregate indicator developed that compares actual energy consumption with the BAT level. Due to problems in reporting, feedstock energy use is included, but the data excludes electricity use. Production volumes for benzene, toulene and xylene have been split between production from steam cracking and naphtha extraction. This split has been calculated based on the production volume of ethylene and is necessary due to the more energy-intensive nature of production from steam cracking versus naphtha extraction. The same split has also been applied for propylene from steam cracking and fluid catalytic cracking.

Other Sectors / Technologies

There is no established structure to assess efficiencies of motor systems, steam systems, process integration and materials/product life cycle improvement options. Data are only available from case studies. Yet, the available data suggest that these areas have been neglected and that there are significant efficiency gains to be achieved. Establishment of an adequate data framework is a first step to unlocking these efficiency potentials.

Table 3.1 ▶ *Summary of Indicators for Each Industry Sector*

Sector	Energy Use Indicators	CO_2 Emissions Indicators	Explanatory Indicators
Pulp and paper	• Heat consumption in pulp and paper production vs. best available technology • Electricity consumption in pulp and paper production vs. best available technology	• CO_2 emissions/tonne of pulp and paper produced	• Recovered paper use vs. recovered paper ratio
Iron and steel	• Total primary and final energy use per tonne of crude steel (including finishing) • Total primary and final energy use per tonne of blast furnace-BOF steel production • Total final energy use per tonne of DRI (split gas and coal-based processes) • Total primary and final energy use per tonne of electric arc furnace steel (excluding finishing)	• Total direct CO_2 per tonne of crude steel	
Non-ferrous metals	• Specific power consumption in aluminium smelting		
Cement	• Energy requirement per tonne of clinker including alternative fuels • Electricity consumption per tonne of cement • Total primary energy equivalent per tonne of cement • Process and energy (including electricity) CO_2 emissions per tonne of cement	• CO_2 emissions from energy consumption (including electricity) per tonne of cement	• Clinker-to-cement ratio • Alternative fuel use in clinker production
Chemicals and petrochemicals	• Total energy consumption vs. best available technology	• Total CO_2 consumption vs. best available technology	

International Initiatives: Sectoral Approaches to Developing Indicators

A number of other international initiatives are developing indicator-based approaches to analyse the energy and CO_2 emissions performance of key industries. In some cases, these initiatives have specific goals, which shape the approach that is used. This section briefly reviews selective initiatives and notes how they relate to the analysis presented in this report. A detailed overview of benchmarking initiatives is provided in Annex B.

Intergovernmental Panel on Climate Change (IPCC) Reference Approach

While not an indicator approach, the IPCC produces guidance on the calculation of CO_2 emissions from fuel combustion and industrial processes. Of relevance to a discussion on indicators is the IPCC treatment of three key areas: combined heat and power, waste used as a fuel and the treatment of emissions from chemical reactions in manufacturing processes.

- Emissions from combined heat and power are attributed to the industrial branch in which the generation activity occurs, regardless of whether the electricity or heat is actually used in that branch.
- In cases where the combustion heat from waste incineration is used as energy, then this waste is treated as a fuel and the emissions are attributed to the industrial branch where the waste incineration occurs. However, only the fossil fuel derived fraction of CO_2 from waste is included in the calculation. Emissions from the biomass fraction of waste are excluded.
- For emissions from gases obtained from processing feedstock and process fuels, if the emissions occur in the industrial sector which produced the gases then they remain as industrial processes emissions in that sector. If the gases are exported to another sector, then the fugitive, combustion or other emissions associated with them are reported in the other sector.

Pulp and Paper Initiatives

The International Council of Forest and Paper Associations (ICFPA), the global forum for the pulp and paper industry has developed a CO_2 calculation tool to facilitate uniform CO_2 emissions reporting. The requirements in the EU emission trading system have now replaced this for the European mills. Under the IEA Implementing Agreement on Industrial Energy-Related Technologies and Systems, the pulp and paper industry is finalising a project to harmonise the global definitions used for energy use, energy efficiency and the different pulp and paper production processes. This project will be completed in mid 2007 and is the start of improved comparisons of international pulp and paper industry energy data.

Cement Sustainability Initiative

Under the umbrella of the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), a number of major cement companies have agreed on a methodology for calculating and reporting CO_2 emissions. The latest edition of the Cement CO_2 Protocol was published in June 2005 and is aligned with the March 2004 edition of the overarching greenhouse gas protocol developed under a joint initiative of the WBCSD and the World Resources Institute.

The Protocol provides a harmonised methodology for calculating CO_2 emissions, with a view to reporting these emissions for various purposes. It addresses all direct and the main indirect sources of CO_2 emissions related to the cement manufacturing process in absolute as well as specific or unit-based terms. The basic calculation methods used in this protocol are compatible with the latest guidelines for national greenhouse gas inventories issued by the Intergovernmental Panel on Climate Change (IPCC), and with the revised WRI / WBCSD Protocol. Default emission factors suggested in these documents are used, except where more recent, industry-specific data have become available. However, one area where the recommendations of the Cement Protocol differ from the IPCC guidelines is in allowing credits for indirect emission reductions related to use of wastes as alternative fuels and for waste heat exports. The premise for this crediting is that the combination of direct emissions impacts, indirect emission reductions, and resource efficiency makes the substitution of alternative fuels for conventional fossil fuels an effective way to reduce global greenhouse gas emissions and the cement industry should be able to account for these wider benefits.

Asia-Pacific Partnership (APP) on Clean Development and Climate

The APP is developing energy efficiency and CO_2 emission indicators for the cement and iron and steel industries. In the case of cement, these indicators are aligned with the CSI Protocol and will be used to help set benchmarks and estimate the potential for CO_2 emissions reductions. Possible energy and CO_2 emissions indicators being considered include:

- Heat intensity of clinker.
- Power intensity of clinker.
- Total energy intensity of clinker.
- Power intensity of cement.
- CO_2 intensity of cement.

For iron and steel, the APP proposes to develop separate indicators for steel production from both main types of furnaces. There is no further breakdown of energy use by individual processes. The approach includes energy consumption and CO_2 emission from energy conversion and material preparation in upstream processes off-site from the steel plant, but does not count mining and transportation. Credits for energy sold to third parties are included in the calculation.

Benchmarking in the Petrochemical Industry

Benchmarking is an approach used by a number of industries to evaluate the energy performance of their processes in relation to best practice, usually within their own industry. One process in the petrochemical industry for which benchmarking is widespread is steam crackers.

Steam cracking of hydrocarbon feedstocks, *e.g.* ethane, naphta, is the most important source of olefins and aromatics, and as such the basis for the petrochemical industry. The key driver for benchmarking steam crackers is that energy accounts for up to 60% of olefin plant operational expenses. Feedstocks and operating conditions (pressure, temperature, and residence time) can significantly affect the specific energy consumption of steam crackers; a performance comparison requires accounting for processing conditions. Solomon Associates Inc. (SAI) set up the first widely-used international benchmarking system for crackers in the 1990s. Companies that participate in the benchmark are requested to fill a detailed survey on the performance of their units, including energy consumption on a semi-annual basis. More than half of all steam crackers in the world participate in the survey, representing more than two-thirds of the total production capacity. SAI acts as a clearing house and provides to individual participants a comparison between their units and a distribution of the other plants participating in the survey, accounting for feedstock use and operating conditions.

Benchmarking provides to the participating companies valuable indicators on their energy efficiencies, operating expenses, manufacturing costs, and ultimately return on investment versus the top performing plants worldwide. However, and due to participation clauses to the benchmarking surveys, detailed results are confidential and country level averages are not made public. This limits its applicability for cross country comparisons.

CHEMICAL AND PETROCHEMICAL INDUSTRY

Key Findings

- *The chemical and petrochemical industry accounts for more than 30% of the total industry energy use worldwide. More than half of it is for feedstock use, which can not be reduced through energy efficiency measures. The CO_2 emission intensity of the industry is low because significant amounts of carbon are stored in the products produced. As the energy and feedstock savings potential for the industry are limited, other types of measures are needed.*

- *A limited number of processes and products account for the bulk of energy use in this industry. The processes are uniform worldwide. Therefore, it is possible to develop meaningful indicators.*

- *Benchmarking is widely applied in the industry. Provided that system boundaries are well defined, benchmarking provides a useful basis for plant efficiency comparisons. The plant level results of current benchmarking studies and even the country averages are usually confidential. Therefore, indicators on a country level can supplement benchmarking.*

- *An indicator method is developed in this study that compares a theoretical sector energy use if best available technology were applied with actual energy use according to IEA statistics. Diversity of feedstock use, process configuration and data access can strongly influence the energy performance analysis. Further work is needed to establish regional sectoral comparisons.*

- *Large gains in energy efficiency for key processes such as steam crackers and ammonia plants have been achieved since the 1970s.*

- *The regional averages for steam crackers suggest a 30% difference in energy use between the best (East Asia) and worst (North America) region. However, feedstock use dominates energy use in steam crackers.*

- *Benchmarking studies suggest that potential energy efficiency improvements for olefins and aromatics range from 10% for polyvinyl chloride to 40% for various types of polypropylene.*

- *About 1 EJ (20%) would be saved if best available technology were applied in ammonia production. Coal-based production in China requires considerably more energy than natural gas-based production elsewhere.*

- *While the chemical and petrochemical industry is already one of the largest combined heat and power users, a significant potential for expanded use remains.*

- *There is negligible waste in the primary production of plastics as any scrap is recycled. However, waste plastics recycling and energy recovery rates of post-consumer plastics from end-of-life products are relatively low in many countries. The potential for energy and feedstock savings of increased recycling and energy recovery is between 2 and 4 EJ per year.*

- *The proposed indicator method needs to be further validated through comparison with bottom-up analysis of efficiency potentials for individual countries based on plant-level benchmarking. The accuracy of energy and feedstock production volume data need to be improved. The present aggregate results are not suited for country comparison purposes.*
- *One or more life-cycle indicator(s) should be developed to give credit for the use of renewable feedstocks and waste plastics use for recycling or energy recovery.*
- *Only a small share of electricity use in the chemical and petrochemical sub-sector can be explained based on process data. It requires further analysis.*
- *Based on country comparisons, improved final energy efficiency potential in the chemical and petrochemical industry is 8.5 to 11 EJ per year. This includes 4 EJ of fuel savings potentials, the remainder is electricity savings, CHP, recycling and energy recovery.*

Introduction

The petrochemical industry generates products such as plastics, synthetics (fibres, rubbers), resins, elastomers, nitrogen fertilizers and detergents. It also contributes to the production of many other products, such as pharmaceuticals, paints, adhesives and aerosols. Basic raw materials for the petrochemical industry are fossil fuels, mainly natural gas and crude oil, but also coal.

The three principal bases for the petrochemical industry are "intermediate" chemical products generated from raw materials:

- ▷ Olefins (C2-C4) – *e.g.*, ethylene, propylene, generally obtained from hydrocarbon feedstocks using steam cracking.
- ▷ Aromatics (C6-C8) – *e.g.*, benzene, toluene, xylene (BTX), generated using steam cracking of catalytic reforming.
- ▷ Other intermediates which include synthesis gas (for ammonia and methanol production), hydrogen, carbon black and sulphur.

Ethylene is a relatively inexpensive product with a high reactivity, hence a number of derivatives can be generated by oxidation, hydration, oligomerisation, alkylation or chlorination, making it the most used petrochemical intermediate.

Synthetic polymers represent the largest end-use of the petrochemical industry. They are used for materials such as plastics, rubber and fibres.

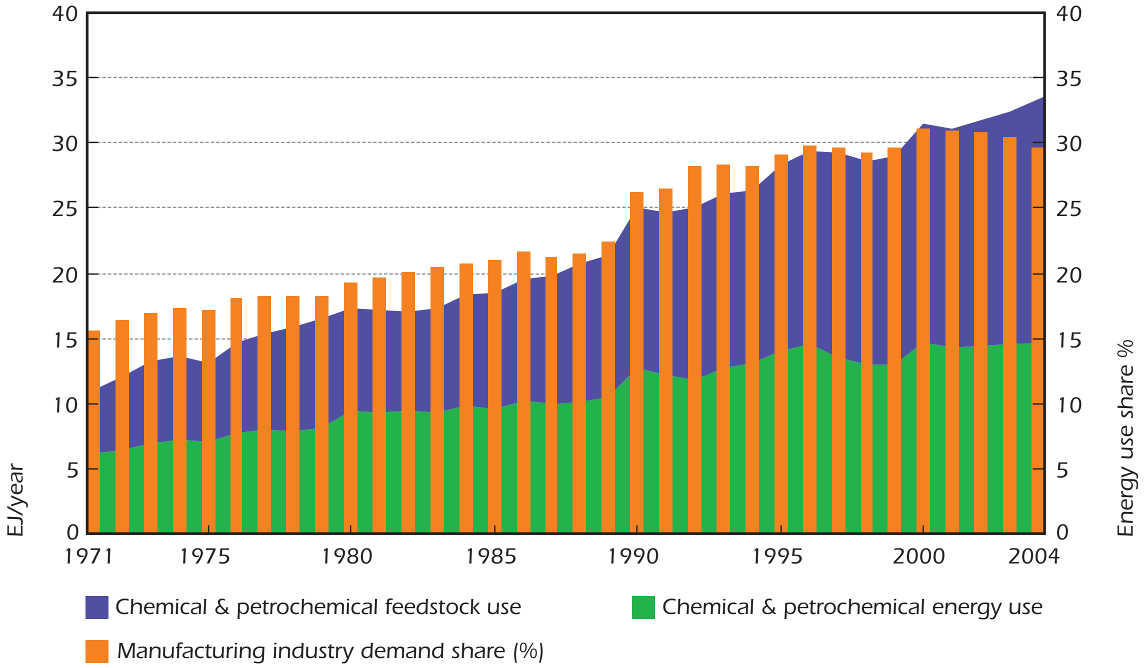
This chapter looks at energy use and CO_2 emissions in the petrochemical and inorganic chemical sub-sector including global production and processes for a number of key products. It assesses opportunities for improved efficiency. Ammonia is also analysed which accounts for 80 – 90% of fertilizer industry energy use. Plastics recovery and the use of combined heat and power in petrochemical and chemical production are considered. A methodology for energy and CO_2 indicators is set out.

Global Importance and Energy Use

The chemical industry includes facilities that produce bulk or specialty compounds by chemical reactions between organic and/or inorganic materials. The petrochemical industry includes facilities that create synthetic organic products from hydrocarbon feedstock, oil and natural gas. The chemical and petrochemical industry consumed 34 EJ in 2004, which was 30% of total global industry final energy use. This share has increased sharply from 15.5% in 1971, an average annual growth of 2.2% (Figure 4.1). Production growth rates have generally outpaced GDP growth. The shares of the petrochemical and chemical industry (including feedstock) in total industrial final energy use in by region in 2004 were: North America – 41%, Western Europe – 31%, China & India – 20%, Japan & Korea – 39%, Middle East – 20% and the Commonwealth of Independent States (CIS) – 24% (IEA statistics).

Figure 4.1 ▶ *World Chemical and Petrochemical Industry Energy Use, 1971 – 2004*

Key point: The share of chemical and petrochemical industry in total manufacturing energy use has doubled from 15 to 30% in the past thirty - five years.



Source: IEA statistics.

The chemical industry is highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousands of tonnes. It is characteristic of the industry that energy constitutes a large portion of the production costs for bulk chemical manufacturing. Energy costs generally represent up to 60% of the production costs and can be as high as 80% for ammonia.

Feedstocks account for more than half of the total energy used in this sub-sector. Most of the carbon from oil and natural gas feedstock is "locked" into final products such as plastics, solvents, urea and methanol. Some of the locked-in energy can be recovered when the waste product is incinerated, which results in CO_2 emissions at the waste treatment stage. Thus, if the locked-in carbon were accounted, the total would be larger than its share of direct industrial CO_2 emissions would suggest (16%).

Three-quarters of all feedstock is oil. It is used for the production of intermediate chemical products like olefins (ethylene and propylene) and aromatics (benzene, toluene and xylenes). These chemicals are further processed into a wide range of plastics, rubbers, resins, solvents and other petrochemical products.

Natural gas, the other major feedstock, is used to produce ammonia, methanol and other products. Ammonia is mostly used for fertilizer production. Ethane, propane and butane are natural gas components that are used to produce olefins.

Table 4.1 shows the energy use in the chemical and petrochemical industry, based on a bottom-up analysis of production volumes and energy efficiencies (electricity use is excluded.). The fossil energy use represented in the table falls short of the industry's total by approximately 19%, yet important conclusions still can be drawn from the analysis. Of primary note is that feedstock energy accounts for more than half of total energy use in the industry: energy used for feedstock can not be reduced through energy efficiency measures.

Table 4.1 ▶ ***Energy Use in the Chemical and Petrochemical Industry, 2004 (Excluding Electricity)***

	Amount	LHV	Feedstock Energy Needed	Fuel		Total Fuel + Feedstock
	Mt/yr	*GJ/t*	*EJ/yr*	*GJ/t*	*EJ/yr*	*EJ/yr*
Ethylene	103.3	47.2	4.9	13	1.3	6.2
Propylene	65.3	46.7	3.0	13	0.8	3.9
Butadiene	9.4	47.0	0.4	13	0.1	0.6
Butylene	20.3	47.0	1.0	10	0.2	1.2
Benzene	36.7	42.6	1.6	7	0.3	1.8
Toluene	18.4	42.6	0.8	7	0.1	0.9
Xylenes	33.7	41.3	1.4	7	0.2	1.6
Methanol	34.7	21.1	0.7	10	0.3	1.1
Ammonia	140.0	21	2.9	19	2.7	5.6
Carbon black	9.0	32.8	0.3	30	0.3	0.6
Soda ash	38.0	0.0	0.0	11	0.4	0.4
Olefins processing excl. polymerization	100.0	0.0	0.0	10	1.0	1.0
Polymerisation	50.0	0.0	0.0	5	0.3	0.3
Chlorine and Sodium Hydroxide	45.0	0.0	0.0	2	0.1	0.1
Total			**17.0**		**8.2**	**25.2**

Note: Feedstock based on lower heating value of products except for ammonia.

Source: IEA statistics and estimates.

The energy intensity of key chemicals (ammonia and petrochemicals) can be reduced by at least 20%, if current state-of-the-art technologies are applied. This potential varies from region to region and from plant to plant (Heinen and Johnson, 2006). A number of consultants are carrying out benchmarking studies in the industry, for example:

- Solomon Associates – benchmarking steam crackers.
- Phillip Townsend Associates – benchmarking various polymers and elastomers.
- Plant Services International – comparing ammonia and urea units.
- Process Design Center – comparing various processes through 50 energy benchmarks (Keuken, 2006).

For a fair comparison, system boundaries, feedstock and product specifications, site integration and environmental issues need to be properly addressed. While detailed results from these studies are not usually publicly available due to confidentiality concerns and anti-trust regulations, regional and time trends can be drawn.

Another approach is the Netherlands voluntary programme which in 1999 set benchmarks for large industrial sites with energy consumption of more than 0.5 PJ. It covers about 150 sites and 80% of the total industrial energy use. However, these data also are not publicly available.

The age of a plant often defines its energy efficiency: older plants generally being less energy efficient. However, retrofits can invalidate this rule of thumb. The Process Design Centre's global analysis indicates that plants built in the 1970s are the least efficient. The 1950 – 60s production plants had a significant amount of upgrading, especially after the 1973 oil price crisis, and show relatively good performance. Plant vintage data are therefore unreliable substitutes for actual measured efficiency data. Analysis of actual energy use data is needed for a proper assessment on efficiency improvement potential.

Nine processes account for 22.5 EJ of final energy use (including feedstock), which is about 65% of global energy and feedstock use in the chemical and petrochemical industry:

Petrochemicals

- Steam cracking of naphtha, ethane and other feedstocks to produce ethylene, propylene, butadiene and aromatics.
- Aromatics processing.
- Methanol production.
- Olefins and aromatics processing.

Inorganic chemicals

- Chlorine and sodium-hydroxide production.
- Carbon black.
- Soda ash.
- Industrial gases.

Fertilizers

- Ammonia production.

Petrochemicals Production

The petrochemical industry commonly converts oil and natural gas feedstocks into monomers and building blocks such as ethylene, propylene, aromatics and methanol, which are further processed into polymers, solvents and resins. Figure 4.2 shows the ethylene chain, illustrating the production of intermediate and final products, *e.g.* diapers and tires. Large amounts of heat are used by distillation columns for product separation and other high-temperature processes, such as steam cracking. Electricity is used for certain conversion processes such as chlorine production, and also for pumps and auxiliary processes.

The petrochemical industry produces materials such as plastics, synthetic rubbers, fibres and solvents which are used in everyday products such as packaging, clothing and plastics. Often these products generate energy savings during their use which outweigh the energy used to produce them, *e.g.*, lighter materials reduce oil consumption in transportation; insulation materials improve building efficiencies. This positive lifecycle perspective is not part of the present analysis.

Today the key producing regions are North America, Western Europe, Korea, China, Japan, and Saudi Arabia, which together represent more than 75% of global production (Table 4.2). With significant investments in Saudi Arabia, Iran and China, their share will be larger in the next decade; this will also affect the age distribution of the production units.

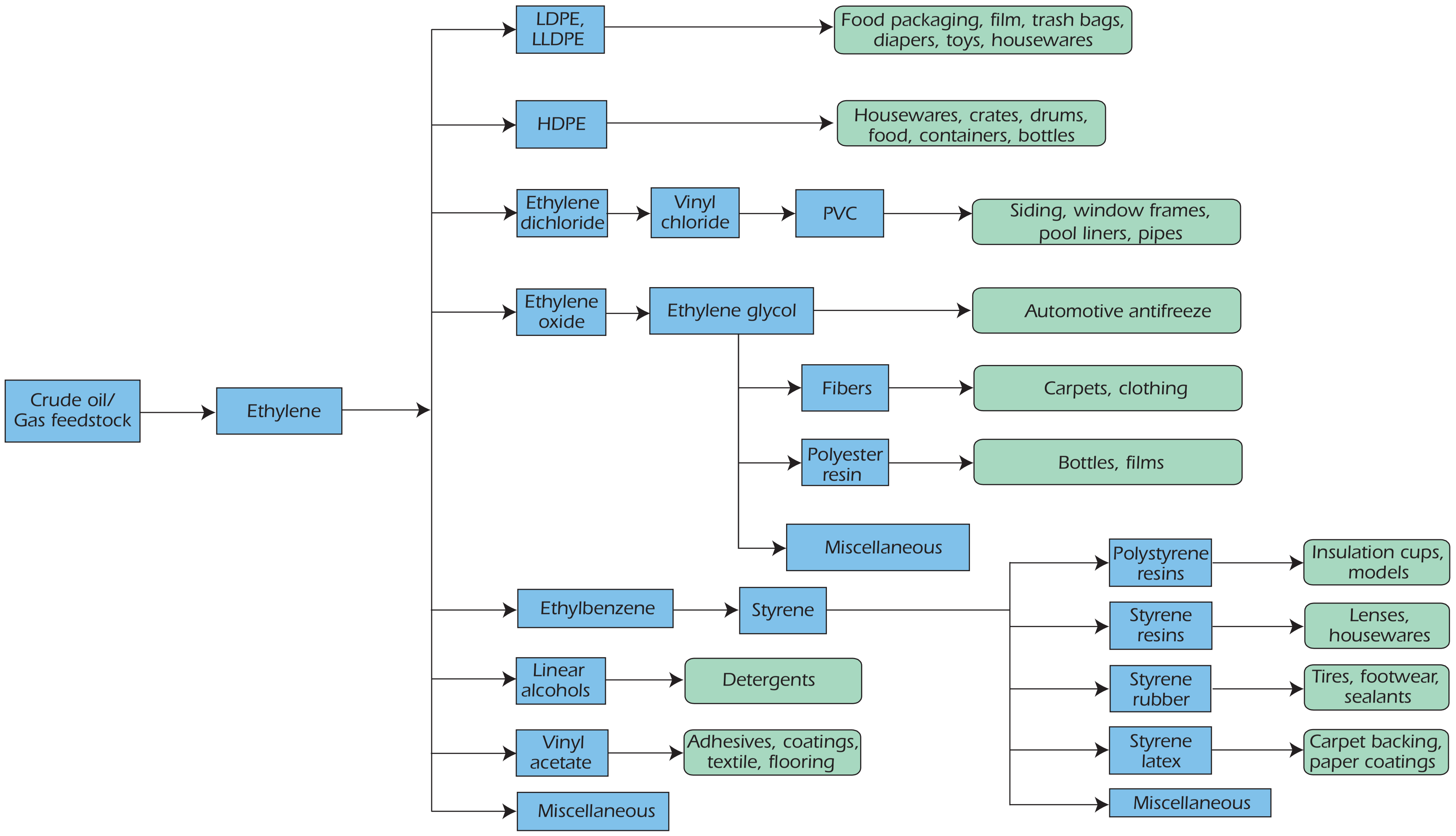
Table 4.2 ▶ ***World Production Capacity of Key Petrochemicals, 2004***

	Total	North America	Western Europe	Middle East	Japan	ASEAN*	China	Korea	Chinese Taipei	India	Other
Ethylene											
(Mt/yr)	**113.0**	38.7	24.0	10.3	7.6	6.1	6.0	5.9	2.9	2.9	8.6
Share (%)	***100.0***	*34*	*21*	*9*	*7*	*5*	*5*	*5*	*3*	*3*	*8*
Propylene											
(Mt/yr)	**77.3**	29.0	17.3	2.5	6.3	3.7	6.1	4.1	2.1	1.5	4.6
Share (%)	***100.0***	*38*	*22*	*3*	*8*	*5*	*8*	*5*	*3*	*2*	*6*
Benzene											
(Mt/yr)	**43.2**	12.4	9.4	2.1	5.7	1.9	2.8	3.4	1.2	0.8	3.4
Toluene											
(Mt/yr)	**24.7**	14.4	2.6	0.7	1.7	0.7	1.1	1.9	0.1	0.3	1.2
Xylenes											
(Mt/yr)	**35.6**	13.0	4.6	1.1	6.1	1.0	3.5	2.5	1.3	0.3	2.2
Total BTX											
(Mt/yr)	**103.5**	39.8	16.6	3.9	13.5	3.6	7.4	7.8	2.6	1.4	6.8
Share (%)	***100.0***	*38*	*16*	*4*	*13*	*3*	*7*	*7*	*3*	*1*	*7*

* Association of Southeast Asian Nations (ASEAN).

Source: Ministry of Economy, Trade and Industry (METI) Japan, 2006.

Figure 4.2 ▶ *The Ethylene Chain*



Source: American Chemistry Council, 2005.

Steam Cracking: Olefins and Aromatics Production

While the petrochemical sub-sector is complex in the number of products it generates, the key process in the industry is steam cracking of ethane, naphtha and other feedstocks. In 2006, worldwide capacity of ethylene production was 116 Mt from 256 crackers (OGJ, 2006). Naphtha cracking represented 45%, ethane 35%, LPG 12%, gas-oil 5% and others 3% of this capacity.

More than 39% of the chemical and petrochemical industry's final energy use is used for steam cracking. Out of a total of 13.3 EJ, only 2.1 EJ is used for energy purposes. Steam-cracking products contain about 11.2 EJ, of which about 1.5 EJ is recycled to the refining industry in the form of by-products for further processing into gasoline and other products.

The energy used in steam cracking depends on a number of factors. The choice of feedstock is a key element as lighter ones such as ethane are cracked at lower temperatures. The ethylene yield decreases as feedstock molecular weight increases; at the same time, the amount of by-products increases. To produce one tonne of ethylene requires 1.25 tonnes of ethane, 2.2 tonnes of propane or 3.2 tonnes of naphtha. Energy consumption for different feedstocks is shown in Table 4.3.

Table 4.3 ▶ ***Energy Use versus Feedstock for Ethylene***

Feedstock	GJ/t ethylene	GJ/t HVC*
Ethane	15 – 25	12.5 – 21
Naphtha	25 – 40	14 – 22
Gas-Oil	40 – 50	18 – 23

* High value chemicals (HVC).

Sources: European Union (EU), 2003; Conseil Européen de l'Industrie Chimique (CEFIC), 2004.

Figure 4.3 shows the feedstock distribution by geographic area. There is a marked difference between Asia-Pacific and Western Europe where naphtha cracking predominates compared with North American plants where ethane cracking is prevalent.

Other factors that effect energy use are the severity of the cracking operation and the furnace design/process technology employed.[1] About 65% of the required energy for a naphtha-fed steam cracker is consumed in the pyrolysis furnace (excluding non-energy feedstock use). Use of gaseous cracking by-products and waste heat can provide about 95% of the process energy demand in naphtha steam crackers. In an ethane-based cracker about 47% of the required energy is used in the pyrolysis furnace and recovering gas and waste heat can provide about 85% of process energy demand.

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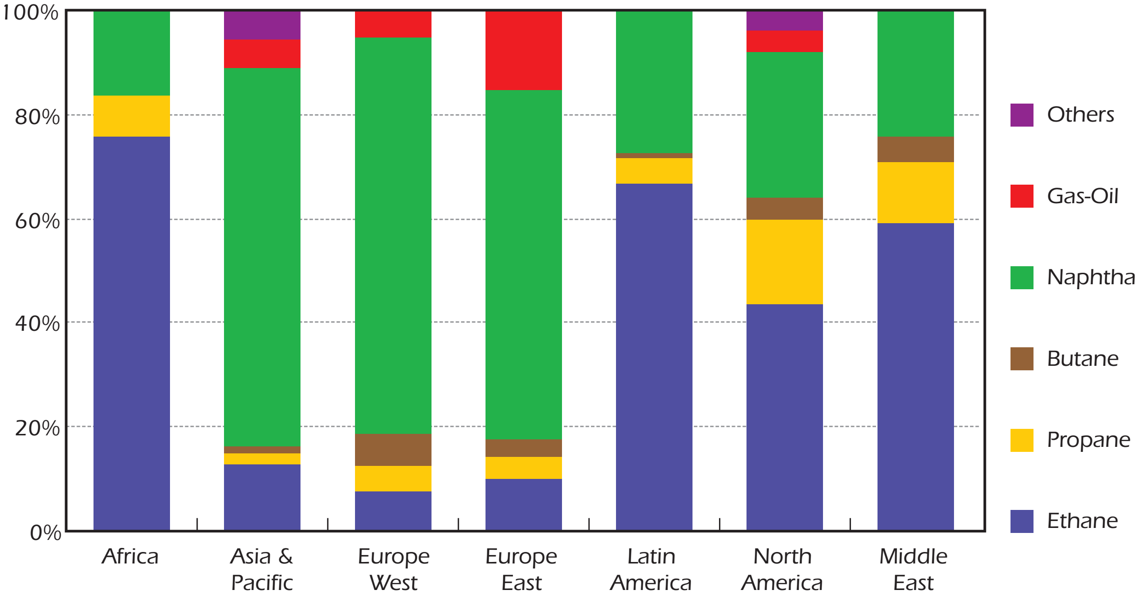
[1] The severity of the cracking operation is dependent upon the desired product ratios and is a function of the temperature and residence time of the feedstock in the furnace.

Figure 4.3 ▸ *Ethylene Plants by Feedstock and Region*

Key point: Naphtha is the main feedstock in Europe and Asia. Ethane dominates in North America, the Middle East and Africa.



Source: Oil & Gas Journal Survey, 2006.

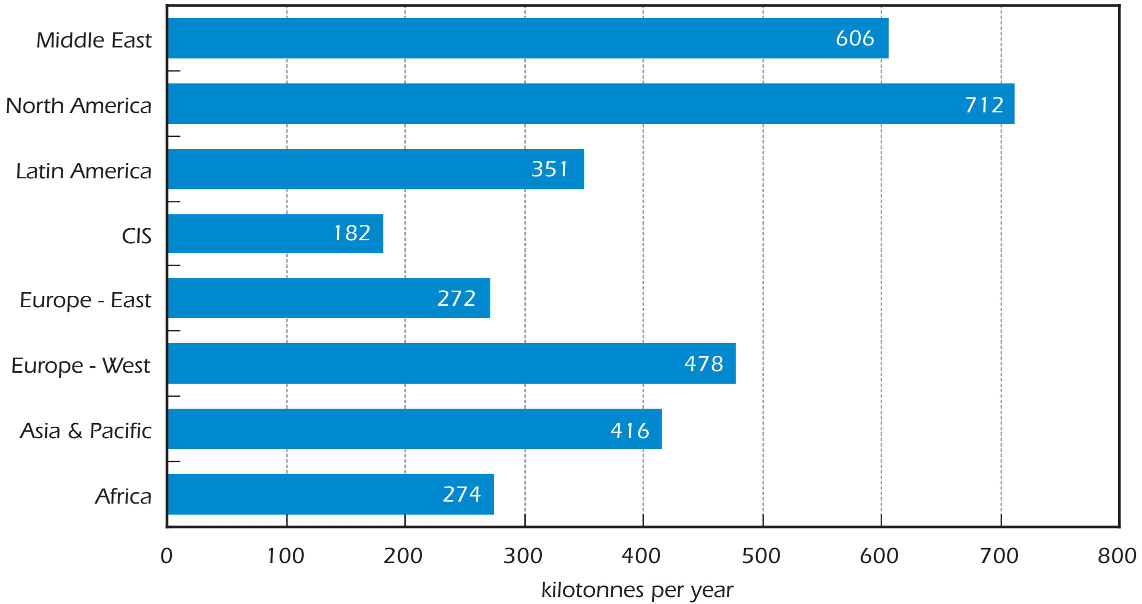
There are many variations of plant configuration to accommodate the feedstock selection and desired products, but all steam crackers include these common components:

- Furnace section in which feedstocks are cracked in the presence of steam.
- Primary fractionation and quench system in which heavy hydrocarbons and water are removed.
- Compression section, including acid gas removal.
- Fractionation section at both cryogenic and moderate temperatures in which the various products are separated and purified.

The capacity of crackers around the world varies widely, with the largest units in the United States and Saudi Arabia (Figure 4.4). While the capacities vary, the core technology designs are similar and are based on the ExxonMobil steam cracking process developed in the early 1940s. Today, more than a third of global ethylene capacity uses Lummus technology (SRT Furnace/short residence time pyrolysis (Kapur, 2005)). Most of the other designs are based on Stone & Webster Ultra Selective Coil and KBR Selective Cracking Optimum Recovery technologies. Linde AG, Technip-Coflexip and Mitsubishi also provide steam crackers. The technologies vary in the furnace design and operating conditions. Specific design focus has been on coil-related furnace features including advanced materials, and on the downstream compression and separation areas. Employing improved technologies can provide 20% energy savings in the pyrolysis section and an additional 15% in the compression and separation sections.

Figure 4.4 ▶ *Average Steam Cracker Capacity*

Key point: The region average cracker size differs by a factor of 3 to 4.



Source: Oil & Gas Journal Survey, 2006.

Table 4.4 details the specific energy consumption (SEC) for state-of-the-art naphtha-based steam cracking technologies developed by the various licensors. SEC is a function of the selected technology feedstock characteristics, its cracking conversion/selectivity, related ambient conditions and degree of upstream/downstream integration. These data include fuel, steam and electricity in primary terms that are used for reactions and subsequent processes.

Since the 1970s steam cracker design changes have led to a more than 50% decrease in SEC. These improvements include gas turbine integration, more extensive process-to-process heat recovery schemes, integral steam super-heaters, higher efficiency rotating equipment, multi-stage refrigeration schemes and integrated heat pump systems (Bowen, 2006).

Table 4.4 ▶ *Specific Energy Consumption (SEC) for State-of-the-Art Naphtha Steam Cracking Technologies*

	Ethylene yield %	SEC *GJ/t ethylene*
Technip	35	18.8 – 20 or 21.6 – 25.2 (typical)
ABB Lummus	34.4	18 (with gas turbine), 21 (typical)
Linde AG	35	21 (best)
Stone & Webster	n/a	20 – 25
KBR	38	no data

Source: Ren, *et al.*, 2005.

Depending on the feedstock, varying amounts of by-products are generated which can be used to fuel the process (Table 4.5). Methane and hydrogen by-products are used to fuel the cracking furnace, or separated out and used elsewhere. Pyrolysis gasoline by-product is recycled to the refinery industry. About 155 GJ of naphtha are needed for the production of 1 tonne of ethylene. About 17% of the energy content of naphtha (25 GJ/t of ethylene produced) is used for energy purposes. The theoretical minimum for this process, *i.e.*, the energy that is needed solely for the chemical conversion, would be 5 GJ/t, or about one-fifth of what is actually used. Since the carbon and most of the feedstock energy is embedded in the products, energy-efficiency measures will not significantly reduce the required amount of feedstock. Other approaches, such as feedstock substitution, would be needed.

Table 4.5 ▶ ***Ultimate Yields of Steam Crackers with Various Feedstocks***

(Kg of Product per tonne of Feedstock)

	Naphtha	Gas Oil	Ethane	Propane	Butane
High-value chemicals	**645**	**569**	**842**	**638**	**635**
Ethylene	324	250	803	465	441
Propylene	168	144	16	125	151
Butadiene	50	50	23	48	44
Aromatics	104	124	0	0	0
Fuel-grade products and backflows	**355**	**431**	**157**	**362**	**365**
Hydrogen	11	8	60	15	14
Methane	139	114	61	267	204
Other C4 components	62	40	6	12	33
C5 and C6 components	40	21	26	63	108
C7 and non-aromatic components	12	21	0	0	0
Losses	5	5	5	5	5

Source: Neelis, *et al.*, 2005.

Early naphtha crackers consumed about 38 GJ/t ethylene (about 20 GJ/t high value chemicals (HVC)). In the 1970s the ethylene industry went through an extensive redesign of its flow sheet and lowered the specific energy requirements by 40 – 50%. Today, typical crackers use 18 – 25 GJ/t ethylene for the furnace and product separation. Improvements in cracking could yield large gains in energy efficiency in the long term. Options include higher-temperature furnaces (with materials able to withstand more than 1 100 °C), gas-turbine integration (a type of high-temperature combined heat and power unit that generates the process heat for the cracking furnace), advanced distillation columns, and combined refrigeration plants. Together, these steps could result in 3 GJ/t of ethylene savings. The total potential for improving energy efficiency from existing technology to the best technology available is about 1 EJ (24 Mtoe).

Solomon Associates have benchmarked 115 olefin plants, representing 70% of the ethylene-producing capacity worldwide. A trend analysis has been made of a group of 50 olefin plants, half of which are in Europe, 27% in North America and the remaining 23% in other parts of the world. The actual data are confidential, but some regional trends and comparisons are public.

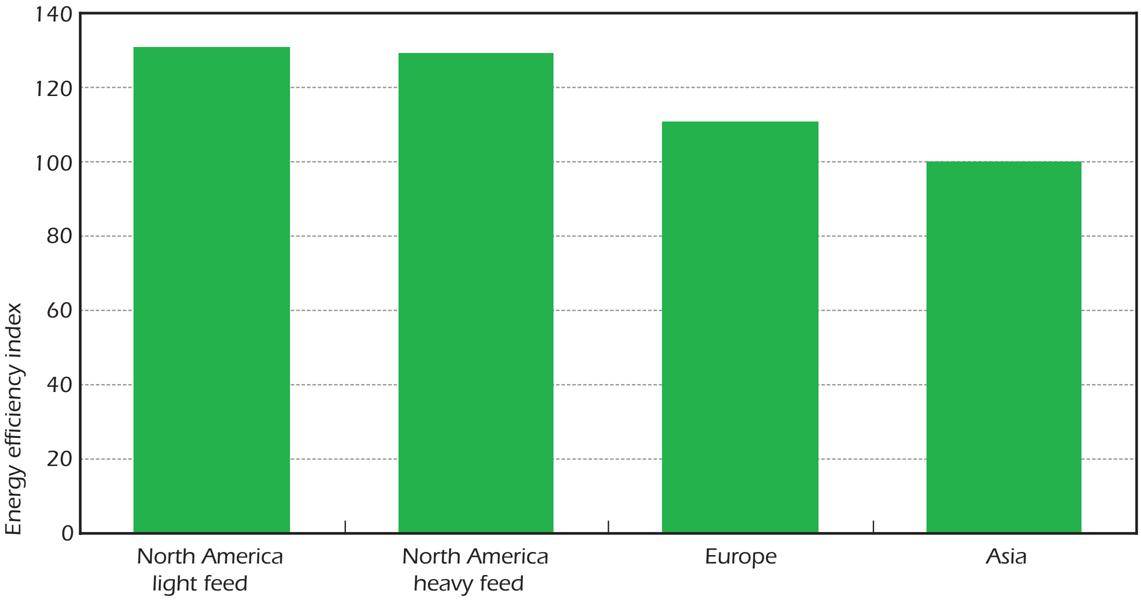
In the 2003 Olefin Study, North America was 111% of average energy consumption, Europe was 95% and Asia was 86%. Part of this difference is due to the different feedstock mix. The average ethane cracker in the study consumed 124% of the study average energy consumption, where the average naphtha cracker only consumed 95% (Cagnolatti, 2005). This can be explained by lower heat integration of ethane crackers due to a more simple design. However, even allowing for feedstock differences, average energy consumption rates are significantly higher for North America (Figure 4.5). North American crackers use on average 32% more energy and European crackers 12% more energy than Asian crackers.

The energy efficiency of European crackers improved approximately 10% from 1999 to 2003. In North America, the improvement was only 3%. The average number of cogeneration units, which produce heat for the process furnace, per plant did not change during this period, but the average size increased by a third.

Figure 4.5 ▶ *Steam Cracking Energy Consumption Index per unit of Product, 2003*

(Corrected for Feedstock Mix)

Key point: North American crackers are 30% less efficient than Asian crackers.



Source: Cagnalotti, 2005.

The integration of gas turbines with cracking heaters reduces the specific energy for ethylene production by about 10 – 20% of the overall energy requirements. The hot off-gas from the gas turbine is used as combustion air for the furnace. Eleven plants designed by Lummus based on the integration concept are operating successfully.

Propylene Recovery in Refineries and Olefins Conversion

Propylene is the second largest petrochemical building block by volume, with a demand growth rate higher than ethylene. Propylene derivatives, *e.g.* polypropylene, are used to produce textiles, coatings, automobiles and fibres (Table 4.8). More than two-thirds of global production is generated by steam crackers and some 30% from refinery off-gases of fluidised catalytic crackers (FCC). A small percentage of propylene production is from methathesis/olefin conversions technology, and from methanol and propane dehydrogenation (Berra, 2005).

Estimates for net energy use in propylene manufacturing by metathesis are: process energy – 5.3 GJ/t, feedstock energy – 50.0 GJ/t (Energetics, 2000). The FCC process is less energy intensive because the energy used in the cracking furnace can be avoided, and product separation is simpler. Conventional FCC units yield about 5 – 12% propylene in the off-gas, depending on the mode of operation. New deep-catalytic cracking processes can increase the yield to 16 – 22%, but at the expense of naphtha and gasoline yields. These new deep-catalytic processes can be retrofitted on existing catalytic cracking units.

Aromatics Extraction

Aromatics are hydrocarbons that contain cyclic chemical structures. The main aromatics are benzene, toluene and the xylenes. They are used as building blocks to make products as diverse as aspirin to CD-ROMs.

The global market is about 30 Mt/ year for benzene, 14.5 Mt/year for toluene, 24 Mt/year for mixed xylenes and 17 Mt/year for p-xylene. About 40% of toluene is used to make benzene, while p-xylene production using selective toluene disproportionation (STDP) process consumes 19%. About 75% of the mixed xylene produced is used to make p-xylene. Some mixed xylene is used as solvent and o-xylene is recovered for chemical processing.

Aromatics are produced from three types of resources:

- ▷ Hydro-treated coke-oven benzole.
- ▷ Hydro-treated pyrolysis gasoline from steam cracking.
- ▷ Reformate from catalytic reformers in refineries.

Currently, about 72% of all aromatics are recovered from reformate, 24% from pyrolysis gasoline and 4% from coke-oven light oil. About 39% of all benzene is recovered from pyrolysis gasoline, 33% from reformate, 6% from coke ovens and 22% from the hydrodealkylation (HDA) of heavier aromatics and toluene disproportionation (TDP). Toluene is produced from catalytic reforming, pyrolysis gasoline and styrene production. Xylene's sources are catalytic reforming (85%), and steam cracking. Ethylbenzene, which is mostly used to manufacture styrene monomer, is produced by liquid or gas-phase alkylation of benzene with ethylene. Liquid-phase alkylation using zeolite catalysts has been used since the mid 1990s to lower catalyst consumption.

A modern benzene extraction unit uses about 1.5 GJ/t of energy in the form of low-temperature heat. The electricity needed for p-xylene separation through crystallisation is about 0.8 GJ/t. If the average energy used in aromatics processing is 5 – 10 GJ/t, then aromatics production accounts for 0.4 – 0.8 EJ. The 61% of feedstock which does not derive from steam cracking accounts for another 1.7 EJ of energy use. Depending on the process configuration, other steps may add to the energy consumption of an aromatics plant. Since most of the hydrocarbon ends up in the product, the potential for reducing CO_2 emissions from aromatics production processes is limited. Heat cascading or new separation technologies could be applied to save process energy.

Methanol

Methanol is the simplest alcohol and is also known as methyl alcohol. It is used as antifreeze, solvent and fuel. In 2006, global methanol production was 36 Mt, of which 19% was used to make methyl tertiary butyl ether (MTBE), a gasoline additive; 10% for acetic acid and 40% for formaldehyde. About 80% of methanol production is natural gas-based, with the remainder being coal-based, essentially in China. A typical methanol plant uses 30 GJ of natural gas per tonne of methanol. The latest large-scale auto-thermal reforming plants operate as low as 28.5 GJ/t (Lurgi, 2006).

The two methods to produce methanol are either high-pressure or increasingly low-pressure synthesis gas processes. In the latter, the reaction uses a copper catalyst at a pressure of 50 – 100 bars, and a temperature of 250 °C. The theoretical minimum energy use, equivalent to the lower heating value (LHV) of methanol, is 20 GJ/t. About 1 EJ of natural gas is used in methanol production worldwide. The latest methanol production plants have a capacity of 1.5 Mt per year and virtually all of them use Lurgi MegaMethanol technology (six such plants have been built so far). Lurgi has supplied 60 – 70% of the world methanol production capacity.

The new standard for world-scale methanol capacity, the 1.75 million metric tonne (5 000 metric tonne per day) Atlas unit began operation in Trinidad in 2004, followed by a second one in 2005. The next unit of this size, the Zagros facility in Iran was inaugurated in March 2007. At least two more units with the same capacity will follow in 2007 – 2008 (Thomasson, 2006).

Seventeen countries represent more than 90% of global methanol production (Table 4.6). Production is shifting to countries with lower natural gas costs (Middle East and Russia).

Methanol production in China has expanded rapidly in recent years largely for use as a gasoline additive. China is the largest methanol producer in the world with a production capacity of 5.36 Mt in 2005 and the only country that uses coal.

Table 4.6 ▶ *Methanol Production, 2004*

Countries/Areas	Production *Mt*	Cumulative Production Share *%*
China	4.4	12.7
Saudi	4.2	24.8
Trinidad/Caribbean	3.6	35.0
United States	3.0	43.7
CIS	3.0	52.3
Chile	2.7	60.1
Venezuela	1.5	64.4
Germany	1.5	68.7
Canada	1.2	72.2
Iran	1.2	75.6
New Zealand	1.1	78.8
Indonesia	1.0	81.7
Norway	0.9	84.3
Qatar	0.8	86.6
Malaysia	0.5	88.0
Benelux	0.5	89.5
Argentina	0.4	90.6
Romania	0.4	91.7
Brazil	0.3	92.0
Other	1.3	100.0
Total	**36.0**	

Sources: IEA; Chemical Markets Associates, Inc.

Coal-based methanol production in China used an average 1.2 tonne carbon equivalent/t methanol (35 GJ/t) in 2003. There was one plant with a capacity of more than 200 kt, eighteen plants with a capacity of 100 kt and six with a capacity of 80 kt (Yu Zunhong, *et al.*, 2005). It should be noted that these plants are one order of magnitude smaller than the largest modern plants. According to incomplete statistics, current methanol production capacity under construction is nearly 9 Mt, with more than 10 Mt planned. The Chinese Government is trying to slow down the expansion by regulating that a project should have at least 1 Mt capacity.

Olefins and Aromatics Processing

Olefins are unsaturated hydrocarbons containing one or more pairs of carbon atoms linked by a double bond. They are obtained by the cracking of petroleum fractions at high temperatures.

Table 4.7 ▶ *Global Ethylene Use, 2004*

	Share %
Polyethylene	58
Ethylene oxide	13
Ethylene dichloride	13
Ethylbenzene	7
Others	9
	100

Source: Nexant, 2005.

The olefin components ethylene, propylene, butene and butadiene are used for the production of plastics and synthetic rubbers (Tables 4.7 and 4.8). In certain cases this is a single step, in other cases an intermediate product is first produced, *e.g.*, vinylchloride from ethylene, or ethylbenzene from benzene and ethylene. The monomers are polymerized to yield plastics. The quantities are significant, at about 200 Mt of plastics per year. Energy use for polymerization depends on the process and the polymer type. Total primary energy use is on the order of 1 EJ per year.

Table 4.8 ▶ *Global Propylene Use, 2004*

	Share %
Polypropylene	55.7
Acrylonitrile	11.7
Oxo-alcohols	8.2
Cumene	6.8
PO	6.9
Isopropanol	3.2
Other	7.5
	100

Source: Phillips, 2006.

Polyethylene is the world's most widely used plastic. Linear low density polyethylene ("LLDPE") is the fastest growing type. It is particularly well suited for making plastic films that are both flexible and strong, but not transparent.

Union Carbide, Dow Chemical and BP are leading developers of polyethylene reactor process technology. Union Carbide's "Unipol" reactor process, in which ethylene is in gaseous state during polymerization ("gas phase"), is the most widely licensed and used polyethylene process in the world. BP's "Innovene" process, also a gas-phase process, is the only other widely licensed process for LLDPE. Dow Chemical does not license its polyethylene reactor technology, in which ethylene is polymerized in solution. Gas phase LLDPE production is generally lower cost than solution production.

Benchmarks of European Union (EU) chemical and petrochemical facilities have been run by several organisations. Schyns (2006) provides a summary of weighted EU averages versus EU best practice for key olefins and aromatics. The data in Table 4.9 indicate energy efficiency improvement potential in the range of 30 – 40% for LDPE, HDPE and polypropylene, and 10% for PVC.

Table 4.9 ▶ ***European Energy Use and Best Practice***

(Final Energy Units)

	Weighted EU Average *GJ/t*	EU Best Practice *GJ/t*
LDPE High pressure process		
Tube & batch reactors	8.53	5.96
HDPE Low pressure process		
Suspension, solvent & gas phase reactors	5.43	3.14
Polypropylene		
Suspension & gas phase processes	3.56	2.27
PolyVinylChloride		
Suspension, emulsion & mass polymerisation processes	3.8	3.4

Note: Low Density Polyethylene (LDPE); High Density Polyethylene (HDPE); Linear Low Density Polyethylene (LLDPE); Polypropylene (PP); PolyVinylChloride (PVC).

Source: Schyns, 2006.

Inorganic Chemicals Production

A number of energy-intensive inorganic chemicals are widely used. This study examines chlorine and sodium hydroxide, carbon black, soda ash and industrial gases. The inorganic chemicals that are of lesser relevance from an energy perspective have not been analysed in more detail in this study.

Chlorine and Sodium Hydroxide

Chlorine is mainly used in the synthesis of chlorinated organic compounds, *e.g.* vinyl chloride. Sodium hydroxide is used for the production of organic and inorganic chemical compounds that are used in the pulp and paper, textile, water treatment and metallurgy industries.

Table 4.10 ▶ *Worldwide Chlorine Production, 2004*

	Production *Mt*
United States	11.2
Japan	4.2
Germany	4.3
France	1.3
Benelux	1.3
Rest of Western Europe	2.6
Rest of the world (Russia, China ...)	15.4
Total	**44.0**

Source: Euro Chlor, 2006.

World chlorine production was 44 Mt in 2004 (Table 4.10), and annual demand for chlorine is forecast to rise to 52 Mt by 2010. Salt (sodium chloride) is decomposed electrochemically to yield sodium hydroxide and chlorine. The industry currently uses 0.44 EJ of electricity per year in three production methods: mercury, diaphragm and membranes processes.

The energy efficiency of these processes differs, depending to some extent on the process design (Table 4.11). The energy efficiency of current membrane cells is about 63%, compared to the theoretical minimum.

Table 4.11 ▶ *Energy Efficiency of Chlorine Production Processes*

	Electricity Consumption $GJ_{el}/t\ Cl_2$	Steam Consumption $GJ/t\ Cl_2$
Mercury process	11.8	0
Diaphragm process	10.0	2.2
Membrane process	8.6 – 9.2	0.6

Note: Membrane process range reflects current densities of 0.3 and 0.4 A/cm^2, respectively.

Source: Gielen, 1997.

Each process generates a sodium hydroxide product of a different quality. The mercury cell produces sodium hydroxide in a 50% concentration and needs no further processing. The diaphragm process requires considerable amounts of heat to upgrade the sodium hydroxide concentration, which is initially only 12%. The membrane process produces a 30% sodium hydroxide product which then needs to be concentrated. The preferred technology in new plants is the membrane cell. Total energy consumption in Western Europe decreased from an average 13.1 GJ/t in 2001 to 12.5 GJ/t in 2004, and the objective is a further 5% decrease by 2010 (Euro Chlor, 2006).

Regional differences in production processes affect the energy savings potential. In Europe, about half of chlorine production is by the mercury cell process. In the United States, three-quarters is by the diaphragm process. In Japan, only the membrane cell process is used.

The main opportunity for energy savings lies in converting mercury process and diaphragm process plants to membrane technology. New technology developments, such as the combination of an electrolytic cell with a fuel cell that uses the hydrogen by-product (from chlorine production), could significantly decrease energy use. This technology, however, is unlikely to be commercially available in this decade. The replacement of hydrogen-evolving cathodes with oxygen-consuming cathodes can result in additional 30% electricity savings for membrane cells, but such electrode materials need further development.

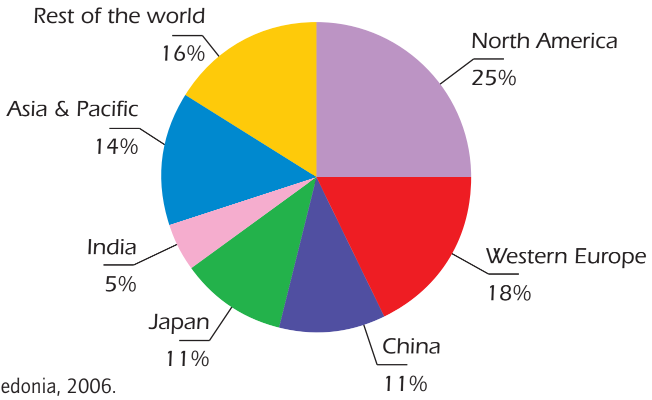
Carbon Black

Carbon black is a form of amorphous carbon that has an extremely high surface area to volume ratio, and is one of the first nanomaterials to find common usage. Carbon black is primarily used as reinforcement in vulcanized rubber goods. The tire industry uses around 85% of all carbon black manufactured. The other 15% is used mainly in the paint and varnish industry and inks and plastics.

The overall global carbon black market is expected to increase by 4% per year from 9 Mt/year today to a level of 9.6 Mt tons through 2008 (Freedonia, 2006). Figure 4.6 shows the regional production split in 2004. Production growth over the next decade is forecast to be three times higher in China and India than the industrialised world.

Figure 4.6 ▶ ***Carbon Black Production by Region, 2004***

Key point: Carbon black production is widely dispersed globally.



Source: Freedonia, 2006.

Basically, there are three different manufacturing processes: flame soot, Degussa gas black and the furnace process. About 95% of all carbon black production is based on the furnace process, a partial combustion process that can use coal, oil or natural gas. The three processes result in a wide palette of black pigments, which differ in the size of their particles, structure, surface and surface chemistry. A typical plant uses 500 kWh/t carbon black. Moreover, 33 GJ feedstock and about 30 GJ process energy are needed (Leendertse and Veen, 2002). This results in a total global energy use for carbon black production of 0.57 EJ per year and about 0.017 EJ of electricity.

The most significant substitute for carbon black in rubber production is precipitated silica. In recent years, up to 25% of carbon black production volumes have been replaced with silica to create what is commonly called a "green" tire, which significantly reduces the rolling resistance of tires to improve traction, wear and fuel efficiency. However, the material cost of adding silica is nearly twice the cost of carbon black, and the cost of processing and compounding the materials is higher. Given a declining market, carbon black has not been considered in more detail.

Soda Ash

Soda ash, also known as sodium carbonate, is a sodium salt of carbonic acid. The most important use of soda ash is in the chemical make-up of glass. It is also used as a water softener, in detergents, photographic processes and brick manufacturing.

Table 4.12 ▶ *Soda Ash Production, 2004*

Country	Production *Mt/yr*	Share *%*	Cumulative Production Share *%*
China	12.7	31.4	31.4
United States	11.0	27.3	58.7
Russia	2.6	6.5	65.2
India	1.5	3.7	68.9
Poland	1.5	3.7	72.6
Germany	1.4	3.5	76.1
France	1.0	2.5	78.6
Italy	1.0	2.5	81.1
United Kingdom	1.0	2.5	83.5
Bulgaria	0.8	2.0	85.5
Ukraine	0.7	1.6	87.1
Turkey	0.6	1.5	88.6
Spain	0.5	1.2	89.9
Japan	0.4	1.0	90.9
Others	3.6	9.1	100.0
Total	**40.3**	**100.0**	

Source: United States Geological Survey (USGS), 2005.

World consumption of soda ash was about 40 Mt in 2004, having increased by an annual average of 2.6% recent years. It is forecast to increase at a higher rate of 3 – 4% per year to 2010. Glass will remain the main market for soda ash in the near term, consuming an estimated 16 – 17 Mt in 2004 and forecast to grow at around 3% per year through to 2010, driven more by flat glass (4% per year) than container glass (2% per year).

Consumption of soda ash in chemicals manufacture was around 8 Mt in 2004 and is forecast to grow by 2 – 3% per year. It is dominated by its use in the production of sodium silicate and sodium tripolyphosphate (STPP) for detergents, which accounted for 5.0 Mt in 2004. Consumption of soda ash in the production of sodium bicarbonate was around 1.8 Mt in 2004.

In the United States, production is based on natural soda ash deposits and soda recovery from lakes. Elsewhere, the production is largely based on synthetic production. Synthetic soda ash is manufactured from common salt and limestone by the ammonia-soda process invented by Solvay in 1865. The Solvay process initially produces light ash which requires a further stage of densification. The two forms are chemically identical but dense ash is the preferred form for glass manufacture. Natural soda is produced only in dense form.

Synthetic production is more energy intensive and more costly than natural soda. The Solvay process requires a large amount of steam, much of which is low-pressure steam (<5 bar absolute), injected directly into the process for the recovery of ammonia (steam-stripping). So it is logical to include combined heat and power (CHP) units for steam and electricity generation in order to improve plant efficiency.

To reduce energy consumption, operators have given up the direct use of fuels (combustion) in other parts of the process where only thermal inputs are needed, *e.g.* the sodium bicarbonate decomposition or the sodium monohydrate drying to dense soda ash. The thermal input in the form of steam has allowed maximised use of CHP.

With the improvement of efficiency in use of primary energy, cogeneration steam-electricity units with gas turbines have been installed in soda ash production units. The electricity generated normally exceeds the needs of the soda ash unit and is available to be fed into the electricity network.

Table 4.13 ▶ ***Typical Energy Use for Energy Efficient Soda Ash Production Using Best Available Technology***

Energy	**GJ/t soda ash** (dense)
Fuels (lime kiln)	2.2 – 2.8
Fuels (soda ash), including electricity*	7.5 – 10.8, 0.18 – 0.47 (50 – 130 kWh/t soda ash)

* excludes fuels for lime kilns
Source: Conseil Européen de l'Industrie Chimique, 2004.

Given fuel needs for the lime kiln and the energy use of 10 – 12 GJ/t soda ash and the production process mix, global energy needs for soda production are 0.3 – 0.4 EJ. Soda ash production capacity is estimated to be about 42 Mt per year. The split between processes and regions is given in Table 4.14.

In 2004, US producers exported 4.7 Mt of soda ash, about 50% of total world exports. Total European output of 12.5 Mt in 2004 was a 5% increase on the stable level of the previous three years, while Russian output increased an average of 9% per year since 1998. However, there has been very little growth in soda ash demand in Europe since 2002, and this is unlikely to change significantly in the near term.

Table 4.14 ▶ *Global Soda Production Capacity, 2000*

(Mt)

	Solvay Process	Sodium Minerals Process	Others	Total
EU25	7.7		0.1	7.8
Rest of Europe	6.6		0.8	7.4
North America		11.6		11.6
Latin America	0.5			0.5
Asia	9.7	0.5	3.7	13.9
Africa	0.1	0.6		0.7
Oceania	0.4			0.4
Total	**25**	**12.7**	**4.6**	**42.3**

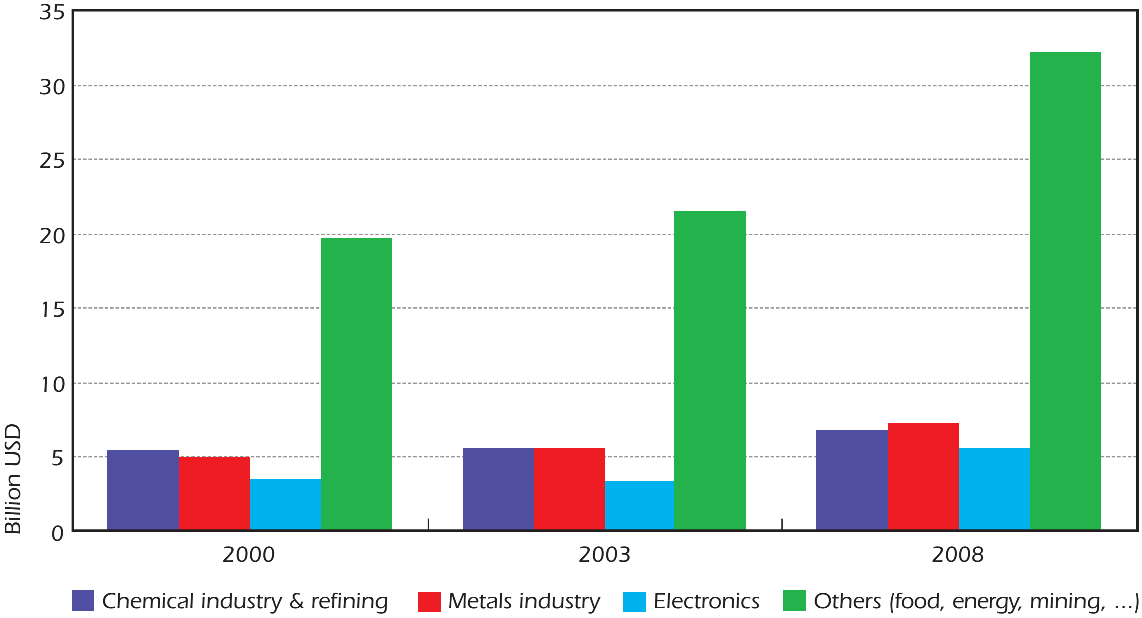
Source: Conseil Européen de l'Industrie Chimique, 2004.

Industrial Gases

Industrial gases are used for a multitude of purposes, including energy and mining, chemical, electronic, food and beverage, healthcare, manufacturing, metals and aerospace industries (Figure 4.7). It includes gases commonly found in the air, rare gases, acetylene, CO_2 and hydrogen. Oxygen is used in steel manufacturing, metallurgy, chemistry (ammonia, ethylene oxide, propylene gas, coal gasification/synthesis gas, and methanol), glass and ceramics, health care, and pulp and paper industries. Some of these industries produce the oxygen they need themselves; others buy it from supply companies. In such a case, the energy needs for gas production are accounted for in the chemical industry. Nitrogen is widely used in the food and beverage, glass-making, chemistry, health care, oil and gas and electronic industries. Hydrogen is used in the synthesis of polymers, solvents, ammonia and methanol, in glass making, for electronics and pharmaceuticals. Rare gases are used in medicine, welding, and lighting. CO_2 is used mostly in the food and beverage, refrigeration, healthcare and oil and gas industries.

Figure 4.7 ▶ *Industrial Gas Demand by Market Segment*

Key point: "Other" industrial gas demand is quickly rising.



Source: BCC Research, 2003.

While the demand for nitrogen was practically nonexistent in 1960, by the early 1990s nitrogen surpassed the sales of all other industrial gases. Together, nitrogen and oxygen sales accounted for approximately 41% of the industry's sales in the late 1990s. Carbon dioxide and acetylene ranked third and fourth. Because nitrogen does not readily react with other materials, several industries use it as a "blanketing agent," which is a compound able to prevent unwanted reactions. For example, when nitrogen is used as a blanketing agent with embers, it prevents them from igniting. Nitrogen is used to ensure product quality and improve plant safety. Oil producers use nitrogen to stimulate and pressurise wells. Nitrogen gas is also valuable in steel processing, food production, cooling, refrigeration and freezing systems, solvent recovery, chemical and glass production, and the electronics and aerospace industries.

Measured in terms of sales volume, the second most significant industrial gas in the late 1990s was oxygen, which is used to intensify or control combustion in a variety of industries. Its other uses include speeding fermentation, providing life support and controlling odours. Chemical manufacturers, brick makers and metal fabricators all rely on oxygen. Innovative uses include processes aimed at restoring or maintaining environmental integrity. Oxygen is used in hazardous-waste cleanup, wastewater treatment facilities and coal gasification systems. One of the fastest growing areas of oxygen use in the late 1990s was as a replacement for chlorine in bleaching, especially by pulp and paper manufacturers because the oxygen process pollutes less.

The two largest companies by sales in 2006 were Linde AG and Air Liquide, followed by Praxair, Air Products & Chemicals and Taiyo Nippon Sanso, with total market sales of USD 49 billion in 2005. Growth rates are expected to be 6% or more per year for the 2006 – 2010 period.

The industry uses three techniques to separate gases from the atmosphere. Cryogenic methods, the oldest and most widely used, rely on cooling and pressurising the air until it becomes liquid. Oxygen, when held at a pressure of 1 013 kPa, liquefies at minus 183˚C; nitrogen liquefies at minus 196 °C. As the atmospheric gases liquefy, they are extracted by means of a distillation process. The air separation plants include air compressors, air purifiers and heat exchangers, distillation and compression units. Large-scale air separation units produce 3 – 4 000 t/day. With the development of applications such as integrated gasifier combined cycle, gas-to-liquids, coal-to-liquids and expansion of blast furnaces for the manufacturing of steel, unit capacity could exceed 7 000 tons/day by 2012 (Frostbyte, 2005; DiZanno, 2004).

Two non-cryogenic approaches are membrane separation and pressure swing absorption (PSA) production methods. Membrane separation uses hollow fibres, usually made of organic polymers, to recover gases such as hydrogen from oil refineries or CO2 from natural gas supplies. A significant investment in membrane technology development is being made by private and public private partnerships, including ion-membrane systems. Pressure swing absorption (PSA), and its lower-pressure variants vacuum swing adsorption (VSA) and vacuum pressure swing adsorption (VPSA), rely on a molecular sieve material that selectively absorbs atmospheric components at specific temperatures and pressures.

There are many variations in the air separation cycles used to make industrial gas products. Design choices are made depending upon how many products are desired; required product purities; gaseous product delivery pressures; and whether products will be generated in liquid form.

Prior to the 1990s, and excluding compression and integration with turbines, electricity consumption in cryogenic air separation averaged 310 KWh/t of oxygen (1.1 GJ/t). Structured packing has been used in distillation columns since the 1990s to reduce pressure drops and improve energy efficiency by more than 30%. Given energy use of about 0.78 GJ/t oxygen and a global market of industrial gases at about 100 Mt per year, represents about 0.078 EJ of electricity or 0.2 – 0.3 EJ in primary energy terms.

Ammonia Production

Anhydrous ammonia is the source of nearly all the synthetic nitrogen fertilizers produced in the world. Ammonia is produced by combining nitrogen with hydrogen. The nitrogen is obtained from the atmosphere, while the hydrogen is obtained from natural gas mainly, and to some extent from naphtha, coke-oven gas, refinery gases and heavy oil.

Global ammonia production was 145.4 Mt in 2005. Growth is mainly concentrated in West and East Asia, which together account for almost 40% of global production (IFA, 2006). About 77% of world ammonia production is based on natural gas steam reforming, 14% on coal gasification, mainly in China, and 9% on the partial oxidation of oil products and heavy hydrocarbon fractions, mainly in India and to a lesser degree in China. A typical heavy-oil-based process uses 1.3 times as much energy as a gas-based process. A coal-based process uses 1.7 times more energy than a gas-based process. In 2004, total energy and feedstock use for ammonia production amounted to about 4.3 EJ of natural gas, 0.6 EJ of oil and 1.2 EJ coal (Table 4.15). This is almost 20% of all the energy used in the chemical industry. A 30% decrease in energy use per tonne of ammonia has been achieved in the last thirty years.

Table 4.15 ▶ ***Energy Consumption in Ammonia (NH_3) Production, 2005***

Region	Production *Mt Ammonia*	Share gas *%*	Share oil *%*	Share coal *%*	Gas-based *GJ/t NH_3*	Oil-based *GJ/t NH_3*	Coal-based *GJ/t NH_3*	Energy intensity *GJ/t NH_3*	Fuel use *PJ/yr*
Western Europe	12.2	90	10		35			35.0	427
North America	14.4	100			37.9			37.9	546
CIS	20.9	100			39.9			39.9	834
Central European countries	6.2	95	5		43.6			43.6	270
China	43.7	20	10	70	34	42	54	48.8	2 133
India	12.2	50	50		36.5	50		43.3	528
Other Asia	13.3	100			37			37.0	492
Latin America	9.0	100			36			36.0	324
Africa	4.0	100			36			36.0	144
Middle East	8.5	100			36			36.0	306
Oceania	1.2	100			36			36.0	43
World	**145.4**	**70.5**	**8.5**	**21**				**41.6**	**6 047**

Sources: IFA for type and production of feedstock, 2006; USGS, 2006; IEA data.

Natural gas costs are 70 – 90% of the production cost of ammonia. So, when natural gas prices increase, production costs for ammonia rise. This may or may not translate into higher ammonia prices, depending on the global supply situation. Because gas prices play such an important role, the energy efficiency of gas-based ammonia plants tends to converge while newer plants have similar efficiencies across regions.

The Integrated Pollution Prevention and Control Directive of 2006 refers to twenty-six techniques and technologies that aim at improved energy efficiency, emissions reduction and waste management. Technologies that can increase energy efficiency in ammonia plants include improvements in the reforming section, such as the use of gas-heated reformers (GHR) that offer smaller surface areas and heat loss. Palladium membrane units for hydrogen separation can provide a 2 GJ/t savings. CO_2 removal technologies, product ammonia separation and developments in ammonia synthesis can all improve energy consumption (Rafiqul, 2005).

In most ammonia plants, CO_2 is separated from hydrogen at an early stage, generally using solvent absorption. Energy savings can be achieved by using new solvents, with a potential of up to 1.4 GJ/t. Much of the CO_2 separated is used to produce urea, a popular type of nitrogen fertilizer. It takes 0.88 tonnes of CO_2 to produce a tonne of urea.

The average natural gas steam reforming plant in the United States or Europe uses 35 – 38 GJ/t ammonia; the most energy efficient technology uses 28 GJ/t (auto-thermal reforming process). The auto-thermal reforming process combines partial oxidation and steam reforming technology. According to the European Fertilizer Manufacturing Association (EFMA), two plants of this kind are in operation and others are at the pilot stage (EFMA, 2000).

The theoretical minimum energy use for the production process is 21.2 GJ/t ammonia, given that three atoms of hydrogen are needed per molecule of ammonia and hydrogen has a lower heating value of 120 GJ/t. But the LHV of ammonia is only 18.7 GJ/t. As a consequence, 2.5 GJ of residual heat is generated in the production process and may be used for other purposes. Given the theoretical minimum, current natural gas-based ammonia production achieves about 60% efficiency.

The International Fertilizer Industry Association conducted an industry wide benchmarking study to compare the energy efficiency of 66 ammonia production plants with ages from one to thirty-five years (IFA, 2006). Average energy use for ammonia production of the benchmarked plants is 36.9 GJ/t, and range is from 28 – 53 GJ/t of ammonia. The highest capacity plants generally had the best efficiency. Older plants (20+ years) had energy efficiencies 8 – 10 % lower than the newer plants. This benchmark excludes plants in China. CO_2 emissions ranged from 1.5 – 3.1 Mt CO_2/Mt ammonia. The average CO_2 emissions were 2.1 Mt CO_2 /Mt of ammonia, with two-thirds process related and one-third from fuel combustion. Significant amounts are captured for the production of urea. Compared to the BAT of 28 GJ/t, the energy saving potential is almost 2 EJ per year. However, this would imply a complete switch to natural gas feedstocks. Hence, a reduction in the energy consumption by 40% and greenhouse gases emissions by an additional 160 Mt CO_2 equivalent is possible.

China and India, which account for 40% of global ammonia production, are interesting case studies. China is the largest ammonia producer in the world and produced 43.7 Mt in 2005, almost 30% of global production. Chinese ammonia production is unique because of its feedstock mix: 70% is derived from coal, 10% from oil products and only 20% from natural gas. The coal-based production is about 10% in medium-scale plants and 90% in small-scale plants. Energy efficiency relates to feedstock type and the scale of production and in China is about 34 GJ/t ammonia for gas-based, 42 GJ/t for oil-based, 55 GJ/t for medium size coal-based and 53 GJ/t for small-scale coal-based ammonia production. The average energy use amounted to 48.8 GJ/t ammonia in 2005. Of the coal-based production, about 2.4 Mt of capacity uses western technology with a plant size of about 0.4 Mt/yr. Many more coal-based plants are planned. Higher natural gas prices may result in a wider uptake of the coal-based technology. A number of Chinese plants use western gasification technology (GE and Shell) which accounted for 2.4 Mt of ammonia capacity in 2004. Seventeen plants with the gasification technology are planned representing 8.3 Mt of ammonia capacity.

India is the second largest ammonia producer in the world with production of 12.8 Mt in 2005 (Karangle, 2007). About two-thirds of the production capacity in India is based on natural gas, the remainder uses naphtha and fuel oil. Gas-based plants use on average 36.5 GJ/t ammonia, naphtha-based plants 39 GJ/t and fuel oil-based plants between 48 – 87 GJ/t. The average energy consumption in India has been significantly reduced from 96 GJ/t in the 1960s to 38 GJ/t today, due to a combination of feedstock changes, increased plant size and use, and process technology improvements.

A case study for revamping a 1980s vintage 900 Mt/day ammonia plant in India is given by Karangle (2007). The upgrade includes modification of the primary reformer and the steam super heaters, changes in the process air compressor, a CO_2 removal system and other schemes. The plant energy consumption declines from 46.9 – 36.4 GJ/t. Such energy efficiency savings could generate about 130 000 Certified Emissions Reduction (CER) financial benefits from the Clean Development Mechanism (CDM) under the Kyoto Protocol.

The China and India cases highlight that it is important to take into account the feedstock situation when energy efficiencies are compared. The energy efficiency of like installations is similar in industrialised and developing countries, and a limited number of equipment suppliers are responsible for most new installations. Therefore, a global technology development approach is needed for improved energy efficiency in ammonia production.

Combined Heat and Power

The chemical and petrochemical industry is one of the largest users of combined heat and power (CHP or cogeneration), particularly since the 1980s (see Chapter 9). CHP offers energy efficiency, economic, emission reduction and energy security advantages.

In the United States, 24 GW or 34% of the CHP capacity was in the chemical industry in 2004 (EEA, 2004). Additional technical potential in the industry in the United States is estimated to be more than 7.8 GW power and 0.5 EJ steam. As most of the installed base is for large facilities, there is significant potential for smaller units, less than 20 MW (Hedman, 2005). However, economies of scale rule against investments in smaller plants.

Table 4.16 ▶ ***CHP Use in the Chemical and Petrochemical Industry***

Country	Estimated CHP Use *GW*	Year
United States	24	2004
Japan	1.6	2006
Germany	2.6	2003
Netherlands	0.3	2003
Spain	0.6	2003
China	3.0	2005
Italy	0.7	2003
Russia	0.7	2004
Canada	1.7	2004

Sources: COGEN Europe; Canadian Industrial Energy End-Use Data and Analysis Centre; Energy Environment Analysis, Inc.; China Energy Conservation Investment Corporation; CENEF; IEA statistics and estimates.

ExxonMobil reports a worldwide installed cogeneration capacity of 3.7 GW in its facilities in 2006, equivalent to a reduction of 9 Mt of CO2 per year. The company plans to increase that capacity 35% by 2010 (Meidel, 2006). Dow Chemical produces 75% of its electricity from cogeneration for a savings of 0.034 EJ in 2004 (energy represents more than 50% of the total company costs) (Mills, 2006).

It is difficult to capture the various flows of CHP use in IEA statistics. For example, if the heat is used by the producer, part of the fuel use of the cogeneration plant is reported under industrial fuel use, rather than under CHP. Moreover, electricity production from CHP is not split by sector in IEA statistics. This makes it difficult to track CHP trends. Table 4.16 is an estimate of CHP use in several key chemical and petrochemical producing countries.

Plastics Recovery Options

Three key recovery options exist for plastics: mechanical recycling; feedstock recycling; and energy recovery. As only 20 – 30% of plastic waste can be mechanically recycled the remainder can be used for energy recovery, for which the industry sees large potential for energy gains. The promotion of plastics recovery is important to enhance the products' sustainability. New advanced recovery technologies could help boost this performance (Plastics Europe, 2006).

Today, only 10 Mt of plastic waste are recycled which is less than 10% of the overall waste generated, however with significantly higher percentages in the United States, Japan and Europe (Table 4.17). About 30 Mt of plastic waste is incinerated. Energy recovery is approximately 500 – 750 PJ (primary energy equivalent) (3% energy use in production). Recycling of 10 Mt represents 500 PJ of energy savings.

The general trend is toward less land fill or incineration without energy recovery and more recycling and energy recovery. Worldwide consumption amounts approximately to 235 Mt/yr and approximately half of this potential could be used for recycling and energy recovery. Assuming energy content on the order of 30 – 40 GJ/t of waste, the primary energy saving potential is estimated to be 2 – 4 EJ per year.

Table 4.17 ▶ *Plastic Recycling and Energy Recovery in Europe*

(%)

	Recycling	Energy Recovery	Un-recovered Waste
Denmark	5.6	66.6	27.8
Netherlands	10.0	50.8	39.2
Sweden	10.1	50.2	39.7
Germany	29.9	25.4	44.7
France	7.9	33.1	59.0
Austria	18.8	21.0	60.2
Belgium	12.8	25.8	61.4
Greece	1.7	17.9	80.4
Italy	8.5	7.2	84.3
Finland	10.3	5.2	84.5
Spain	7.5	5.6	86.9
United Kingdom	6.2	5.9	87.9
Portugal	3.0	8.7	88.3
Ireland	4.1	0.0	95.9
EU Average	**11.3**	**19.3**	**69.5**

Sources: Ingham, 2006; Association of Plastics Manufacturers in Europe, 2001; Plastics Europe, 2004.; EPRO, 2006; Ida, 2006.

Energy and CO_2 Emission Indicators for the Chemical and Petrochemical Industry

Energy indicators for petrochemicals are different than for other sectors because most of the carbon and a large share of the feedstock energy content are stored in the products (Patel, 2003). A lack of energy use data on a specific product level makes individual process indicators infeasible. Much of the energy data necessary to perform a more detailed analysis is not available due to anti-trust issues, limitations on statistical data and site energy integration. Thus an aggregate product indicator is proposed. Forty-nine products have been identified to be included in an aggregate indicator (Table 4.18). These products represent more than 95% of all energy used in the chemical and petrochemical industry (Tam and Gielen, 2006). These indicators are intended for comparisons across different material categories; life cycle analysis (LCA) methods are better suited for such comparisons.

Energy Efficiency Index Methodology

The proposed methodology for calculating an energy efficiency index (EEI) is:

- Use IEA energy statistics for final energy use in the chemical and petrochemical sub-sector.
- Define a best practice technology (BPT) value for each of the 49 products.
- Multiply production volumes and BPT to calculate practical minimum energy use.
- Divide practical minimum energy use and actual energy use (final energy). This is the energy efficiency index.
- 1 – Energy efficiency index = improvement potential.

Feedstock energy use is included, but electricity use is excluded. The reason is that analysis showed that the bottom-up process data can explain only a small share of total electricity use. The bulk of the electricity use is accounted for by pumping equipment for pipelines and storage tanks and auxiliary use for which no detailed data exist. More analysis is recommended.

Production volumes for benzene, toluene and xylene (BTX) have been split between production from steam cracking and naphtha extraction. This split has been calculated based on the production volume of ethylene and it accounts for the more energy-intensive nature of production from steam cracking versus naphtha extraction. The same split has also been applied for propylene from steam cracking and fluidised catalytic crackers (FCC).

Best practice technology (BPT) energy values are provided on a worldwide consolidated basis in Table 4.18. More than 16% energy efficiency improvements can be obtained by applying state-of-the-art technologies. This is a limited potential with a projected growth in chemicals and petrochemicals of more than 100% over the next three decades, energy and feedstock use will increase significantly (IEA, 2006).

The energy efficiency analysis results are shown in Table 4.19. While the present efficiency indicators should not be used for country comparisons, monitoring their evolution over time provides valuable information on trends in the industry's efforts to improve energy efficiency. The calculated BPT energy use (excluding electricity) for the 49 products was 24 EJ compared to actual energy use (excluding electricity) of 29 EJ. As the calculated BPT figure covers 95% of total energy use in the industry, an adjustment is required and hence the total BPT for the industry is estimated to be 25 EJ, which represents a savings potential of 4 EJ if energy use (excluding electricity) were based on BPT.

Table 4.18 ▶ *Best Practice Technology Energy Values, 2004*

2004	Production Volume	Feedstock	Heat	Steam	Energy Use Excluding Electricity	Calculated Global Best Practice Energy Use
	Ktonnes/yr	*GJ/tonne*	*GJ/tonne*	*GJ/tonne*	*GJ/tonne*	*PJ/year*
Organic						
Acetic acid	9 300		30	4.48	34.48	321
Acetone	4 942			9.77	9.77	48
Acrylonitrile	5 372		–6		–6	32
Benzene (steam cracking)	14 680	42.6	20.07	7.01	69.68	1023
Benzene (naphtha extraction)	22 020	42.6	2.4	5	50	1 101
Butadiene	9 441			6	6	57
Butylene	20 334	47	3		50	1 017
Butanol	2 791			3.27	3.27	9
Cumene	9 690		2.05	–2.8	–0.75	–7
Ethylene	103 283	47.2	12.8		60	6 197
Ethylbenzene	27 163			3.28	3.28	89
Ethylene dichloride	37 608		4.42		4.42	166
Ethylene glycol	15 251		0.94	4.37	5.31	81
Ethylene oxide	16 725		3.09		3.09	52
Formaldehyde	25 803	10		–4.77	5.23	135
Isopropyl alcohol	1 881		5.2	5.4	10.6	20
Maleic anhydride	1 441			2	2	3
Melamine	1 566			2	2	3
Metacrylate	2 636			2	2	5
Methanol	34 668	20		8.5	28.5	988
Methyl tert butyl ether	19 218			3.9	3.9	75
Phenol	7 588			9.1	9.1	69
Phthalic anhydride	3 815		20		20	76
Propylene	42 928	46.7	13.3		60	2 576
Propylene FCC	23 682	46.7	3.3	1.5	51.5	1 153

Table 4.18 ▶ ***Best Practice Technology Energy Values, 2004*** *(continued)*

2004	Production Volume *Ktonnes/yr*	Feedstock *GJ/tonne*	Heat *GJ/tonne*	Steam *GJ/tonne*	Energy Use Excluding Electricity *GJ/tonne*	Calculated Global Best Practice Energy Use *PJ/year*
Purified terephthalic acid	29 015			2.6	2.6	75
Styrene	24 284			3.6	3.6	87
Toluene (steam cracking)	7 340	43.5	23.5		67	492
Toluene (naphtha extraction)	11 010	43.5	6.5	5	55	606
Toluene diisocyanate	1 566	24.8		21.7	46.5	73
Xylene (steam cracking)	10 541	41.3	25.7		67	706
Xylene (naphtha extraction)	15 810	41.3	8.7	5	55	870
p-Xylene	6 588		6.3	0.8	7.1	47
Vinyl chloride monomer	30 753		2.7		2.7	83
Plastics						
Phenolic resins	3 195	20		10	30	96
Polycarbonate	2 700			12.9	12.9	35
Polyethylene, high densit	29 969			1.4	1.4	42
Polyethylene, low density	29 969		0		0	22
Polyethylene terephthalate	37 798		4.1		4.1	155
Polypropylene	38 214			1.4	1.4	54
Polystyrene	15 298		0.5	0	0.5	8
Polyvinyl chloride	30 042			2.2	2.2	66
UF & other resins & fibres	57 683			2.5	2.5	144
Synthetic rubber & latex	9 097		6		6	55
Inorganic						
Ammonia	140 000	21	7		28	3 920
Carbon Black	9 000	32.8			32.8	295
Sodium Hydroxide & Chlorine	45 000		0.6		0.6	27
Titanium dioxide	4 400		22	5.6	27.6	121
Soda Ash	38 000			10	10	380
Total – Calculated Excluding Electricity						**23 682**

Sources: Neelis, *et al.*, IPPC; SRI Consulting; MET; IEA estimates.

The results of this analysis highlight a number of issues related to data quality. BTX produced from naphtha extraction and propylene from FCC generally are produced in refineries which may lead to some accounting issues in IEA energy statistics as energy use for petrochemicals produced at a refinery will likely be accounted for in the refinery category rather than the chemical and petrochemical category. Feedstock energy use was reported in IEA statistics under total energy use for the sub-sector until recently, but now is excluded, which may have lead to some problems in country reporting and subsequent analysis based on the data. In this study, energy and feedstocks are aggregated. Concerns on under-reporting arise when the EEI is found to be almost 1: United Kingdom and Italy have EEI's above 0.9. Further analysis is recommended.

Table 4.19 ▶ ***Indicator Use for Country Analysis of Global Chemical and Petrochemical Industry***

	Reported Energy Use *PJ*	BPT Calculated Energy Use *PJ*	Energy Efficiency Index	Improvement Potential *%*
United States	6 862	4 887	0.70	29.8
Japan	2 130	1 917	0.90	10.0
China	3 740	2 975	0.80	20.5
Saudi Arabia	1 115	917	0.82	17.8
Germany	1 157	1 044	0.90	9.8
Netherlands	618	508	0.82	17.8
France	654	582	0.88	11.0
Brazil	577	478	0.83	17.2
United Kingdom	490	460	0.94	6.2
India	1 091	910	0.84	15.8
Chinese Taipei	741	599	0.81	19.2
Italy	389	365	0.94	6.2
World	**28 819**	**23 682**	**0.82**	**17.8**

Sources: IEA statistics; SRI Consulting; METI.

CO_2 Emissions Index

A CO_2 emissions index has been developed that builds on the energy efficiency index. It covers only direct CO_2 emissions and excludes emissions for power generation and emissions in energy recovery from petrochemical products. The emissions have been calculated based on energy and feedstock use data from IEA statistics. The fossil fuels have been multiplied with their carbon content and a correction has been applied for carbon storage in synthetic organic products. The carbon storage has been calculated based on physical production volumes and carbon content of individual petrochemical products. Carbon storage in urea fertilizer has not been credited due to the short life span of this application. One could argue that this is not a direct industry emission. Worldwide about 95 Mt of CO_2 are used per year for urea production (0.88 tonnes of CO_2 per tone of urea).

The CO_2 emissions index compares the industry's calculated direct CO_2 emissions with an ideal minimum based on using only natural gas for the BPT-based process steam and heat requirements. To make this index comparable across countries, electricity related emissions have been excluded. Emissions from feedstocks are based on actual feedstock use. Table 4.20 shows the estimates for carbon storage in plastics for the countries in this analysis.

Table 4.20 ▶ ***Carbon Storage for Plastics in Selected Countries, 2004***

	Mt CO_2 equivalent / *year*
United States	131.2
Japan	38.1
France	17.6
Germany	30.9
Netherlands	10.3
Italy	14.3
Chinese Taipei	36.1
United Kingdom	8.8
Saudi Arabia	15.3
Brazil	17.8
China	131.9
India	25.0
Carbon storage	**477.3**

Source: IEA estimates.

Some of the locked-in energy value can be recovered when the product is incinerated, which results in CO_2 emissions at the waste treatment stage. The appropriate CO_2 credit for energy recovery from plastics waste is unclear and for simplicity energy recovery and plastics recycling is not included in this CO_2 index. Moreover, it is small, as 30 Mt is incinerated (Chapter 10): 100 Mt CO_2, 1 EJ energy content. It is proposed to develop a separate life cycle CO_2 index that would include waste treatment, energy recovery and recycling at a later stage.

Table 4.21 shows the total direct emissions for the key chemical and petrochemical producing countries. The CO_2 index reflects not only CO_2 savings from fuel switching, but also reductions related to improved energy efficiency if energy use was based on

BPT. As for the energy efficiency index, the results show that there are some uncertainties around the quality of available statistics. For CO_2 emissions an under- or over-reporting of feedstock use, which is now accounted separately, will alter the results. The results of the CO_2 index indicate that this appears to be the case.

Table 4.21 ▶ ***Total CO_2 Emissions and CO_2 Index, 2004***

	Mt CO_2 / *yr*	CO_2 Index
United States	275.0	0.50
Japan	120.1	0.73
France	24.3	0.70
Germany	46.8	0.62
Netherlands	22.7	0.77
Italy	10.1	0.55
Chinese Taipei	13.4	0.16
United Kingdom	19.4	0.71
Saudi Arabia	53.1	0.76
Brazil	13.6	0.43
China	117.7	0.17
India	51.0	0.68
World	**1 141.8**	**0.68**

Sources: SRI Consulting; IEA statistics and estimates.

Life Cycle Index

In addition to the energy efficiency and CO_2 emissions index, a life cycle indicator is proposed to give credit for renewable feedstocks and recovery of post-consumer plastic wastes for recycling or energy recovery. The methodology proposed for this indicator is:

1) Use IEA energy statistics for final energy use in the chemical and petrochemical sub-sector.
2) Define a best practice technology (BPT) value for each of the 49 products.
3) Multiply production volumes and BPT to calculate practical minimum energy use.
4) Account for energy and feedstock use for bio-plastics and other synthetic organic materials from natural feedstocks
5) Add energy use for recycling to actual energy use. Subtract energy recovery (from waste plastics) from actual energy use.
6) Add energy that would have been used in primary olefins and plastics production for the recycled production volume to practical minimum energy use. This is the adjusted practical minimum energy use
7) Divide adjusted practical minimum energy use and adjusted energy use (defined as the IEA energy use adjusted for recycling and waste plastic energy recovery). This is the life-cycle index.

Data availability on waste plastics recovery, mechanical recycling and energy recovery is an issue for certain countries. This methodology has been applied to Japan to show how a life cycle approach could impact this analysis. An adjusted energy use of 2 121 PJ is calculated for Japan and an adjusted practical minimum energy use of 1 974 PJ, which gives a life cycle index of 0.93 in 2003. When credit is given for waste plastics recovery, the efficiency potential falls from 17 – 7%. Japan's waste plastics recovery represents an efficiency gain of 10%.

The advantage of the proposed indicator methodology presented in this chapter is that it is feasible based on existing energy data and allows for country comparison, provided the data quality is improved. The disadvantage to this approach is that it is not suited to identify which processes to focus on efficiency gains. The list of products may also be incomplete and accounting issues related to petrochemicals produced at the refinery may underestimate energy efficiency opportunities. The quality of IEA energy statistics as reported by countries is not fully transparent and constitutes a source of uncertainty.

Energy Efficiency Potential

The results of the indicators analysis show a potential savings of 4 EJ in heat use in the chemical and petrochemical industry (Table 4.22). This analysis excludes electricity. However, assuming a general industrial electricity savings potential of 25%, there is an additional savings potential from electricity of 1 EJ for a total process energy savings potential of 5 EJ. Potential savings from increased recycling and energy recovery is estimated to be 2 – 4 EJ. Assuming that one-third of the overall CHP potential at 5 EJ is available in the chemical and petrochemical industry sector, then an additional 1.5 – 2 EJ could be saved from more use of CHP. Total energy savings potential from process energy use and systems/life cycle options are estimated to be 8.5 – 11 EJ per year. This includes 1 EJ electricity so final and primary energy saving potentials are almost equal.

Table 4.22 ▶ ***Energy Savings Potential in the Chemical and Petrochemical Industry***

	Estimated Savings *EJ*
Heat	4
Electricity	1
Recycling and Energy Recovery	2 – 4
CHP	1.5 – 2
Total	**8.5 – 11**

Note: Heat, electricity and recycling are expressed in final energy units. Energy recovery and CHP refer to the energy content of the waste and saved fuel.

Source: IEA estimates.

IRON AND STEEL INDUSTRY

Key Findings

- *Iron and steel has a complex industrial structure, but only a limited number of processes are applied worldwide and they use similar energy resources and raw materials. A large share of observed differences in energy intensities and CO_2 emissions on a plant and country level are explained by variations in the quality of the resources that are used and the cost of energy, which determines the cost-effectiveness of energy recovery technologies.*
- *The boundaries used to develop indicators of energy use in the iron and steel industry must account for common practices: iron ore pellets, coke and scrap are widely traded commodities; blast furnace gas and coke oven gas is sold for power generation; slag by-products can be used as a substitute for cement clinker. Uniform boundaries are needed for proper comparison purposes.*
- *More detailed data are needed to better separate the blast, basic oxygen, electric arc furnaces and direct reduced iron processes because a comparison of the energy efficiency of these fundamentally different processes is of limited value. It is not possible to develop suitable indicators for steel rolling and finishing on an aggregate level.*
- *On a worldwide basis, the iron and steel industry has achieved important efficiency gains in over the last two decades. Yet the world average, however, has not improved substantially since most growth was concentrated in China, which has relatively low average efficiency.*
- *Waste energy recovery in the iron and steel industry is most common in countries with high energy prices and ambitious efficiency policies. The waste heat is used in steel production processes or for power generation.*
- *The energy and CO_2 emission benefits of some technology options such as dry coke quenching and top pressure-turbines are viewed differently by experts particularly concerning the benefits on the level of the full production process or the site. The cost-effectiveness of these options depends on the local energy prices.*
- *The average efficiency of the iron and steel industries in China, India, Russia and Ukraine account for nearly half of global iron production and more than half of the industry's CO_2 emissions. Their average efficiency is notably lower than in OECD countries. Outdated technologies such as open hearth furnaces are still in use in Russia and Ukraine. In India, coal-based direct reduction iron production can use the local low quality resources and be developed on a small scale, but such developments carry a heavy environmental burden. In China, low energy efficiency is mainly due to a high share of small-scale blast furnaces, a high share of inefficient coking plants and low quality ore.*
- *The average efficiency of the iron and steel industries in OECD countries is close and data are not sufficiently detailed to allow a ranking.*
- *Based on country comparisons with best available technology, the remaining energy efficiency potential in the iron and steel industry at today's production level is about 2.3 to 2.9 EJ per year of primary energy and 220 to 270 Mt CO_2 emissions reduction. Saving effects outside the iron and steel industry, e.g. increased recovery of steel scrap (about 0.5 EJ per year), and further potentials in the industry for which accurate data are lacking may increase the savings to 5 EJ per year of primary energy and 360 Mt CO_2 emissions. Further analysis to validate this estimate is recommended.*

Introduction

The manufacture of iron and steel has a complex industrial structure. Yet it only has a small number of processes that are employed worldwide and they use similar raw materials and energy forms. What matters from an energy efficiency and carbon dioxide (CO_2) emissions perspective are the quality of the resources used and the costs of energy, which determines the cost-effectiveness of energy recovery technologies.

This chapter looks at the significance of drawing boundaries for analytical purposes for an industry in which commodities are traded, waste heat is sold and by-products can be useful inputs to other industries to improve efficiency and reduce CO_2 emissions. It describes the steps from iron ore agglomeration to making coke for the chemical reduction of the iron ore to various furnace technologies and practices to steel finishing and their energy use. It estimates technical potential for energy efficiency gains and CO_2 emission reductions based on best available technology.

Global Importance and Energy Use

According to IEA statistics, total final energy use by the iron and steel industry, including coke and blast furnaces, was 21.4 EJ in 2004. Global steel production was 1 057 million tonnes (Mt) in 2004. The average energy intensity is 20.2 gigajoules per tonne (GJ/t) of steel. Globally the iron and steel industry accounts for the highest share of CO_2 emissions from the manufacturing sector, at about 27%. This is due to the energy intensity of steel production, its reliance on coal as the main energy source and the large volume of steel produced.

There are two basic methods for making crude steel:

- Coke oven – blast furnace – basic oxygen furnace process, which uses iron ore and scrap;
- Electric arc furnace process, which uses direct reduced iron, scrap and cast iron.

The first process uses mainly iron ore and accounts for two-thirds of steel production. The electricity arc furnace process uses mainly scrap and accounts for 34% of steel production. Only 3% of all steel is produced in other processes such as open-hearth furnaces, which are out-dated.

Iron ore is used to make iron which is then converted into steel. There are two types of iron products: pig iron and direct reduced iron (DRI). For nearly the past twenty years, almost 60% of steel has been derived from pig iron (also called hot metal), although the share of steel produced from DRI has steadily increased. Pig iron is produced in blast furnaces. Today, about 5% of global steel is produced from DRI, while 35% of all crude steel is derived from scrap.[1] These developments are important because they significantly affect energy use and CO_2 emissions.

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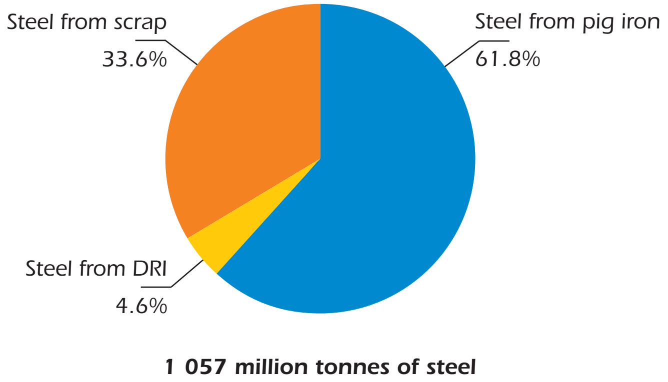
[1] According to the International Iron and Steel Institute (IISI), the scrap recycling rate is 42.3% (IISI, 2005). This is calculated as the ratio of steel scrap used and crude steel produced. In this study, however, the recycling rate is defined as the ratio of crude steel produced from scrap and total crude steel production. This results in a somewhat lower ratio because of material losses during scrap conversion into steel. The basic material flows for both approaches are the same. The contribution of scrap can also be calculated as the difference of total crude steel production and steel production from pig iron and DRI, which confirms the figures in this study. What is of most interest here is not the actual recycling rate, but rather the additional recycling potential.

Figure 5.1 shows steel production by process. This categorisation differs from the conventional split between basic oxygen furnace (BOF) and electric arc furnace (EAF) production to allow a more detailed analysis of the importance of DRI and scrap recycling. EAFs can use scrap, DRI or pig iron. But some amounts of scrap are also recycled in BOFs (10 – 30% in some countries), and also DRI can be added to BOFs. Total scrap consumption for steel making amounted to about 450 Mt in 2004; significant amounts of steel scrap are also used for the production of cast iron.

While the amount of scrap that is recycled into steel production has increased significantly, its share in total steel production has decreased slightly. This is due to rapid growth of steel production worldwide and improved plant production yields. Another significant factor is that the growth of steel production in the last decade has been concentrated in China, a country without scrap reserves. In absolute terms, total recycling of scrap from used products for steel making has increased substantially from 100 Mt in 1970 to 260 Mt in 2003, as more products have reached the end of their useful life and scrap recovery systems have improved.

Figure 5.1 ▶ ***Global Steel Production by Process, 2004***

Key point: Most steel is produced from pig iron.

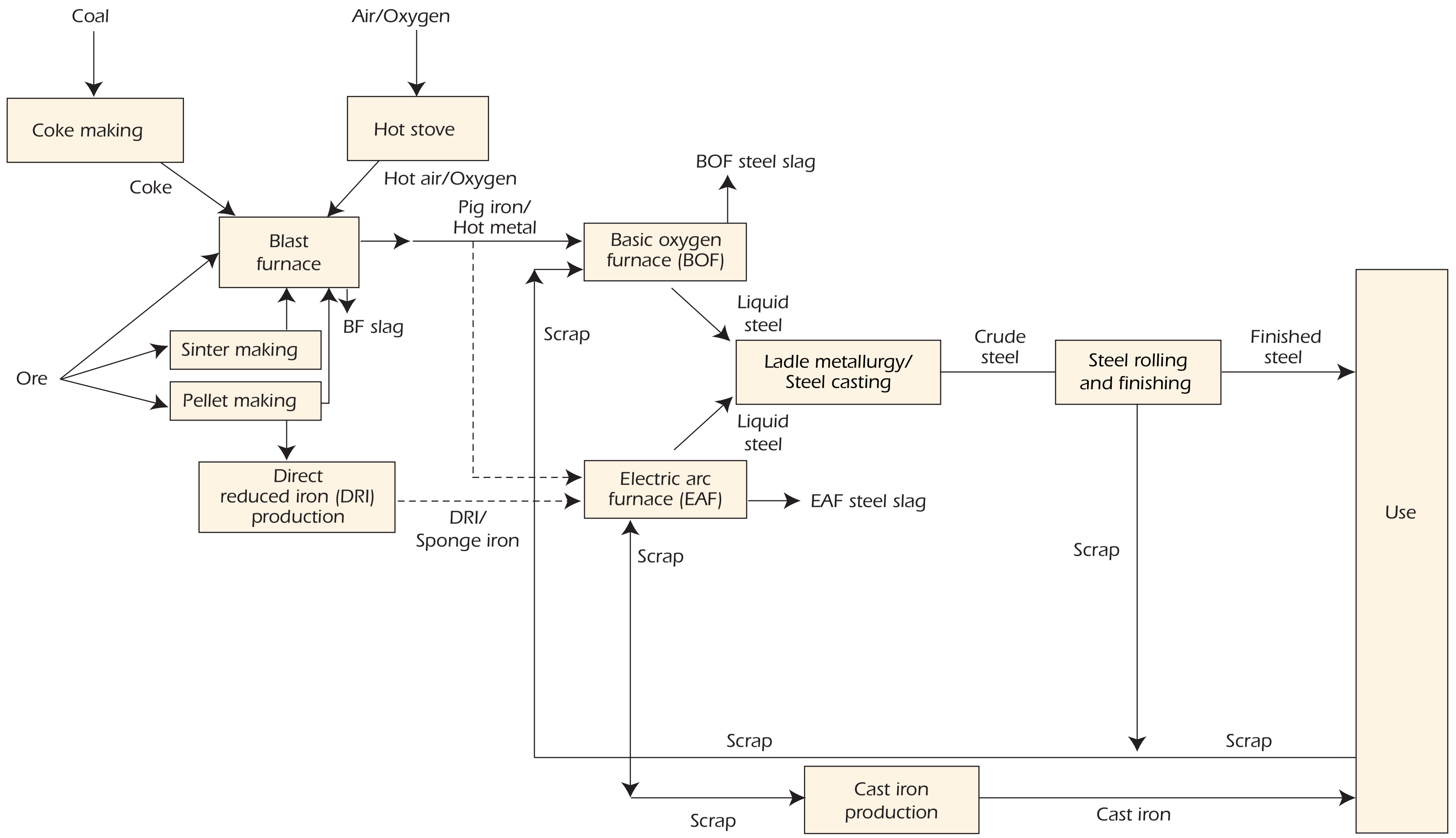


Sources: International Iron and Steel Institute (IISI), 2005; IEA, 2006.

Figure 5.2 shows the steel production processes and flows. Iron ore is either directly used or is converted into sinter and pellets. The blast furnace is fed with coke from the coke oven, preheated air (blast) from the hot stove and ore, sinter and/or pellets. Liquid hot metal is tapped at the bottom of the blast furnace and is further refined into liquid steel in the basic oxygen furnace. The liquid steel product is further purified in ladle metallurgy processes and cast. The crude steel product is further processed by hot and cold rolling, tempering, annealing and coating, depending on the desired product shape and quality.

Figure 5.2 ▶ ***Steel Production Scheme***

Key point: All steel making processes are closely interlinked.



Most of the energy consumption is related to the blast furnace process at about 10 – 13 GJ/t crude steel, including the hot stove. Other big uses of energy are in sintering (2 – 3 GJ/t crude steel), coke-making (0.75 – 2 GJ/t crude steel) and steel-rolling (1.5 – 3 GJ/t crude steel). Ladle metallurgy and casting is of secondary importance (0 to 1 GJ/t steel). Production of DRI using natural gas requires approximately 12 GJ/t crude steel, while electric arc furnaces use 1 – 1.5 GJ of electricity per tonne of crude steel. Cast iron is usually produced in small-scale blast furnaces with a low efficiency compared to large blast furnaces for steel production.

Indicator Issues

This section discusses the methodological issues for energy indicators analysis in the iron and steel industry and the approaches taken in this study.

System Boundaries

Coke ovens and blast furnaces are reported separately in the energy transformation category in IEA statistics. The iron and steel industry category in IEA statistics includes ISIC Group 271 (manufacturing of basic iron and steel) and Class 2731 (casting of iron and steel). Production of steel alloys and production of cast iron is included in this iron and steel industry category (UN, 2002).

Product and Process Differentiation

In order to analyse energy use in iron and steel production it needs to be clear whether the data treat products and feedstocks equally or if they are differentiated. For example, are steel and cast iron treated as a single product category, and are steel from ore and scrap treated as a single category? Trying to assess energy use in a production category that contains both cast iron and steel is not meaningful, as they are quite different products.

As well, scrap availability is influenced by the maturity of the economy and trade patterns. It is not useful to compare countries that have ample scrap to those with poorer resources and conclude that scrap-rich countries are more energy efficient. Virtually all available scrap is recycled. So steel production from ore and scrap needs to be treated as separate processes. However, there is overlap as some 20 – 30% scrap (including about 10 percentage points in-plant scrap) is added to basic oxygen furnaces in the ore-based blast furnace process.

Energy demand for mining and beneficiation of iron ores is not included in this analysis. As most iron ore pellets are produced at the mine, the energy use for pellet making is usually not accounted for in the iron and steel making category. This creates an implicit energy and CO_2 "benefit" for producers that buy pellets, compared to those that use sinter, which is always produced on-site.

Allocation Issues

The iron and steel industry has complex flows of energy and materials. Most of the commodities can be sold "over the fence" and some can be shipped long distances.

As a consequence, the full production chain of energy use and CO_2 emissions may be considerably higher or lower than the site footprint would suggest. The main issues are:

Effects that reduce CO_2 emissions at the site, but increase CO_2 emissions elsewhere:

- ▷ Buying pellets (pelletising);
- ▷ Buying coke (coke making);
- ▷ Higher scrap use rate for basic oxygen furnace (implies less scrap for electric arc furnace);
- ▷ Buying direct reduced iron;
- ▷ Buying oxygen (oxygen making, often outsourced to industrial gas suppliers);
- ▷ Buying lime (used for pellet making and in blast furnaces);
- ▷ Buying steam and electricity.

Effects that do not reduce CO_2 emissions at the site, but reduce CO_2 emissions elsewhere:

- ▷ Selling coke by-products;
- ▷ Selling granulated blast furnace slag as cement clinker substitute;
- ▷ Selling steel slag as feedstock for cement kilns;
- ▷ Selling blast furnace gas (to power producers);
- ▷ Selling coke oven gas (to power producers);
- ▷ Selling electricity, steam and low-temperature heat;
- ▷ Selling nitrogen (a by-product of oxygen production).

While these issues can be significant at the level of individual plants, they are less relevant at a country level.

As the production of primary steel is the basis for steel recycling, one could argue that steel producers that use ore could be credited with future CO_2 savings from steel scrap use. Obviously such an approach would create complicated allocation problems and would do nothing to reduce CO_2 emissions in steel production. This approach is not used in this study.

Table 5.1 shows the relevance of certain allocation issues, given a reasonable set of assumptions for their relevance on a country level. The impact is calculated in three ways: at the iron and steel plant; elsewhere; and the total net impact. For example, if the coke is produced at the iron and steel plant and subsequently the company decides to buy its coke instead, this will reduce energy use and CO_2 emissions on-site, but there will be zero net effect on a global scale.

Table 5.1 suggests the impacts on energy use and CO_2 emissions of various practices depending on the system boundary choice. Two approaches are possible: very broad system boundaries or standardised comparisons with corrections for energy use and CO_2 emission effects elsewhere. The latter approach is used in this analysis within the constraints of data availability.

Table 5.1 ▶ ***Energy and CO_2 Emission Impacts of System Boundaries***

	Savings Steel Plant		Unaccounted Elsewhere		Net Effect Final	
	Final energy *GJ/tcs*	Emissions *$t\ CO_2/tcs$*	Final Energy *GJ/tcs*	Emissions *$t\ CO_2/tcs$*	Energy *GJ/tcs*	Emissions *$t\ CO_2/tcs$*
Ore mining			0.75	0.05	0.75	0.05
Ore + coking coal transport			1 – 2	0.1 – 0.2	1 – 2	0.1 – 0.2
Buying pellets	0.55	0.03 – 0.15	0.55	0.03 – 0.15	0	0
Buying coke	1 – 1.5	0.05 – 0.1	1 – 1.5	0.05 – 0.1	0	0
Buying scrap (less scrap for EAF) (+10 percentage points)	1.5	0.15	1.5	0.15	0	0
Buying DRI (+10 percentage points)	1.5	0.15	1.2 – 2	0.07 – 0.15	-0.3 – 0.5	-0.08 – 0
Buying oxygen	0.25	0 – 0.075	0.25	0 – 0.075	0	0
Buying lime	1	0.22	1	0.22	0	0
Selling granulated blast furnace slag			-0.7	-0.17	-0.7	-0.17
Selling steel as limestone substitute for cement kilns			0	-0.1	0	-0.1
Selling blast furnace gas (full allocation of CO_2 content to user)	0	-0.4	0	-0.4	0	0
Selling electricity & heat			-1	-0.1	-1	-0.1
Selling nitrogen	-0.2	0 – -0.06	-0.2	0 – -0.06	0	0
Total	**5.6 – 6.1**	**0.14 – 0.45**	**5.35 – 7.65**	**-0.16 – 0.33**	**-0.25 – 1.55**	**-0.3 – -0.12**

Note: tcs – tonne crude steel.
Source: IEA estimates.

Feedstock Quality Issues

Ore qualities differ in their chemical composition and iron content, which affects the energy needed for the reduction reaction to produce iron. The iron content of the ore affects the amount of slag by-product. The chemical composition of the gangue affects the amount of lime and limestone that must be added to achieve basicity of the slag.[2] In total these matters can make a 1 – 2 GJ/t difference in energy needs for a blast furnace. As steel producers tend to rely on local ores, this can make an important difference in country comparisons.

Coke quality is also important. Coal and coke are the main sources of sulphur, which must be removed with the slag. The higher the sulphur and gangue content, the more slag that will be generated. Moreover, the coke quality affects the amount of coke and coal that is needed in the blast furnace. While it affects total CO_2 emissions, it does not directly affect the net energy balance of the blast furnace, as a higher coke use rate implies production of more blast furnace gas. The coke quality depends on the coal quality, but also on the characteristics of the coking process. Most steel production facilities use good quality coking coal. However, in some countries, for example in India, some local coal with high gangue content is used.

Generally, it is not possible to account for differences of a few percentage points on a country level for developing indicators of energy use. However, some indicators can identify differences on the order of ten percent or more. Benchmarking and energy audits at a plant level are needed to identify more accurate improvement potentials. Results presented in this study are not suited for short-term target setting for reasons given.

Energy Indicators

Energy Intensity Indicators and Benchmarks

A broad based comparison on total sub-sector energy use per tonne of crude steel is of limited use because the production processes are so different. The blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) (scrap) processes need to be treated separately. Direct Reduced Iron (DRI) should also be treated separately. It is not possible to develop suitable indicators for steel finishing. The following list gives a set of ideal indicators. The data are lacking today to put this list into practice:

- Total final energy use per tonne of crude steel (including finishing).
- Total primary energy use per tonne of crude steel (including finishing).
- Total final energy use per tonne of BF-BOF steel (excluding finishing, with 12% bought scrap/DRI use, assuming 100% own production sinter/pellets/coke/oxygen/lime, no correction for feedstock quality).
- Total primary energy use per tonne of BF-BOF steel (excluding finishing, with default 12% bought scrap/DRI use, assuming 100% own production sinter/pellets/coke/oxygen/lime, no correction for feedstock quality).
- Total final energy use per tonne of DRI (split gas and coal-based processes).
- Total final energy use per tonne of EAF steel (excluding finishing).
- Total primary energy use per tonne of EAF steel (excluding finishing).

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[2] Gangue is the waste materials left over after removing the minerals from ore.

- ▷ Total direct CO_2 per tonne of crude steel (including finishing, with default 12% bought scrap/DRI use, assuming 100% own production sinter/pellets/coke/oxygen/lime, no correction for feedstock quality).
- ▷ Total CO_2 per tonne of BF steel (including correction for blast furnace slag+ steel slag use, BFG counted as coal in terms of CO_2 content per GJ, no correction for feedstock quality).[3]

It is recommended to improve the data collection to enable such analysis. New international efforts in this area are on-going in the framework of the Asia-Pacific Partnership (APP).

There is no international benchmarking activity in the iron and steel industry where plants with different ownership are compared. However, some national and regional comparisons have been developed, as summarised for Canada in Box 5.1. A similar benchmarking approach could be applied in other parts of the world. It is recommended to expand benchmarking for the iron and steel industry.

Box 5.1

Benchmarks in the Iron and Steel Industry in Canada

A recent benchmarking study In Canada assesses and compares four integrated steel plants and eight electric arc furnaces (NRCAN/CSPA, 2007). It considers fifteen separate processes and compares the efficiency of the Canadian plants with the Ecotech model plant, as defined by the International Iron and Steel Institute.

The average efficiency improvement potential for the Canadian plants is 25 – 30%. The study concludes that the blast furnaces and electric arc furnaces are close to the Ecotech plant level of efficiency. Further it finds that the coke oven efficiency is relatively low, but improvements would not be economic. Other key areas for efficiency improvements include:

- ▷ Enhanced by-product gas recovery;
- ▷ Improved cogeneration from waste gas;
- ▷ Enhanced efficiency of steam use;
- ▷ Improved efficiency of slab reheating furnaces.

Sources: IISI, 1998; Natural Resources Canada/Canadian Steel Producers Association, 2007.

Energy Intensity Analysis

This analysis focuses on the key iron producing countries. The seventeen countries listed in Table 5.2 represent more than 90% of global pig iron production. The analysis also focuses on the main steel producing countries of which the twenty-two listed in Table 5.3 represent 90% of total steel production. The lists differ somewhat because some countries, *e.g.* Turkey, Spain and the Other Asia region have a strong position in scrap-based EAF steel production.

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[3] The correction factor for blast furnace slag is 0.8 t CO_2/t slag; the factor for steel slag use in cement kilns is 0.5 t CO_2/t slag.

Table 5.2 ▶ *Pig Iron Production, 2005*

	Production *Mt/yr*	Share *%*	Cumulative Production Share *%*
China	330.4	42.1	42.1
Japan	83.1	10.6	52.6
Russia	48.4	6.2	58.8
United States	37.2	4.7	63.5
Brazil	33.9	4.3	67.9
Ukraine	30.8	3.9	71.8
Germany	28.9	3.7	75.5
Korea	27.3	3.5	78.9
India	26.1	3.3	82.3
France	12.7	1.6	83.9
Italy	11.4	1.5	85.3
Taiwan	9.4	1.2	86.5
United Kingdom	10.2	1.3	87.8
Canada	8.3	1.1	88.9
Belgium-Luxembourg	7.3	0.9	89.8
Australia	6.2	0.8	90.6
South Africa	6.1	0.8	91.4
Other	67.8	8.6	100.0
World	**785.5**	**100.0**	**100.0**

Source: IISI, 2006.

There is considerable difference in the energy efficiency of primary steel production among countries and even individual plants. For the blast furnace-BOF process, the gap in energy efficiency between the top and bottom country is about 50%. This is due to variations in plant size, level of waste energy recovery, quality of iron ore and quality control. A few plants still use outdated technologies such as open hearth furnaces and iron-and-steel-ingot casting (Table 5.3).

Figure 5.3 shows the energy intensity distribution of global steel production. The x-axis indicates the total final energy use and the y-axis indicates the final energy intensity, expressed in units of final energy per tonne of crude steel produced. It includes total energy use for steel production from coke making to furnace firing to steel finishing from IEA statistics, and divides it by total crude steel production.

Table 5.3 ▶ *Steel Production, 2005*

Total	Production Mt/yr	Share %	Cumulative Production Share %	BOF Steel %	EAF Steel %	Open Hearth Furnace Steel %
China	349.4	30.9	30.9	87.1	12.9	
Japan	112.5	10.0	40.9	74.4	25.6	
United States	94.9	8.4	49.3	45.0	55.0	
Russia	66.1	5.9	55.1	61.6	16.3	22.1
Korea	47.8	4.2	59.4	55.9	44.1	
Germany	44.5	3.9	63.3	69.3	30.7	
Ukraine	38.6	3.4	66.7	49.9	9.8	40.2
India	38.1	3.4	70.1	52.5	44.9	2.6
Brazil	31.6	2.8	72.9	76.2	22.0	
Italy	29.3	2.6	75.5	39.9	60.1	
Turkey	21	1.9	77.4	29.2	70.8	
France	19.5	1.7	79.1	62.5	37.5	
Taiwan	18.6	1.6	80.7	53.7	46.3	
Spain	17.8	1.6	82.3	24.5	75.5	
Mexico	16.2	1.4	83.7	27.8	72,2	
Canada	15.3	1.4	85.1	58.5	41.5	
United Kingdom	13.2	1.2	86.3	79.6	20.4	
Belgium	10.4	0.9	87.2	74.6	25.4	
South Africa	9.5	0.8	88.0	55.4	44.6	
Iran	9.4	0.8	88.9	26.2	73.8	
Poland	8.4	0.7	89.6	59.1	40.9	
Other	117.5	10.4	100.0			
World	**1 129.36**	**100.0**	**100.0**			

Source: IISI, 2006.

Each horizontal step represents a single country. Electricity use is not corrected for the efficiency of power generation. The graph shows a wide range of energy intensities from 4 – 40 GJ/t crude steel. However, 90% of the production is in the range of 14 – 30 GJ/t, but this is still a very wide range. The fact that primary steel making and EAF steel recycling are combined in one graph adds to the wide range. More detailed indicators are needed for meaningful comparisons.

In the IEA statistics, coke ovens, blast furnaces and other energy uses in the iron and steel industry are reported separately. Yet, analysis reveals that this data submitted from national sources need to be improved. For example, in some cases energy used to produce iron and steel is allocated and reported in the "other industry" category, which results in an under-estimation; or the use of energy by-products for power generation is improperly allocated to the iron and steel sector. Therefore, other sources of supplementary data were used for the detailed analysis of process energy efficiencies.

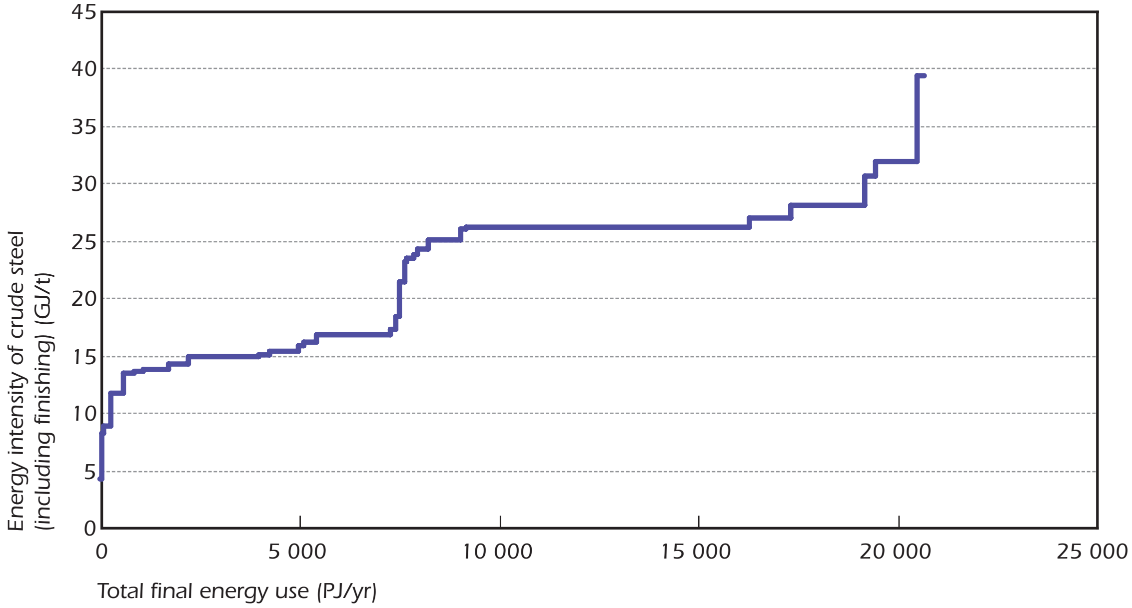
Efficiency Improvements

Worldwide the iron and steel industry has achieved important efficiency gains during the last twenty years. Iron and steel manufacturing in all countries have improved their efficiency; however, the global average level has not improved substantially. This reflects a concentration of growth in China, which has a relatively low average efficiency. In 2005, China accounted for 50% of global coke production, 42% of pig iron production and 31% of steel production.

The energy efficiency of BOF steel production in the United States improved 1.5% per year between from 21.2 GJ/t in 2002 to 20.3 GJ/t in 2005, according to the American Iron and Steel Institute. Energy efficiency in EAF plants improved from 5.2 GJ/t in 2002 to 4.9 GJ/tin 2005. EAF production growth was faster, contributing to an average gain of 12% during this period.

Figure 5.3 ▶ *Final Energy Intensity Distribution of Global Steel Production, 2004*

Key point: An aggregate comparison of the energy intensity of steel production based on existing energy statistics is of limited value as the wide range does not provide meaningful insights regarding actual technological and operational differences.



Source: IEA analysis.

In Europe, the CO_2 emissions per tonne of finished product showed a 58% decrease from 1975 to 2000 because of four factors: 20% of the reductions by improvement of material efficiency including continuous casting, quality control and process management. The materials efficiency increased from 72% in 1975 to 92% in 2005; 14% by increased scrap use – from 55 Mt/y in 1975 to 80 Mt/y in 2005; 18% by improvement of blast furnace management and feedstock preparation 6% by adopting higher quality of iron ores (Debruxelles, 2006).

The energy efficiency of the Japanese iron and steel industry improved by about 20% from the 1970s to 1990, but this growth slowed to only 7% between 1990 and 2005 (Nakano, 2006; Ono, 2007). This trend can be explained by the fact that major energy efficient technologies had been deployed prior to 1990: process continuation and integration such as continuous casting were deployed in the 1970s. CDQ, TRT, and large scale waste energy recovery facilities were introduced in the 1980s. From the 1990s, the additional energy use for high value-added product and environmental protection was outdone by energy saving measures such as waste heat recovery, pulverised coal injection and regenerative burners. Also use of waste material such as plastics and tires has contributed to a reduction of fossil fuel consumption.

In China, the overall average energy efficiency of plants has not changed much in recent years (Table 5.4). However, there is a gap between the average and the best plant in China of about 20%, part of which is due to blast furnace size and the level of heat recovery.

Scrap recycling in electricity arc furnaces (EAF) requires less energy than the blast furnace-basic oxygen furnace (BF-BOF) process and the direct reduced iron (DRI)-EAF process, because the energy intensive ore reducing process can be avoided. This process requires about 6.6 GJ of chemical energy per tonne of iron when hematite ore (the most abundant type) is used. However scrap recycling in EAFs or BF-BOFs is limited by its availability. The amount of steel that is stored in capital stock is more than ten times annual steel production and it is still increasing continuously.

Table 5.4 ▶ ***Net Energy Use per tonne of Product***

(Primary Energy Equivalents)

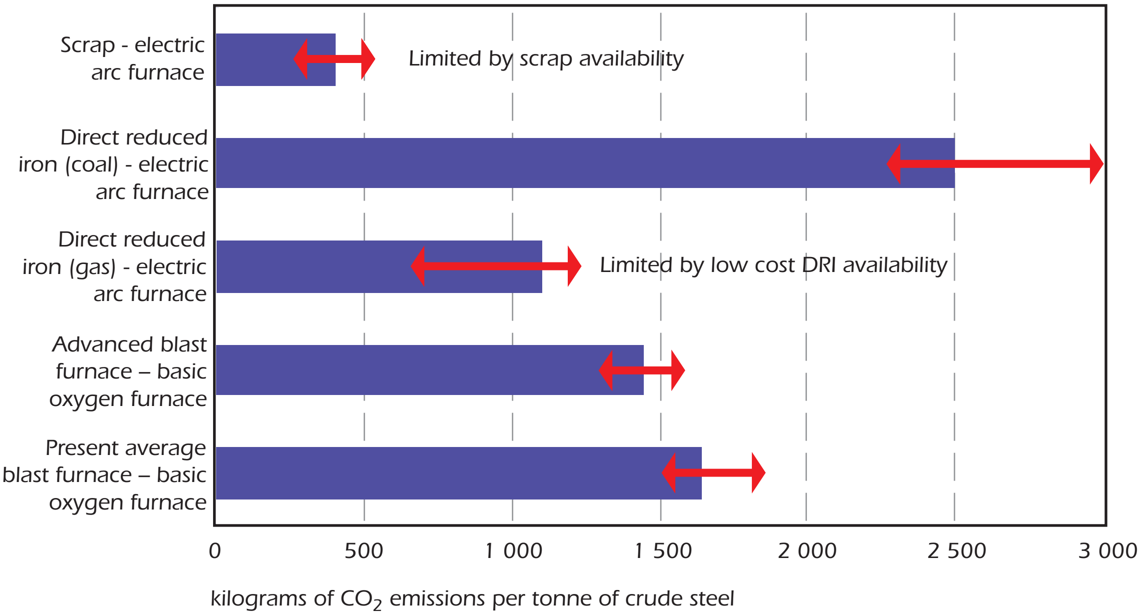
			Sintering *GJ/t*	Coking *GJ/t*	Blast Furnace *GJ/t*	BOF *GJ/t*	EAF *GJ/t*	Rolling *GJ/t*
International	1994		1.7	3.8	12.8	–0.3	5.8	
China	2002	Average	2.0	4.3	13.3	0.8	6.7	3.0
China	2003	Average	1.9	4.1	14.2	0.7	6.2	2.9
China	2004	Average	1.9	4.2	13.7	0.8	6.2	2.7
China	2004	Advanced	1.5	2.6	11.6	–0.1	4.3	1.6
China	2004	Laggard	3.2	6.7	17.3	2.2	9.5	8.4

Sources: China Iron and Steel Association (CISA), 2005b; IEA data.

Figure 5.4 compares the CO_2 emissions for the three key processes now in general use (BF-BOF, DRI-EAF and scrap-EAF). It suggests a potential for CO_2 emissions reduction of 30 – 80%. However, this assumes that the processes are interchangeable, which does not take account of actual available options, *e.g.*, scrap and low carbon fuels availability is limited. DRI process can reduce CO_2 emissions by using natural gas instead of coal and coke, but generally depends on the use of low cost stranded gas which is only available in parts of the world such as the Middle East. Note that options such as CO_2 capture from blast furnaces are not considered here.

Figure 5.4 ▶ ***CO_2 Emissions per tonne of Crude Steel***

Key point: Crude steel production using scrap yields lower CO_2 emissions than other processes, but is limited by scrap availability.



Note: The high and low-end ranges indicate CO_2-free and coal-based electricity, and account for country average differences based on IEA statistics. The range is even wider for plant based data. The product is crude steel, which excludes rolling and finishing.

Source: IEA data.

Coke Ovens

Coke is used in blast furnaces for the chemical reduction of iron ore. Coke is produced by heating coal for several hours or days to high temperatures in a pyrolysis process. According to IEA statistics, global coke production was 408.5 Mt in 2004, of which 88% is used in the iron and steel industry.

China is a key coke producer. Of the 208.7 Mt it produced in 2004, 83% was from slot ovens and the remainder from beehive ovens (CISA, 2005). About 15 Mt was exported.

Coke ovens are of two general types: recovery ovens, which collect hot gas and are usually slot ovens; and non-recovery ovens, which are usually beehive ovens. The vast majority of plants make coke in slot ovens (about 90% of total production). Recent developments suggest a modest revival of modern beehive (heat recovery) ovens. The old type of beehive coke ovens in China and charcoal ovens in Brazil are statistically significant.

To make coke, selected coals are blended, pulverised, and oiled for proper bulk density control and then carbonised in an oven. In slot ovens, coal is loaded from the top and heated from the side by burning gas in flues built into the walls. Ovens are grouped together in a battery. Gas, oils and tars are collected and further processed in a by-products plant. Slot ovens evolved for two reasons: to collect the by products; and to manufacture coke oven gas (a fuel co-product).

Beehive ovens, which date to 1735, are normally of rectangular shape with a dome. The investment and operating cost of non-recovery ovens are generally lower than for recovery ovens and since they operate with free space above the coke-cake they can use cheaper grades of coal. The by-products are not recovered and coke oven gas and

Table 5.5 ▶ ***Energy Balance of Slot Ovens for Coke Production***

	German Typical Modern Plant 2003	Japan Average for all Plants 2002	China Efficient Wet Quenching Plant 2004
Input			
Coal	39.04		37.83
Gas	3.25		3.51
Electricity[1]	0.16		0.12
Steam	0.25		
Other	0.53		
Total input	**42.7**		**42.0**
Output			
Coke	29.73		
Coke oven gas	7.65		
Tar	1.18		
Steam			
Other	0.44		
Total output	**39.0**		**37.82**[2]
Net energy consumption	**3.69**	**3.49**	**4.18**

Data basis: Japan: average data for all plant in financial year 2002; China: data for selected new wet quenching plant for 2004; Germany: typical modern plant for 2003.
Note: 1 This is secondary energy consumed on-site.
2 This includes the steam recovery from coke oven; conversion efficiency is not considered.

Sources: Diemer, *et al.* (2004); JISF communication; Wei J. (2006).

other by-products are combusted in the battery. The energy use and specific CO_2 emissions of non-recovery ovens are about one and a half times those of a conventional slot oven.

The production of one tonne of coke typically requires 1.25 – 1.65 tonnes of coal and generates 300 – 360 m^3 of coke oven gas (6 – 8 GJ/t coke). About 10% of the coke product consists of fines which are not suited as blast furnace feed. They are mainly used for the sintering process or sold.

Coke must be cooled quickly when it leaves the oven, in order to prevent burn-off and to achieve a high mechanical stability. Rapid cooling is called quenching. There are two types of quenching. Water is added in wet quenching processes, while an inert gas is used for dry quenching processes.

The energy use figures for coke ovens are often less reliable because the energy throughput is much higher than the energy use and a large number of energy flows must be considered for proper assessment. Coal and coke energy content can vary with quality. The energy consumed for coking is about 3.5 – 5 GJ/t coke produced (Table 5.5). The most efficient coke ovens use dry quenching and may use up to 40% less energy, if the full energy content of the recovered steam is accounted for. There is a high share of dry coke quenching in Japan, where energy is recovered from the hot coke and used for power generation. Data from the Japanese iron and steel industry suggest a country average of 3.5 GJ/t final energy use for coke production in 2002. The impact of coking on the total energy use in steel production is limited, as less than half a tonne of coke is needed per tonne of crude steel.

The kind of quenching affects the coke strength. Coke dry quenching (CDQ) and a new advanced wet quenching process (Coke Stabilization Quenching (CSQ)) may lower energy demand in the blast furnace. The new wet coke technology, which to date has only been applied in Germany (ThyssenKrupp and Hüttenwerke Krupp Mannesmann GmbH), brings the coke into contact with water from both top and bottom.

The impact of the process used on coke quality and the coke use in the blast furnace also depend on the coal quality. This may reduce coke consumption by 1 – 2%, but the optimal system choice needs to be assessed on a case-by-case basis. Coke quality is also related to ash content. A 1% rise in the coke ash content results in a 2% increase of coke use, as more molten slag is produced. Especially in India, use of high ash coal may have a detrimental impact on energy efficiency. Given a 10% share of coke making in total energy use for the BF-BOF process, these seemingly secondary effects are relevant.

According to the China Iron and Steel Association (CISA, 2005b), the average Chinese coke making energy consumption dropped from 180 kg coal equivalent (kgce) per tonne of coke in 1995 to 166 kgce (4.9 GJ/t coke) in 2000 due to the installation of more than ten sets of coke dry quenching (CDQ) and new advanced wet quenching installations. From 2000 to 2004, it had decreased further to 4.2 GJ/t coke (142 kgce), which is close the level of most OECD countries. However, it should be noted that this data does not cover the outdated beehive ovens that account for a fifth of Chinese coke production. There are no reliable data available for these ovens.

Coke Oven Gas Use

Coke oven gas (COG) is rich in hydrogen and therefore has a relatively high heating value of 17.6 MJ/m^3, compared with 3.5 MJ/m^3 for blast furnace gas. About 70% of COG is used in iron and steel production processes, 15% to heat coke ovens and 15% for power generation. At most steel plants, COG is used to heat the coke oven and to fuel equipment such as boilers and reheat furnaces. The boilers supply steam for electricity generation, turbine-driven equipment such as pumps and fans and for process heat. The overall efficiency can be improved if the coke oven is fired with blast furnace gas and the COG is put to a higher quality use, *e.g.* power generation. Some plants convert COG to chemicals. While COG-fired steam cycles achieve about 30% efficiency, combined-cycles can reach more than 42% electric efficiency.

In China, one-third of coke production in 2005 was in integrated steel plants where 97% of the COG is recovered (CISA, 2005b). Reportedly, COG is still flared from some coke ovens. The other two-thirds were produced by coke making enterprises that are located close to coal mines. Only 24% of the COG was recovered at these plants (Zhen, 2005). This leaves 250 PJ of COG that could be recovered and used, *e.g.* power generation, a savings potential of 25 Mt CO_2.

Coke Dry Quenching

The coke dry quenching (CDQ) process was originally developed on an industrial scale in the former Soviet Union in the early 1960s (Giprokoks process). The main driver was that wet quenching is not suited for the cold winter conditions.

In the CDQ process the carbonised coke initially passes from the battery to the cooling unit where it is emptied through an aperture into the shaft. As the coke column descends it emits its sensible heat into a largely inert, counter-flowing gas. The cooled coke is discharged at the bottom of the shaft through sluices. The gas, which is recycled by a blower, has a temperature of 750 – 800°C and is used in a waste heat boiler for steam generation.

With CDQ about 0.5 t steam (480°C, 60 bar)/t coke corresponding to 1.5 GJ/t coke can be recovered and used for power generation. This process at the Kimitsu steelworks in Japan yields an electric efficiency of about 30%. In a recent CDQ project proposed for a Chinese plant, the efficiency of use would be 22%.

CDQ increases the quality of the coke which reduces the coke consumption in the blast furnace by about 2%. This savings affect amounts to 0.6 GJ/t coke.

Worldwide, some sixty coke oven plants employ CDQ (Figure 5.5). The Commonwealth of Independent States countries have 25 plants with 109 units, accounting for 52% of coke production in Russia (Moscow Energy Institute, personal communication). In Japan, CDQ is installed at 95% of plants (20 plants with about 33 units). In Korea, 90% of all plants are equipped with CDQ. In principle, CDQ can be applied at new and retrofitted at existing plants. While CDQ is widely applied in Asia it is not applied in the United States and Canada and the use rate is below 5% in Europe.

CDQ has energy benefits compared to conventional wet quenching. However, the energy benefits compared to advanced wet quenching (CSQ) are not so clear. For example, at a plant in Germany air had to be added to the CDQ cooling gas to reduce the hydrogen build-up for safety reasons. This resulted in a burn-off of about 2% of the coke produced.

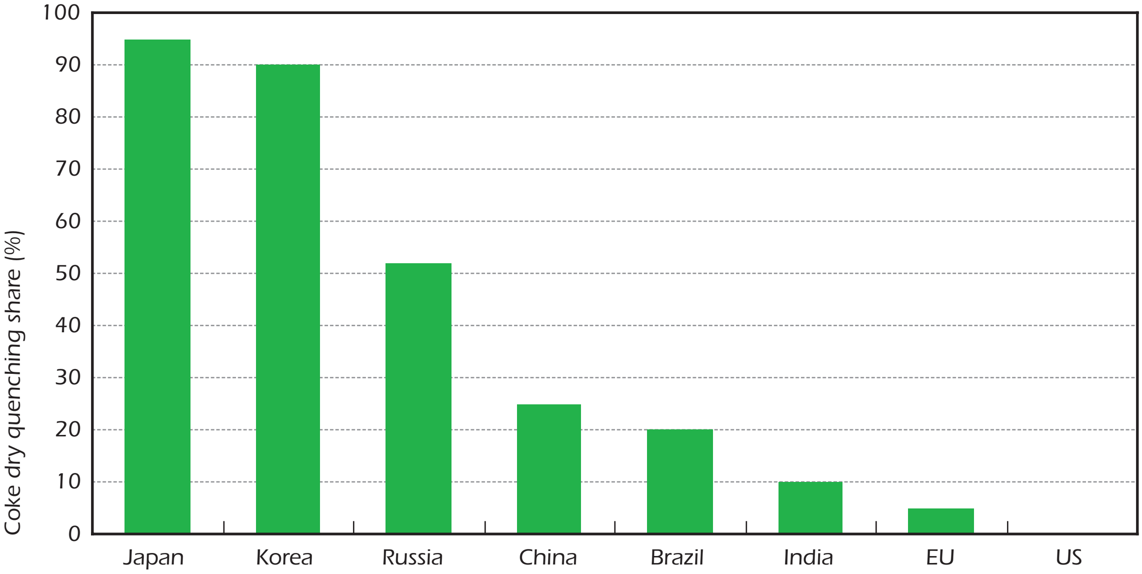
The only plant using CDQ in Europe is Raahe Steel in Finland. ThyssenKrupp is no longer using the CDQ process. The German experience with the energy "costs" of CDQ and EU environmental regulations regarding fine dust emissions have resulted in limited interest for CDQ.

The low rate of CDQ use in Europe and North America contrasted with the high rate in Japan and Korea may reflect differences in electricity price and business finance. Also ambitious energy efficiency policies have played a role in the case of Japan. Investment and operation costs are high for CDQ. Where these costs are balanced by high electricity prices and 10% rates of return are applied, CDQ makes sense. In parts of the world with low electricity prices and higher rates of return, CDQ may not be economically viable. An incentive of USD 25/t CO_2 will not affect the economics significantly (Schoenberger, 2000; Stoppa, *et al.*, 1999).

Given about 300 Mt coke production without CDQ and a saving of 600 g CO_2/kWh, the global potential for CO_2 emission reductions from using coke dry quenching processes is about 25 Mt CO_2.

Figure 5.5 ▶ *Use of Coke Dry Quenching Technology, 2004*

Key point: Country average CDQ use ranges from zero to 95% of total production.



Sources: IISI communication; Institute of Energy Economics Japan (IEEJ) (2006).

Iron Ore Agglomeration

Seven countries account for 85% of global iron ore mining and produced 1 342 Mt ore in 2004 (Table 5.6). Iron ore in its natural state occurs as lump ore or fine ore. High quality lump ore is a suitable feed material for blast furnaces, but its availability is limited. Fine ore must be converted into larger aggregates for use in blast furnaces, which are often better feedstock than lump ore. Sintering and pelletising are two common ore agglomeration processes. New iron reduction processes that can consume fine ore have an important cost advantage in that they can avoid the additional costs of either ore agglomeration or of the purchase of more expensive lump ore. A 1.5 Mt Finex plant that can use ore fines directly is due to start operation in Korea in 2007. Other processes for ore agglomeration are under development but are not discussed in more detail here.

Lump ore requires simple crushing and screening before shipment. It must meet strict minimum chemical characteristics (62+% Fe) and physical characteristics in terms of size and handling as it is fed directly into the blast furnace. It commands a premium compared with ore fines. About 25% of all iron ore is used directly, without an agglomeration process.

Global pelletising capacity stood at 332 Mt in 2004. About 25% of all iron ore is processed into pellets. Most of the production serves as feed for blast furnaces and about one-third of the pellets are used in DRI production. Pelletising is especially suited for certain types of low quality iron ores, *e.g.* ores in the United States require pelletising because of high gangue content. Various factors such as the high capital cost of pellet plant construction, energy costs of grinding the fine-grained ores to produce concentrate and other process energy demands, and the stringent specifications of feedstock required to produce a quality pellet have limited the expansion of pellet use.

Sintering is the most efficient and effective process for making direct feed for blast furnaces. More than 50% of all iron ore is converted into sinter. Sintering involves the heating of fine ore, causing it to agglomerate into larger granules. Iron ore, coke breeze or anthracite and flux materials are mixed and fed onto a travelling grate and ignited. Air is pulled through the feed to burn the mixture by down-draft combustion, creating sufficient heat to sinter the fine ore particles into porous clinker. The incorporation of blast furnace flux in the sinter saves fuel in the blast furnace. Data indicate 201 kg of saved coke for each tonne of limestone fed into the sinter plant instead of in the blast furnace. Use of sized sinter further increases iron production rates in the blast furnace.

All blast furnaces use a combination of sinter, lump and/or pellets as input (direct charge). Steel producers in the United States generally use 75+% pellets while the rest of the world uses sinter feed (60+%) in blast furnaces. Increasingly steel producers blend and mix the types of ores used as direct charge to reduce swelling, increase throughput, reduce energy cost and coke consumption and generally improve the production process while reducing pollution. Pre-treatment technologies for blast furnace feedstock are highly effective in reducing energy consumption.

Table 5.6 shows a breakdown of various heat recovery options in a blast furnace-BOF process, including a sintering plant. The *exergy* value accounts for the quality of the energy, higher temperature being better suited for electricity generation. The sensible heat value is a relevant indicator if low temperature steam is the main target product. The values suggest a significant energy recovery potential for sintering, more important than for coke dry quenching.

Table 5.6 ▶ ***Heat Recovery Options in Various Steel Production Steps***

(Per tonne of Rolled Steel (trs) Product)

	Sensible heat *GJ/trs*	Exergy *GJ/trs*	Temperature *°C*	Status
Coke making				
Hot coke	0.24	0.14	1 100	Commercial
Coke oven gas	0.24	0.12	850	Stopped
Sintering				
Cooler gas	0.97	0.28	100 – 350	Commercial
Exhaust gas	0.23	0.12	100 – 350	Commercial
Blast				
Waste heat recovery in hot stove	0.82	0.33	250 – 400	Commercial
BF Slag	0.39	0.26	1 500	Stopped
BOF				
BOF gas	0.19	0.12	1 600	Commercial
BOF slag	0.02	0.01	1 600	Stopped
Casting				
Cast steel slab	1.39	1.06	700	Commercial
Reheating furnace	1.04	0.62	900	Commercial
Hot Rolling mill				
Total		**5.53**	**3.06**	

Source: Beer, *et al.*, 1998.

Typically the sintering process requires about 1.5 - 2 GJ/t sinter. The heat consumed for sintering reaction is about 33% of the total heat input into the plant, with about 49% released to the atmosphere. Waste heat recovery is a key strategy for improved efficiency. One system recovers 60% of the waste heat from sinter cooling gas. Another technology recirculates the waste heat to other parts of the production process. The heat of the circulation gas raises the sintered ore temperature to be fed to the sinter cooler and reduces the coke consumption. New plant designs combine both systems. All the waste heat from both the sintering process and sinter cooling gases is effectively recovered (JP Steel plantech, 2002). No detailed data are available regarding the efficiency of waste heat recovery from sinter plants on a country or plant level.

Ore Quality

The chemical composition of iron ores varies. The most widely used are hematite and magnetite. The energy needs of a blast furnace depend to some extent on the quality of the ore. The metal content is increased in the ore preparation process, using grinding and separation technologies. The higher the metal content, the lower the energy needs for iron making. A lower metal content results in more slag, a need for more limestone addition and higher energy use. Variations in the chemical composition of ore can make a difference of about 10 – 15% in blast furnace energy use.

Table 5.7 ▶ *Iron Ore Mining and Ore Quality, 2004*

	Mining *Mt/yr*	Metal *Mt/yr*	Metal Content %
Australia	231	143	62
Brazil	255	169	66
China	310	102	33
India	121	77	64
Russia	97	56	58
Ukraine	66	36	55
United States	55	34	62
Other	207	122	59
World	**1 342**	**739**	**55**

Source: United States Geological Survey (USGS), (2005a).

Chinese research indicates that if the iron content of the feedstock improves by 1%, the coke use decreases by 1.5 – 2% (Yu, 2003; Wei 2006). The use of prepared burden (sinter and pellets) reduces the coke ratio substantially. Data for European blast furnaces suggest that a reduction of the prepared burden ratio from 95 to 65% increases the coke ratio from 330 to 410 kg/t (Lacroix, *et al.*, 2001). However, the impact on the total blast furnace balance is less evident.

No detailed data are available regarding the metal content in prepared feedstock, but a typical range is 60 – 67%. Given the low metal content and special chemical composition of Chinese ore (Table 5.7), more analysis of prepared feedstock quality is recommended.

Blast Furnaces

A blast furnace is the vessel where iron ore is chemically reduced and converted into liquid hot iron metal. Coke and iron ore agglomerate are added from the top and gradually move down the vessel as the coke oxidises and the ore melts. Oxygen enriched air is heated in the hot stove and injected from the bottom of the furnace (hot blast) and pulverised coal also is injected.

Basically a blast furnace is an energy efficient reactor. The following analysis of technologies and practices for blast furnaces suggests that given an average savings potential of 75 kg coal and coke per tonne of hot metal (thm), iron and steel manufacturing has an energy efficiency improvement potential of 1.5 EJ/yr and could reduce CO_2 emissions by 150 Mt CO_2 /yr. This includes measures such as closure of inefficient small-scale blast furnaces, use of better coal, higher pulverised coal injection rate, wider use of top-pressure turbines and increased efficiency of hot stoves. It excludes the CO_2 benefits of switching to waste plastic or charcoal.

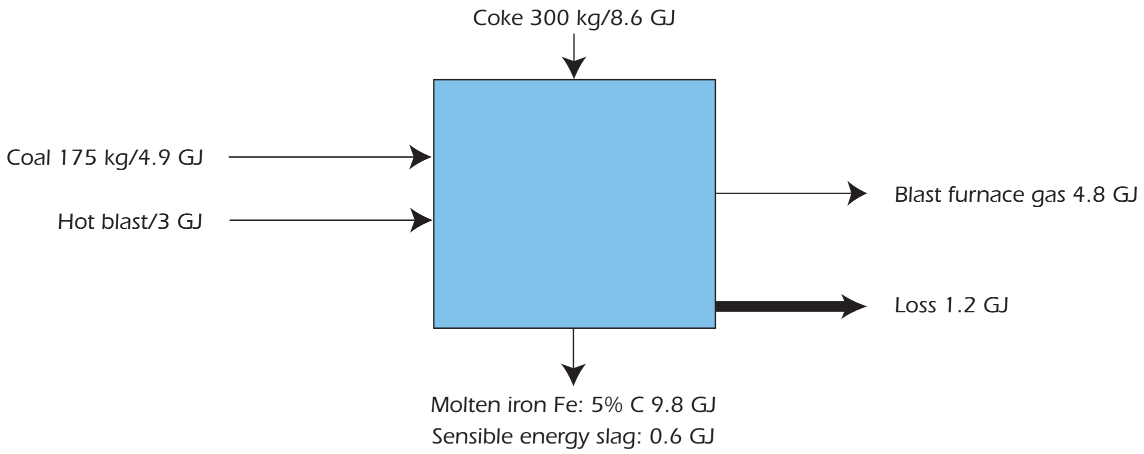
The blast furnace has a vertical cylindrical structure externally covered with a shell of thick steel plate and internally lined with refractories. The size range of blast furnaces covers almost two orders of magnitude, from less than 100 to more than 5 000 m^3 (Nippon Steel, 2004). Larger blast furnaces have lower heat losses than smaller ones and the installation of heat recovery equipment is more cost-effective.

The practical minimum energy use for a blast furnace is 10.4 GJ/t, which is the sum of the chemical energy, the carbon content of the hot metal, the energy in the hot metal and the energy needed for limestone calcination, if limestone is added.

About 35 – 40% of the energy content of the reducing agents is extracted from the reactor as blast furnace gas. Part of the blast furnace gas is used to heat the hot blast. The energy losses from the reactor are less than 10% of the total energy input (Figure 5.6).

Figure 5.6 ▶ ***Energy Balance of a Typical Efficient Blast Furnace***

Key point: The heat losses of a blast furnace are small compared to the energy through-put.



Source: IEA estimate.

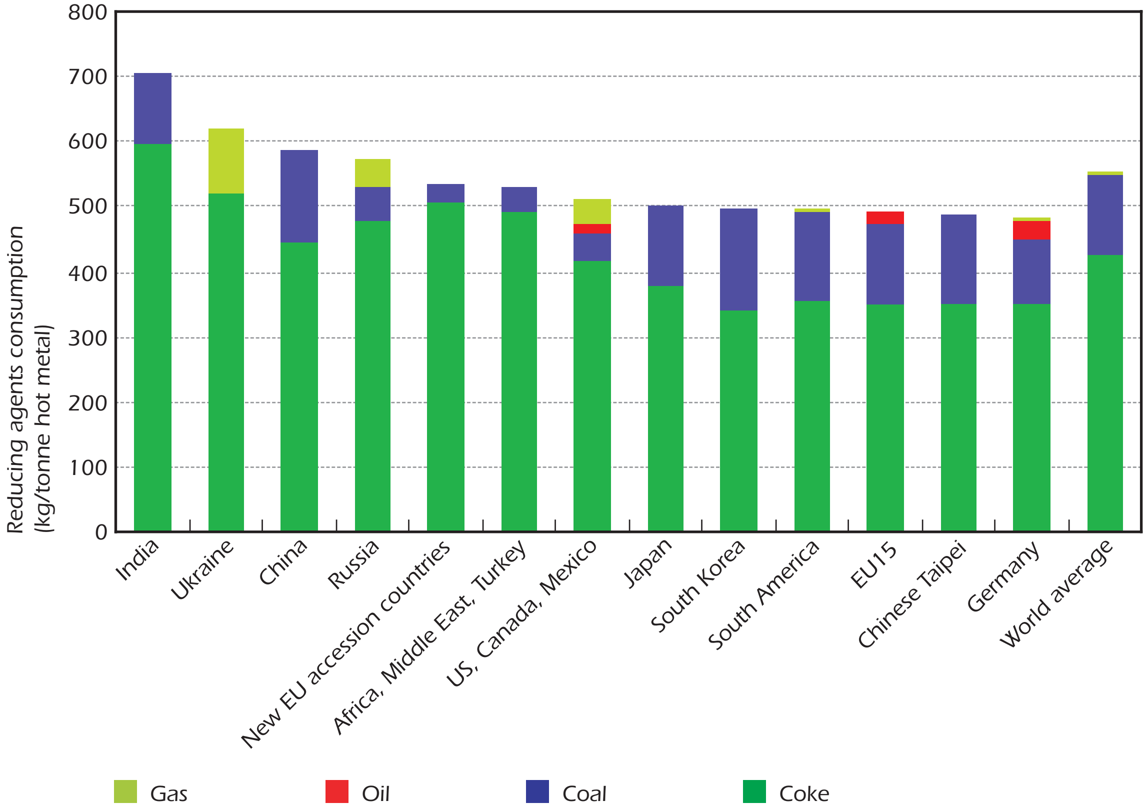
Blast furnaces which use injected pulverised coal have equipment for pulverising the coal and injecting it under pressure. The amount of coal used for pulverised injection worldwide was on average about 125 kg/t in 2005. In many OECD countries, average coal and coke use for blast furnaces is in the range of 500 – 600 kg/t.

Coke consumption of about 286 – 320 kg/tonne hot metal (thm) has been achieved in some blast furnaces by the pulverised coal injection of 170 – 200 kg/thm. A modern large blast furnace uses 460 – 480 kg total reductants/thm, if good quality sinter and good quality coke are used. Furnaces can be operated in different ways. For example, the carbon rate can be lowered by using sponge iron or scrap in the burden.

Figure 5.7 shows blast furnace reductant use per tonne of hot metal in a number of countries and regions. The highest levels are in Ukraine, Russia and China. The difference between the lowest and highest country average is about 150 kg coal and coke/t hot metal. It should be noted that this does not equate with energy efficiency, as a furnace with a high coal and coke consumption will generate more blast furnace gas by-product. Also the quality of the iron feedstock and the coke differs. Significant amounts of natural gas and oil are injected in some plants, but accurate data are not available. Figure 5.7 contains estimates. Blast furnace size and oxygen use are also important factors and they depend on the technology choice and business strategy.

Figure 5.7 ▶ ***Blast Furnace Reductant Use, 2005***

Key point: Country average blast furnace reductant use ranges from less than 500 to 700 kg/thm, with a global average of 550 kg/thm.



Source: Stahlinstitut VDEh, 2007.

Reductant use also varies within countries. For example, in China, the coke use rate of the best producer was only 288 kg/thm in 2004. However, smaller furnaces emit up to 25% more CO_2 than large furnaces (Table 5.8).

For blast furnaces of a certain size the energy efficiency is independent of the production capacity. There are many energy efficient mid-size blast furnaces with productions of 3 500 – 6 500 t/day. In China and India there is a trend to use mini blast furnaces to feed electric arc furnaces. This allows small-scale steel production, which is better adjusted to local market circumstances and requires less capital. However, this results in low energy efficiency. Based on the data in Box 5.2, CO_2 emissions in China can be reduced by 37 Mt/yr, if all furnaces were as efficient as the largest ones that are currently in operation.

Box 5.2

The Impact of Size on the Energy Efficiency of Blast Furnaces in China

Size affects blast furnace efficiency. A larger blast furnace is usually more efficient because the heat losses are lower (lower surface/volume ratio) and it is usually more economical to install energy efficient equipment (Table 5.8). Switching to larger blast furnaces requires modern technologies.

The Government policy target in China is to close all blast furnaces below 100 m^3 by 2007 and close all furnaces below 300 m^3 by 2010. All steel making furnaces of less than 20 tonne capacity are to be closed in 2007.

Table 5.8 ▶ *CO_2 Emissions of Chinese Blast Furnaces as a Function of Size, 2004*

	CO_2 Intensity *t CO_2/yr*	Number of Installations	Production Capacity *Mt/yr*	Share *%*	Annual Production *Mt/yr*	Annual CO_2 *Mt/yr*
Total	1.25	395	230.9	100.0	251.9	314.9
>3 000m^3	1.09	6	16.6	7.1	17.8	19.4
2 000–2 999m^3	1.17	28	50.9	22.0	55.5	65.0
1 000–1 999m^3	1.21	39	38.3	16.6	41.8	50.6
300–999m^3	1.31	231	107.8	46.7	117.6	154.1
101–299m^3	1.33	82	16.5	7.1	18.0	23.9
<100m^3	1.37	9	0.9	0.4	1.0	1.3

Sources: CISA, 2005(2); IEA data.

There are considerable differences in energy efficiency within the various categories of blast furnaces due to the resource quality and furnace productivity. For mini blast furnaces, an increase in the iron content of the ore from 50 – 55% reduces fuel use from 750 – 600 kg/thm – a 20% savings. An increase in daily furnace productivity from 1 – 1.5 t/m^3 reduces the fuel rate from 750 – 600 kg/thm.

The quality of the iron ore and the quality of the coal influence the energy needs for iron production. A proper comparison should account for such quality differences that may result in up to 20% difference in energy efficiency. However, such analysis would require more detailed data that are not readily available.

Coal and Coke Quality

The chemical reactions in blast furnaces are very complex. There are two main reactions in the blast furnace, the "indirect reduction" with carbon monoxide between solid and gas, and "direct reduction" with carbon between solid iron oxide and solid carbon. Indirect reduction requires more carbon for the reduction, but less energy to maintain the reaction temperature. Direct reduction requires less carbon for the reduction, but much more energy to maintain the reaction temperature. The blast furnace operation controls these two chemical reactions by controlling temperature distribution in the furnace to maintain the equilibriums of each reaction.

Coke performs three functions in a blast furnace:

- chemical function, as reductant by providing reducing gases for iron oxide reduction;
- thermal function, as fuel for endothermic chemical reactions and to maintain gas permeability in the furnace for stable control of melting of iron and slag;
- mechanical function, as a permeable grid to provide passage of liquids and gases in the furnace, particularly in the lower part of the furnace.

When coke passes through a blast furnace to a high temperature zone, the coke degrades and generates fines which affect bed permeability and affects the process efficiency. The rate at which coke degrades is mainly controlled by the solution loss reaction, thermal stress, mechanical stress and alkali accumulation.

Coke quality is often characterised by measuring cold and hot strength, ash composition and chemistry, which are largely dictated by the coal properties. A range of laboratory tests and procedures have been developed to characterise physical and chemical properties of coke and their potential impacts in a blast furnace. The most often used and well-known tests are the Coke Reactivity Index (CRI) and the Coke Strength after Reaction (CSR) developed by Nippon Steel Corporation (NSC) in Japan in the early 1970s, in order to assess the effect of CO_2 reactions on coke. CSR measures the potential of the coke to break into small size under a high temperature CO/CO_2 environment that exists throughout the lower two-thirds of the blast furnace. A large mean size with narrow size variations helps maintain a stable void fraction in the blast furnace permitting the upward flow of gases and downward flow of molten iron and slag thus improving blast furnace productivity.

A CSR difference of 10% results in a 5% difference of total coke and coal injection rate. Moreover, the pulverised coal injection rate is 50 kg higher for coal with a high CSR, which reduces coke needs and energy use for coke making (Veld, 2006). However, there is an upper limit above which the reactivity becomes too low. CSR is not only a function of the coal characteristics, but it may also depend on the coke oven. Tests suggest that alkali components play a key role in the coke chemistry in a blast furnace, which is not captured by the CSR/CRI test (Hilding, 2005). There are no detailed publicly available statistics on coke quality.

China represents more than half of global coke production and it is largely based on indigenous coal. Some Chinese coke is of very high quality (CSR >70%) (Valia, *et al.*, 2004), but other coke from small coking plants is of low quality, with a CSR of 50 – 60%, up to 18% water content and 16% ash content (Qian Kai, *et al.*, 2004). In 2006, 218 Mt coking coal were traded, 60% of which came from Australia from the Bowen Basin in Queensland. This Australian coal reach a CSR in the 50 – 70% range and the ash content is low (Bistrow, 2002). Russian and US coal is generally of low quality in terms of coke CSR, which results in a higher coke use rate.

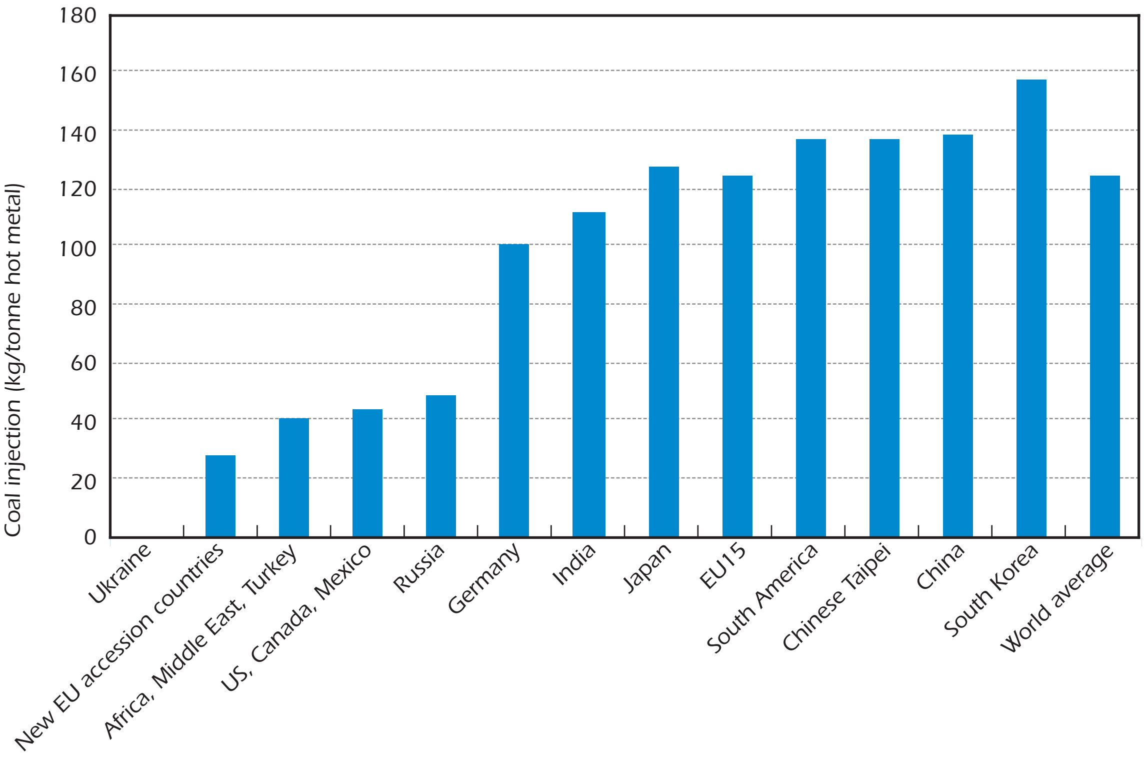
The amount of coke and coal that is needed also depends on the ash content. A 1% rise in the coke ash content results in a 2% increase of coke use (about 1 kg/thm), as more molten slag is produced. For each percentage increase in the ash content of injected coal, there is a coke rate disadvantage of about 1.5 kg/thm.

Coal Injection

Worldwide, pulverised coal injection per tonne of hot metal rose from 45 kg/thm in 1995 to 125 kg/thm in 2005 (Figure 5.8) (Stanlay, 2003; Stahlinstitut VDEh, 2007). Several individual furnaces, however, have achieved higher injection rates, 180 – 200 kg/thm. Use of coal reduces the need for coke in iron and steel production and reduces CO_2 emissions.

Figure 5.8 ▶ ***Pulverised Coal Injection in Blast Furnace Use by Region, 2005***

Key point: Country average coal injection ranges from zero to 160 kg/thm, with a global average of 125 kg/thm.



Sources: StahlZentrum; IEA Coal Statistics, 2005; JISF, 2006.

Low volatile coal replaces more coke than high volatile coal. For example, 150 kg of low volatile coal reduces coke consumption by 18 – 26 kg more than the same amount of high volatile coal.

The amount of coal that can be injected depends on the gas permeability of the coke-ore bed, which decreases as less coke is added and the pressure drops. The coke particle size in the lower part of the furnace is much smaller if more coal is injected. According to IISI, an increase of coal injection above 180 kg does not reduce the coke amount, and the additional coal is just gasified and produces more top gas. Given the current world average of 125 kg/thm, however, there is still potential to increase the rate of pulverised coal injection. If the world average was 180 kg/thm, some 10 Mt CO_2 could be saved.

Plastic Waste Use

Plastic waste can also be injected into blast furnaces as a substitute for coke and coal. The technology has been developed and applied in Germany and Japan. Plastic waste can also be added to the coke oven. About 0.4 Mt of plastic waste is used per year in the Japanese iron and steel industry, which equals about 20 PJ/yr.

Factors that influence the increased use of plastics in blast furnaces include: the need to control the polyvinyl-chloride content of the plastic pellets; regulations on the use of waste as a fuel and environmental concerns; capital costs to modify the fuel injection system. The option is limited by the availability of plastic waste and by the claims of other uses, such as recycling and incineration.

Burning waste plastic releases CO_2 emissions whether it is burned in a conventional waste incinerator or a blast furnace. However, much more energy can be recovered by injection in blast furnaces than by conventional incineration. Moreover, coal is replaced in a blast furnace, a fuel with high CO_2 emissions. The reference primary energy source for power generation is in many cases less CO_2 intensive. Therefore blast furnace use reduces CO_2 emissions compared to conventional waste incinerators.

Charcoal Use

Charcoal is used in iron production only in South America, notably in Brazil. In 2005, one third of Brazilian iron was produced using charcoal (Box 5.3). Charcoal has a lower mechanical stability, much lower ash content and much higher volatile material content (20 – 35%) than coke. The use of charcoal in large blast furnaces is limited due to its low mechanical resistance. The largest charcoal blast furnaces are one order of magnitude smaller than the largest coke blast furnaces. Because charcoal furnaces are smaller they can operate with lumpy iron ore alone, no ore preparation is needed. The slag rate in charcoal blast furnaces is usually less than 150 kg/thm. A typical charcoal use rate is less than 500 kg/thm. While charcoal use does not result in any energy efficiency gains, it reduces CO_2 emissions substantially, provided that it is produced in a sustainable manner.

Box 5.3

Energy Efficiency and CO_2 Emissions in the Iron and Steel Industry in Brazil

Brazil produced 33.9 Mt of pig iron and 31.6 Mt of crude steel in 2005, of which 12.5 Mt of steel and 7.1 Mt of pig iron were exported. This pig iron trade is a unique characteristic of the Brazilian industry. There were eleven companies manufacturing steel in Brazil, while pig iron had 69 independent producers (MME, 2006a). In 2005, 71% of the pig iron produced came from integrated steel works and the rest from independent producers. About 83% of the output from independent producers was used for steel making and the rest for iron casting.

The production of both steel and pig iron consumed 731 PJ in 2005, almost 24% of total final energy demand in Brazil's industry sector (MME, 2006b). About 20% came from primary energy sources – natural gas and coal – and 80% from secondary energy sources – coke (34.7%), charcoal (27.5%), electricity, coke oven gas, fuel oil and other fuels.

The use of significant amounts of charcoal for reducing iron ore is another special characteristic of the Brazilian iron and steel industry. Blast furnaces can use either coke and coal or charcoal. About one-third of all pig iron is produced using charcoal. The share of charcoal has been rising in the last five years. In 2004, 1.4 Mt of integrated steelworks and 10.1 Mt of independent pig iron production were based on charcoal. Arcelor Brasil and Acesita are the main integrated steelworks that use charcoal. The independent producers operate 153 blast furnaces that use charcoal with capacities ranging from 18 to 180 kilotonnes of pig iron per year. The average energy efficiency of charcoal making was 53% in 2005, well below the efficiency of coke making from coal. Just over half of the charcoal came from planted forests, the remainder from native forest.

The current specific consumption in the blast furnaces of integrated mills in Brazil is about 330 kg coke and 170 kg coal per tonne of pig iron, which corresponds to 15.5 GJ/t. The independent producers use on average 25.6 GJ charcoal/t pig iron. The most efficient charcoal-fired blast furnace at Acesita used 16.2 GJ charcoal/t pig iron in 2004. This is close to the figure for coke - fired furnaces.

A third special characteristic of the iron and steel industry in Brazil is that most of the pellets produced are exported. Of the 51 Mt of pellets produced in 2005, 47 MT were exported (MME, 2006b). The energy consumed in pellet making is accounted for in the mining industry in the Brazilian statistics. Assuming a total specific final energy consumption of 1.089 GJ/t pellet, the pellet production consumed 55.54 PJ of energy in 2005, including 17 – 50 kWh/t of electricity (MME, 2006b). In 2003, the total production of sinter in Brazil was 28.49 Mt, with an average specific energy consumption of 1.82 GJ/t of sinter (ABM, 2004).

Table 5.9 provides an overview of the CO_2 emissions in steel production in Brazil. The average is 1.41 – 1.66 t CO_2 /t of steel. This average is augmented by the high pig iron to steel production ratio, on the other hand it is reduced by the use of charcoal and the low CO_2 intensity of Brazilian electricity.

An average annual investment of USD 3.11 billion is forecast for the iron and steel industry in Brazil for the period 2006 – 2010. Production capacity is due to expand from 36.6 Mt to 50.4 Mt of crude steel per year by 2010. As a consequence, the energy intensity of the iron and steel industry in Brazil may change significantly in the coming years.

Box 5.3 (continued)

Table 5.9 ▶ *Average CO_2 Emissions from Steel Production in Brazil, 2005*

	t CO_2/t steel
Mineral Coal	0.92
Charcoal from native forests	0.30 – 0.55
Limestone and dolomite	0.09
Natural gas	0.08
Fuel oil	0.01
Electricity	0.01
Total	**1.41 – 1.66**

Source: Bajay, *et al.*, 2007.

Top-Pressure Recovery Turbines

Many blast furnaces are operated at high pressure to increase the furnace productivity. A typical pressure in the top part of such blast furnaces is about 3 bar, given a blast pressure of 4.5 bar. The pressure drop ranges from 1.25 – 1.5 bar from the bottom to the top of the blast furnace (Lacroix, *et al.*, 2001).A top-pressure recovery turbine can be used to generate electricity from the remaining pressure in the top gas. The power output of top-pressure recovery turbine can cover about 30% of electricity necessary for all equipment for the blast furnace including air blowers.

Top-pressure recovery turbines (TRT) use a wet or a dry system. The dry TRT system saves on water and electricity use, produces more power and has more favourable economics.

TRTs are widely used in Japan and elsewhere. In China, 66 blast furnaces representing nearly half the total production capacity were equipped with TRT in 2004. A TRT can produce 15 – 40 kWh/t of pig iron. If the technology were installed worldwide in all furnaces that are operated at elevated pressure, it could reduce CO_2 emissions by 10 Mt.

Blast Furnace Gas Use

Blast furnace gas is a by-product of the furnace process. About 40% of the coal and coke energy input is converted into blast furnace gas. This gas contains about 4% hydrogen, 25% carbon monoxide, 20% CO_2 and the remainder is nitrogen. The heating value of this gas is low: about 3.5 MJ/m^3 while its CO_2 content is high. Therefore, a minimisation of blast furnace gas production will reduce CO_2 emissions.

Global blast furnace gas use was about 3.5 EJ in 2004 (Table 5.10). Its low heating value limits its use mainly for blast heating, hot mill reheating furnaces, coke oven heating, power production, or recycled to the blast furnace. Significant amounts of blast furnace gas are still flared during periods when supply exceeds demand. Larger storage systems have been used, *e.g.* in Japan, in order to minimise flaring. There are no available data on the flaring of blast furnace gas.

Table 5.10 ▶ *Global Blast Furnace Gas Use, 2004*

	Amount *PJ/yr*	Share *%*
Power generation	602.9	17
CHP plants	376.1	10
Heat plants	97.3	3
Coke ovens	154.5	4
Blast furnaces	121.0	3
Iron and steel industry (including hot stoves)	2 066.7	58
Other	166.3	5
Total	**3 584.7**	**100**

Source: IEA data.

Older power plants use blast furnace gas together with natural gas or oil, often in a steam cycle. In the United States, by-product gases are usually ducted to steam boilers where the gas is burned to produce steam for process needs. If there is sufficient energy, steam can be produced at a sufficiently high pressure to drive an extraction or back-pressure steam turbine, generating electrical savings for the mill (an electrical efficiency of about 15%). Use of by-product gas in a dedicated steam cycle typically yields efficiencies of 30% or lower.

Combined gas turbines and steam cycles can produce electric efficiencies in excess of 42% in steel mill applications. This represents an important efficiency gain. A critical factor is the gas turbine inlet temperature, which directly impacts the gas turbine efficiency. The latest designs operate at 1 300°C. The company Mitsubishi Heavy Industries (MHI) has a 70% share of the blast furnace gas turbine market (Komori, *et al.*, not dated).

Blast Furnace Slag Use

Blast furnace slag is a co-product of blast furnace iron production. The slag captures all ash residues from the coal, coke and ore. There is considerable variation in individual integrated plant practices and in the quality of ores used. Small integrated plants are at a disadvantage to the larger more efficient plants because the combination of ash from the coke and pulverised coal injection requires more lime, to meet the required lime to silica ratio. Typical blast furnace slag production is in the range of 250 – 300 kg/thm. Higher values result if high ash coal is used, such as in India. Given a global iron production of 718 Mt, total slag production is in the range of 180 – 220 Mt. The current blast furnace slag production is 400 kg/t iron due to the low ore quality, and rising.

Blast furnace slag can be cooled with air or with water. If water is used, the slag is granulated and can be a substitute for cement clinker. The use of blast furnace slag as clinker substitute results in significant CO_2 emission reductions in cement manufacturing.

Global granulated slag production increased from about 84 Mt in 2000 to 110 Mt in 2005, 50 to 60% of total blast furnace slag production. Only about 60 Mt is used in the cement industry according to Caffrey (2005). If the gap between total slag production and granulated blast furnace slag use for cement production is considered, the remaining potential today is about 120 – 160 Mt , which represents a 90 – 135 Mt CO_2 emission reduction potential. For example, Japan produced about 25 Mt of blast furnace slag in 2004, but made use of only 9.2 Mt in cement production (JCA, 2006). Other sources quote even lower use rates (Nippon Slag Assoc., 2006).

The major uses of air-cooled slag are as aggregates for road construction and as a feed for cement kilns. Air-cooled slag also is used as an aggregate for concrete. The energy and CO_2 benefits of air cooled slag use are limited.

Table 5.11 shows blast furnace slag use rates. Most granulated slag is used for cement production, but not all slag is granulated. In the United States, air-cooled slag is the majority of all slag. This suggests there is some additional potential for blast furnace slag use as clinker substitute, even in OECD countries. About 11 Mt of blast furnace slag is traded internationally. Increased trade may be a way to enhance granulated slag use for cement making (Caffrey, 2005). It should be noted that figures for China are uncertain. According to the China Building Materials Industry Association, 110 Mt of granulated slag were used in China in 2004 (Cui and Wang, 2006). This is significantly higher than the quantity reported by the China Iron and Steel Industry Association. Similar to the situation in the United States, significant amounts of GBFS are directly used for ready-mix concrete production.

Table 5.11 ▶ *Use of Blast Furnace Slag, 2004*

	Europe		Japan		United States		China	
	Mt/yr	*%*	*Mt/yr*	*%*	*Mt/yr*	*%*	*Mt/yr*	*%*
Air-cooled slag	**5.9**	**25**	**5.4**	**22**	**7.4**	**67**		
Granulated slag	**17.6**	**75**	**19.1**	**78**	**3.6**	**33**	**75.6**	**100**
Of which								
Cement	1.2	73	14.9	61	3.6	33	49.1	65
Other	0.4	2	4	16	0	0	26.5	35
Total	**23.5**	**100**	**24.5**	**100**	**11**	**100**	**75.6**	**100**

Sources: Euroslag, 2006; Utsi, 2006; Nippon Slag, 2006; USGS, 2005; CISA, 2005c.

Hot Stoves

In hot stoves, compressed air is blended with additional oxygen, heated to about 1 100° C and injected at the bottom of the blast furnace. The hot stove is a cylindrical furnace about 12 m in diameter and 55 m in height, and has a chamber filled with chequered silica bricks. It serves as a type of heat exchanger in which the heat produced by combustion of the blast furnace gas is stored in the chamber, after which cold air is blown through the hot checker-work to produce the preheated hot air blast for the furnace. Two or more stoves are operated on alternate cycles, providing a continuous source of hot blast to the furnace.

In an integrated steel works, hot blast stoves account for 10 – 20% of the total energy requirement, typically 3 GJ/thm. About one-third of the energy used in making iron is used in pre-heating the air for the blast furnace. Therefore, improving the efficiency of hot blast stoves will result in substantial energy savings.

Normally, mixtures of gases are used to heat a hot blast stove. A typical mix consists of 60% blast furnace gas and 40% coke oven gas or natural gas. The application of gas enrichment is relatively expensive as enrichment gas is more expensive than blast furnace gas. To minimise the costs associated with enrichment gases, waste heat can be recovered and used for preheating the combustion gas and/or combustion air for the stove. Besides reducing costs for enrichment gases, a waste heat recovery unit will increase the overall stove system efficiency by up to 8 percentage points, a saving of 0.24 GJ/t HM (Celissen and Haak, 2004). The waste gas of the stove heating cycle could be used for preheating of the gas and air of the cold blast of another stove. On a global level, the savings potential is 0.2 EJ/yr, equivalent to about 20 Mt CO_2/yr.

Basic Oxygen Furnaces

The liquid hot metal from the blast furnace is converted into steel in the basic oxygen furnace. The main operation is adding oxygen in order to remove the carbon from the iron to make steel. In recent years more extensive ladle metallurgy processes have been developed in order to improve the steel quality. Few energy data are available for these operations.

Open hearth steel production (also called Martin steel production) uses about 5 GJ/t steel, compared to virtually no energy use or net energy production in case of a basic oxygen furnace. Open hearth production is still widely used in Russia and the Ukraine, though its share is declining. In Russia its share declined from 53% in 1990 to 20% in 2005.

Similarly outdated equipment is still used in the CIS countries in other parts of the steel industry. For example, electric arc furnaces use on average 630 kWh/t versus 400 kWh/t in OECD countries. The low efficiencies reflect traditionally very low energy prices and shrinking production volumes. Russian steel production in 2005 was only 74% of the production volume in 1990. Production has increased in recent years and energy prices have risen considerably. Consequently energy efficiency is improving.

Basic Oxygen Furnace Gas Recovery

In basic oxygen furnace steel production, more than 100 m^3 of by-products (converter gas) with a heat value of 8.35 MJ/m^3 is generated per tonne of steel produced (0.84 GJ/t). The gas generation will be somewhat lower if the scrap use rate of the converter is high. This gas can be recovered, cleaned and used for heating of coke ovens or for power generation. Table 5.12 shows residual gas use for integrated plants in China.

Off-gases from the basic oxygen and electric arc furnaces are at a temperature above 1 650°C, low pressure, and can approach 6 – 8 MJ per cubic metre. They have a low fuel value during much of the steel making cycle. The off-gases are generated intermittently, vary greatly in temperature, carbon monoxide and nitrogen concentrations, and are very dirty. For this reason, off-gases are still flared at many sites. Yet technologies exist to use the energy content of the gas. Larger gas storage systems can be part of the solution. Currently, some steel producers capture and reuse basic oxygen furnace gases. Higher energy prices may make this option more attractive. The estimated saving from blast furnace gas recovery is approximately 250 PJ and 25 Mt CO_2.

Table 5.12 ▶ *Residual Gas Use in China*

	1995 %	2000 %	2001 %	2002 %	2003 %
COG	98.1	98.0	96.2	97.2	96.6
BFG	88.0	91.7	90.0	92.5	91.6
BOF gas	54.7	40.7	68.8	70.0	89.0

Source: CISA, 2005b.

Steel Slag Use

About 100 – 200 kg of BOF slag is generated per tonne of liquid steel. Steel slag, which is a by-product of the steel production process, is widely used for road construction. It can also be used in the cement clinker manufacturing process. The result is an increase in clinker production of up to 15% with no net increase in CO_2 emissions. More specifically, the process involves the addition of slag into the back or feed end of the kiln through a relatively uncomplicated and inexpensive delivery and metering system. Due to the chemical composition of the slag and the energy-intensive nature of the steel production process, the material requires little or no additional fuel to convert it into cement clinker. In addition, lower total fuel per tonne of clinker is required. The result is a net reduction in CO_2 emissions per tonne of clinker produced.

Furthermore, the flexibility of this technology means that it can easily be integrated into virtually any existing cement plant at low capital cost and provide a significant increase in production. Other major benefits are lower CO_2 emissions and reduced fuel consumption with the potential of eliminating the need for traditional raw materials such as shale or clay (Perkins, 2000). The main limitation for increased steel slag use for cement production is its high phosphor content. Phosphor can be removed in the ladle metallurgy process, but this is not yet widely done. Some steel slag also can directly be added as clinker substitute, but grinding of steel slag is a very energy intensive process, therefore this option is not widely applied.

Table 5.13 shows both basic oxygen and electric arc furnace slag use in Europe, Japan and the United states. Most slag is used for road construction and civil works. This application generates some CO_2 benefits, but they are limited. The steel slag use for cement production is still very limited and could be expanded significantly. The credits are roughly 0.6 t CO_2/t clinker substitute. The total savings potential is approximately 50 Mt CO_2. The energy efficiency gains are limited.

Table 5.13 ▶ ***Steel Slag Use***

	Europe		Japan		United States		China	
	Mt/yr	*%*	*Mt/yr*	*%*	*Mt/yr*	*%*	*Mt/yr*	*%*
Road construction and Civil works	6.9	40	6.3	64	6.6	71	38.2	90
Internal recycling	1.5	9	2.0	20		0		
Cement		0	0.3	3	0.4	4		
Interim storage	1.2	7		0		0		
Final deposit	6.4	37	0.1	1		0		
Fertilizer	0.7	4	0.1	1		0		
Hydraulic engineering	0.3	2		0		0		
Other		0	1.2	12	2.2	24	3.8	10
	17.2	**100**	**10.0**	**100**	**9.2**	**100**	**42.0**	**100**

Sources: Euroslag 2006, Nippon Slag, 2006; USGS, 2005b; CISA, 2005c.

Electric Arc Furnaces

Electric arc furnaces are used to melt scrap, direct reduced iron (DRI) or pig iron. Scrap is by far the most important resource, accounting for about 80% of all electric arc furnace metal feedstock.

Before the melting and heating operations, the furnace is charged with recycled steel scrap using a basket that has been carefully loaded. Then, the roof is closed and three graphite electrodes are lowered towards the scrap. On contact electrical power is transformed into heat as arcing takes place between the electrodes and the solid feedstock. As the scrap melts, a liquid steel pool starts to form at the bottom of the furnace. Most electric arc furnace installations are based upon the three phase, three electrode design, although, because of its lower energy requirements, there is renewed interest in the two electrode direct current arc.

As the scrap is melted, more volume is made available inside the furnace and at a certain point, the power is switched off, the furnace roof is opened and another scrap basket is loaded into the furnace. The power is again switched on and melting of the second basket starts.

To melt steel scrap, it takes a theoretical minimum of 300 kWh/t. To provide superheat above the melting point requires additional energy and for typical tap temperature requirements, the total theoretical energy required usually lies in the range of 350 – 370 kWh/t. This energy can be supplied from the electric arc, fossil fuel injection or oxidation of the scrap feedstock. The energy distribution is highly dependent on product mix, local material and energy costs and is unique to the specific furnace operation.

Factors such as raw material composition, power input rates and operating practices, *e.g.*, post-combustion, scrap preheating, can greatly alter the balance (Table 5.14). In

Table 5.14 ▶ ***Energy Use for Electric Arc Furnaces with Different Feed and with/without Preheating***

Energy *kWh/t*	**Conventional Scrap** *No Preheating*	**Shaft Scrap** *Preheating*	**EAF HBI/DRI** *No Preheating*	**Furnace HBI/DRI** *Preheating*
Input				
Electrical	433	358	588	488
Burners	81	81	81	81
Oxidation	189	189	220	220
Total	703	628	889	789
Output				
Steel	394	394	394	394
Slag	43	43	74	74
Off-gas	120	48	119	37
Wall loss	102	103	154	140
Electric loss	26	22	35	29
Reduction	11	11	104	106
Dust	7	7	9	9
Total	**703**	**628**	**889**	**789**

Source: Honeyands and Truelove, 1999.

operations using a large amount of charge carbon or high carbon feed materials, up to 60% of the energy contained in the off- gas may be calorific due to large quantities of un-combusted carbon monoxide. Recovery of this energy in the electric arc furnace could decrease energy input by 8 – 10 %.

The use of DRI or hot briquetted iron ((HBI), a solid iron product similar to DRI) increases electricity needs by 0.8 kWh per percentage point. The use of hot metal decreases power consumption by 3.5 kWh per percentage point (Köhle, 2002). Scrap pre-heating using off-gas heat reduces the electricity demand.

There are four basic types of charge pre-heating systems for the electric arc furnace currently in operation; bucket, twin shell, Consteel, and shaft. These systems differ in the percentage of the charge that can be pre-heated and in the efficiency of contact between the off-gas and the charge.

Preheating can result in a saving of 79 kWh/t scrap. HBI and DRI have heat capture efficiency up to 25% higher than an all-scrap charge, as it can pick up sensible and chemical energy. This represents an electrical energy saving of 101 kWh/t for HBI and DRI (Honeyands and Truelove, 1999).

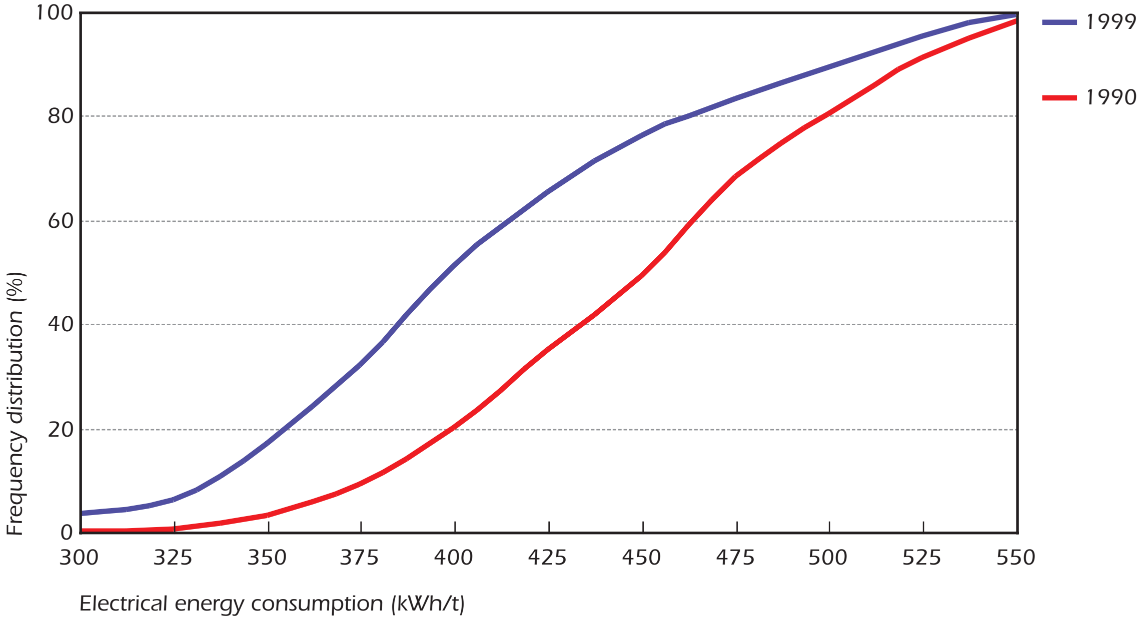
The electric arc furnace is most efficient when it is melting. During the flat bath period it is inefficient, which provides justification for secondary metallurgical processes. Oxyfuel burners increase productivity and replace electricity with a cheaper fuel. By using a fuel-efficient oxy-fuel flame at the beginning of the melting process, a greater overall melting efficiency is achieved with a faster melt rate. Further temperature homogeneity benefits can be achieved by using the burners to direct thermal energy at cold spots caused by uneven energy distribution from the electrode arcs. Additionally, the burners can be positioned in front of the slag door to enable early, efficient oxygen lancing, or over the tap hole area to promote quick, trouble-free tapping. Electrical savings of 80 kWh/tonne and 20% production increases have been achieved. Oxygen injected in the post-combustion zone of the furnace promotes combustion of carbon monoxide inside the furnace rather than in the off-gas handling system. This reaction produces heat that is transferred to the charge, reducing energy consumption (typical electrical savings of 10 – 20 kWh/tonne) and increasing productivity by up to 4%.

The electricity use for electric arc furnaces ranges from 300 – 550 kWh/t. The average electricity use decreased by about 10% between 1990 and 1999 to 425 kWh/t (Figure 5.9). Total energy into the system has declined due to increased productivity: better heat recovery and decreased retention time in the vessel. But the energy efficiency gain was somewhat less because fuel injection into electric arc furnaces increased.

Given an electricity use of about 425 kWh/t, and EAF steel production of 391 Mt in 2005, the energy use of electric arc furnace for steel production is 0.6 EJ per year. If the average electricity use could be reduced to 350 kWh/t, the level of new furnaces, it could provide electricity savings of 0.1 EJ per year.

Figure 5.9 ▶ *Electricity Use for Electric Arc Furnaces*

Key point: Global average EAF electricity consumption decreased about 20% between 1990 and 1999



Source: IISI, 2000.

Cast Iron Production

Global production of cast iron is about 50 Mt, about 5% of total ferrous metal production. In some countries such as India, cast iron production is more prominent as a share of total ferrous metals production. This requires an adjustment of energy use data when indicators are calculated. Cast iron is a sink for scrap and primary metal.

Cast iron is used for a range of applications such as engine blocks, machinery, fences, buildings and construction. Certain industry sub-sectors and countries dominate the market in volume of production and specific type of product. For example, Spheroidal Graphite Cast Iron (SG) is widely used in the water, gas and oil industries for the transportation purposes. Consequently, the volume of SG produced is high compared to other cast irons and production tends to be concentrated in France, Germany, United States, South Africa, Korea and Japan.

Cast iron is made when scrap or iron is remelted in small cupola furnaces (similar to a blast furnace in design and operation) and poured into molds to make castings. Cast iron contains 2 – 4% carbon and 1 – 3% silicon. Scrap iron or steel is often added.

Gray cast iron (gray iron) is produced when the iron in the mold is cooled slowly. Gray iron is brittle, but soft and easily machined. White cast iron (white iron) which is harder and more brittle, is made by cooling the molten iron rapidly. A malleable cast iron can be made by annealing white iron castings in a special furnace. A ductile iron may be prepared by adding magnesium to the molten pig iron; when the iron is cast the carbon forms tiny spherical nodules around the magnesium. Ductile iron is strong, shock resistant and easily machined.

The total energy use for the iron melting is 5 – 10 GJ/t iron. The most efficient cupolas use 3 GJ of coke per tonne of cast iron. Its relevance in energy terms on a global basis is limited at about 250 PJ coke, equal to 2% of total global coke production.

Direct Reduced Iron Production

A limited amount of steel is produced through processes other than blast, basic oxygen and electric arc furnaces. Direct reduced iron (DRI) (also called sponge iron) production is also widely used, yielding 56 Mt in 2004. In the DRI process, iron ore is reduced in its solid state (unlike in blast furnaces, where liquid iron is produced). DRI can be converted into steel in electric arc furnaces. DRI can use coal or natural gas as feedstock, although more than 90% of the production is based on natural gas, primarily cheap stranded gas. DRI production is widespread in the Middle East, South America, India (where it is coal-based) and Mexico. DRI fills a niche because the scale is smaller and less capital investment is required and some raw material situations make it attractive. Global DRI production has increased rapidly over the past three decades (Figure 5.10).

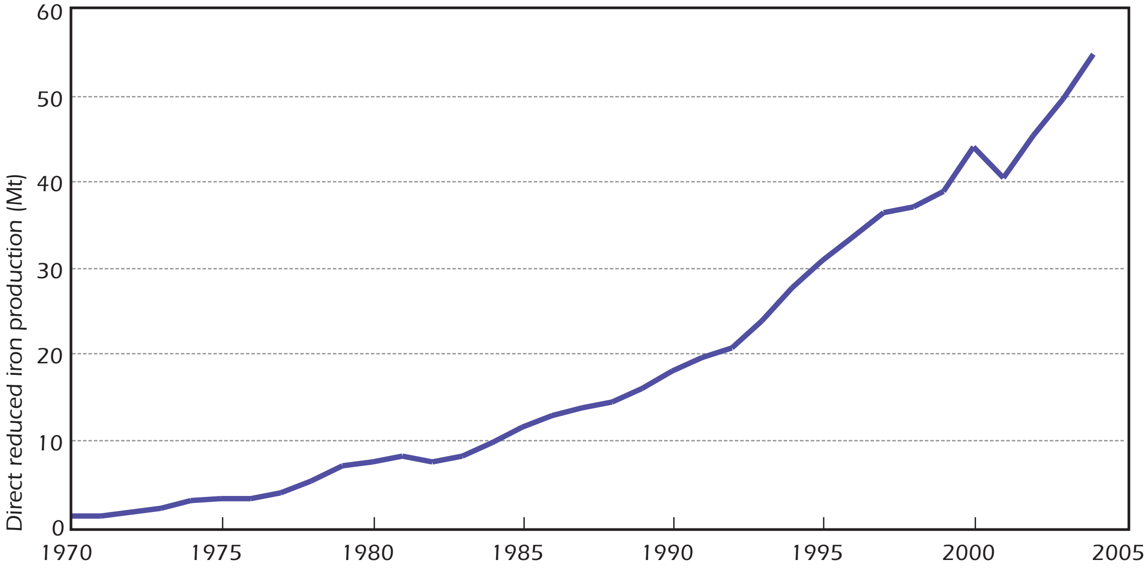
The energy use of natural gas-based DRI production processes is well defined because two technologies (Midrex and HYLIII) constitute 83% of the market. Both technologies use 10.4 GJ natural gas/t DRI produced (Table 5.15).

If natural gas is used instead of coal for DRI, CO_2 emissions are much lower. Assuming 360 g CO_2 /kWh of electricity, 0.77 t of CO_2 is emitted per tonne of steel (with zero scrap additions when gas is used). If the average CO_2 intensity of 600 g/kWh is used, the CO_2 emissions amount to 0.92 t/t. In cases where DRI is imported from regions with cheap stranded gas, this can reduce energy use and CO_2 emissions in the consuming country if it replaces production from blast furnaces. The significant growth of DRI use seems likely to continue.

India is the largest DRI producer and is a special case because its production is coal-based (Table 5.16). Production in India is rapidly expanding. In 2005 – 2006, India's 206 DRI plants had a capacity of 19 Mt and produced 11.3 Mt. Today some 225 coal-based DRI plants are at various stages of commissioning and construction. Plus 77 of the existing plants are expanding production. In the very near future, India will have 431 DRI plants with a production capacity of 44 Mt. About 60% of the current production comes from the small-scale industry. DRI plants are relatively easy to build with the help of local fabricators and suppliers. For a 100 tonne per day (tpd) DRI, the initial investment can be recovered in 12 – 18 months. Typically these plants use 1.2 – 1.5 t coal/t DRI, and produce 0.25 – 0.35 t of char by-product per tonne of DRI (Radikha, *et al.*, 2006). The char may be used for energy recovery. Ore

Figure 5.10 ▶ Global Direct Reduced Iron Production, 1970 – 2004

Key point: DRI production has grown exponentially during the past thirty-five years.



Source: MIDREX, 2005.

Table 5.15 ▶ Natural Gas-based DRI Production Processes

Process	Company	Market Share 2004 %	Reactor	Feedstock	Gas Use GJ/t	Metallisation %	Carbon %
MIDREX	Midrex/Kobe steel	64.1	Shaft	Lump/pellets	10.4	93	1.5 – 2.5
HYL III	HYLSA	18.9	Shaft	Lump/pellets	10.4	94	1.5 – 4.5
FINMET	Fior/Voest Alpine	2.9	Multi-Fluidised Bed	Ore fines	12.4	92 – 93	1.8 – 2.0
Circored	Lurgi	<0.1	Circulating fluid bed	Ore fines	11.5	93	0

Sources: IISI, 2000; MIDREX, 2005.

pre-heaters that use the sensible heat from the waste gas can reduce the coal consumption by 25%. Advanced plants use 1.05 - 1.2 t low grade coal/t DRI, which equals 20 - 25 GJ/t DRI (Pandey, 2006).

Table 5.16 ▶ *DRI Production, 2004*

	2004 *Mt/yr*	Share *%*	Cumulative Production Share *%*
India	9.1	16.8	16.8
Venezuela	7.8	14.4	31.2
Iran	6.4	11.8	43.1
Mexico	6.3	11.6	54.7
Saudi Arabia	3.4	6.3	61.0
Russia	3.1	5.7	66.7
Egypt	3.0	5.5	72.3
Trinidad and Tobago	2.2	4.1	76.3
Argentina	1.8	3.3	79.7
Malaysia	1.7	3.1	82.8
Libya	1.6	3.0	85.8
South Africa	1.6	3.0	88.7
Indonesia	1.5	2.8	91.5
Other	4.4	8.5	100.0
World	**54.1**	**100.0**	

Source: IISI, 2005.

The wide range of energy efficiency in India is related to the range of technologies in use. At least six technologies can be discerned (Midrex, 2004). A general characteristic is that most plants are small, with less than 0.2 Mt capacity. This hinders the economic viability of installing energy efficiency equipment.

All the plants use a counter current rotary kiln. Because a rotary kiln is not well suited for heat exchange, only about 60% of the heat is used in the reduction process and 40% is discharged with the kiln waste gases. This heat can be used for power generation. The power consumption has been reduced from 110 – 130 kWh/t DRI to 80 – 90 kWh/t DRI (Pandit, *et al.*, 2006). After deducting the internal power consumption between 400 – 500 kWh/t DRI is generated, if the waste heat is used for power generation. Power generation from kiln off-gases is eligible for credits under the Clean Development Mechanism of the Kyoto Protocol and can be highly profitable (Tata Sponge, 2006).

The Dunswart plant in South Africa represents the world standard for DRI production from coal. This plant is reported to use 15 – 19 GJ/t DRI. Thermal loads for DRI production facilities are linked to a large extent to the quality of coal and to a lesser degree to the reducibility of iron ore. Non combustible constituents (ash and moisture) of the coal used in the average Indian DRI plant comprise 32% of the total constituents, compared with 16% in the Dunswart plant. Those qualities contribute significantly to the observed differences in both electrical and thermal efficiencies (Sindwani, 2006).

Steel Finishing

Steel finishing operations use a relatively small percentage of total energy in iron and steel production. Energy for finishing is required in many different unit operations such that it is difficult to identify a few technologies that will significantly impact the overall energy and CO_2 intensity. The areas of focus are the reheat furnace, hot charging, energy recovery, scheduling, furnace design and process controls.

Today, in most steel mills the casting and rolling process is a multi-step process. The liquid steel is first cast continuously into blooms, billets, or slabs in the continuous casting process where liquid steel flows out of the ladle into the tundish (or holding tank) and then is fed into a water-cooled copper mold. Solidification begins in the mold, and continues through the caster. The strand is straightened, torch-cut, then discharged for intermediate storage. Most steel slabs are reheated in reheating furnaces, and rolled into final shape in hot and cold rolling mills or finishing mills.

The amount of finishing energy depends on the product. Steel reinforcement bars and steel plate need only hot rolling. However, steel for cars and white goods needs hot rolling and cold rolling, and often galvanizing or coating. Typical energy use for hot rolling is 2 – 2.4 GJ/t, and 1 – 1.4 GJ/t for cold rolling.

In large integrated steel plants, the hot strip rolling process is the third largest user of energy after iron and steel making. Typically, slabs are superheated in reheating furnaces to compensate for temperature losses (about 13%), which occur during the roughing and transfer operations prior to finish rolling. Most of the energy losses are from the tail ends of transfer bars due to their long exposure times on the transfer roller table prior and during finish rolling. The resultant head to tail temperature variations together with edge temperature losses cause problems with product rolling and quality uniformity.

In the traditional steel production process, the thick slab of red-hot steel is cooled to room temperature after it leaves the furnace. Thin slab or strip casting processes reduce the steel rolling energy needs significantly. The new technology enables faster production of thin products and considerable savings in capital cost outlay, completion and delivery times and energy costs. Today, less than 10% of world production is based on this technology, but certain companies achieve substantially higher shares.

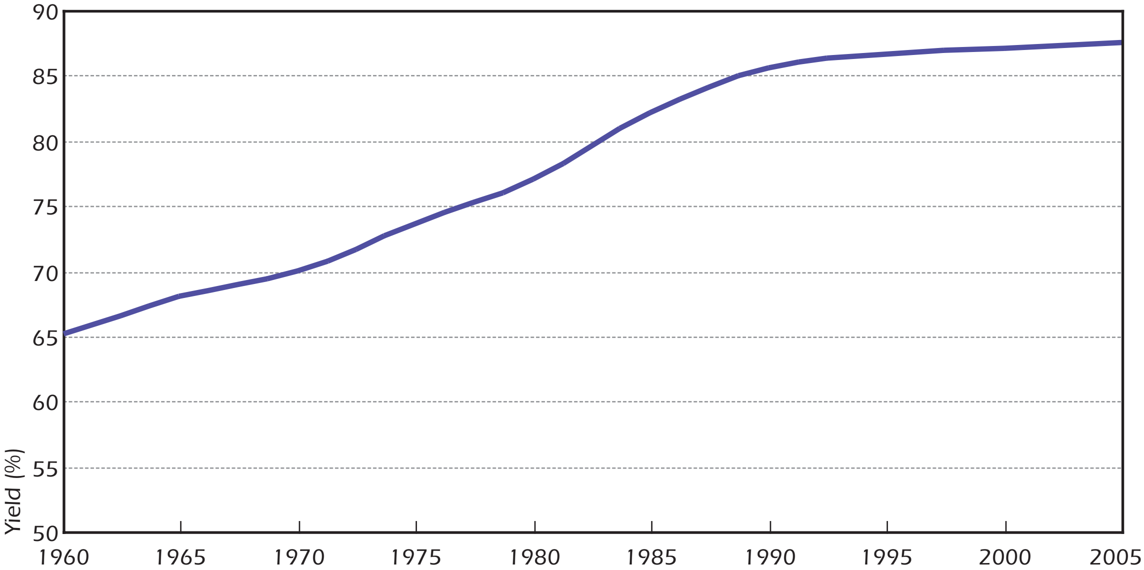
The energy savings are in the range of 1 – 2 GJ of primary energy per tonne of product. Assuming that this technology can be applied to a quarter of world production, the savings potential is about 0.3 – 0.4 EJ of primary energy per year and 20 – 40 Mt of CO_2. This is a long-term potential, assuming gradual improvements in process control to maintain steel materials quality.

Loss of yield in steel finishing equates to loss of product into which a great deal of energy has been invested. If the waste product is allowed to oxidise, it must go back through the reduction process to be recycled.

Figure 5.11 shows the average steel yield in Germany, measured as the ratio of the metal sold and the metal in the pig iron and steel scrap. It increased from 65% in 1960 to 87.5% in 2005. About 12.5% of all metal is still lost as oxide or in-plant off-spec product that is recycled to an electric arc furnace or a blast furnace. About half of this amount is oxide created during the rolling process. The yield in other countries is often considerably lower. Higher yields imply a reduced need for crude steel production and therefore a substantial CO_2 reduction potential. Residues from steel rolling are recycled to the blast furnace or the basic oxygen furnace, therefore the net savings of yield gains may be 4 – 5 GJ primary energy per tonne of reduced losses. Given a remaining potential of 2 – 4 percentage points, the total global savings potential may amount to 75 – 150 PJ and 10 – 15 Mt of CO_2 reductions.

Figure 5.11 ▶ *Trend of Average Steel Yields, Germany, 1960 – 2005*

Key point: Steel yields in Germany have improved significantly between 1960 and 1990 and have stabilised at a high level.



Source: Debruxelles, 2006.

Energy Efficiency and CO_2 Reduction Potentials

Table 5.17 summarises the theoretical (physical) or technological potentials estimated for the iron and steel industry. They take into account technologies that are applied somewhere in the world today and assume that this best available technology could be applied globally at current production levels. Economic feasibility, transition rates, regulatory and social factors have not been included.

Table 5.17 ▶ *Technical Energy Efficiency and CO_2 Reduction Potentials in Iron and Steel Production*

	EJ/yr	*Mt CO_2/yr*
Coke making: apply coke dry quenching	0.2 – 0.3	25
Coke making: coke oven gas recovery	0.2 – 0.3	25
Blast furnace improvements	1.2 – 1.5	115 – 140
Enhanced efficiency of blast furnace gas use	Not quantified	Not quantified
Increased blast furnace slag/steel slag use for cement making	Not quantified	Not quantified
Increased basic oxygen furnace gas recovery	0.25	25
Electric arc furnace: Reduce average electricity use to 350kWh/t	0.25	15
Steel finishing improvements	0.3 - 0.4	20 – 40
Total	**2.3 - 2.9**	**220 – 270**

Note: Energy efficiency potentials are in primary energy equivalents.

Some estimated potentials take place in other sectors. For example, increasing the use of blast furnace and steel slag as a substitute for clinker in cement production could contribute 140 - 185 Mt CO_2 reduction, which can reduce emissions for cement, but not in iron and steel production.

The total identified savings potential is 2.3 - 2.9 EJ of primary energy and a CO_2 emissions reduction, of 220 - 270 Mt per year. This excludes enhanced recovery of residual gas and higher efficiency of residual gas use for power generation. Also closure of remaining outdated plants using open hearth furnace and ingot casting, more efficient operation of coke ovens, waste heat recovery from sintering plants have been excluded. It is estimated that these options can raise the potential to about 4.5 EJ of primary energy. Including recycling, the potential is 5 EJ of primary energy. Increased slag use for cement making can yield significant efficiency gains but most benefits would occur outside the iron and steel industry. The full range of CO_2 emission reductions is estimated to be even broader, from around 220 - 360 Mt CO_2 per year.

The use of waste plastic and charcoal in iron and steel production can increase the potential of CO_2 reductions further, as would a large switch to natural gas-based DRI processes. Neither these options nor the use of technologies such as CO_2 capture and storage have been considered in these estimates.

NON-METALLIC MINERALS

Key Findings

- *Cement production accounts for about 8 EJ of energy or 70 to 80% of all energy use in non-metallic minerals production. It is an important source of CO_2 emissions, accounting for 1.8 Gt CO_2 in 2005.*
- *China is by far the largest cement producer with 46% of world cement production in 2005. India, the second largest producer, accounts for only 6%.*
- *Production of cement is a relatively simple process with well defined system boundaries and a uniform product, which makes it well suited to indicator analysis. A number of energy efficiency and CO_2 indicators are proposed that will allow energy and CO_2 intensity trends to be tracked over time.*
- *The available data are best used to track energy and CO_2 intensity trends within a country. Comparisons of absolute levels between countries are complicated by uncertainties over the consistency of data collection. Data for clinker substitutes and alternative fuels need to be improved. National data collection processes need to be checked to ensure if electricity use for grinding stations is reported in the correct category.*
- *The country average primary energy intensity for cement production ranges from 3.4 to 5.3 GJ/t. Averages at a country level have improved everywhere, with the weighted average primary energy intensity declining from 4.8 GJ/t in 1994 to 4.4 GJ/t in 2003. Much of this decline has been driven by improvements in China. The efficiency of cement production is relatively low in countries with old capital stock based on wet kilns and in countries with a significant share of small-scale vertical kilns.*
- *The country average CO_2 intensity of cement ranges from 0.65 to 0.92 t CO_2/t of cement (weighted average 0.83). The average CO_2 intensity has declined at 1% per year between 1994 and 2003. Half of the CO_2 emissions are due to the chemical reaction in clinker production, which are not affected by energy efficiency or fuel switching.*
- *Indicator data for cement production suggest that fuel use could be reduced by around 2.5 to 3 EJ if all production used the best available technology and more clinker feedstock substitutes were used. However, this potential could not be easily realised in the near term without significant investment in capital stock replacement.*
- *It might be possible to reduce clinker production by 300 Mt if more extensive use of clinker substitutes such as granulated blast furnace slag, steel slag, fly and bottom ash, and natural pozzolanas was made. This could reduce CO_2 emissions by about 240 Mt CO_2 per year.*
- *Other non-metallic mineral materials, such as lime, glass, bricks and ceramic products, account for the remaining 20 to 30% of energy use and less than 20% of CO_2 emissions in the sub-sector. Two-thirds of lime production is for captive use and is not accounted for in this sub-sector. Therefore, energy use in lime production is more important than the statistics suggest. CO_2 process emissions occur in lime production, but most of the CO_2 is captured from the atmosphere during lime use.*
- *Indicators could be developed for lime production. Benchmarking has been done for glass furnaces. Bricks and ceramic products are rather diverse, which affects energy use per unit of product. Moreover, there are no good statistical data on product weight. China is the largest producer of these products. The total global savings potential is less than 1 EJ per year for these other non-metallic minerals.*

Introduction

The most energy intensive part of the non-metallic minerals industry is the production of ceramic materials. While the energy intensity per tonne is not very high compared to other energy intensive materials, this is the materials category with by far the largest volume. The industry accounts for about 10% of total final industrial energy use and has significant process CO_2 emissions, notably in the production of cement and lime. It accounts for more than a quarter of the direct CO_2 emissions from the manufacturing industry.

Cement

Global Importance and Energy Use

Cement accounts for about 70 – 80% of the energy use in the non-metallic minerals sub-sector, consuming 8.2 exajoules (EJ) of energy a year (7% of total industrial fuel use). Cement accounts for almost one-quarter of total direct CO_2 emissions in industry. Cement is the "glue" that holds a concrete mixture together, which is used extensively in construction. Its stone-like qualities and ability to be poured into different forms makes concrete an excellent construction material and it is used extensively in buildings, bridges, walls and a multitude of other uses. In many respects it is the backbone of modern infrastructure, in conjunction with iron and steel.

Cement is generally produced from a feedstock of limestone, clay and sand; which provide the four key ingredients required: lime, silica, alumina and iron. Mixing these ingredients and exposing them to intense heat causes chemical reactions that convert the partially molten raw materials into pellets called "clinker." After adding gypsum, the mixture is ground to a fine grey powder called "Portland cement", a key ingredient of concrete.

Global cement production grew from 594 million tonnes (Mt) in 1970 to 2 292 Mt in 2005, with the vast majority of the growth occurring in developing countries, especially China. In 2005, China accounted for 46% of global cement production, while India, Thailand, Brazil, Indonesia, Iran, Egypt, Vietnam and Saudi Arabia accounted for 15% (Table 6.2).

Cement Production Process

The first step in the Portland cement manufacturing process is to obtain the raw material feedstocks. At the quarry, the raw materials of limestone, clay and sand are reduced by primary and secondary crushers. The primary crusher reduces the material to about the size of baseballs, while secondary crushing reduces it to the size of gravel.

When the raw feedstock arrives at the cement plant, the materials are proportioned to create cement with a specific chemical composition. The raw materials are analysed at the plant to make certain the chemical composition is correct, they are then blended in the proper proportion and ground even finer. The material is ground with heavy, wheel-type rollers that crush the materials into powder against a rotating table. After grinding, the material is fed into a rotating kiln, in most cases passing first through a pre-heater and pre-calciner, before being heated in the kiln to around

Box 6.1

Energy Use and CO_2 Emissions in the Ceramic Building Materials Industry in China

The building materials industry in China accounts for about half of global production. The industry used 6.6 EJ of fossil fuels and 0.8 EJ of electricity in 2006, which equals about 6% of all manufacturing industry final energy use and 23% of CO_2 emissions. Cement accounts for half of this energy use and three-quarters of CO_2 emissions. The industry can reduce its energy use by 29% and CO_2 emissions by 10%, if the government's policy targets for introduction of new technologies by 2010 are met (Table 6.1). It should be noted that the savings potential for products excluding cement exceeds the reported energy use in IEA statistics. This points to the fact that these estimates are optimistic or energy use is not fully reported.

Table 6.1 ▶ *Energy Use, CO_2 Emissions and Short-Term Reduction Potentials in the Chinese Building Materials Industry, 2006*

Products	Output in 2006	Fuel Consumption *PJ/yr*	Power Consumption *TWh*	Direct CO_2 Emissions *Mt/yr*	BAT for Near and Medium Term	Energy Saving Target (in 2010) *PJ/yr*	CO_2 Emissions Reduction Target *Mt/yr*
Cement	1 235 Mt	3 047	123.5	986	NSP	615	105
Clay brick and tile	520 billion standard bricks	1 319	15.9	148	Tunnel kilns	565	29
Building ceramics	5 024 million m^2	967	24.2	23	Roller kilns	440	1
Lime	162 Mt	791	8.9	190	Maerz kiln	164	4
Flat glass	22.75 Mt	264	10.0	7	Float process	47	0
Glass fibres	1.41 Mt	88	0.0	2	Direct melt process	18	0
Sanitary wares	131 million pieces	41	0.7	1	Large batch kiln	8	0
Others	–	147	40.0	30	Energy saving technologies	76	3
All ceramic building materials	–	6 645	223.2	1 387	–	1 934	142

Source: Cui, 2007.

Note: NSP= New Suspension Pre-heater.

Table 6.2 ▶ *Global Cement Production, 2005*

	Production Mt/yr	Share %	Cumulative Production Share %
China	1 064	46.4	46.4
India	130	5.7	52.1
United States	99	4.3	56.4
Japan	74	3.2	59.6
Korea	50	2.2	61.8
Spain	48	2.1	63.9
Russia	45	2.0	65.9
Thailand	40	1.7	67.6
Brazil	39	1.7	69.3
Italy	38	1.7	71.0
Turkey	38	1.7	72.6
Indonesia	37	1.6	74.3
Mexico	36	1.6	75.8
Germany	32	1.4	77.2
Iran	32	1.4	78.6
Egypt	27	1.2	79.8
Vietnam	27	1.2	81.0
Saudi Arabia	24	1.0	82.0
France	20	0.9	82.9
Other	392	17.1	100.0
World	**2 292**	**100.0**	

Source: US Geological Survey (USGS), 2006.

1 500°C. The kiln is a horizontally sloped steel cylinder, lined with firebrick, turning from about one to three revolutions per minute.

From the pre-heater or pre-calciner the raw material enters the kiln. It slides and moves down the kiln through progressively hotter zones toward the flame. Fuels such as pulverised coal, natural gas, fuel oils and petroleum are burned to feed a flame at the lower end of the kiln that reaches about 2 000°C, allowing the materials to be heated to around 1 500°C, where they become partially molten. The intense heat triggers the chemical and physical changes that transform the raw feedstock into cement clinker.

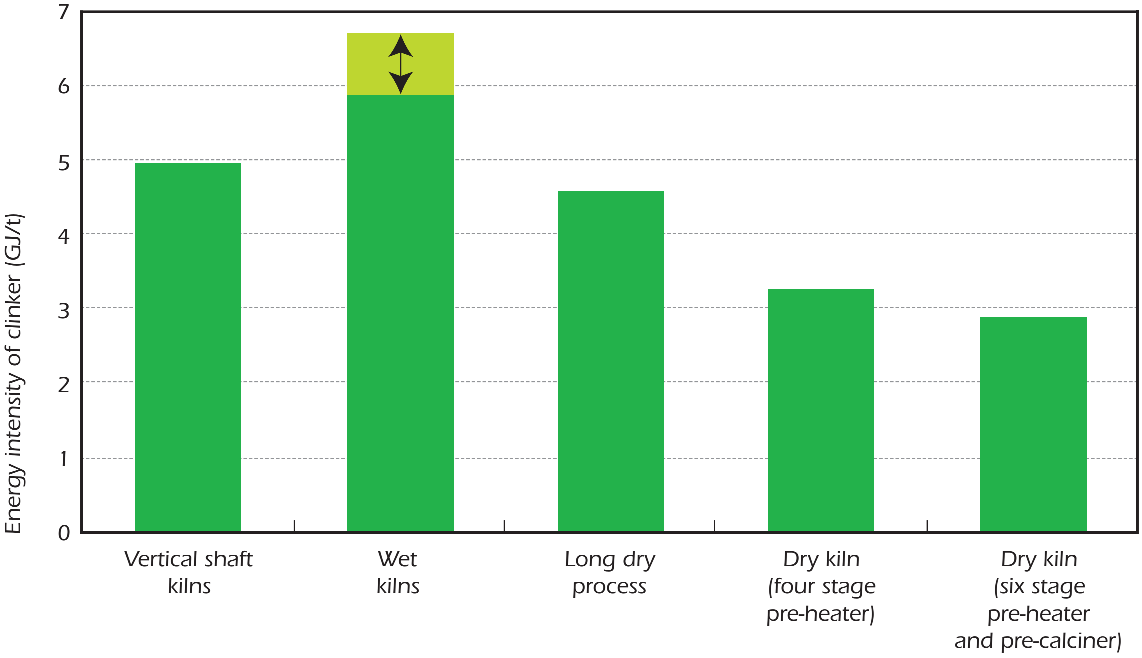
Essentially, a series of chemical reactions converts the calcium and silicon oxides into calcium silicates, cement's main constituent. The main chemical reaction is: $CaCO_3 \rightarrow CaO + CO_2$. When the limestone ($CaCO_3$) reaches about 900°C, it undergoes a chemical reaction called "calcination" whereby CO_2 is released and calcium oxide formed, before this converts to clinker. The clinker is then ground with the appropriate additives or clinker substitutes to form cement and is ready for storage or packaging.

There are two basic types of cement production processes and a number of different kiln types. Cement production is either "wet" or "dry", depending on the water content of the raw material feedstock. The wet process allows for easier control of the chemistry and is better when moist raw feedstocks are available. However, it has higher energy requirements due to the need to evaporate the 30%+ slurry water before heating the raw materials to the necessary temperature for calcination. The dry process avoids the need for water evaporation and is, as a consequence, much less energy intensive (Figure 6.1). The other major difference is between vertical shaft kilns and their more efficient counterparts, rotary kilns.

Today's state-of-the-art dry-rotary kilns are fairly fuel efficient. The thermodynamic minimum to drive the endothermic reactions is approximately 1.8 GJ per tonne (GJ/t) clinker for dry limestone feedstock, but is much higher for feedstocks with significant moisture content. The superior performance of rotary kilns makes them the likely technology of choice for the next several decades.

Figure 6.1 ▶ ***Energy Efficiency of Various Cement Clinker Production Technologies***

Key point: Modern dry process cement kilns use half as much energy as the wet process to produce a tonne of cement.



Note: For wet kilns, the arrow represents the range of energy consumption for different wet kiln types.

Source: FLSmidth, 2006.

Box 6.2

Shaft Kilns in China

China has very high levels of cement production from relatively inefficient vertical shaft kilns, which increased 42% between 1997 and 2003. Vertical shaft kilns, of which there are three main types, consume between 4.8 – 6.7 GJ/t clinker. A decline in production from vertical shaft kilns since 2004 (Figure 6.2) is linked to the National Development and Reform Commission's (NDRC) 2004 plan that:

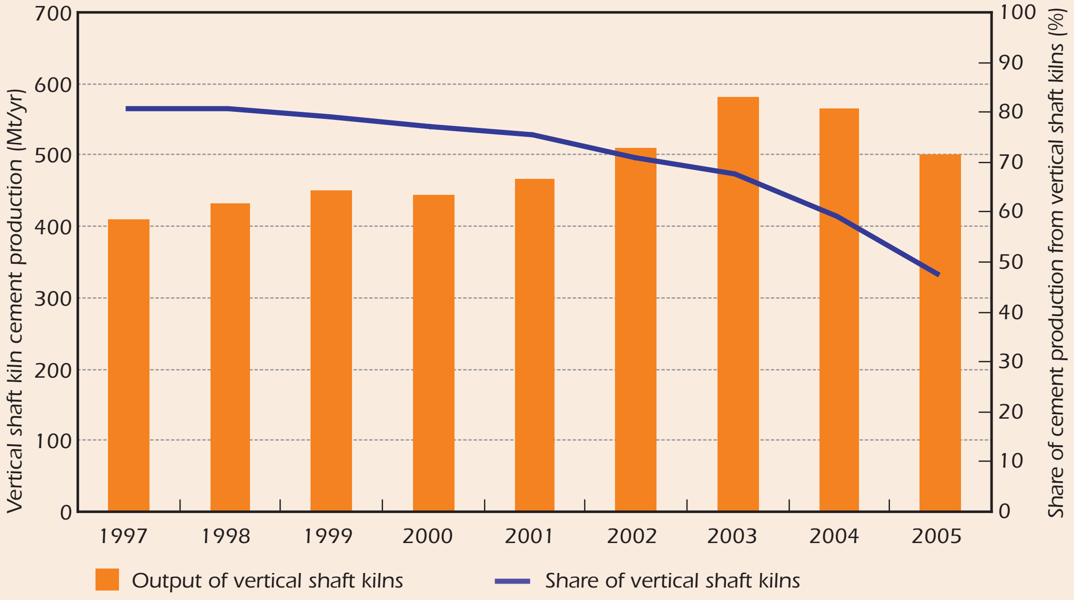
"By 2010, China's products as a whole are expected to reach or approach the advanced international level of the early 1990s... by 2020 China is expected to reach or approach the advanced international level".

In 2006, the NDRC set specific goals for the structural adjustment of cement manufacturing between 2005 and 2010, including a 15% improvement in the thermal energy intensity of clinker production and that 250 Mt of old inefficient plant should be closed (Cui, 2006; Price, 2006). The plan stipulates that new construction must be dry process kilns and that there is to be no expansion of existing vertical shaft kiln plant.

The share of total production from vertical shaft kilns which was 47% in 2005 looks likely to decline. The increased share of large-scale dry process kilns will reduce the energy intensity of cement production in China.

Figure 6.2 ▶ ***Cement Production from Vertical Shaft Kilns in China, 1997-2003***

Key point: The share of cement production from inefficient vertical shaft kilns in China has declined since 1996, but is still high.



Source: LBNL; IEA data.

The long dry process requires around 4.6 GJ/t of clinker, while the addition of pre-heaters and pre-calciners further reduces the energy requirement for cement production. Table 6.3 shows the evolution of cement kiln technology options and the consequent reduction in the energy intensity. It is unlikely that the fuel efficiency of the today's dry process rotary kilns can be reduced much below their current level of 2.9 – 3.0 GJ/t of clinker.

As a result of the different energy intensities of the different processes and kiln types, the energy intensity of cement production varies significantly by region depending on whether a wet or dry process is used and on the kiln technology itself.

Table 6.3 ▶ *Heat Consumption of Different Cement Kiln Technologies*

Process	Fuel Consumption *GJ/t clinker*
Wet process	**5.9 – 6.7**
Long dry process	**4.6**
1 stage cyclone pre-heater	4.2
2 stage cyclone pre-heater	3.8
4 stage cyclone pre-heater	3.3
4 stage pre-heater+pre-calciner	3.1
5 stage pre-heater+pre-calciner	3.0 – 3.1
6 stage pre-heater+pre-calciner	2.9

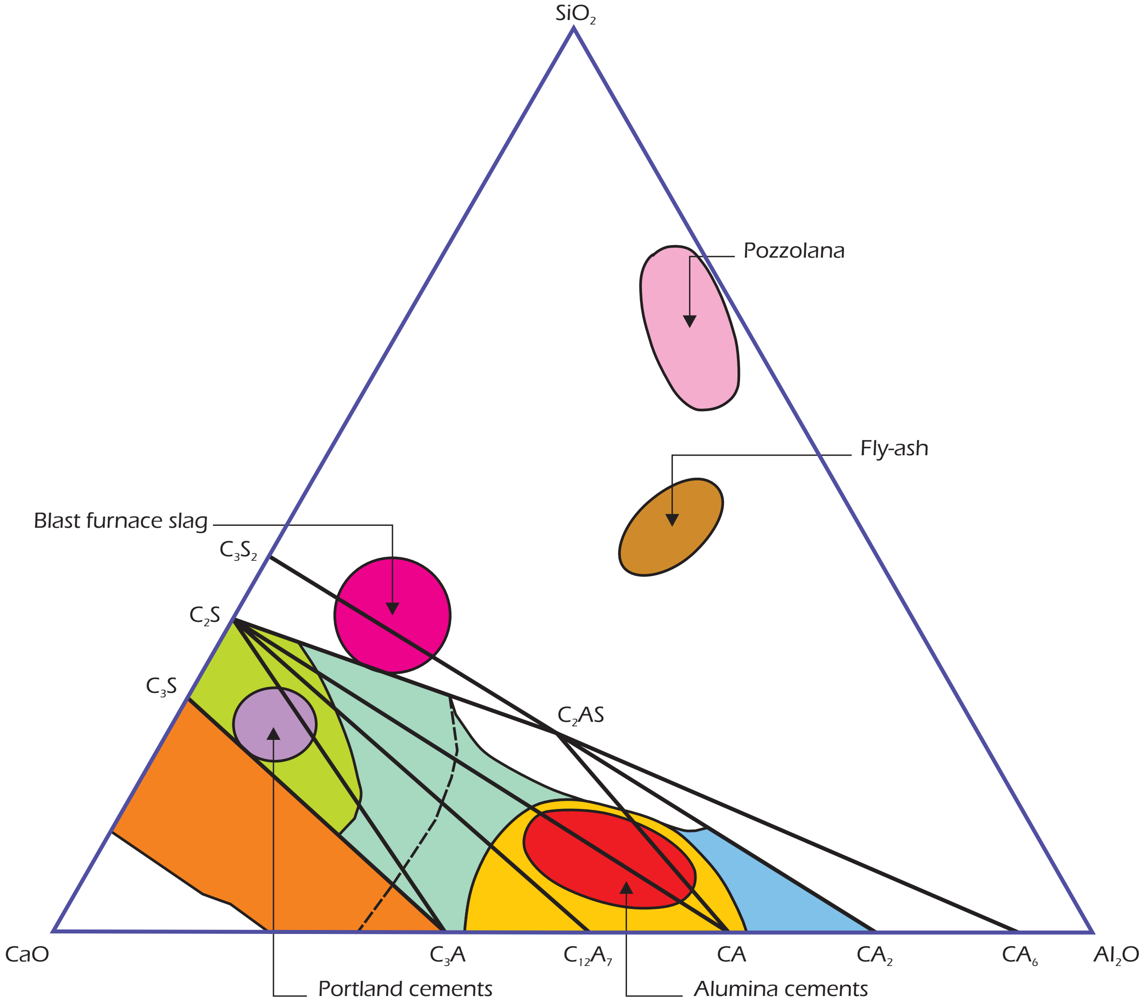
Source: FLSmidth, 2006.

The production of cement clinker from limestone and chalk is the main energy consuming process in the industry. Cement production is an energy-intensive process and energy typically represents 20 – 40% of total production costs. The most widely used cement type is Portland cement, which contains 95% cement clinker. However, there is a range of other types of cement that use a variety of clinker substitutes to reduce clinker costs and CO_2 emissions. These other feedstocks for cement have properties similar to cement and therefore can be substituted for clinker either in the cement or in the kiln as an alternative to the feedstock mix. Figure 6.3 shows the chemical composition of Portland cement and the various clinker substitutes in a ternary phase diagram. A point halfway on one of the three sides consists of 50% each of the components of the adjoining angles. A point in the centre of the triangle represents a component with a third of each of the components. The three corners represent the pure basic chemical building block of cement. Various cement types have a different ratio of the three building blocks and therefore different chemical compounds dominate.

One option for reducing the energy and process emissions from clinker production is the direct use of steel slag in the kiln as a substitute for limestone. The process involves adding steel slag into the back or “feed-end” of the kiln through a relatively uncomplicated and inexpensive delivery and metering system, which can be used at virtually all kiln types. Due to the chemical composition of the steel slag and the energy-intensive nature of the steel production process, the material requires little or no additional fuel to convert it into cement clinker. CO_2 emissions per tonne of clinker are reduced due to lower energy needs and the avoidance of some process emissions. Fly-ash may also be used directly in the cement kiln as a substitute for clay or bauxite, also helping to reduce resource consumption and CO_2 emissions. The use of alternative raw materials is increasing in Europe, from around 12 Mt in 2003 to 14 Mt in 2004 (CEMBUREAU, 2006).

Figure 6.3 ▶ ***Chemical Composition of Cement and Clinker Substitutes***

Key point: Blast furnace slag, fly-ash and natural pozzolans can all be used as clinker substitutes.



Note: Acronyms refer to cement minerals with different chemical compositions.
Source: CEMBUREAU, 2006.

The second option is to use waste products with similar properties to clinker as substitutes. The most common clinker substitutes are waste products such as fly-ash or granulated blast furnace slag or natural pozzolana (volcanic ash).[1] Producing alternative cement types including these products is far less energy intensive than producing normal cement and avoids the process CO_2 emissions in the clinker production displaced. However, the cement properties are not exactly the same and can not therefore be used in all applications.

The typical composition of various cement types is shown in Table 6.4. Generally, cement types are defined by the quantity of clinker substitutes used by weight. Within each blended cement type, different grades are identified based on the percentage of clinker substitutes used.[2] There is no fixed proportion at which they should be mixed. Generally speaking, a cement type is referred to as a Portland cement if clinker substitutes are 40% or less by weight, whereas they are identified by the main clinker substitute used if it exceeds that level, *e.g.* Portland fly-ash cement compared with blast furnace slag cement.

The availability of waste slag is limited and pozzolana can be obtained only in certain locations. This tends to limit their use, as the long distance transportation of cement or cement feedstocks would result in significant additional energy use and cost, which is not an attractive option given the low value of the product. Fly-ash with high carbon content can not easily be used in cement; however, a US company has developed a technology to separate the carbon from the fly-ash. This reduces the carbon content from 18 to 2.5% and allows it to be used as a clinker substitute. This technology is currently applied in the United Kingdom and Israel. There is an appreciable potential for clinker substitutes that is not yet fully exhausted.

Table 6.4 ▶ ***Typical Composition of Different Cement Types***

Cement type	Portland cement %	Portland fly-ash cement %	Blast-furnace cement %	Pozzolanic cement mixes %
Clinker	95 – 100	65 – 94	5 – 64	45 – 89
Fly-ash	–	6 – 35	–	–
Blast-furnace slag	–	–	36 – 95	–
Pozzolana	–	–	–	11 – 55
Additional constituents (*e.g.* gypsum)	0 – 5	0 – 5	0 – 5	0 – 5

Source: Based on CEN, 2000.

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[1] NAHB (2006).

[2] See CEN (2000) for a comprehensive listing of the 27 products in the family of common cements and the ranges of clinker substitutes that characterise each cement type.

The use of blended cement varies widely from country to country, but it is high in continental Europe. There is currently little use of blended cement in the United Kingdom and the United States. However, in the United States and China, significant clinker/cement substitutes are blended directly into the concrete at the time of pouring; this practice is rare outside of those two countries.

Blended cement offers a major opportunity for energy savings and CO_2 emission reductions, but will depend on the availability of waste products. Granulated blast furnace slag availability is expected to increase from about 102 Mt in 2003 to 150 Mt in 2010 (Harder, 2006). The availability of fly-ash is significant and could be 445 Mt given current production (Smith, 2005). The availability of fly-ash could increase by 20% by 2010 given the current projections for coal demand growth (IEA, 2006a).

In the long term, new cement types may be developed that do not use limestone as a primary resource. These new types of cement are called "geopolymers". Though they are outside the scope of this analysis, the technological feasibility, economics and energy effects of such alternative cements remain speculative.

Clinker-to-Cement Ratio

Using clinker substitutes reduces CO_2 emissions from energy consumption in the kiln and avoids the process emissions that stem from clinker production. The clinker-to-cement ratio (hereafter referred to as the "clinker ratio") tends to vary between 0.7 – 0.95 tonnes of clinker per tonne of cement, depending on the types of cement produced. A clinker ratio of 0.95 represents 100% production of Portland cement with 5% gypsum added, while lower values are achieved by increasing the share of blended cement types.

The absence of clinker production data for some countries makes estimates of the clinker ratio important in estimating clinker production and energy intensity. Figure 6.4 presents estimates of the clinker ratio in a number of different countries and regions. Significant uncertainty surrounds some of these estimates; and in many cases only a snapshot of the industry is available from the 1990s. More accurate data for the current clinker ratio are needed if reliable projections of the clinker production to meet cement demand are to be made.[3]

In general, there has been a gradual reduction in the clinker ratio since 1990. The only exception appears to be Brazil, but this could also be due to data issues. The decline in the weighted average clinker ratio of the countries with data available for 1994 – 2004 was 1.0 % per year. Much of this decline is due to the 1.3% per year decline in the clinker ratio in China between 1994 and 2004.

Of the major cement producers, for which data is available, China appears to have had the lowest clinker ratio in 2004. This is due to the extensive use of granulated blast furnace slag, fly-ash, boiler bottom-ash and a variety of other substitutes. However, the data for China is uncertain as various sources give different data,

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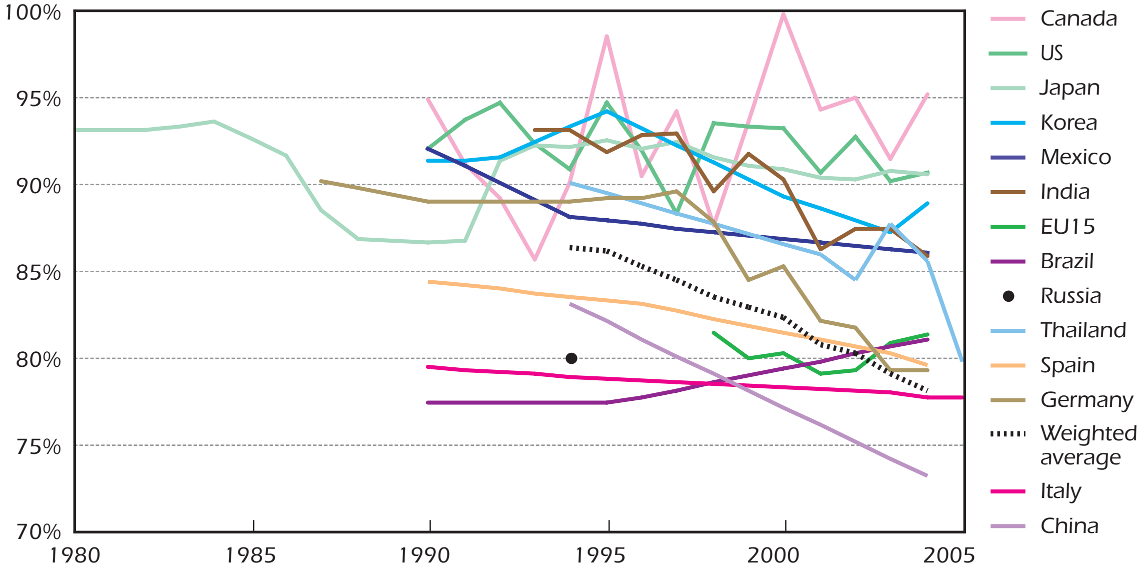
[3] Although data for Canadian clinker production and imports are collected, the information for 1995 and 2000 appears to identify data issues, because even pure Portland cement has a clinker ratio of 95% at most.

Figure 6.4 ▶ *Clinker-to-Cement Ratio by Country and Region, 1980-2005*

Key point: China has achieved a significant reduction in its clinker ratio, helping to reduce the weighted average between 1995 and 2004.



Note: The weighted average excludes EU15. Data for Thailand are based on Siam Cement Company only.

Sources: Soares and Tolmasquim, 2000; Dong-Woon, 2006; Worrell, *et al.*, 2001; Siam Cement Company Ltd, 2005; CEMBUREAU, 2006; EC, 2006; AITEC, 2000 – 2005; USGS, 2006; PCA, 2005; NRCAN, 2006; Statistics Canada, various years; Japan Cement Association, 2006; Cui and Xiao, 2006; VDZ, 2006; Siam Cement Company Ltd, 2005; and Battelle, 2002.

particularly for granulated blast furnace slag use, while in addition, there is no guarantee that the data collected in the study of the 1994 clinker ratio and that in 2004 are consistent. China produced 330 Mt of fly-ash in 2005, of which about 63% was used in cement production and 37% was disposed of in land fills (Cui and Xiao, 2006). This implies that China alone uses 180 – 210 Mt of fly-ash for cement and concrete production.

An additional complicating factor is that in some countries, notably the United States, significant blending of clinker substitutes occurs when the concrete is mixed, rather than at the time of cement production. This obviously has important implications for any assessment of the role that clinker substitutes can play in reducing clinker production and CO_2 emissions. The clinker ratio presented in Figure 6.4 for the United States has not been adjusted to take into account the use of cement substitutes that are blended directly into the concrete at the time of pouring.

In the United States, 12.3 Mt of fly-ash and 0.3 Mt of bottom-ash were directly used for concrete production in 2003 (ACAA, 2003). This represents about 17% of all fly-ash and 2% of bottom-ash. It should be compared to 92.8 Mt cement production, so this is equivalent to a lowering of the clinker/cement ratio by 12 percentage points. In the same year, 3.2 Mt of blast furnace slag were used in concrete. This is equivalent to the lowering of the clinker ratio by another 3 percentage points. In total, this is equivalent to a reduction of the clinker ratio by 15 percentage points to 77% in 2003. China also adds significant amounts of clinker substitutes directly into concrete. This practice results in important energy savings and CO_2 reductions. This type of measure must be considered when country energy efficiency and CO_2 emission indicators are compared. In the case of China it is not clear if this is accounted for in the cement production data. Further analysis is recommended.

Clinker substitutes are not only used in cement production. Significant amounts of pozzolanic materials are directly used for road bases and other uses where they substitute for cement and concrete. Such practices reduce energy use and CO_2 emissions in cement production, but it does not show up when the energy use and CO_2 emissions per tonne of cement are compared. However, the CO_2 benefits are lower than if the same substitutes were used for cement production.

Table 6.5 presents estimates of the current global use of clinker substitutes and their availability. Significant quantities of fly-ash are unused, but the balance for granulated blast furnace slag is much more in balance. In a carbon constrained world, using these clinker substitutes to avoid the process and energy emissions of clinker production would probably represent their highest value use. As Figure 6.4 shows, there is considerable opportunity to increase the use of clinker substitutes in many countries, perhaps by 300 Mt per year, which could reduce CO_2 emissions on the order of 240 Mt per year.

Table 6.5 ▶ *Current Use and Availability of Clinker Substitutes*

Cement type	Current use *Mt*	Availability *Mt*
Total Blast Furnace Slag	n.a.	180 – 220
Granulated blast furnace slag	90	110
Fly-ash [4]	222	445
Pozzolana	50	n.a.

Note: Data in Table 6.5 are consistent with data for 2004 in the Iron and Steel chapter (5), but other sources indicate 120 Mt of granulated blast furnace slag use in China alone in 2006 (Cui, 2007).

Sources: Harder, 2006; Japan Cement Association, 2006; Smith, 2005; IEA estimates.

Technology and Fuel Consumption in Cement Production

The most widely used production process for Portland cement clinker is the relatively energy efficient dry process, which is gradually replacing the wet process. In the last few decades, pre-calcination technology has also been introduced as an energy saving measure.

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[4] Significant uncertainty surrounds the current availability of fly-ash in China. The estimate for China is conservative – an additional 100 Mt may be available, but its suitability for use in the cement industry due to high carbon content is not clear.

Table 6.6 ▶ *Cement Technologies and Fuel Mix by Region*

	Process Type				Fuel Share			
	Dry %	Semi-dry %	Wet %	Vertical %	Coal %	Oil %	Gas %	Other[1] %
United States	82	0	18	0	66	1	3	30
Canada	71	6	23	0	52	5	18	25
Europe	92	4.5	3.5	0	29	4	1	66[2]
Japan	100	0	0	0	79	2	0	18
Australia & New Zealand	24	3	72	0	58	<1	38	4
China	50	0	3	47	94	6	<1	0
Southeast Asia	80	9	10	1	82	9	8	1
Thailand[3]					80	4	0	16
Brazil	98	n.a.	n.a.	n.a.	1	2	1	96
South Korea	93	0	7	0	87	4	0	9
India	50	9	25	16	96	1	1	2
Former Soviet Union	12	3	78	7	7	24	68	<1
Latin America	67	9	23	1	20	36	24	12
Africa	66	9	24	0	29	36	29	5
Middle East	82	3	16	0	0	52	30	4

1. Includes petroleum coke, biomass and alternative fuels.
2. 48% is petroleum coke.
3. Siam Cement Industry Company Ltd. only.

Sources: Battelle, 2002; PCA, 2005; USGS, 2006; LBNL, JCA, 2006; CEMBUREAU, 2006; Siam Cement Industry Company Ltd, 2005.

Pre-heating also helps to reduce the energy needed in the kiln. The technology used in the cement industry in developing countries, notably in China, differs from that used in industrialised countries. While small-scale vertical kilns used to predominate in China, large-scale rotary kilns are now more common. Large-scale kilns are considerably more energy efficient.

Process types and fuel shares for the current stock of cement kilns differ considerably by region, which affects the CO_2 emissions per tonne of cement (Table 6.6).

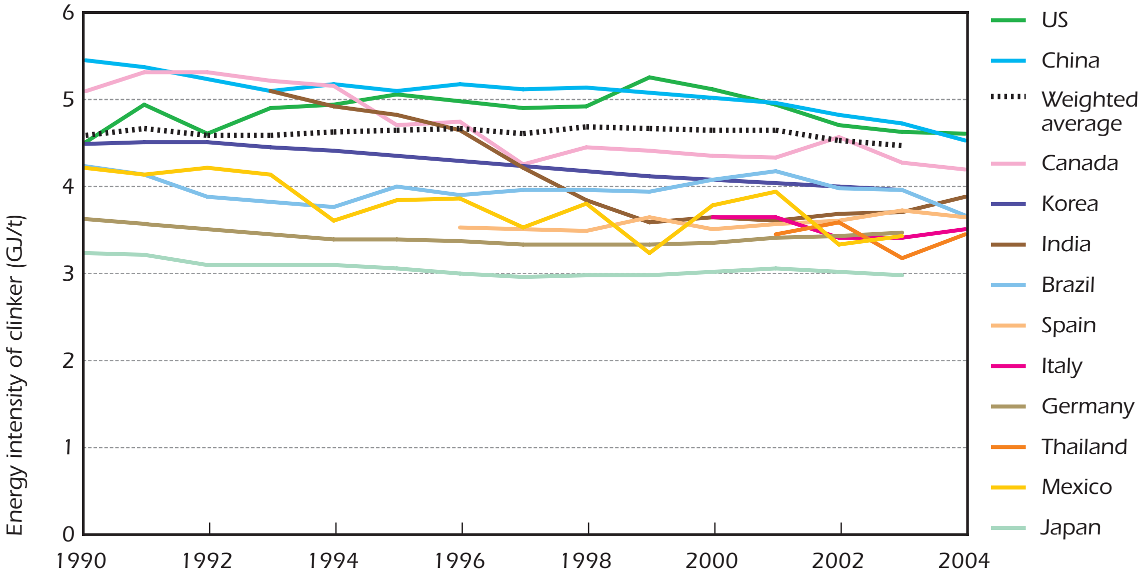
Figure 6.5 presents the data for the average energy consumption per tonne of clinker in some of the largest cement producing countries. Efficient dry kilns using pre-heaters use approximately 3.3 GJ/t clinker, a wet kiln uses 5.9 – 6.7 GJ/t clinker, while a dry kiln with pre-heaters and pre-calciners consumes around 2.9 GJ/t clinker (FLSmidth, 2006). In the European Union, the average energy consumption per tonne of Portland cement is currently about 3.7 GJ/t. China, Canada and the United States require between 4.2 and 4.6 GJ/t of clinker. Together, these three countries accounted for around half of total cement production. For most of the other countries presented the range is between 3 – 4 GJ/t of clinker.

Most countries experienced a downward trend in the thermal energy intensity required to produce a tonne of clinker between 1990 and 2004. Generally, this has been due to the increasing share of dry process cement kilns. However, many countries that already had high shares of dry process kilns have improved their thermal energy intensity per tonne of clinker as even more efficient dry process kilns have been introduced. For instance, the latest six stage pre-heater and pre-calciner kilns offer significant energy savings over earlier two stage pre-heater kilns.

Rapid economic development and demand growth for cement has provided an opportunity for some developing countries to achieve relatively high levels of energy efficiency by building efficient dry process plants. Until recently, this was not the case in China, where small-scale kilns and inefficient shaft kilns dominated production. For instance, in 1995 the output from dry kilns in China was only 6% of the total and large and medium-scale kilns accounted for only 33% of total output (Cui, 2006).

Figure 6.5 ▶ *Energy Requirement per tonne of Clinker by Country including Alternative Fuels*

Key point: Japan is the most efficient clinker producer, while most countries have achieved only modest reductions in the energy required to produce one tonne of clinker since 1990.



Note: Care must be taken in interpreting the absolute values of data in this figure, due to the possibility that different system boundaries have been used and that in some cases it is not clear whether LHV or HHV have been used.

Sources: Coal Statistics, India; ERI, 2004; Soares and Tolmasquim, 2000; Worrell, *et al.*, 2001; IBGE, 2006; CEMBUREAU, 2006; EEA, 2006; AITEC, 2005; USGS, 2006; PCA, 2005; NRCAN, 2006; Japan Cement Association, 2006; OFICEMEN, 2007; Siam Cement Company Ltd, 2005; INEGI, 2006; VDZ, 2006; Battelle 2002; LBNL, IEA and Tshinghua University estimates.

However, the situation is changing rapidly. By 2004 large and medium-scale plants accounted for 63% of production and that from dry kilns for around 45% of total output. This means that the energy intensity per tonne of clinker has declined from about 5.4 GJ/t clinker in 1990 to 4.5 GJ/t clinker in 2004. Plans are that cement from large-scale dry kilns should reach 80% of total production by 2010 and 95% by 2030, reducing the contribution from shaft kilns to just 5%. If this is the case, then the thermal energy intensity of clinker production in China would fall accordingly.

Japan appears to have the most efficient clinker production and is at or near the theoretical lower limit of heat consumption for advanced dry kilns with pre-heaters and pre-calciners. China and the United States currently have the highest energy use per tonne of clinker, although continued improvement in the thermal energy requirement per tonne of clinker will occur if China succeeds in increasing the share of modern large-scale dry kilns. Generally, there has been little improvement in the energy requirement per tonne of clinker in the last ten years in most countries. Over the last fifteen years, some countries have achieved modest improvements, with significant reductions only in Canada, China, Korea and India.

Care must be taken in interpreting the absolute levels in Figure 6.5, because not all of the results presented are based on actual energy consumption and clinker production statistics. In some cases, weighted average energy requirements per tonne of clinker have been estimated based on kiln efficiency estimates for each country, which could underestimate the actual energy used. If survey data are used, then this can be the case if operational characteristics differ. For instance, the frequency of start-stop operation cycles can often differ significantly between plants, while less than optimal operating conditions are common. This can lead to differences in energy consumption of 15% or more.

Figure 6.6 presents the energy intensity of clinker production for non-OECD regions and new EU accession countries (plus twelve) where only a snapshot view of their efficiency is available.[5]

The energy saving potential of all production using the best available technology and the increased use of clinker feedstock substitutes in the kiln is around 2.5 – 3 EJ given current cement production. However, this could not be achieved readily without significant economic costs, as it would require extensive capital stock replacement.

One area not well covered by statistics is the potential for using waste heat for power generation. Although modern pre-heater and pre-calciner kilns have low useful heat outputs due to the pre-heaters, there are still opportunities to economically produce electricity. For instance, cement plants in Japan generate around 10% of their

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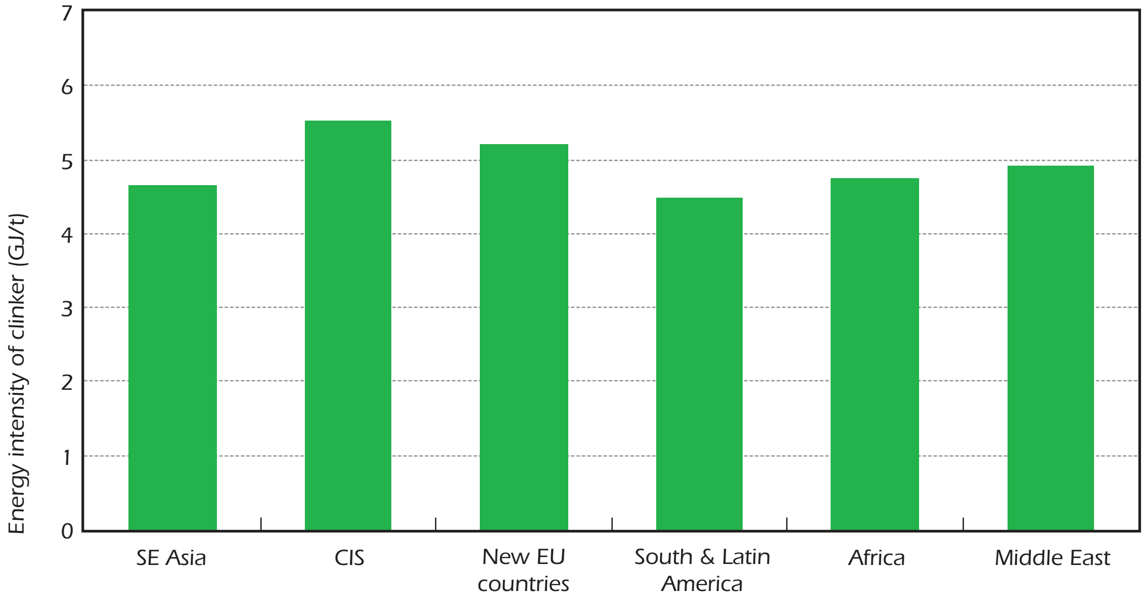
[5] Also efficiency data differ by source. For example, in the case of India, data from the Bureau of Energy Efficiency indicate a considerably higher efficiency and a continuous efficiency improvement for the period 2003 – 2006. However, the reported thermal energy use for some kilns is well below the most efficient kilns in OECD countries, and the average efficiency exceeds that of Japan. Therefore, further analysis is needed.

Figure 6.6 ▶ *Energy Requirement per tonne of Clinker for Non-OECD Regions and New EU Accession Countries, 2000*

Key point: Energy consumption per tonne of clinker in non-OECD countries and Eastern European Union countries ranges between 4.5 and 5.5 GJ/t clinker.



Source: Battelle, 2002.

electricity needs from combined heat and power (CHP) (JCA, 2006). China is also interested in electricity generation from waste heat and estimates a potential of 35 – 40 kWh/t clinker (Cui, 2006). New large-scale dry kilns with a capacity of 2 000 tonnes per day or more can take advantage of CHP production. However, it appears only Japan has so far taken up a significant part of the CHP potential. To some extent this can be explained by high electricity prices that make such energy recovery economical.

Alternative Fuel Use in Cement Production

The use of alternative fuels in the cement industry offers the opportunity to reduce production costs, dispose of waste and in some cases reduce CO$_2$ emissions and fossil fuel use. Cement kilns are well-suited for waste combustion because of their high process temperature and because the clinker product and limestone feedstock act as gas-cleaning agents. Used tires, wood, plastics, chemicals and other types of waste are co-combusted in cement kilns in large quantities. This use of waste as alternative fuel in cement kilns can contribute to lower overall CO$_2$ emissions, if fossil fuels are replaced with alternative fuels that would otherwise have been incinerated or land filled (Figure 6.7).

Box 6.3

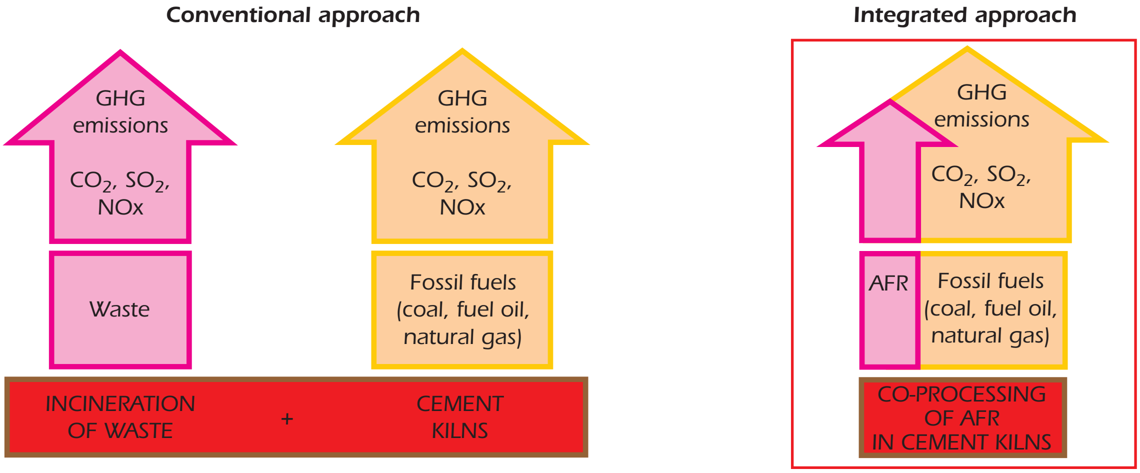
Natural Gas Use in Cement Kilns in Russia and the Former Soviet Union

Russia and to a lesser extent the rest of the Former Soviet Union (FSU) consume significant quantities of natural gas to fire their cement kilns. In 2000, an estimated 68% of fuel use in the cement industry in Russia and the FSU was natural gas due to low gas prices. The average industrial and household gas price in Russia is about 15% of the average German import price for gas, so the incentive for energy efficiency is weak (IEA, 2006b).

As part of the European Union's support for Russia's bid to join the World Trade Organisation, Russia agreed in 2004 to increase natural gas tariffs in line with what had been outlined in the Government's Energy Strategy approved in 2003. The Russian Government has promised to raise gas prices to industry from USD 27 per thousand m^3 in 2004 to between USD 49 – 57 per thousand m^3 in 2010. Domestic gas prices for industry have reached close to USD 50 per thousand m^3 in 2007 and a recent statement by the Minister of Economic Development and Trade outlined an even more ambitious plan to increase gas to more than USD 100 per thousand m^3 by 2010.

This could lead to an increase in the use of coal at cement kilns over time and a corresponding increase in their CO_2 emissions. However, this will depend on the local availability of cheap coal and to some extent on improvements in Russian rail infrastructure for coal deliveries.

Figure 6.7 ▶ *Impact of Alternative Fuels on Overall CO_2 Emissions*



Note: AFR = alternative fuels.

Source: CEMBUREAU, 2006.

European cement manufacturers derived 3% of their energy needs from waste fuels in 1990 and 17% in 2005. Indications show a further increase since then (CEMBUREAU, 2006). Cement producers in Belgium, France, Germany, the Netherlands and Switzerland have reached average substitution rates from 35% to more than 70% of the total energy used (Figure 6.8). Some individual plants have achieved 100% substitution using waste materials. However, very high substitution rates can only be accomplished if a tailored pre-treatment and surveillance system is in place. Municipal solid waste, for example, needs to be pre-treated to obtain homogeneous calorific values and feed characteristics. Another potential source of energy is carpets, the equivalent of about 100 PJ per year are disposed of in land fills and could instead be combusted in cement kilns.

Used car and truck tires represent an attractive fuel source in many regions. The cement industry in the United States combusted 377 kilo tonne (kt) of used tires in 2004, or about 12 PJ (USGS, 2006). Kilns in the United States also consumed around 125 kt of other solid waste and 1 billion litres of liquid wastes.

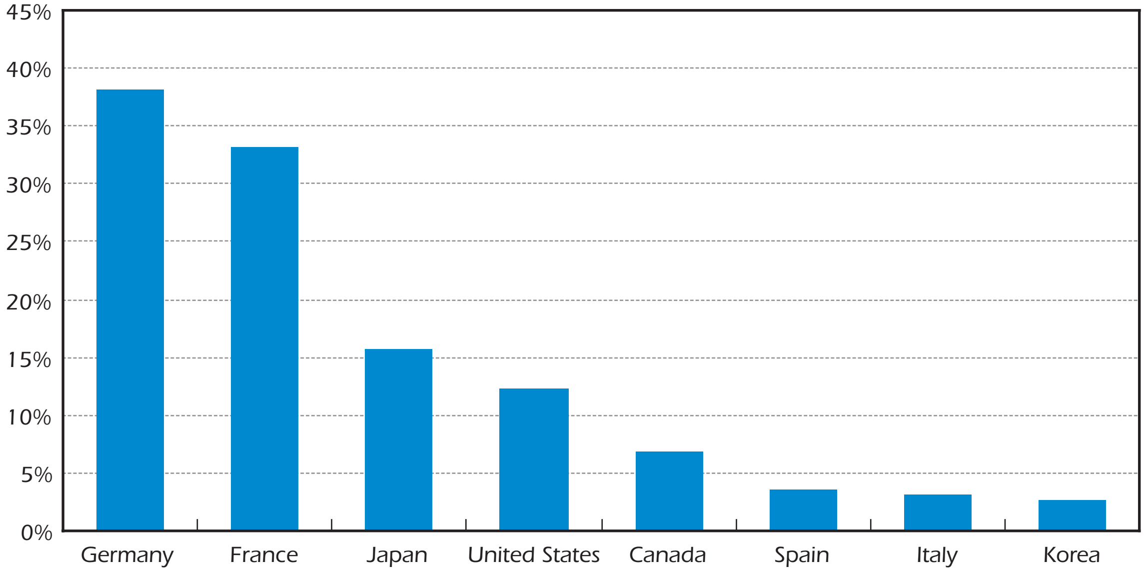
The cement industry in Japan burned around 221 kt of used tires in 2004, down from a peak of 323 kt in 2000 (Japan Cement Association, 2006). In 2005 the Japanese industry burned around 447 kt of waste oil 2005, 340 kt of wood chips and 302 kt of waste plastic. This is equivalent to about 35 PJ of energy from alternative sources assuming 42.6 GJ/t for waste oil, 16.6 GJ/t of wood chips and 35.6 GJ/t of waste plastic.

The cement industry in Germany burns a range of alternative fuels including waste paper, textiles, oil, plastic and solvents; as well as animal carcasses, oil and sewage sludge and construction waste. They achieved 38% alternative fuel use in 2003 (VDZ, 2006).

Figure 6.8 ▶ ***Alternative Fuel Use in Clinker Production by Country***

(Percentage of Total Thermal Fuel Use)

Key point: Alternative fuel use in the cement industry has reached high levels in some European countries, but is less significant elsewhere.



Sources: VDZ, 2006; Japan Cement Association, 2006; USGS, 2006; NRCAN, 2006; AITEC, 2005; OFICEMEN, 2007; Observatoire de l'énergie, 2003; and Dong-Woon, 2006.

In Europe, the burning of alternative fuels in cement kilns is covered by Directive 2000/76/EC of the European Parliament and Council. However, in some countries their use is controversial, because cement kilns are not subject to emission controls as stringent as waste incineration installations. Clear guidelines and public information campaigns could help increase the use of waste in cement kilns.

Significant uncertainty surrounds the total global consumption of alternative fuels in the cement industry. According to IEA statistics, the cement industry in OECD countries used 66 PJ of combustible renewables and waste in 2003, about half of it industrial waste and half wood waste. Worldwide, the industry consumed 112 PJ of biomass and 34 PJ of waste. However, this is likely to be a substantial underestimate. There is apparently little use of alternative fuels outside the OECD countries, although the comparison of country data from various sources with IEA statistics tends to imply that alternative fuel use is systematically under-reported. From a technical perspective, the use of alternative fuels could be increased to 1 – 2 EJ per year, although there would be differences among regions due to the varying availability of alternative fuels.

Electricity Consumption in Cement Production

Grinding is the largest electricity demand in the cement industry. Currently about 100 kWh/t of cement is consumed in rotary kilns for grinding raw materials, at the kiln and for grinding cement.[6] The current state-of-the-art technologies, using roller presses and high-efficiency classifiers, are much more efficient than previous ones. Current best practice is thought to be around 80 – 90 kWh/t of clinker (Sathaye, J., *et al.*, 2005; FLSmidth, 2006). Still, the energy efficiency of grinding is typically only 5 – 10%, with the remainder converted to heat. There can be an enormous variation in the consumption of electricity per plant, for example, cement plants in Brazil were found to consume between 90 – 200 kWh/t of cement (Soares and Tolmasquim, 2000). Figure 6.9 presents electricity consumption for cement production by country.

With the exception of the United States and Canada, most countries for which data is available fall within the range of 90 – 120 kWh/t of cement. Electricity consumption per tonne of cement has been trending downwards in many countries, although in some cases this trend is not very strong. In some countries, part of the decline in electricity consumption may be due to reductions in the clinker ratio and are not due to improved energy efficiency of the process. In countries where electricity consumption per tonne of cement declined, the rate of decline was between 2.1 – 0.2% between 1990 and 2003/2004. In some cases, such as Japan, China and Mexico, electricity consumption has actually increased in recent years. In Japan, this has been due to the increased electricity used in handling alternative fuels and materials.

It is not clear if structural or operational considerations in different countries explain the quite wide range in electricity consumption, or whether this simply reflects different electricity prices and hence incentives to minimise electricity use. One

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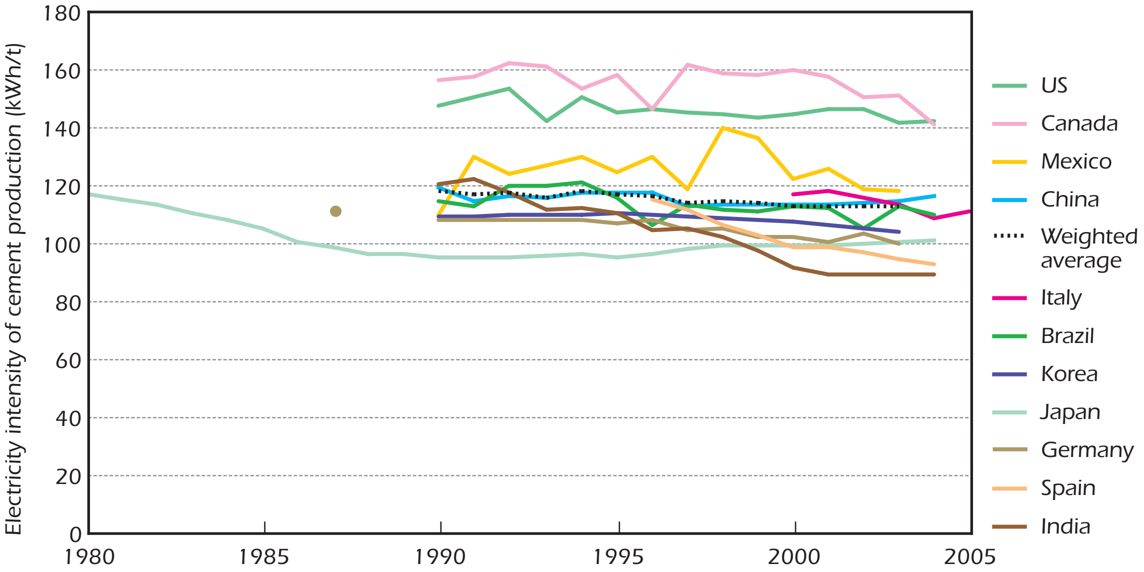
[6] A small amount is also used for miscellaneous utilities on-site and packing.

Figure 6.9 ▶ *Electricity Consumption per tonne of Cement by Country, 1980-2005*

Key point: Modest improvements in the electricity consumption per tonne of cement have been achieved since 1990 in many countries.



Note: Care must be taken in interpreting the absolute values of data in this figure, due to the possibility that different system boundaries have been used and that electricity produced on-site from waste heat has not been included in the totals for some countries. For example in Japan, about 10% of all electricity consumed is generated on-site from waste heat. If this electricity were subtracted, the electricity intensity of Japanese production would be 10% lower.

Sources: Raina, 2002; and as for Figure 6.5.

potential source of discrepancy is that the grinding of blast furnace slag for use as a clinker substitute or in the kilns is an electricity intensive process. If this grinding takes place at a grinding facility separate to the cement kiln, then electricity use might be under-reported.

Total Primary Energy Consumption in Cement Production

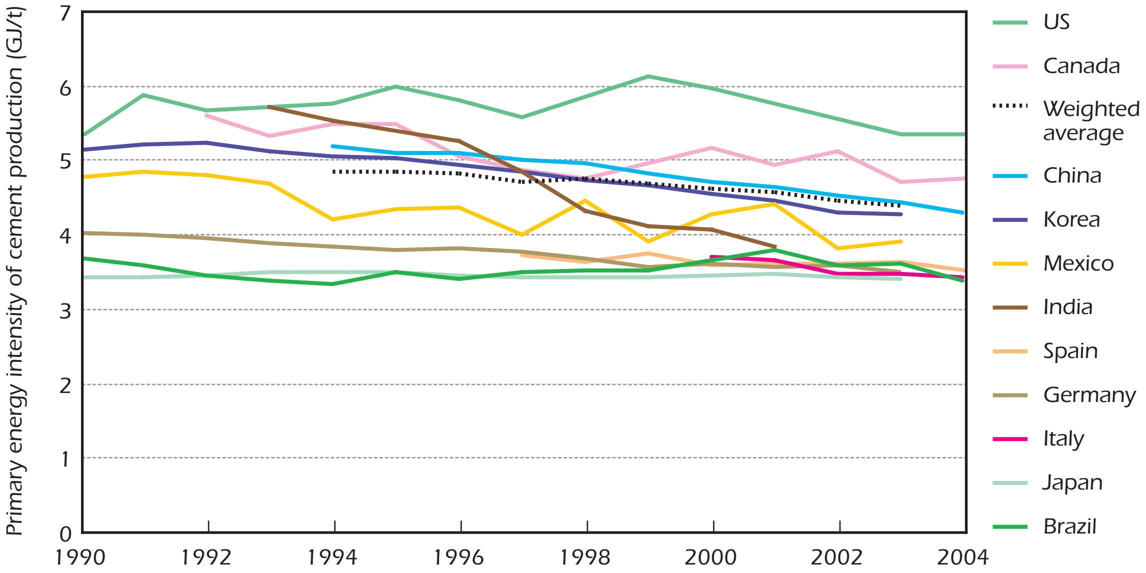
The use of electricity in cement production is significant, totalling between 220 – 265 TWh in 2004. This has notable implications for the total energy required to produce a tonne of cement, depending on the efficiency of the production of electricity.

Figure 6.10 presents the total primary energy supply (TPES) equivalent consumption per tonne of cement. This is calculated by dividing the electricity per tonne of cement by the average efficiency (including distribution losses) of electricity generation in each country and adding this to the thermal energy required per tonne of cement, taking into account the clinker ratio.

Germany, Japan, Brazil, Italy and Spain all consume about 3.4 – 3.5 GJ/t of cement on a TPES equivalent basis. India appears to have significantly reduced the TPES equivalent consumption per tonne of cement as the share of dry process production increased. However, significant uncertainty surrounds their data and there is a wide variation in the estimates.

Figure 6.10 ▶ *Total Primary Energy Equivalent per tonne of Cement by Country, 1990-2004*

Key point: With the exception of Canada, China, India and Mexico, little improvement in the TPES equivalent per tonne of cement has been achieved since 1990.



Note: Includes impact of CHP electricity generation for Japan. Care must be taken in interpreting the absolute values of data in this figure, due to the possibility that different system boundaries have been used and that in some cases it is not clear whether LHV or HHV have been used.

Sources: As for Figures 6.4, 6.5, 6.8 and 6.9; IEA statistics.

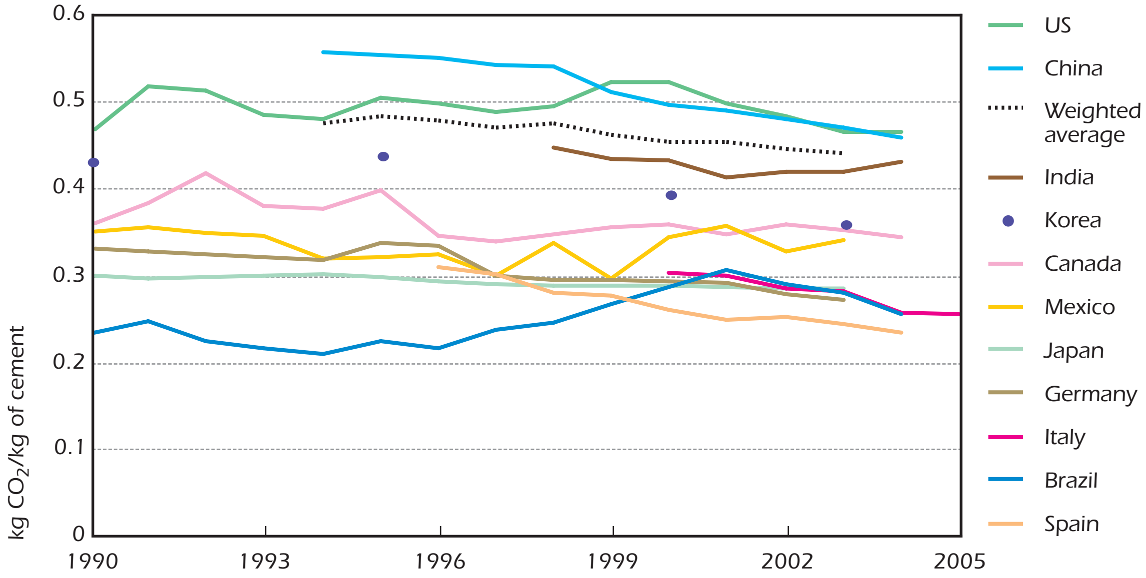
The interaction between the clinker ratio, thermal energy requirements and electricity consumption per tonne of cement and the efficiency of electricity generation lead to some interesting results. With the exception of Canada, China, Germany, Mexico and India, the TPES equivalent consumption per tonne of cement has not exhibited much of a downward trend since 1990. Despite some fluctuations it has been more or less unchanged in the United States and Japan, while it has decreased by 1.1% per year in Germany between 1990 and 2003 and by 1.6% per year in Mexico. Between 1994 and 2004 the TPES equivalent in China fell by 1.9% per year. China is also not that inefficient at a TPES equivalent level, despite its high energy consumption for clinker production, due to its low clinker ratio. The range of TPES equivalent was 3.4 – 5.3 in 2004. In some countries, part of the TPES decline can be explained by the reduced clinker ratio, which may be considered as a structural change, not related to process improvements.

CO_2 Emissions from Cement Production

The CO_2 emissions per tonne of cement produced depend on the energy and electricity intensity of clinker and cement production, the clinker ratio, the fuel types used at the cement kiln and the CO_2 emissions profile of the electricity consumed. To this must be added the process emissions from calcination in the clinker production process to arrive at a total CO_2 emissions per tonne of cement.

Figure 6.11 ▶ ***CO_2 Emissions from Energy Consumption (including electricity) per tonne of Cement by Country, 1990-2005***

Key point: With the exception of China, Germany, Korea and Spain, little improvement in the CO_2 intensity of cement production from energy consumption has been achieved since 1990.



Note: Includes impact of CHP electricity generation for Japan.

Care must be taken in interpreting the absolute values of data in this figure, due to the possibility that different system boundaries have been used and that in some cases it is not clear whether LHV or HHV have been used.

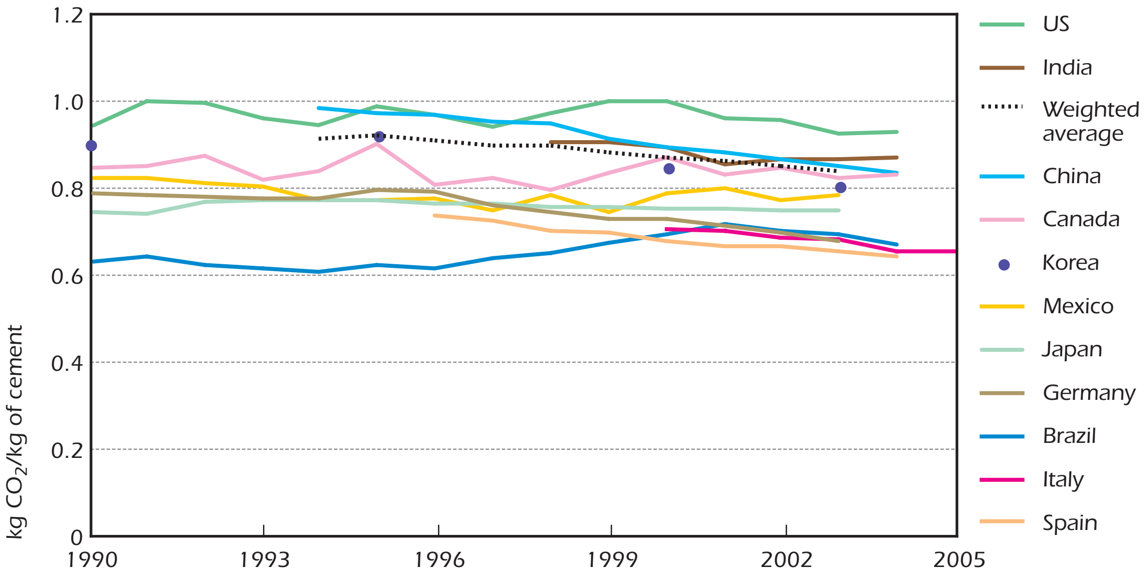
Sources: As for Figures 6.4, 6.5, 6.8 and 6.9; IEA statistics.

With the exception of India, China and the United States, CO_2 emissions per tonne of cement from energy consumption (including the upstream emissions from electricity generation) are within a reasonably narrow band of 0.25 – 0.35 kg CO_2/kg of cement (Figure 6.11). Canada's relatively low emissions from electricity generation offset its relatively high energy consumption to some extent, while the opposite is true of India.

The United States, Canada, India and Mexico have experienced little change in their CO_2 emissions per tonne of cement from energy use over the period that data are available. China has reduced CO_2 emissions per tonne of cement from energy consumption by 1.9% per year between 1994 and 2004, albeit from a high starting point. Germany achieved a reduction of 1.5% per year between 1990 and 2003, while Spain reduced emissions by 3.5% per year between 1996 and 2004. Brazil is the only country that experienced a significant increase in CO_2 emissions per tonne of cement from energy consumption. This is primarily due to the substitution of petroleum coke for fuel oil in kilns. However, the low CO_2 emissions profile of Brazil's electricity industry means their overall emissions from energy consumption are quite low.

Figure 6.12 ▶ ***Process and Energy (including electricity) CO_2 Emissions per tonne of Cement by Country, 1990-2005***

Key point: China, Germany, Italy, Korea and Spain have achieved significant improvements in the CO_2 intensity of cement production including energy consumption and process emissions.



Note: Includes impact of electricity generation from waste heat in Japan. Boundary definitions may differ by country.

Sources: As for Figures 6.4, 6.5, 6.8 and 6.9; IEA statistics.

Figure 6.12 presents total CO_2 emissions per kilogramme (CO_2 /kg) of cement including thermal energy, upstream electricity emissions and process emissions. The standard emission factor of 0.51 kg CO_2 /tonne of clinker has been multiplied by the clinker ratio in order to determine the CO_2 emissions attributable to calcination process. Generally, the trend in CO_2 emissions per tonne of cement including process emissions is similar to the trend excluding process emissions. This is because trends in the clinker ratio impact on the CO_2 emissions related to clinker production. So part of the decline in total CO_2 emissions can be explained by a reduction in the clinker ratio and are not directly related to process improvements.

Total CO_2 emissions per tonne of cement from energy and calcination in 2003 – 2004 range from about 0.65 kg CO_2/kg of cement in Spain, Brazil and Italy to 0.93 kg CO_2/kg of cement in the United States. The potential CO_2 emissions reduction potential in the cement industry from the use of best available technology, the increased use of clinker feedstock substitutes in the kiln and the use of more clinker substitutes in finished cement is between 480 and 520 Mt CO_2. However, significant uncertainty exists around this figure due to the absence of comprehensive data and the problems with the quality of the data that is available. It is also important to note that these savings could not be achieved in the short- to medium-term without significant economic costs.

Energy and CO_2 Emission Indicators for the Cement Industry

The key challenge in compiling physical energy and CO_2 emission indicators for the cement industry is the poor availability of data, particularly time series data. In general, national energy statistics do not include sub-sector information for the non-metallic minerals sector. The approach taken here has been to use national energy and CO_2 emissions statistics for the cement industry where these are available, while supplementing these with survey information, data from industry associations, cement companies and academic or government studies where available.

As a result, although the information presented here is the best publicly available data, there are uncertainties about the accuracy of some data. Caution must therefore be exercised in comparing the absolute level of indicators between countries given that the quality of data is not always the same. Despite this qualification, however, the data here are in close agreement with an industry sponsored study that was based on a consistent approach (Battelle, 2002).[7] Table 6.7 presents the indicators that have been examined for the cement industry in this study.

Table 6.7 ▶ *Indicators for the Cement Industry*

Indicator	Unit
Clinker ratio per tonne cement	*%*
Energy intensity of clinker	GJ/t clinker
Alternative fuel use for clinker production	%
Electricity intensity of cement	kWh/cement
Total energy intensity of cement	GJ/t cement
Total primary energy intensity of cement (including upstream energy use in electricity)	GJ/t cement
Energy related CO_2 emissions per tonne cement	t CO_2/cement
Energy and process CO_2 emissions per tonne cement	t CO_2/cement

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7. For instance, for total CO_2 emissions from cement production per tonne (including process emissions), the data collected for this analysis differs by between 1 - 6% from the data in the Battelle report for China, Canada, India, Japan, Korea and the United States.

Other indicators are possible. For example alternative fuels can be excluded from the energy intensity, or the electricity intensity can be corrected for auto-generation from waste heat. Also electricity intensity could be split into electricity use for clinker making and for cement grinding. However such a split requires detailed data that are not readily available.

The development and estimation of energy and CO_2 indicators for the cement industry is aided by the clear system boundaries that can be set for clinker production and cement production, as well as the homogeneity of the product. Another factor that facilitates the indicator analysis is that there is currently little combined heat and power (CHP) production at cement kilns. Modern dry process plants with pre-heaters and pre-calcinators mean that the residual useful heat has dropped to between 270 – 300°C. In the past this has been too low to economically support CHP applications in most countries, although this is changing to some extent. However, it is not clear that different data sources have applied the same system boundaries. In particular, it is possible that electricity used at grinding only plants may not be included. In some cases, it is also not clear whether data includes or excludes electricity generated on-site.

The approach taken here is similar to that being used by the Asia Pacific Partnership in their indicators work in the cement industry, with the exception that the IEA does not have any indicators covering nitrogen oxide, sulphur oxides or kiln dust emissions. The IEA has also not attempted to separate electricity consumption for cement grinding or from waste heat power generation due to an absence of publicly available data. The Asia Pacific Partnership's work on detailed data for energy indicators in cement will be a valuable addition to research in this area when it is completed.

The approach taken here is also consistent with the World Resources Institute and World Business Council on Sustainable Development Cement CO_2 Protocol for direct and indirect emissions (WBCSD, 2005). The IEA uses its own data for emission factors and CO_2 emissions factors for electricity generation rather than the Intergovernmental Panel on Climate Change (IPCC) defaults, although these are used in the absence of any data. For alternative fuels, direct emissions have been included; an analysis of their net CO_2 profile (whether higher or lower) has not been attempted. The WBCSD Cement Sustainability Initiative is in the process of updating data for a new study using their CO_2 Protocol which will provide a valuable update of the 2002 Battelle study.

Lime

Overview

Lime is used in a wide range of products with the largest application in the iron and steel, pulp and paper, sugar and construction industries. Lime is also an important material in the control of sulphur dioxide emissions in power stations and as a precipitation agent in water treatment facilities.

There are no detailed statistics on global lime production. Estimated production is 120 Mt, excluding regenerated lime or captive lime production (Miller, 2003). Estimates may not give the complete picture, however, as a significant portion of lime is produced in captive kilns, *e.g.* in iron and steel, pulp and sugar industries. The European Lime Association (EuLA) estimates the total world production of lime, including captive lime at 300 Mt. Total Chinese lime production is estimated at 154 Mt in 2005 (Box 6.4), about half of the global production. The largest lime producing countries are China, United States, Japan, Russia, Germany, Mexico and Brazil.

Box 6.4

Lime Production in China

Chinese lime production was 154 Mt in 2005. About 62% is used for buildings, 23% for steel making and 12% for chemicals (calcium carbide, calcium hydrogen, chlorine and alkali industries). Coal accounts for 96% of all fuel used in China's lime industry. The lime industry accounts for 12% of total energy use in the Chinese building materials industry. Its relevance in CO_2 terms is even higher because of significant process emissions. Lime production is projected to grow as it is a key component for flue gas desulphurisation.

Between 2003 and 2006, energy use for lime production increased from 610 to 780 PJ, while the energy use per tonne of lime was constant. The average fossil fuel use is 4.5 GJ/t burned lime. This efficiency is comparable with kilns in OECD countries. Total direct CO_2 emissions amounted to 179 Mt in 2005. About two-thirds were process emissions. A significant share of the process CO_2 emissions are captured during the lime use stage.

The lime made from earthen kilns, an outdated technology, accounts for more than 60% of the total output. In order to improve the energy efficiency the use of semi-mechanised and mechanised vertical kilns should be promoted and earthen kiln should be eliminated. This would result in about 20% energy efficiency gain.

Source: Shi, 2007.

Lime Production Process

Lime is produced by burning limestone or dolomite in small-scale, vertical or large-scale, rotary kilns. In most industrialised countries, the industry consists of a small number of large corporations. In most developing countries, lime kilns are typically small operations using local technology. However, even in industrialised countries, *e.g.* Greece, independent small-scale vertical kilns operate. Pulp and sugar mills may have captive lime production to internally regenerate lime.

The minimum energy requirement for lime production is 3.20 GJ/t. For dolomite, the minimum energy requirement is 3.02 GJ/t. Energy use is 3.6 – 7.5 GJ/t lime in the European Union (EC, 2001), 7.2 GJ/t in Canada (CIEEDAC, 2004) and for lime kilns in US pulp mills (Miner and Upton, 2002), and up to 13.2 GJ/t for small vertical kilns in Thailand. Average energy intensities in China are estimated to vary from 4.2 GJ/t for large shaft kilns to 5.8 GJ/t for small-scale primitive kilns

(Shi, 2007). In China, the majority of lime is produced in outdated small-scale kilns, suggesting a large potential for efficiency improvements. In Europe, fuel-related CO_2 emissions are estimated to be 0.2 – 0.45 t CO_2/t lime (EC, 2001). Electricity use for lime production is 40 – 140 kWh/t lime, depending on the type of kiln and the required fineness of the lime (EC, 2001).

Typical heat and electrical power use by various types of lime kilns are shown in Table 6.8. Energy use for a given kiln type also depends on the quality of the stone and on the degree of conversion of calcium carbonate to calcium oxide. The net heat use per tonne of quicklime varies considerably with kiln design. Rotary kilns generally require more heat than shaft kilns. The heat use tends to increase as the degree of burning increases.

Table 6.8 ▶ ***Typical Specific Energy Consumption for Various Types of Lime Kilns***

	Fuel Use *GJ/t*	Electricity *kWh/t*
Calcium Quicklime, Light and Hard Burned Dolomite		
Mixed feed shaft kiln	4 – 4.7	5 – 15
Double-inclined shaft kiln	4.3	30
Multi-chamber shaft kiln	4 – 4.5	20 – 45
Annular shaft kiln	4 – 4.6	18 – 35
Parallel-flow regenerative shaft kiln	3.6 – 4.2	20 – 40
Other shaft kilns	4 – 5	10 – 15
Long rotary kiln	6.5 – 7.5	18 – 25
Grate pre-heater rotary kilns	5 – 6.1	35 – 100
Shaft pre-heater rotary kilns	4.8 – 6.1	17 – 45
Cyclone pre-heater rotary kilns	4.6 – 5.4	23 – 40
Travelling grate kiln	3.7 – 4.8	31 – 38
Gas suspension calcination	4.6 – 5.4	20 – 25
Fluidised bed kiln	4.6 – 5.4	20 – 25
Dead-burned dolomite		
Mixed feed shaft kiln	6.5 – 7	20
Grate pre-heater rotary kilns	7.2 – 10.5	35 – 100

Note: Electricity use excludes grinding of raw materials and finished product.

Source: EC, 2001.

CO_2 emissions arise in lime production from the decarbonisation of limestone and magnesium carbonate, fuel combusted in the process and indirect emissions from electricity consumed in the process. In efficient lime kilns about 60% of the emissions are process emissions due to decarbonisation of the raw materials.

Energy Consumption and CO_2 Emissions from Lime Production

No estimates of global CO_2 emissions due to lime production are available. In Europe, process emissions are estimated at 750 kg CO_2 /t lime (EC, 2001). Regeneration of lime in pulp and sugar mills does not necessarily lead to additional CO_2 emissions, as the CO_2 is from biomass sources (Miner and Upton, 2002). The process emission is the most important source of CO_2 in the lime production process. However, a significant part of this CO_2 is fixed when the slaked lime is subjected to air. Only in applications where lime is converted into glasslike materials, *e.g.* the steel and glass production processes, or into gypsum in desulphurisation processes, this CO_2 fixation will not occur.

CO_2 emission reductions can be achieved by the use of more efficient kilns and through improved management of existing kilns using similar techniques to those in the cement industry (EC, 2001). In the United States, the National Lime Association has agreed to a 9% reduction of CO_2 production intensity in the industry by 2012. This reduction target does not include process emissions. A higher use rate of by-product dust and higher energy efficiency will be applied. As more than 50% of the lime in China is produced in outdated kilns, a change towards large-scale shaft kilns would result in energy savings of up to 21% (Cui, 2007). Switching to low carbon fuels can further reduce CO_2 emissions. It may also be possible to reduce the consumption of lime in various processes, *e.g.* in the sugar industry (Vaccari, *et al.*, 2005).

Glass

Overview

There are four main glass categories: container, flat, fibre (mineral wool, textile and optical) and specialty glass. The glass industry is dominated by the production of container glass and flat glass.

Global glass production was around 130 Mt in 2005 (Wang, 2007). Container glass accounts for about three fifths and flat glass for about one third of the production (Pilkington, 2005). Production volumes for fibre and speciality glass are small. The European Union (33 Mt), China (32 Mt) and the United States (20 Mt) account for 60% of the world production (Wang, 2007). Over the past twenty years, glass demand has grown more quickly than GDP and is still growing at nearly 4% per year. The EU25 production of container glass was 21 Mt in 2005, followed by the United States (10 Mt) and China (8.5 Mt) (Wang, 2007).

Flat glass production was about 43 Mt in 2005. Of this, around 70% is for windows, 10% in glazing products for automotive applications and 20% in furniture and other interior applications (Pilkington, 2005). The key production route for flat glass is the float process, which accounted for 80 – 90% of flat glass production in 2005

(Wang, 2007). Chinas float glass output accounted for 38% of the world float glass output, and float glass accounted for 76% of total Chinese flat glass production. Flat glass accounts for 65% of Chinese glass production. This high share is caused by the present building boom.

Glass Production Process

Glass is produced by melting raw materials (mainly silica sand, soda ash and limestone), and often cullet (recycled container glass or waste glass from manufacturing) in glass furnaces of different sizes and technologies. There is a large variety of glass products with varying characteristics and, hence, different production and processing routes. Yet, the main production steps found in virtually all glass plants are:

- ▷ Raw materials selection;
- ▷ Batch preparation – weighing and mixing raw materials;
- ▷ Melting and refining;
- ▷ Conditioning and forming;
- ▷ Post-processing – annealing, tempering, polishing or coating.

More than half of energy consumption in the glass production process is for the melting process. With the exception of a few specialty glass manufacturing processes, continuously operated tank furnaces are commonly used for the melting of glass.[8] Common heating methods are combustion-heating (oxy-fuel, air-fuel burners) and direct electrical heating ("Joule heating"), as well as combinations of both ("electric boosting"). Many furnaces use electric boosting to increase production rates, or to increase the flexibility of the furnace operation, *e.g.* choice of energy source and production rates. Electric boosting typically accounts for 10 – 30% of the total energy input.

Today, most furnaces for glass manufacturing are heated with natural gas or fuel oil. To increase fuel efficiency and reduce emissions of nitrous oxides, oxygen is increasingly replacing combustion air. Large container glass furnaces, in particular, are using more and more oxy-fuel technology.

Float glass furnaces, the largest in the industry, have an average capacity of 550 tonnes/day (t/d), but can be as large as 1 100 t/d whereas container glass furnaces generally have a capacity of 250 – 350 t/d. Regenerative furnaces are common in both float and container glass production.

Air-fuel furnaces typically recover heat from exhaust gas streams with recuperative or regenerative systems to preheat the combustion air to improve efficiency and achieve higher flame temperatures. In recuperative systems, heat is continuously transferred from the exhaust gases to the combustion air in a heat exchanger. In regenerative systems, the exhaust gases stream through large chambers packed with refractory bricks arranged to form open conduits. During the first part of the firing cycle, flue gases pass through the conduits and heat the bricks before

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[8] All-electric, cold-top furnaces are primarily used for mineral wool type fibre glass and specialty glass production.

leaving through the stack. After a certain time, the exhaust port is closed and the firing direction is reversed: cold combustion air is passed through the heated brickwork in the opposite direction, and mixed with the fuel in a combustion chamber. The cycle time is usually automatically adjusted by a control system to improve efficiency.

Excess heat in the off-gas stream of recuperative or regenerative systems can be used to generate steam in a waste-heat recovery boiler or to preheat cullet. Both measures can increase the overall efficiency of the glass furnace from 40 – 50% to 50 – 65% (Whitemore, 1999). Modern glass furnace technology aims to increase the use of oxygen as a way to increase fuel efficiency and reduce emissions of nitrogen oxides (NOx). Due to the high temperatures in the furnace, glass melting is a large source of NOx emissions. State-of-the-art technology aims to further reduce NOx emissions, while simultaneously reducing energy costs.

Energy Consumption and CO_2 Emissions from Glass Production

About 0.5 – 0.8 EJ of energy is used for glass production worldwide. Assuming that half of this energy is provided by natural gas and half by fuel oil, and an average of 7 GJ/t of product, yields an emission factor of 450 kg energy related CO_2/t of product. Globally, energy used in the production of container and flat glass results in emissions of about 50 – 60 Mt CO_2 per year. Emissions from the decarbonisation of soda ash and limestone can contribute up to 200 kg CO_2/t of product depending on the specific composition of the glass and the amount of cullet used.

The theoretical minimum energy use is 2.8 GJ/t for soda-lime glass and 2.35 GJ/t for borosilicate and crystal. The minimum energy requirement is 0.5 GJ/t for chemical reactions and 1.8 GJ/t for melting. The theoretical minimum depends to some extent on the glass type. In practice, average energy use varies between 5.75 – 9.0 GJ/t, so 2 – 4 times as high as the theoretical minimum (Levine, *et al.*, 2004). Structural heat losses account for 20 – 25% of the energy input (0.85 MJ/t) and the losses due to the heat content of flue gases account for 25 – 35% of the energy use (1.18 GJ/t) (Beerkens and Limpt, 2001).

A recent analysis for 123 container glass and 23 float glass furnaces in Europe and North America showed a wide distribution of energy intensity in glass furnaces. Beerkens and van Limpt (2001) report the energy intensity of continuous glass furnaces in Europe and the United States as 4 – 10 GJ/t of container glass and 5 – 8.5 GJ/t of flat glass, depending on the size and technology of the furnace and the share of cullet used. The most energy efficient furnace identified shows an energy consumption of 3.82 – 3.85 GJ/t, based on 50% cullet and taking into account the primary energy consumption for electricity generation. The analysis has shown that there is a factor two difference between the lowest and the highest energy users, when normalised for cullet use and size, *i.e.* larger furnaces are more efficient than small ones. The difference is due to variations in the raw material mix as well as efficiency of the furnace. It has been estimated that the energy efficiency of the melting furnaces, on average, improves by about 0.5 – 0.6% per year in the container glass industry. A recent survey for 28 Chinese float glass furnaces (normalised for 25% cullet) resulted in an average of 7.8 GJ/t float glass, which is 20% above the world average and 32% above the most advanced countries (Wang, 2007).

After the melting process, packaging glass is shaped and annealed. Shaping, annealing and additional processes require 0.52 GJ electricity and 0.42 GJ natural gas. For floating glass, the energy requirements for annealing are in the range of 0.8 – 1.5 GJ/t depending on the glass thickness.

The main energy efficiency opportunities include: improved process control, increased use (up to 100%) of cullet, increased furnace size, use of regenerative heating, oxy-fuel technology, batch and cullet pre-heating and reduction of reject rates. Oxy-fuel furnaces with cullet pre-heating now offer the most energy efficient furnace technology. The energy efficiency improvement potential is estimated to be 30 – 40%. Research is underway on new more efficient furnace designs that separate the chemical reactions from melting, offering the opportunity to further reduce energy use. CO_2 emissions can be reduced by the use of natural gas instead of fuel oil and CO_2 capture for large oxy-fuel furnaces.

Increased recycling is one way to reduce the energy consumption, because the energy for the chemical reactions can be saved. As a general rule, 10% extra cullet results in a 2.5 – 3% reduction of the furnace energy consumption (from 5.2 – 4.0 GJ/t for the range 0 – 100% cullet). Moreover, the production of soda is reduced. About 18% soda is added to sand to make new glass in order to reduce the melting temperature. Soda production requires approximately 10 GJ/t. Less soda is needed when recycled glass is used as feedstock. Using 10% extra cullet results in 1.0 GJ/t additional savings due to reduced soda production. The current average glass recycling rate is about 50%, but varies widely for various glass types and by country. The highest recycling rates are obtained for green and brown container glass. Higher recycling rates seem feasible, as in some regions there is an excess availability of waste glass or recovery rates are low.

Ceramic Products

Overview

The ceramic products industry is generally split in two parts; the heavy ceramic products, *e.g.* bricks, roof tiles, and fine ceramics, *e.g.* floor tiles, sanitary and table stoneware and porcelain. Reliable international statistics on the production of ceramics products are not available. The annual per capita consumption of bricks, tiles and other ceramic products in tonne per capita per year is estimated at 1.2 in China; 0.4 in the EU (EU-BREF Ceramics, 2005), 0.1 in the United States (USGS, 2004), and 0.25, 0.12, and 0.05 for Pakistan, India and Bangladesh. This suggests that the global production of ceramic products exceeds 2 Gt/year. China accounts for more than half of total world production.

Bricks are the main output of the ceramics industry in weight terms. It should be noted that specifications for bricks produced in different types of kilns differ strongly, *e.g.* solid, hollow or perforated bricks. Industrial and small-scale producers use the energy contained in the organic fraction of clay and shale as well as in pore forming agents, *e.g.* saw dust, added to the clay in the production process.

Bricks are produced in virtually every country, from the less developed countries to industrialised countries. China is by far the largest manufacturer of bricks in the world, producing an estimated 1.7 Gt bricks in 2005 (Box 6.5). Among IEA countries, the major producers are in the European Union (55 Mt in 2000) and the United States (14.4 Mt in 2004). Bricks have many different forms and compositions, resulting in strong variations weight and size.

The ceramic materials industry is a sub-sector where few reliable production statistics are available, and the available data are often not in weight units. Within the fine ceramics industry, floor tiles are the major product. Global floor tile production is estimated at more than 5 200 Mm^2 or about 45 Mt (Ceramic World Review, 2001). The key producing countries are China (33%), Italy (12%), Spain (12%), Brazil (9%), Indonesia (4%), Turkey (3%), Mexico (3%) and India (2%). However, data are uncertain. Other sources state that the Chinese production alone amounts to more than 5 000 Mm^2, which would equal half of total world production and double total world production to about 100 Mt (Cui, 2007). In 2000, the EU produced about 25 Mt of tiles, while the United States produced only 0.4 Mt (64 Mm^2).

Sanitary stoneware production is estimated at approximately 150 million pieces in 2006 (although Chinese data indicate 131 million pieces in 2006). Assuming an average weight of 25 – 50 kg, the total production of sanitary stoneware is 3 – 8 Mt per year. Production data for other products are not available.

The main raw materials used in the brick and ceramics industries are clay and kaolin, which are most often produced at local quarries. This has contributed to the distribution of the production sites, *e.g.* near large clay reserves found near rivers, and also to the more small-scale nature of most plants. Clays and shale used in ceramic production contain calcium carbonates. The presence of the carbonates results in different product characteristics such as colour. The carbonates are calcined in a kiln, which is a source of process emissions. The emissions of the total ceramic industry are estimated at more than 400 Mt CO_2 per year from energy use and calcination of carbonates.

Production technologies and energy efficiencies vary tremendously from large industrial operations to cottage and artisan production, which are still very common in many developing countries. All ceramic industries use basically the same production route: after clay preparation, the clay is shaped automatically or by hand (as found for specialty products or in many small-scale plants in developing countries); bricks are dried before being baked in a kiln. There are various types of kilns: intermittent and continuous, *e.g.* tunnel and roller kiln. The kiln and drier (if not air dried) are the main energy users in the manufacture of ceramic products.

Box 6.5

Brick and Ceramic Products Industry in China

China accounts for about half of global brick production. In 2005, about 90 000 brick making enterprises were in operation in China and they produced 662 billion bricks. This included 495 billion solid clay bricks and 145 billion sintered hollow bricks. Total production of wall materials amounted to 305 billion pieces. The category new wall material includes: sintered hollow products, fired bricks of colliery waste, fly-ash bricks and lime sand bricks.

At 2.7 kg per solid brick and 1.6 kg per hollow brick the total production amounts to about 1.7 Gt bricks. The production of solid bricks has been declining by 10% in the past decade. At the same time the production of sintered hollow bricks has grown twenty-five fold since 1995. The use of solid bricks is projected to continue to decline.

The brick industry is a large energy consumer in China. In 2005, 42 Mt of standard coal equivalents were used to produce bricks and CO_2 emissions were 84 Mt CO_2. The specific energy intensity was 0.628 t standard coal per 10 000 bricks (0.78 GJ/t), including 0.53 t coal and 245 kWh/10 000 bricks. About one-third of the energy is alternative fuels, mainly coal residues. The energy consumption varies widely. Depending on the technology it can range from 0.3 – 1 GJ per 10 000 bricks (Table 6.9).

Note that the energy use per unit of weight is less than half that in Europe and the United States. The compressive strength in Chinese bricks is one fifth that of OECD countries, which reduces the brick firing energy needs. Also natural drying and possibly use of energy from waste materials that is outside the energy statistics may explain the difference. More analysis is recommended.

The annual output of the fired perforated bricks and hollow bricks is only about 20% of the total production of sintered wall materials. In European countries, the fired perforated bricks and the hollow bricks account for as much as 70 – 90% of the sintered wall materials production. Compared with the common solid bricks, the production of the perforated and hollow bricks can reduce the energy consumption by 15 – 30%.

Table 6.9 ▶ ***Energy Consumption of Main Kiln Types in the Bricks and Tile Industry in China, 2006***

	Annular Kiln or Simply-Constructed Annular Kiln	Annular Kiln	Tunnel Kiln
Share of enterprises	63 – 68	29 – 32	3 – 5
Typical production capacity (milion bricks/yr)	0.3 – 15	15 – 20	>30
Energy consumption (GJ/t of standard coal/10 000 bricks)	0.8 – 1.0	0.5 – 0.6	0.30 – 0.35
Energy consumption index (Annular kiln = 100)	100	60	35

Source: Chinese Bricks and Tile Association.

Box 6.5 continued

Coal use for tile production is about 15% of that for brick production. In total, tiles and bricks account for 18% of coal consumption in the Chinese building materials industry, which used 6.5 EJ coal in 2005. The total is dominated by energy use for cement making.

Compared to developed countries the energy saving potential in the brick and tile industry is about 40% and CO_2 emissions can be reduced by 36 Mt. Measures include a reduction of solid clay brick use to 40 – 50%, use of flue gas heat from brick kilns and closure of small-scale kilns. Also the use of waste fuels and residues should increase. Variable speed drives and properly sized motors can help to save electricity.

The government policy target is to limit the total number of solid clay bricks to 380 billion per year by 2010. The use of clay substitutes will rise further to 230 billion of standard brick equivalents per year.

Ceramics Production Process

Brick Production

There is a wide variety of kiln types used in brick production. In developing countries various designs of intermittent kilns, *e.g.* flame, ring, annular or Hoffman kilns, mostly fired with coal or biomass are used. In most industrialised countries the tunnel kiln is the most prevalent, mostly fired with natural gas or oil. Apart from the kiln design, the brick type is an important variable that determines the energy requirements. The difference is accounted for by the kiln temperature and kiln residence time. Brick quality is characterised by the design strength, water absorption rate and colour.

In intermittent kilns, the dried bricks (mostly air dried), are piled into the kiln. The fuel can be added into the kiln chamber or through burners in the side. The chamber is then closed with a brick wall. The chambers are heated to dry the product, followed by calcination and sintering. The bricks are cooled in the chamber. Intermittent brick kilns consume between 3.4 – 10.4 GJ/t product, while tunnel kilns consume between 2.1 – 4.4 GJ/t. In developing countries, small-scale kilns using manual labour are often used. Wood, agricultural residues and coal are the main fuels. Specific energy consumption varies widely between 3 – 10 GJ/t.

In tunnel kilns, the dried bricks are transported on a cart through the drier (heated with waste gas from the kiln), which then enter the kiln. The cart travels at a set speed through different temperature zones of the kiln (optimised for the production cycle): heating, calcination, sintering and a cooling zone. The improved process control also warrants a consistent high product quality, resulting in energy savings due to lower reject rates.

Tunnel kilns represent the most widely accepted kiln type, gradually replacing older types. Larger kilns use less energy per tonne of bricks than small kilns. The energy consumption of a modern tunnel kiln (2.3 GJ/t) is approximately 20% lower than for the older kiln designs. In the EU15, the average energy intensity has declined from 2.65 GJ/t in 1980 to 2.31 GJ/t in 2003. A further improvement to 2.0 GJ/t seems technically feasible.

Fine Ceramics Production

In the production of fine ceramics similar types of kilns are used: intermittent and continuous, *i.e.* tunnel and roller kilns. Kilns vary widely in size and production rates. While intermittent kilns are more energy intensive than continuous kilns, specific energy consumption largely depends on the product type and specifications (Table 6.10). Given global tile production of 5 – 10 billion m^2, 0.4 – 1 EJ per year are used.

Table 6.10 ▶ ***Energy Consumption per weight unit for Different Types of Ceramic Products***

	GJ/t
White tiles, glazed	9
Red tiles, not glazed	6
Table stoneware	10
Fine ceramics	70
Sanitary stoneware	30

Source: Gielen, 1997.

Energy Consumption and CO_2 Emissions from Ceramics Production

Energy efficiency and greenhouse gas mitigation options exist in all ceramics production steps. Reduction of the moisture content of the clay through dry forming techniques will result in energy savings in the drying step and the kiln. Kiln options are most important as it is the dominate energy use. Options in the kiln include the use of more efficient (tunnel) kiln design (including low-thermal mass carts, burner design, insulation); operating practices (process controls); fuel switching from coal to fuel oil, natural gas and biomass; waste heat recovery; and partial substitution of clay and shale by alternative raw materials such as fly-ash.

The potential savings vary widely for each country depending on the type of brick produced and kiln types used. It is estimated that the potential would vary between 10% for countries with state-of-the-art tunnel kilns to more than 30% for countries with a high number of intermittent kilns. If all Chinese brick production shifted to efficient tunnel kilns, estimated energy savings of up to 40% would result. Addition of biomass to the clay is another way to reduce the fossil energy consumption and CO_2 emissions in brick production. However, the product quality may be affected.

The roller kiln is an important improvement option for the fine ceramics industry, where it has been demonstrated for a wide variety of products. It is now being demonstrated for heavy ceramic products as well (roof tiles, bricks). The energy consumption is lower because of a lower residence time and less materials intensive transportation systems for the bricks in the ovens. These transportation systems must also be heated. The roller kiln is currently used for production of sanitary stoneware products. Roller kilns use about 1.6 GJ/t product.

Mitigation options also include the use of alternative building materials such as concrete or wood, as well as the use of bricks made from concrete or lime and sand. However, informed decisions will consider CO_2 emissions over the whole life cycle of the products including their impact on the energy performance of the building. The current choices of building materials and kiln technologies are deeply related to local traditions, climate, and the costs of labour, capital, energy and transportation, as well as the availability of alternative fuels, raw materials and construction materials.

Indicators for Lime, Glass and Ceramics Industries

Energy intensity (and efficiency) indicators for most non-metallic mineral products could be devised based on the energy intensity of the overall production produced in each industry, *e.g.* energy use per tonne of lime. A further improvement could be made to differentiate between the main products in the various industries, *e.g.* container, flat, fibre and specialty glass in the glass industry. In brick production it is important to distinguish the different types of bricks, *e.g.* varying weight and size, solid versus hollow. Some countries only report the number of bricks produced while others also report the volume. Using tonnage as activity indicator would be more suitable, as it would account at least for some variation in product type. Product types vary widely in the ceramics industry, making it virtually impossible to devise reliable indicators that allow a comparison of energy intensity differences between countries.

The IEA statistics and most national statistics do not contain data on a sufficiently disaggregated level to allow construction of such indicators. The IEA energy statistics do not distinguish the individual sub-sectors, while only a limited number of countries report on energy use for a number of industries discussed in this chapter. Hence, the construction of the indicator would need to rely on a varied set of national and industry sources, which are not always consistent between sources or over time, nor cover all countries. The sections discuss the main types of indicators that would be useful in the selected industries and provide a range of the energy intensities found in the industries.

PULP, PAPER AND PRINTING INDUSTRY

Key Findings

- *The pulp, paper and printing industry consumed 6.45 EJ of final energy in 2004, accounting for 5.7% of total industry energy use. Printing represents a small share of the industry's energy demand. In pulp and paper production, the industry generates about half of its own energy needs from biomass residues and makes extensive use of combined heat and power (CHP) technology.*
- *The industry's heavy reliance on bioenergy means that the CO_2 intensity in manufacturing is not very high, and therefore CO_2 reduction potentials are limited.*
- *An indicator method is developed in this study that compares a theoretical sector energy use if best available technology (BAT) were applied with actual energy use according to IEA statistics. The method discerns energy use for mechanical and chemical pulp, pulp from recovered paper and various paper qualities. These indicators are suited to identify areas where further analysis is warranted. They can supplement benchmarking, but are not a substitute.*
- *This indicators analysis raises a number of issues concerning data quality which requires further discussion on the availability, quality and consistency of data across countries.*
- *There are notable differences in energy use for pulp and paper production between countries, due to a range of factors such as product mix, processes used, plant size, technology, technical age, feedstock quality, fuel prices and management attention to energy efficiency.*
- *Energy efficiency gains can be achieved if existing mills are retrofitted with current energy efficient technology, but investment costs and competitiveness are key determinants.*
- *There is potential for more use of heat recovery. Putting excess heat to use in a more effective way could provide savings, but the economic viability depends on the need for low grade heat.*
- *Increased paper recycling and recovered paper use could help reduce energy consumption in the industry. While Europe, Japan and Korea appear to be close to the practical limits for paper recycling, North America and parts of Asia could benefit from more effective policies on waste disposal to encourage higher rates of paper recycling.*
- *In the pulp and paper industry as a whole, the efficiency of heat consumption showed real gains from 1990 to 2003, but there remains an improvement potential of 14% compared to energy use with BAT.*
- *The indicators reveal little change in the overall efficiency of electricity use from 1990 to 2003. There is an estimated improvement potential of 16% compared to energy use with BAT.*
- *Based on country comparisons, the remaining energy efficiency potential in the pulp and paper industry is estimated to be 1.0 EJ per year of final energy, or 1.3 to 1.5 EJ in primary energy terms, depending on the efficiency for power and steam generation. If higher recycling rates and CHP were also considered, the total final savings potential would be 2.1 to 2.4 EJ of final energy per year.*

Global Importance and Energy Use

The pulp, paper and printing industry is the fourth largest industrial consumer of energy, consuming 6.45 exajoules (EJ) of final energy in 2004 (5.7% of total industrial energy use). Unlike other industrial sectors, the pulp and paper industry also produces energy as a by-product and already generates about 50% of its own energy needs from biomass residues. In the long term, the industry could even develop into a clean energy supplier if residues are used efficiently.

Most energy used in paper production is for mechanical pulping and paper drying. This is an area where further efficiency gains are available. The need for large amounts of steam makes combined heat and power (CHP) an attractive technology. Most modern paper mills have their own CHP unit. Chemical pulp mills produce large amounts of black liquor which is used to generate electricity at relatively low efficiencies. New technologies that promise higher conversion efficiency could have important energy benefits, particularly for electricity and possibly biofuels.

In theory, pulp and paper could be produced without CO_2 emissions, provided sufficient biomass is used and black liquor is converted into electricity with sufficient efficiency. This would imply minimal recycling as waste paper is used for energy recovery. This may not, however, be the optimal use of biomass resources. From the viewpoint of the energy and resource system as a whole, it makes more sense to recycle as much paper as possible, while using the wood surplus to produce biofuels or electricity. Moreover, more intensive use of forests could bring further environmental degradation if the forests are not sustainably managed. The best pathway depends therefore on system boundaries and complex trade-offs.

Methodological and Data Issues

The results of this analysis have raised a number of questions regarding the applicability of using indicators of energy use to compare pulp and paper production across countries. The product mix of each country varies to a degree that may not be accurately reflected in the current methodology and hence may result in certain biases. Compared to the other industries analysed here, the issue of product mix appears to be much more sensitive.

Industry experts have noted that no two paper mills are identical and as a result an attempt to compare energy use even across similar mills requires strict adherence to system boundaries. When such an analysis is extended across countries, discrepancies in system boundaries may distort outcomes. For example, Canada and the Nordic countries that produce large amounts of virgin pulp may be penalised under this methodology, while countries such as Korea, Germany and Japan, which produce paper and paperboard (packaging) from recycled pulp, tend to have more favourable results.

Differences in fuel availability across countries can also skew results in energy use comparisons. This is especially true where large pulp producing countries have greater access to biomass than countries that are mainly paper and paperboard producers which often rely on more costly imported fuels.

An international effort to harmonise data collection is needed to allow for the type of energy intensity comparisons that are the aim of this activity. The industry recognises that there is a need for better and more comparable data. Improving international data collection efforts will lead to a better understanding of energy consumption trends and where more focused policies and practices can have the greatest impact on reducing energy consumption and CO_2 emissions.

Such an undertaking requires significant international collaboration. The business sensitivity and confidentiality of the underlying data implies that a trusted third party will be needed to perform the data collection and analysis. As part of the IEA Industrial Energy-Related Technologies and Systems (IETS) Implementing Agreement, Paprican has been working on a benchmarking analysis that potentially could be adapted for a worldwide approach. A benchmarking methodology is being finalised that provides a procedure for reporting energy use in a pulp and paper mill by process areas.

By reporting energy use by process area, instead of for the entire mill, meaningful comparisons can be made on energy use across mills and countries with widely varying processes and product mix. A comparison for a specific process area, such as energy use in recycled pulp processing, can be performed with similar process areas in other mills. This methodology would then allow for country comparisons on a process level. Comparisons can then also be made with best available technology, (BAT).

In order to determine the energy use in a pulp and paper mill, the mill is divided into different process areas and data is collected on auto-generated energy, purchased energy, energy sold and pulp and paper production for the mill.[1] The energy data is then allocated to the different process areas. The report being prepared by Paprican recommends covering eleven different paper types and twenty-one different pulp manufacturing areas.

This indicators analysis raises a number of issues concerning data quality which requires further discussion on the availability, quality and consistency of data across countries. IEA statistics include energy use in pulp, paper and printing. Separate energy use figures for pulp and paper production are available from some national statistics offices. Detailed data on energy use by product in the pulp and paper industry does exist among different companies, consultants, countries and associations, but they do not provide a full picture and the data quality and consistency differ from source to source. In addition, the data are often confidential.

How energy use is allocated in an industry with large amounts of auto-production can vary, particularly in accounting for energy sales to a grid and/or to district heating systems. In IEA statistics electricity produced by auto-producers (including CHP) is accounted for in the transformation sector and not under industry, but as IEA data come from national sources there is concern that this may not be consistent across all countries. A significant amount of fuel consumption, especially biomass, is reported by many countries in the "other industries" category and thus potentially leads to an under reporting of fuel consumption in the pulp, paper and print sub-sector. The use of wood residues and waste in boilers in the industry that is omitted in the statistics could be another cause of statistical problems.

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[1] This follows from a previous method for reporting energy use in pulp and paper mills by process area, based on the approach developed by the International Energy Agency (IEA) Programme on Advanced Energy-Efficient Technologies for the Pulp and Paper Industry for life cycle studies.

Pulp and Paper Production and Demand Drivers

Total paper and paperboard production was 355 million tonnes (Mt) in 2004. Chemical pulp production was 128 Mt; mechanical wood-pulp production was 36 Mt and non-wood pulp production was 17 Mt. Total fibre supply (pulp and waste paper) amounted to 339 Mt. Recovered paper accounted for 159 Mt, or 44% of the total fibre supply. Of the chemical pulp produced, the vast majority (121 Mt) was sulphate (Kraft) pulp. Half of the product mix is packaging, wrapping and paperboard; about one-third is printing and writing paper; and the remainder is newsprint, household and sanitary paper.

Table 7.1 ▶ *Paper and Paperboard Production, 2004*

	Paper & Paperboard *Mt*	Share *%*	Cumulative Production Share *%*
United States	83.61	23.6	23.6
China	53.46	15.1	38.7
Japan	29.25	8.3	46.9
Canada	20.58	5.8	52.7
Germany	20.39	5.8	58.5
Finland	14.04	4.0	62.4
Sweden	11.59	3.3	65.7
Korea	10.51	3.0	68.7
France	10.25	2.9	71.6
Italy	9.67	2.7	74.3
Brazil	8.22	2.3	76.6
Indonesia	7.22	2.0	78.6
Russia	6.79	1.9	80.6
United Kingdom	6.24	1.8	82.3
Spain	5.49	1.5	83.9
Norway	2.29	0.6	84.5
Portugal	1.67	0.5	85.0
Chile	1.17	0.3	85.3
Others	52.04	14.7	100.0
World	**354.49**		

Source: Food and Agricultural Organization of the United Nations (FAO), 2006.

The United States is the world's largest producer of paper and paperboard accounting for 23.6% of production in 2004. The next largest producers are China (15.1%), Japan (8.3%) and Canada (5.8%). These four countries account for more than half of all global production. The eighteen countries listed in Table 7.1 are the largest producers of paper and paperboard and together account for 85% of world production. China has shown the strongest growth with paper and paperboard production more than tripling from 17.41 Mt in 1990 to 53.46 Mt in 2004. Rapid demand growth for paper and paperboard over the last two decades has led to tremendous investments in the Chinese paper industry. Global demand for paper and paperboard will be strongly influenced by demand in China.

Table 7.2 ▶ *Chemical and Mechanical Wood Pulp Production, 2004*

	Chemical Wood Pulp *Mt*	Share *%*	Mechanical Wood Pulp *Mt*	Share *%*
United States	**46.11**	**36.3**	**4.21**	**11.6**
China	1.79	1.4	0.57	1.6
Japan	**9.35**	**7.4**	**1.24**	**3.4**
Canada	**13.45**	**10.6**	**12.14**	**33.6**
Germany	0.85	0.7	1.40	3.9
Finland	**7.78**	**6.1**	**4.34**	**12.0**
Sweden	**8.42**	**6.6**	**3.40**	**9.4**
Korea	0.43	0.3	0.12	0.3
France	1.55	1.2	0.70	1.9
Italy	0.04	0.0	0.37	1.0
Brazil	**8.92**	**7.0**	**0.47**	**1.3**
Indonesia	**5.21**	**4.1**	**0.00**	**0.0**
Russia	**5.01**	**3.9**	**1.26**	**3.5**
United Kingdom	0.00	0.0	0.26	0.7
Spain	1.78	1.4	0.10	0.3
Norway	**0.56**	**0.4**	**1.78**	**4.9**
Portugal	1.95	1.5	0.00	0.0
Chile	2.83	2.2	0.51	1.4
Others	11.83	8.5	3.30	9.1
World	**127.7**		**36.1**	

Source: United Nations Food and Agricultural Organization (FAO), 2006.

The production of chemical and mechanical pulp is even more concentrated than paper and paperboard production. The nine countries shown in bold in Table 7.2 represent 80% of the global chemical and mechanical pulp production.

In OECD countries, demand in the pulp and paper sub-sector is fuelled by demand for paper for printing and writing. In contrast, in non-OECD countries, pulp and paper consumption is concentrated in the category "other" paper and paperboard as paper consumption is closely linked to manufacturing output. As per capita income rises, it is expected that demand increases for printing and writing paper.

Table 7.3 ▶ ***Global Paper and Paperboard Consumption, 1961 and 2004***

Global Consumption *Mt*	1961	Share %	2004	Share %	Average Growth Rate
Newsprint	14	19	38	11	2.4% per year
Printing and writing paper	15	20	105	30	4.6% per year
Other paper and paperboard	48	61	211	59	3.5% per year
Total	**78**		**355**		**3.6% per year**

Source: Whiteman, 2005.

Table 7.3 shows that global growth in paper and paperboard consumption from 1961 – 2004 was led by increased demand for printing and writing paper with annual growth of 4.6% versus 3.6% for total paper and paper board consumption. The increased use of computers and printers caused a change in consumer tastes with higher demand for printing and writing paper. The rapid uptake of the internet has reduced the demand for newsprint as electronic media replace traditional newspapers and periodicals.

Higher demand for pulp for printing and writing paper and lower growth rates for newsprint has increased demand for chemical pulp and lowered demand for mechanical pulp. In non-OECD countries, such as China and India, where wood pulp is relatively scarce, other fibres make up an important share of the pulp mix. Pulp demand has grown at a lower rate than paper demand during past decades as recycling rates have increased.

Energy Use in the Pulp and Paper Industry

Energy use in the pulp and paper industry is divided among a number of different pulp production and paper production processes. The main processes are:

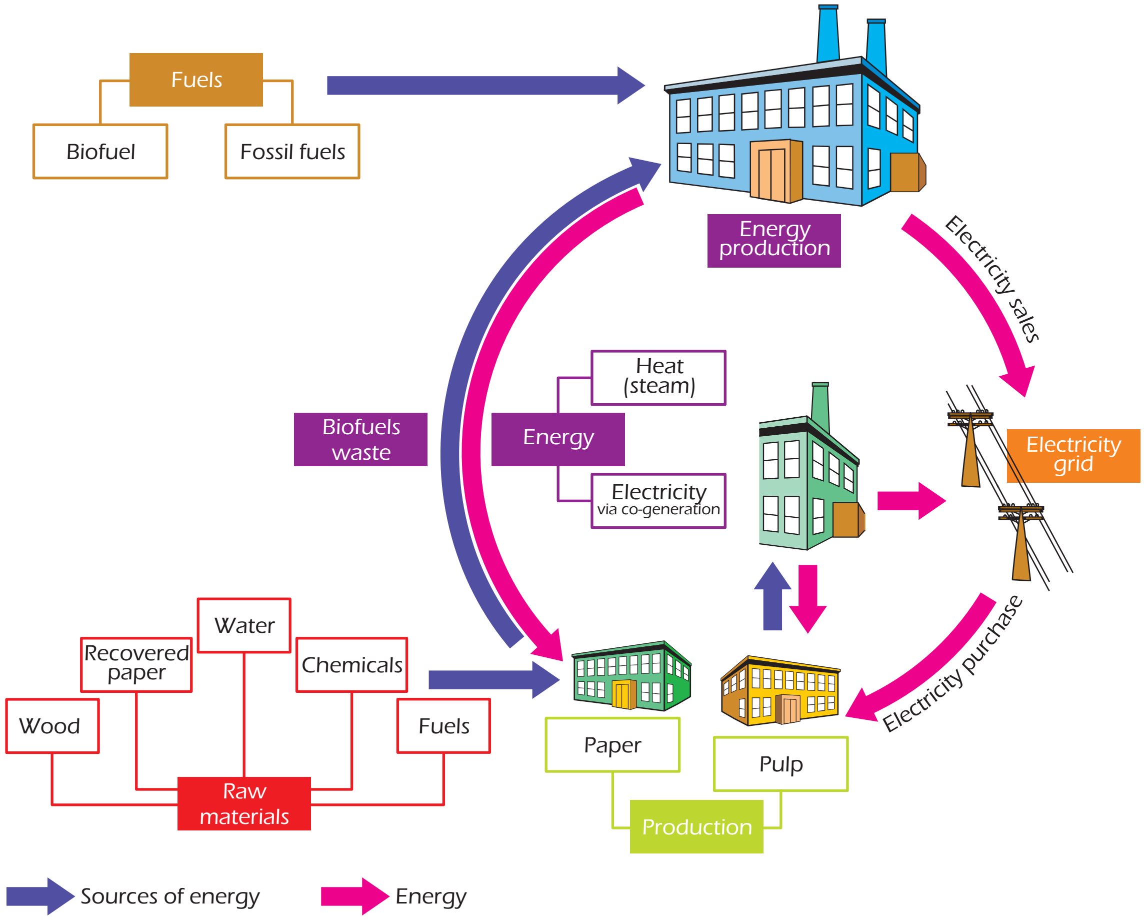
- Chemical pulping;
- Mechanical pulping;
- Paper recycling;
- Paper production.

In 2004, according to IEA statistics, the pulp and paper industry used 2.05 EJ of bioenergy, mainly in the form of black liquor. Actual use may be somewhat higher, as a significant amount of bioenergy is reported in IEA statistics under "non-specified industry use", part of which may actually be in pulp and paper production. Actual black liquor use in 2004 is estimated at approximately 2.4 EJ. This means that more than one-third of all energy is biomass.

The industry's heavy reliance on bioenergy means that the CO_2 intensity of the energy is not very high, and the CO_2 reduction potentials in the pulp and paper industry are limited. But more efficient use of bioenergy makes sense from an energy systems perspective, as it frees up scarce bioenergy resources to replace fossil fuels elsewhere.

Figure 7.1 ▶ *Energy in Pulp and Paper Production*

Key point: Pulp and paper industry generates a significant portion of its own energy needs from biomass residues.



Source: Confederation of European Paper Industries (CEPI).

Figure 7.1 illustrates the uses and source of energy in the pulp and paper production process. Unlike other energy intensive industries, a significant portion of the heat and electricity required is supplied internally. Approximately two-thirds of final energy consumption is fuel that is used to produce heat, while the remaining third is electricity, either from the grid or produced on site.

Pulp Production

Mechanical pulping uses large amounts of electricity. Chemical pulping, on the other hand, yields black liquor as a by-product, which is then incinerated in a recovery boiler to produce heat and electricity. Roughly, 22 gigajoules (GJ) of black liquor per tonne of pulp can be combusted. Depending on its recovery efficiency and its configuration, a mill that uses chemical pulping can be a net energy producer. Chemical pulp mills require less external energy than mechanical pulp mills, but require approximately 2.2 tonnes of wood to produce a tonne of bleached Kraft paper, as half of the wood is incinerated in the recovery boiler with 1.05 – 1.08 tonnes of wood are used per tonne of mechanical grades.

The main production facilities are either pulp mills, or integrated pulp and paper mills, depending on the proximity to markets and transport facilities. An integrated mill is more energy efficient than the combination of a stand-alone pulp mill with a paper mill because pulp drying can be avoided and the excess energy from the chemical pulp mill can be used efficiently in the papermaking. However, such an integrated plant requires electricity from the grid, as well as additional fuel.

A large modern chemical pulp mill is self-sufficient in energy terms, using only biomass and delivering surplus electricity to the grid. Such a mill typically has a steam consumption of 10.4 GJ/air dry tonne pulp (adt) and an excess of electricity production of 2 GJ/adt. A future integrated chemical pulp and fine paper mill will require greater amounts of energy and is expected to have a typical steam consumption of 13.6 GJ/adt paper, *i.e.* a small biofuel surplus, and a deficit in electricity production of 1.8 GJ/adt paper (STFI-Packforsk, 2005).

High yield mechanical pulping processes are electricity intensive, and there has been relatively little progress in decreasing electricity demand in mechanical pulping so far. Much of the improvement in energy efficiency has resulted from increased heat recovery where the recovered steam is used to dry the pulp and paper. More than 90% of the electricity used in mechanical pulping is transformed to heat. The main source of energy efficiency gains is heat recovery. The key question then is how to best integrate a mill to benefit from heat recovery.

Integrated mechanical, chemical, recycled pulp and paper mills provide the best solution for improving efficiency, as heat recovered can be used in chemical pulp and papermaking processes. These large integrated mills allow the maximum energy efficiency and minimise CO_2 emissions. Stand-alone mechanical pulp mills offer the potential needed to make investments in heat recovery systems attractive when the fuel prices are increasing and the excess biomass (bark) can be sold in the fuel market. If there is no heat recovery, then efficiency will be low.

The minimum electricity demand, in principle, to produce mechanical pulp from logs is far below actual electricity use and thus suggests that major improvements should be possible. Industry experts cite that significant advances in mechanical pulping may be possible, but concerted efforts have not yet produced such an advance. Large investments have been made in Canada and Scandinavia to improve energy efficiency in mechanical pulping, but these savings have been primarily offset by a shift towards higher quality mechanical pulp which has a higher specific energy consumption per tonne.

Paper Production

Paper production involves preparing the stock from pulp, forming a sheet, dewatering and drying and sometimes coating the paper. All paper machines have three basic elements: wet end, press section and drying section. Economies of scale have resulted in larger and faster paper machines. The latter increases electricity use however, there is a parallel trend toward low cost, simple, and small paper machines for recycled paper mini-mills in Asia. Heat (steam) is needed for the drying section. Electricity is used in all process steps.

Table 7.4 ▶ ***Typical Energy Consumption in Paper Production for a Non-integrated Fine Paper Mill***

	Process Heat *GJ/t*	Electric Power *kWh/t*
Stock preparation		202
Paper machine	8.0	350
Coating		4
Total paper mill	**8.0**	**670**

Source: European Commission, 2001.

During the production of different paper grades either virgin fibres (chemical or mechanical pulps) or recycled fibres are used as the main raw material. Today, the composition of raw material used for paper is influenced more than ever by the cost of the individual components. The electricity use for stock preparation depends on the paper type and may vary from 60 – 1 200 kWh/t. Table 7.5 provides an overview of the electricity needs for the production of various types of paper.

Table 7.5 ▶ ***Typical Electricity Consumption for the Production of Various Types of Paper***

	Electricity *kWh/t*
Newsprint	500 – 650
Uncoated mechanical	550 – 800
Uncoated wood-free	500 – 650
Coated mechanical	550 – 700
Coated wood-free	650 – 900
Kraft papers	850
Tissue and specialty	500 – 3 000
Boxboard	550
Containerboard	680

Source: European Commission (EC), 2001.

Table 7.6 ▶ ***Breakdown of Energy Use in Paper Production in the United States***

Process/Description	Percent of Total Energy Use		
	Steam %	Electricity %	Total %
Raw Materials Preparation. Processing of logs prior to pulping. Includes debarking, chipping, conveying chips to pulping lines.	0	8	2
Pulping. Separation of wood fibres from lignin, which binds fibres into solid wood. Major alternative processes are:			
• **Mechanical Pulping.** Grinding and shearing of wood chips. Primarily used for low-grade papers. High yield, but substantial impurities.	15	18	14
• **Chemical (Kraft) Pulping.** This is a thermo-chemical process in which chips are combined with strong solvents and heated under pressure to separate fibres from lignin. Spent liquid (black liquor) can be concentrated and burned for process heat.	0	15	3
• **Pulping from Recovered Paper/Other Pulping Processes.** This is primarily a mechanical process.	1	1	1
Chemical Recovery. Extraction and reuse of pulping chemicals. Involves concentration of the black liquor, energy recovery (burning), and recaustisation of the remaining liquor. Many of these processes involve several stages of evaporation under high heat.	8	4	7
Bleaching. Removal of remaining lignin after chemical pulping. Involves several stages of mixing pulp with chemicals, removal of chemicals and washing.	19	2	19
Pulp Drying. Necessary only when pulp must be transported to a paper mill or for certain specialty papers.	2	1	2
Papermaking. Three basic steps:	55	36	47
• **Stock Preparation.** Blending pulps and additives to form a uniform slurry.			
• **Sheet Formation.** Spray low consistency pulp onto moving wire mesh, where pulp drains.			
• **Finishing.** Sheets are pressed to remove water, dried on steam-heated rollers, then coatings applied.			
Other Process Uses	0	6	4
Non-process Uses. Facility lighting, HVAC, plug loads.	0	10	2
Total	**100**	**100**	**100**

Source: PA Consulting, 2002.

Table 7.6 provides a detailed breakdown of the energy use in the pulp and paper production process in the United States. Papermaking accounts for the largest share at 47% of total energy use, while the pulping process, including bleaching, accounts for 44%. The breakdown of energy use in other countries will vary depending on each country's production mix of pulp and paper and the different grades of paper produced.

Printing

Total energy use in printing is less than 6% of energy consumption in the industry. Approximately 350 PJ of energy are used in the printing industry worldwide and almost all is electricity consumption. On a value-added basis, the printing industry represents a much larger share of GDP, but in terms of energy consumption in industry its importance is relatively insignificant.

Box 7.1

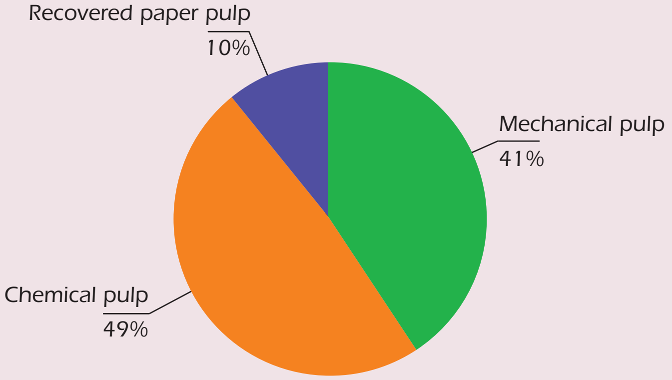
Benchmarking Energy Efficiency Data for the Pulp and Paper Industry in Canada

In 2004, Canada produced 12.1 Mt of mechanical pulp, 13.5 Mt of chemical pulp and 2.8 Mt of recycled pulp (Figure 7.2). Canada is the world's largest producer of mechanical pulp (33.6% of global supply) and the second largest producer of chemical pulp (10.6%). Total paper and paperboard production in Canada was 20.6 Mt in 2004 and represents 5.8% of global production. Newsprint accounts for the largest share (40%) of paper production in Canada with 8.2 Mt produced in 2004 (Figure 7.3).

Table 7.7 shows the results of benchmarking analysis for Kraft and newsprint mills in Canada. The energy efficiency improvement potentials range from 20 – 96% for demand for steam. This result supports the IEA indicators analysis. Energy use figures for the modern mill are based on best available technology, while energy consumption in the best mill in this analysis is well above what is possible for a modern mill.

Figure 7.2 ▶ ***Pulp Production Mix in Canada, 2004***

Key point: Virgin pulp dominates the Canadian pulp market.

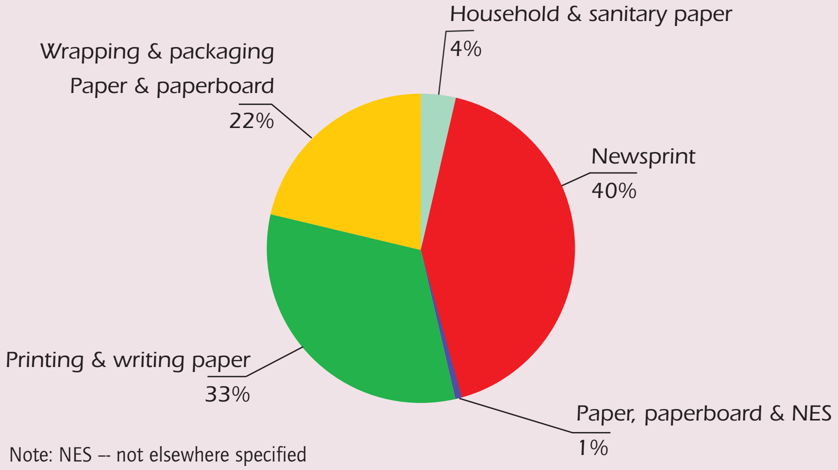


Source: FAO statistics.

Box 7.1 continued

Figure 7.3 ▶ *Paper and Board Product Mix in Canada, 2004*

Key point: Newsprint accounts for the largest share of paper production in Canada.



Note: NES -- not elsewhere specified
Source: FAO statistics.

Table 7.7 ▶ *Benchmarking Results for Canadian Pulp and Paper Industry*

	Reference Year	Modern Mill	Best	Worst	Median	Improvement Potential %	Source
Kraft mills (GJ steam/t)	2001	10	15	26	20	50	PAPRICAN, 2002, p. 11
Kraft mills (GJ steam/t)	2003	10	12	22	17	40	Francis & Browne, 2004
Kraft mills (kWh/t)	2001	600	650	1 200	850	30	PAPRICAN 2002, p. 11
Newsprint mills (GJ steam/t)	2001	0.4	2.2	12	7	96	PAPRICAN 2002, p. 20
Newsprint mills (GJ steam/t)	2003	0.4	2	14	6.5	94	Francis & Browne, 2004
Newsprint mills (kWh/t)	2001	2 475	2 475	3 500	3 100	20	PAPRICAN, 2002, p. 20
Paper machines in newsprint mills (GJ/adt)	2003		3.3	8	6	45	Francis & Browne, 2004

Sources: PAPRICAN (2002); Francis & Browne (2004).

Energy Indicators

Energy Intensity Indicators versus Benchmarking

Benchmarking is a comparison of the competitive situation among similar types of mills producing the same product. Benchmarking can be complemented by a range of country level indicators for analysis of status and trends. The goal of this indicators analysis is not benchmarking on a mill or machine level, but a cross country comparison of energy intensity. There are a number of benchmarking studies, *e.g.* Paprican (Canada), Pöyry (Finland) and IETS (Canada, United States and Sweden), which look at energy consumption on a mill or machine level. Industry experts clearly favour the use of these benchmarks over the IEA cross country analysis for the assessment of efficiency potentials, but see the need for a first IEA reconnaissance in this area and the limitations of existing benchmarking studies. Benchmarking studies, which are often confidential, can be used to validate this analysis. The IEA analysis is intended to complement various on-going benchmarking studies and is not intended as a substitute.

The energy indicators developed here are intended for a country comparison of energy intensity in the pulp, paper and printing industry and as a first indication of potentials. Countries presented in this analysis represent more than 80% of global paper and paperboard production and 90% of wood pulp production.[2] The lack of publicly available energy use data on the level of specific products makes individual process indicators infeasible and thus aggregate product indicators are proposed.

Three indicators have been developed:

- energy efficiency index based on fuel use for *heat*;
- energy efficiency index based on *electricity* use;
- CO_2 emissions index.

Energy Efficiency Index Methodology

The proposed methodology for calculating an energy efficiency index is as follows:

1) Use IEA energy statistics for final energy use.[3]
2) Define a best available technology (BAT) value for mechanical pulping, chemical pulping, waste paper pulp, de-inked waste paper pulp and seven different paper grades.
3) Multiply production volumes and BAT to calculate practical minimum energy use.
4) Divide practical minimum energy use and actual energy use (final energy). This is the energy efficiency index.
5) One hundred minus the energy efficiency index = improvement potential.

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[2] China, which is part of the global production, has been treated separately in Box 7.2.

[3] As IEA statistics also include printing, an adjustment is made to remove energy use from printing based on available energy data from national sources or estimated based on countries with similar industry structure. For the United States, data is based on the US Energy Information Agency's MECs survey.

The physical energy intensity of the pulp and paper industry in a country is calculated based on its energy consumption relative to BAT in order to compare relative energy intensity across countries. Various assumptions of BAT are applied to heat and electricity consumption in mechanical pulping, chemical pulping, waste paper pulp, de-inked waste paper pulp and seven different grades of papermaking (Table 7.8). The European Commission (EC) BAT reference document was the main source for the BAT figures.[4] While specific countries may have their own national figures for BAT, the EC document is an internationally recognised and widely used BAT reference document. Heat and electricity are treated separately to allow for CHP analysis.

Table 7.8 ▶ ***Best Available Technology***

	Heat *GJ/t*	**Electricity** *GJ Electricity/t*
Mechanical pulping		7.5
Chemical pulping	12.25	2.08
Waste paper pulp	0.50	0.36
De-inked waste paper pulp	2.00	1.62
Coated papers	5.25	2.34
Folding boxboard	5.13	2.88
Household & Sanitary paper	5.13	3.60
Newsprint	3.78	2.16
Printing & writing paper	5.25	1.80
Wrapping & packaging paper and board	4.32	1.80
Paper and paperboard not elsewhere specified	4.88	2.88

Sources: EC (2001); Finnish Forestry Industries Federation (2002); Jochem, *et al.*, 2004.

By multiplying the BAT figures with the quantities of mechanical pulp, chemical pulp, waste paper pulp and paper and paperboard produced by each country, yields the total heat and electricity consumption if production was based on BAT. This is then compared to the actual total energy used. Figures for heat (steam) demand in each country are estimated based on reported fuel consumption in the industry and assume 80% efficiency.

The analysis used to compare energy intensity across different countries does not differentiate for integrated and non-integrated mills. Energy efficiency of integrated pulp and paper mills are approximately 10 – 50% better, depending on the grade of

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[4] In the EC BAT reference document, also known as IPPC BREF document, a range was often given to reflect an assessment of costs versus benefits and thus could also be considered as best practice. Where a range was given, a comparison was made with other papers to determine a suitable BAT value.

Box 7.2

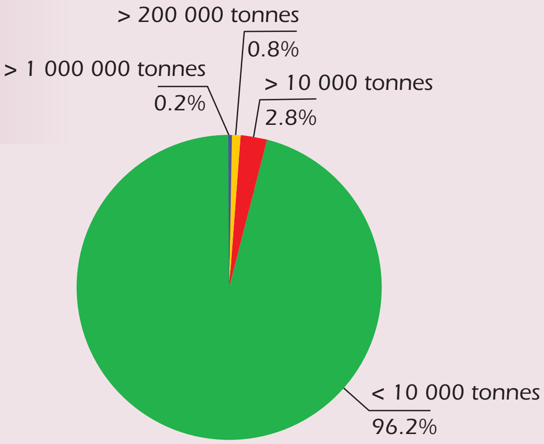
Pulp and Paper Industry in China

The results of an energy indicator analysis based on official energy statistics showed virtually no energy efficiency improvement potential in the Chinese pulp and paper industry and highlighted substantial under-reporting of energy consumption data in national accounts. Given the small average plant size and technology employed, one would expect the industry in China to be among the least efficient. Although some of the largest and most modern mills are located in China, the vast majority are very small mills with capacity below 10 000 tonnes (Figure 7.4).

Small mill size makes many energy efficiency solutions uneconomic. Many of the small pulp and paper mills still use technologies from the 1960s and 1970s. In an effort to reduce the number of small mills, the Chinese Government has introduced a minimum size of 34 000 tonnes for new pulp mills and announced the closure of all pulp mills with capacity of less than 10 000 tonnes. There is a push to develop large and modern mills. The enforcement of minimum plant sizes has proven difficult on the local level and a significant portion of these small mills remain in operation.

Figure 7.4 ▶ ***Number of Pulp and Paper Mills by Capacity in China***

Key point: China is dominated by small pulp and paper mills with capacity below 10 000 tonnes.



Source: China Cleaner Production Centre of Light Industry.

The recovered paper use rate in China has jumped from 38% in 1997 to 51% in 2004. This change in the production structure has had a dramatic impact on the energy intensity of the industry as pulp from recovered paper has been used to replace non-wood fibre pulp which requires roughly twice the amount of energy as wood pulp and three times that of recovered paper pulp. In 2004, 27% of all pulp came from non-wood pulp versus 53% in 1990.

The processing of non-wood pulp or straw also differs significantly from wood pulp and the efficiency potential from heat recovery systems is not possible due to the high level of silicon present in the black liquor produced from non-wood pulp. The silicon deposit in boilers reduces the recovery boiler efficiency to approximately 60 – 70%.

Based on case studies of energy use in Chinese pulp and paper plants, it is estimated that the actual energy consumption is approximately 30 – 50% greater than what is reported in current statistics (China State Statistical Bureau and Tsinghua University). Based on this adjustment and using 2003 data, the adjusted EEI (heat) for China is between 86 – 73 and represents a 14 – 27% energy efficiency potential, while the EEI (electricity) is 77 – 67 and represents a 23 – 33% energy efficiency potential.

paper produced, than in stand-alone mills. For example, in a stand-alone pulp mill, a significant amount of heat is required to dry the pulp prior to transport and greater use of heat recovery systems can be exploited by integrated mills versus stand-alone ones. An analysis of energy intensity should also take into consideration the level of integrated mills within the industry, but data limitations make a more detailed structural analysis difficult at this stage. Under the current methodology, a higher EEI may indicate that a country has a higher portion of integrated mills. One could argue that this is indeed an efficiency gain, but structural effects may limit the potential to use integrated mills.

Energy requirements for different paper grades can vary widely. The overall production of these higher grades of paper is in general much less than for lower to medium grades of paper. Table 7.9 shows the paper production mix for the seven paper types in this analysis and the weighted BAT for all paper types by country. The country weighted BAT for these seven paper types varies from 6.54 GJ in Norway to 7.28 GJ in Finland. Narrowness of this range indicates that product differentiation by paper type will have a moderate impact on the overall results.

Table 7.9 ▶ ***Paper Production by Type of Paper and by Country, 2004***

	Coated Papers %	Folding Boxboard %	Household + Sanitary Paper %	News-print %	Printing & Writing Paper (Non Coated) %	Wrap + Packaging Paper + Board %	Paper + Paper-board NES %	Country Weighted BAT for All Paper Types *GJ*
Brazil	6.7	6.8	8.9	1.6	22.1	48.5	5.3	6.87
Canada	6.9	5.1	3.6	39.7	27.2	16.8	0.7	6.61
China	1.8	0.0	6.9	5.5	20.4	49.3	16.2	6.77
Finland	40.9	13.0	1.3	5.2	26.5	10.9	2.3	7.28
France	19.7	4.7	7.0	10.9	14.2	39.7	3.9	6.86
Germany	22.9	7.4	5.3	11.8	15.8	29.9	7.0	6.97
Italy	24.2	7.4	14.2	2.0	8.0	38.9	5.3	7.14
Japan	23.7	6.6	5.8	12.6	9.6	35.1	6.6	6.92
Korea	16.8	11.3	3.9	16.0	6.7	38.2	7.0	6.83
Norway	5.2	0.0	1.2	37.5	36.4	17.1	2.6	6.54
Spain	10.7	7.3	9.2	5.9	12.1	45.6	9.2	6.91
Sweden	9.6	19.8	2.7	22.9	16.6	27.3	1.1	6.84
United Kingdom	11.1	3.1	12.5	17.3	12.4	34.6	8.9	6.90
United States	10.4	7.0	7.9	6.2	15.7	50.2	2.7	6.79

Note: Wrapping + packaging + paper + board category excludes folding boxboards.

NES – not elsewhere specified.

Sources: EC (2001), FAO, Finnish Forestry Industries Federation (2002), and Jochem, *et al.*, 2004.

A country's energy efficiency index (EEI) would be at a level of one hundred if the energy used to produce its commodities was at the same level as BAT. Figures well below one hundred indicate that energy consumption is above BAT levels and signifies an opportunity for greater energy efficiency, if current BAT were applied. Figures above one hundred could indicate that BAT figures may be too conservative, imply accounting inconsistencies across countries or indicate a high level of integrated mills. Figure 7.5 shows heat consumption compared to BAT and Figure 7.6 shows electricity consumption compared to BAT for the key pulp and paper producing countries.[5] Countries with more modern pulp and paper mills should normally have EEI ratios close to one hundred, while those with older facilities would be expected to have significantly lower figures.

Energy Efficiency Index: Heat

For heat consumption, Korea and Japan appear to be the most efficient with EEI levels well above one hundred. Over the last decade, the Korean paper industry has invested heavily in relatively efficient capacity expansion. Korea's EEI rose substantially, from 102 in 1990 to 145 in 2003. Korea and Japan's EEI ratios well above 100 could indicate that the BAT figures are too conservative or alternatively raise a question of data consistency and comparability across countries. Different reporting methodologies, system boundaries, problems related to CHP accounting, high recovered paper use rate and high level of integrated mills (in the case of Japan) could explain the unexpectedly high EEI of Japan and Korea.

Norway also appears very efficient in heat consumption, but this could be misleading as it produces mainly mechanical pulp and relatively small quantities of paper. Mechanical pulping uses large amounts of electricity and zero or negative net quantities of steam. During the refining process, large quantities of heat can be recovered and used for paper drying.

Canada appears to be the most energy intensive with EEI heat levels of 63 in 1990 and 70 in 2003. Although this does show a 7% improvement, it is still relatively low given the low base at which it began. Canada's comparatively low energy efficiency may be attributed to the high level of energy use in newsprint mills, which account for more than 30% of all energy used in the pulp and paper industry. Newsprint mills in Canada use between 2.52 – 12.69 GJ/t of process heat compared to 0.64 GJ/t for a modern newsprint mill (Francis, *et al.*, 2002).[6] The low process heat use for the modern newsprint mill is the result of significant amounts of waste heat recovery from mechanical pulping. The ability to reach levels of the modern mill will depend on site specifications and implies that both mechanical pulp and newsprint are being produced at the mill.

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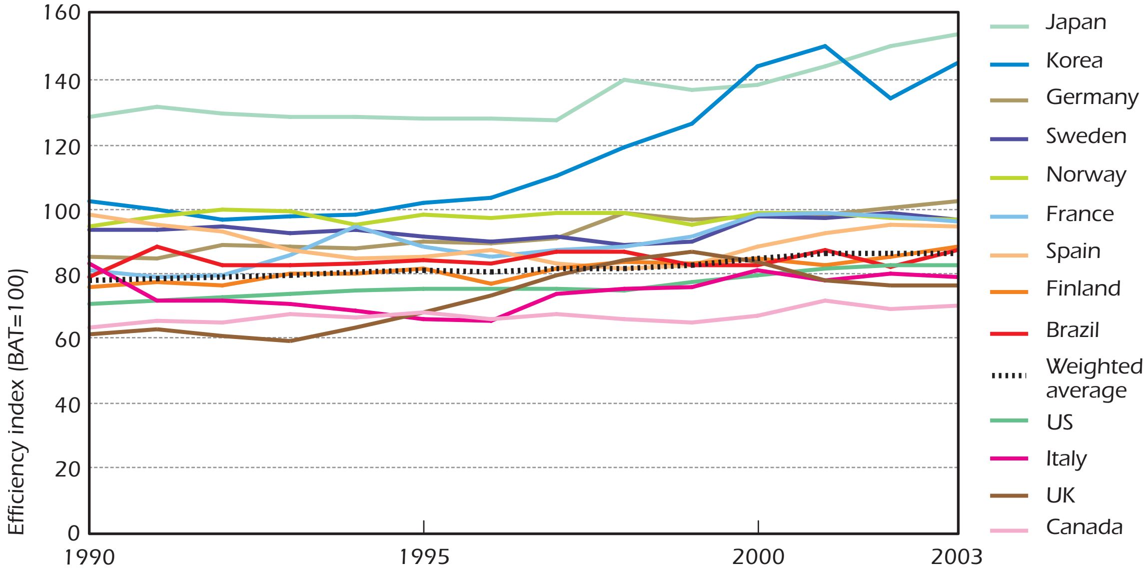
5. Heat consumption for each country was calculated based on total final fuel consumption assuming 80% efficiency. The pulp and paper sub-sector, especially in Europe, in many cases supplies heat to a district heating system or to other industrial users and may sell surplus electricity to a grid. Sale of surplus heat and electricity can cause inconsistencies in energy data as the allocation of heat and power may be subject to different methodologies within and across countries. Accounting of CHP may also lead to additional inconsistencies in data.

6. The figure of 0.64 GJ/t for the modern newsprint mill implies 4.4 GJ/t of heat recovery from mechanical pulping. http://oee.nrcan.gc.ca/publications/infosource/pub/cipec/pulp-paper-industry

Figure 7.5 ▶ *Heat Consumption in Pulp and Paper Production versus Best Available Technology, 1990 – 2003*

Key point: Efficiency of heat consumption showed real improvement from 1990 to 2003, but further improvements are possible.



Sources: United States Energy Information Agency (EIA), IEA statistics and estimates.

In the pulp and paper sub-sector as a whole, the weighted EEI heat figure for the thirteen countries analysed has risen from 77 in 1990 to 86 in 2003.[7] This shows a significant improvement in energy efficiency over this period. There remains an additional 14% improvement potential compared to energy use based on BAT. In this analysis, many countries appear to have an EEI close to or above one hundred which raises concerns about data consistency and comparability.

Energy Efficiency Index: Electricity

Figure 7.6 shows the efficiency ratios for electricity consumption. In 2003, the best EEI are seen in Germany at 98, France at 93 and Italy at 93. The relatively better performance of these countries may or may not be linked to fact that they are large paper producing countries with very little virgin pulp making facilities. More detailed data to compare energy use on a process level is required to better understand the structural impacts on energy efficiency.

Contrary to seemingly good efficiency for heat use, countries such as Sweden and Norway with high proportions of mechanical pulping appear less efficient in electricity use. Mechanical pulping is very electricity intensive. The minimum electricity demand for mechanical pulping is well below actual levels and represents an important area for efficiency improvements.

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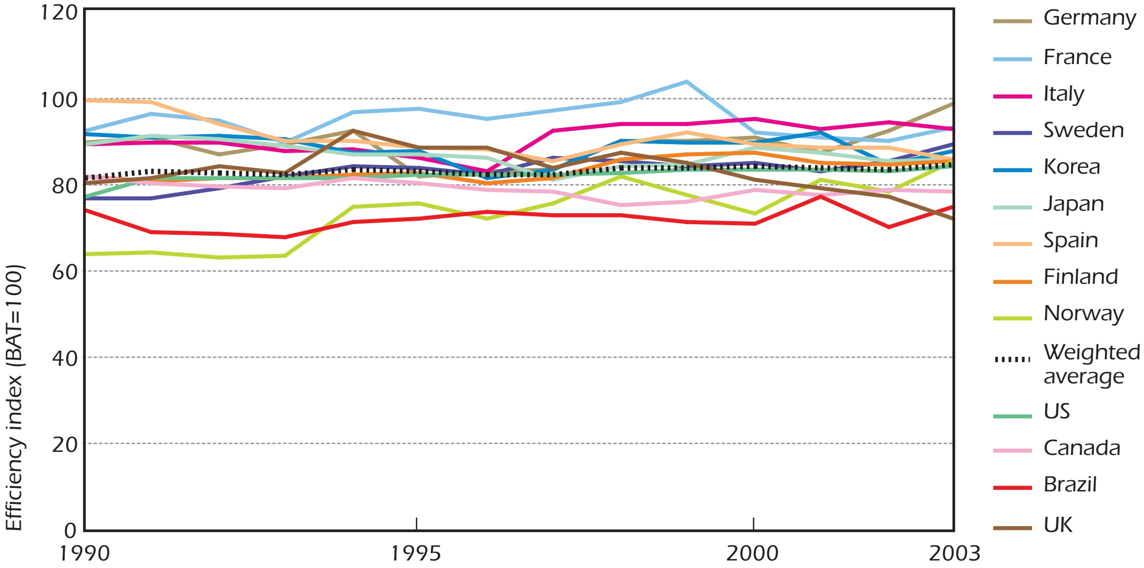
[7] The weighted average for the thirteen countries analysed is based on total share of production of pulp and paper and paperboard. Based on an assumption that a country could not have an EEI above one hundred, all figures that exceed that have been adjusted to one hundred in the calculation of the weighted average EEI.

Canada and Brazil appear to be the least efficient in terms of electricity use in the industry with EEI figures of 78 and 74 in 2003. Cheap hydroelectric power and the use of wood waste with low efficiency ratios could explain this under performance.

Figure 7.6 ▶ ***Electricity Consumption in Pulp and Paper Production versus Best Available Technology, 1990 – 2003***

Key point: Overall, there has been little improvement in the efficiency of electricity use.



Sources: EIA; IEA statistics and estimates.

In contrast to the efficiency improvement in heat consumption, there has been relatively little change in the overall energy efficiency of electricity consumption in the pulp and paper industry in these thirteen key producing countries. The weighted average for countries remained relatively flat increasing only slightly from 81 in 1990 to 84 in 2003. Only in two countries have the industries shown any significant efficiency improvement in electricity consumption with their EEI rising from 63 – 85 in Norway and 89 – 98 in Germany between 1990 and 2003.

Efficiency gains from improved technology can be offset by structural changes. For example, higher electricity demand for faster paper machines and strong growth in demand for speciality papers, which are more energy intensive, have masked improvements in electricity efficiency from process and machine advances.

There are important differences in energy use patterns in the pulp and paper industries in OECD and developing countries. Average primary energy use for paper and paperboard making in China, including pulping, is 45 GJ/t. Even higher figures are reported for India. Small-scale plants based on second-hand equipment and the use of coal for steam generation contributes to this very low energy efficiency.

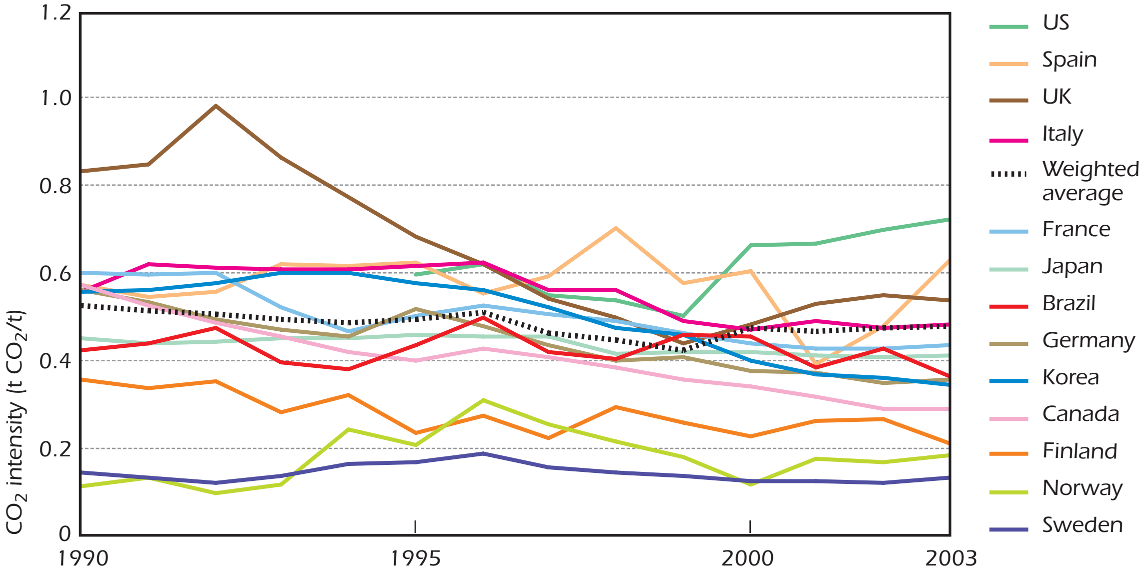
CO_2 Emissions Index

In addition to the EEI indicators, a CO_2 indicator has been developed to track differences in biomass use across countries. Figure 7.7 shows indirect CO_2 emissions per tonne of product. IEA statistics were used for CO_2 emissions and represent indirect emissions from fossil fuel combustion. Total production includes paper and paperboard, plus pulp exports.[8,9]

Sweden, Norway, Finland and Canada have the lowest emissions per tonne of product thanks to high levels of hydroelectric power and high biomass use for energy. The United States and Spain have the highest emissions per tonne due to high fossil fuel use for energy production. CO_2 emissions per tonne of product have fallen significantly since 1990 in the United Kingdom, Korea and Germany as a result of higher recycling rates. The weighted average CO_2 emission for these thirteen countries has fallen 9% from 0.52 tCO_2 per tonne to 0.47 tCO_2 per tonne.

Figure 7.7 ▶ ***CO_2 Emissions per tonne of Pulp Exported and Paper Produced, 1990 – 2003***

Key point: CO_2 emissions per tonne of pulp exported and paper produced have declined significantly.



Sources: IEA statistics; FAO.

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[8] CO_2 emissions are calculated using the default methods and emissions factors from the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. The estimates calculated by the IEA use a Tier 1 Sectoral Approach based on the IPPC Guidelines. The carbon emission factors are from IEA, *CO_2 Emissions from Fuel Combustion (2005 Edition)* pg. I.25.

[9] CO_2 figures for the United States were adjusted for inaccuracies in IEA statistics.

The CO_2 indicator does not include methane emissions from waste paper disposal in land fills, energy recovery from waste paper or CO_2 emissions from CHP electricity (which are reported under transformation in IEA statistics). An additional CO_2 indicator could be developed that took a life cycle approach to tracking CO_2 emissions in the pulp and paper industry.

Expanding Indicators Analysis in the Pulp and Paper Industry

The advantage of the proposed indicator methodology is that it is feasible based on existing energy data and allows for a country comparison of energy intensity in the pulp and paper industry. These indicators are not intended for benchmarking, which should be done on an individual mill or machine level. The lack of publicly available detailed energy production data makes process level indicators infeasible for this analysis. The disadvantage is that this analysis is not suited to identify which processes to focus on for efficiency improvements. The quality of IEA energy statistics is not clear and may be a source of uncertainty. It is recommended that countries collect more detailed energy data at the process level so that future indicators in the pulp and paper industry can be developed to compare energy intensity at the process level. It is recommended that these indicators follow the categories outlined in Table 7.8.

The level of energy data available today differs widely across countries. Canada has the most detailed and regular reporting of energy data which is broken down into energy use in pulp mills, newsprint mills, paper mills (except newsprint), paperboard mills, converted paper products industry and printing. Many other countries report only total energy use in pulp, paper and print. In order to develop more detailed process indicators, energy data needs to be collected for energy use in mechanical pulping, chemical pulping, waste paper pulp and several grades of paper and paperboard. The collection of this additional data is not an easy task and will require significant time and effort from both industry and national governments.

The United Nations Food and Agricultural Organization (FAO) provides comprehensive statistics on pulp and paper production, but categories for different paper grades do not match what is required for a more detailed indexed comparison of energy use by different paper grades. Categories used by various bodies are not always comparable. This analysis breaks down paper production by seven different paper grades, but many experts have advocated that this should be broken down even further. Paper production data from the FAO does not allow further breakdown, but such data are commercially available.

There is a need to collect better CHP data that account for fuel input, electricity and steam production, and the type of technology (back-pressure turbines or combined cycles) in the pulp and paper industry. This will result in a better assessment of remaining CHP potentials. Different CHP accounting practices further complicate the country comparison.

Additional physical and energy data should also be collected on integrated versus non-integrated mills. The use of heat recovery systems plays an important role in the energy efficiency of the pulp and paper industry. The most efficient mills are integrated mills that can benefit from extensive heat recovery systems which take advantage of waste heat produced from different processes. Stand-alone pulp mills are inherently less energy efficient as the ability to maximise the use of waste heat within the pulp mill is limited.

Combined Heat and Power in the Pulp and Paper Industry

The cogeneration of steam and heat can reduce total energy needs where the energy efficiency of stand-alone electricity production and heat production is relatively low. The greatest gains come when low-temperature heat production from fossil fuels is replaced with a CHP system.

The higher the temperature of the heat that is needed, the lower the electricity yield and the lower the efficiency gain. Typically, the introduction of CHP results in fuel savings of 10 – 20%. Data availability for CHP use in the pulp and paper industry in IEA statistics poses a challenge. Fuel use of CHP plants is allocated to power generation industry. If the heat is not sold, but used by the producer, part of the fuel use of the cogeneration plant is reported under industrial fuel use, rather than under CHP. Moreover, electricity production from CHP is not split by sector in IEA statistics. This makes it difficult to track the importance of CHP in the pulp and paper industry. Table 7.10 is an estimate of CHP use in several key pulp and paper producing countries.

Table 7.10 ▶ *CHP Use in the Pulp and Paper Industry*

Country	Estimated CHP Use %	Year
Canada	19	2003
Finland	32	2003
France	18	2003
Germany	27	2003
Italy	26	2003
Spain	61	2003
Sweden	22	2003
United Kingdom	40	2003

Note: Calculated based on the percentage of total electricity demand.
Sources: COGEN Europe, CIEEDAC, IEA statistics and estimates.

CHP plants can be designed to meet the heat or electricity requirement of mills. In most cases, when natural gas fired combined cycle systems are considered, it is designed to meet the electricity requirement with the remaining heat supplied by a low cost package boiler. With biomass or coal as fuel the CHP is usually designed to match the heat demand and additional electricity demand not met by the CHP plant is purchased from the grid. To maximise thermal efficiency; the CHP plant should be designed to meet heat demand with excess electricity sold to the grid, but still in many cases this is not the most economical option as electricity prices do not justify the additional investment cost.

A full CHP analysis is not possible at this stage due to limitations on data availability. However, the results shown in Table 7.11 do provide some insights into the impact CHP can have on energy efficiency. For this analysis, a combined energy efficiency indicator for heat and electricity is used to derive an energy efficiency index for total energy use. To calculate a CHP adjusted energy efficiency index, the total amount of CHP electricity was deducted from total energy use and then divided by the BAT energy use. This is based on the observation that electricity output matches primary energy savings benefit of CHP. All countries showed a significant improvement in their energy efficiency index once this CHP adjustment was made, which illustrates the positive impact of higher CHP deployment. The United Kingdom, Spain and Finland appear to have the highest rates of CHP use in the industry and as a result the adjusted CHP index appears to have had the largest impact on these countries.

Table 7.11 ▶ *CHP Adjusted Energy Efficiency Indicators, 2003*

	EEI *Electricity & Heat*	CHP Adjusted *EEI*	CHP Electricity *PJ/yr*
Canada	72	78	39.10
Finland	87	97	29.35
France	95	101	6.83
Germany	101	111	16.66
Italy	83	90	8.53
Japan	127	131	10.17
Spain	92	113	15.16
Sweden	94	101	17.71
United Kingdom	74	88	12.73

Sources: COGEN Europe; CIEEDAC; Japan Cogeneration Centre; IEA statistics and estimates.

Compared to other industries, the use of CHP in the pulp and paper industry is very high. In most large pulp and paper producing countries, it is estimated that CHP use accounts for between 20 – 50% of electricity generation in the industry. More than 50% of the CHP equipment used in the pulp and paper industry is likely to be black liquor Tomlinson boilers.

Falling investment costs for gas turbines over the last decade has helped to boost CHP investments in the paper industry, but high gas prices could dampen this trend. Potential for further CHP use in the industry has been limited by economies of scale which make investments in small plants less viable. The ability to sell excess power to the grid is also crucial in making CHP investments more attractive. The availability of natural gas will also have a determining factor on the up-take of CHP.

Few countries have good statistics on CHP use in industry. In order to make a more detailed analysis on CHP use in the pulp and paper industry, better data is needed. It is suggested to collect data based on the following categories:

Table 7.12 ▶ ***Data Required for CHP Analysis in the Pulp and Paper Industry***

	Fuel in *PJ*	Energy Out *PJ*	MW
Tomlinson boilers	black liquor	electricity & steam out	Installed capacity
Combined cycle (NGCC)	gas	electricity & steam out	Installed capacity
Other CHP	gas, oil, coal, biomass	electricity & steam out	Installed capacity

Source: IEA.

In addition, it is also recommended to collect detailed data on back-pressure turbines. Unlike the three categories in the table, which have higher efficiency ratings, these turbines are added on to stand-alone steam generation units. It is also suggested to collect data for MW of installed capacity in pulp and paper mills, fuel in (by fuel type) for steam generation, PJ of electricity produced and PJ of steam produced.

Paper Recycling and Recovered Paper Use

Almost half of all paper is produced from recovered paper, with recycling usually taking place close to where the waste paper is collected. Recycling plants tend to be smaller and more dispersed than primary paper production facilities and their external energy needs for papermaking are higher. On the other hand, the energy that would have gone into pulp production is saved. This savings by far exceeds the additional energy used. In many developed countries, paper recycling actually exceeds paper production from primary biomass.

Increased paper recycling is a key contributor to energy efficiency improvements in the pulp and paper sub-sector. Each ton of recycled pulp used offers a net energy savings potential of 10.9 GJ/t (CEPI, 2006). Taking into account that some paper cannot be recycled such as archives and construction materials, the maximum theoretical recycling rate for paper is 81% (CEPI, 2006). Each 1% increase in paper recycling would represent a total energy savings of 39.2 PJ. Although increased recycling does present a benefit for energy efficiency, its impact on CO_2 reductions is less clear. If the increased use of recycled pulp replaces chemical pulp from modern mills this could actually cause CO_2 emissions to increase as modern chemical pulp mills are CO_2 neutral, while recycling mills use fossil fuels.

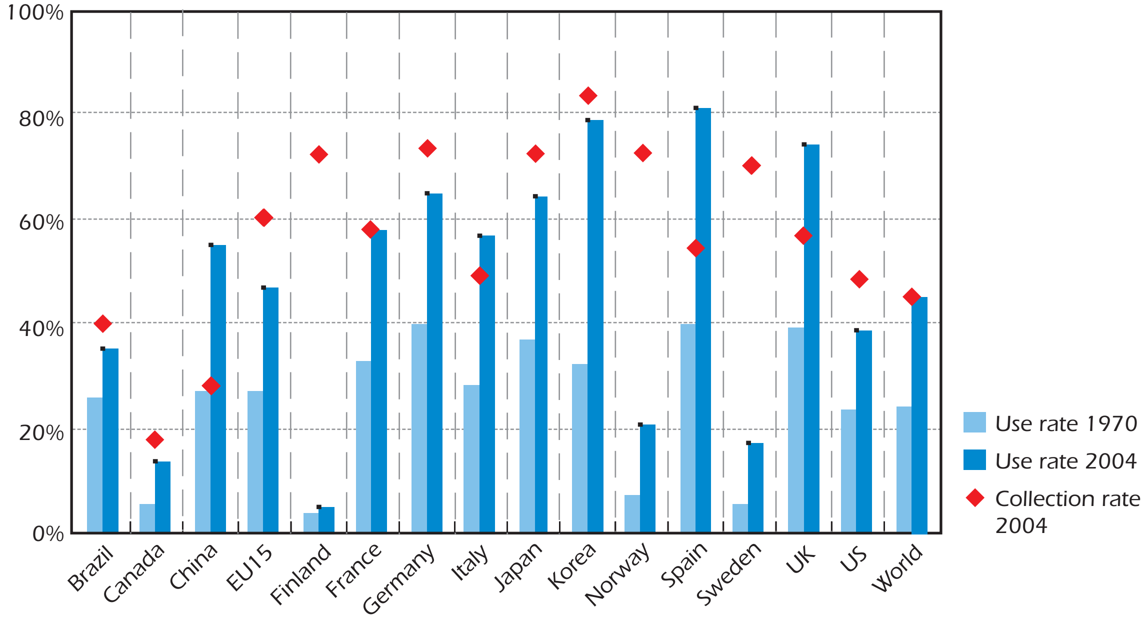
The leaders in paper recycling are Europe with a recycling rate of 52% (EU15 excluding exports) and Japan at 60%, compared to a global rate of 45% (CEPI, 2006 and METI). Theoretically, there remains a global recycling potential of 35%.

The recycling rate in Europe is defined as use of recovered paper plus exports to third countries divided by the consumption of paper. The use rate is defined as the use of recovered paper divided by total production. A European Declaration announced in 2006 aims to increase recycling rates to 66% by 2010 (ERPC, 2006). This Declaration covers the EU27 as well as Norway and Switzerland.

Although the global recovered paper rate must be equal to the global use of recovered paper rate, rates for different countries and regions are significantly different and reflect imports and exports of recovered paper. The collection rate is defined as total recovered paper collected divided by consumption. Forecasts for additional recovered paper will depend on future demand trends for paper as not all types of recovered paper can be used as recycled pulp and certain types of paper require higher percentages of virgin pulp.

Figure 7.8 ▶ ***Waste Paper Collection Rate versus Use Rate***

Key point: The use rate for recovered paper has shown tremendous growth worldwide, and in most pulp and paper producing countries since 1970.



Sources: FAO; CEPI.

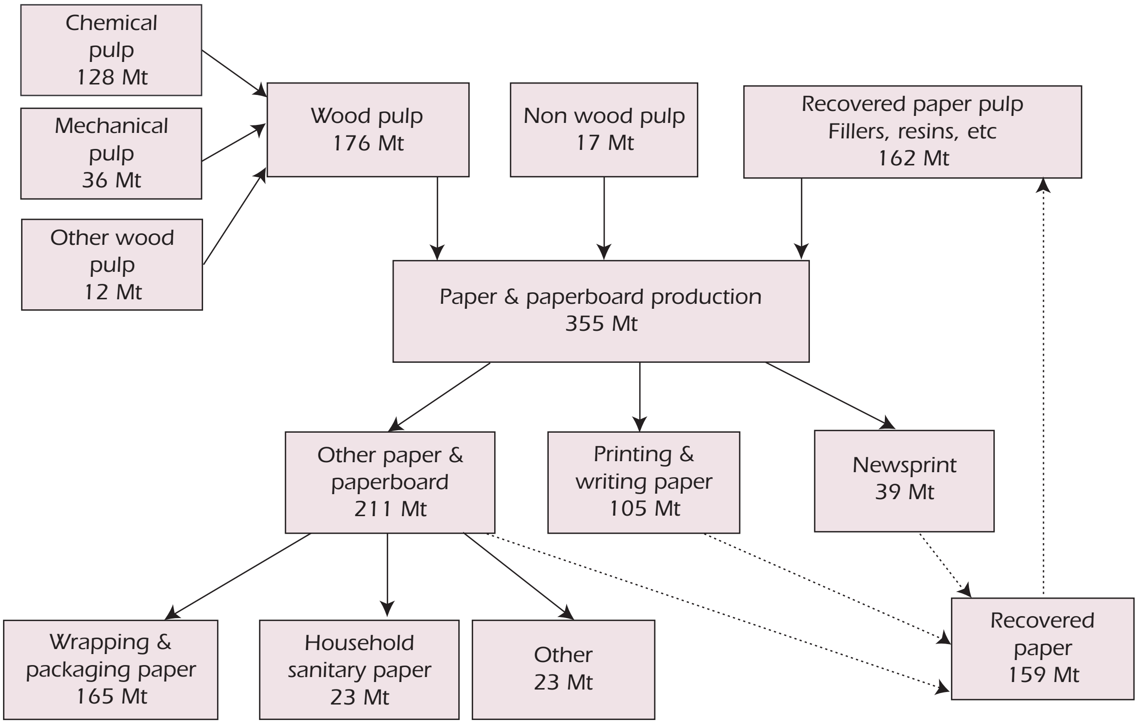
Globally the paper collection rate increased sharply from 24.3% in 1970 to 45.3% in 2004. Europe has shown the strongest increase in paper recycling; North America is the largest exporter of recovered paper; and Asia, especially China, is the main importer of recovered paper. According to the FAO, urbanisation has reduced the cost of recovered paper collection and recycling; and thereby increased the availability of recovered paper (FAO, 2005). Specific requirements from consumers on minimum recovered paper pulp content have also led to increased use rates. The types of paper produced in a country also impact the collection rate and its use rate.

Recovered paper supply is strongly influenced by government policies on waste disposal and renewable energy policies. Tighter policies on waste disposal can lead to higher recycling rates and policies promoting the use of renewable energy can cause competition for wood and fibre and thus impact the supply of wood pulp. There is concern among the industry that the current push towards increased use of renewable energy would encourage the use of wood as an energy source. As higher paper recovery rates may be exponentially more expensive to attain and depending on policies on waste disposal in each country, the global economic potential for recovered paper collection in certain countries may not be much higher than current rates.

Figure 7.9 ▶ ***World Paper Production, Processing and Recycling Balance, 2004***

(Mt/yr)

Key point: Recycling plays a key role in the global paper production balance.



Sources: FAO; CEPI.

Use of Technology to Increase Energy Efficiency and Reduce CO_2 Emissions

Technology can play an important role in increasing energy efficiency and reducing CO_2 emissions in the pulp and paper industry. Energy efficiency gains from using the latest technology differ depending on whether they are greenfield mills or retrofits.

Current pulp and paper facilities in many OECD countries are nearing the end of their operating life and will need to be replaced over the next ten to fifteen years. This presents an excellent opportunity for new technology deployment to have an impact on energy savings in the medium term. The most promising energy savings technologies in the industry are gasification, advanced drying technologies and high temperature and high pressure black-liquor recovery boilers (Worrell, *et al.*, 2001).

Energy efficiency gains can also be achieved if existing mills are retrofitted with energy efficient technology. Potential to retrofit paper machines with energy efficiency equipment is limited by the paper machine design.

There is also significant potential for additional excess heat recovery systems. The use of available excess heat in a more consistent way could lead to substantial heat savings. Use of recovered heat depends on the demand for lower grade heat. In cold areas, *e.g.* Scandinavia and Canada, heat is needed to increase the temperature of incoming streams (water, air, raw materials), especially during the winter. In warmer areas, *e.g.* Asia, South America, southern United States, there is not necessarily a use for all recovered heat. The decreased heat consumption also impacts the CHP potential and heat savings may be unprofitable if the CHP is designed for meeting the "old" heat demand.

Lignin removal offers interesting possibilities in cases where an excess of steam exits or could be achieved through process integration. It can also be used for de-bottlenecking of the recovery boiler when the pulp production in a mill is to be increased.

Integrated pulp and paper mills are usually more efficient than stand-alone mills. Integration offers synergy potential, *e.g.* excess steam produced at the pulp mill can be used in the integrated paper mill. A stand-alone pulp mills can be as efficient as an integrated mill if it can sell excess steam, electricity and/or lignin to the local community, other industrial users or the electricity grid. However, the logistics of feedstock (wood and waste paper) and product transportation can limit the potential to use integrated mills.

In many cases, big paper machines are more efficient than small machines. However, certain producers, notably in China and India, opt for small mills that allow more flexibility in the product mix, which is more suited for local market circumstances. In recent years, several very large more efficient mills have been built in China.

Differences in Energy Intensity and CO_2 Emissions across Countries

There are important differences in energy use for pulp and paper production between countries, due to a range of factors such as product mix, processes used, plant size, technology, technical age, feedstock quality, fuel prices and management attention to energy efficiency. This analysis shows that the energy intensity of *heat* use across the key countries varied from a remaining improvement potential of 30% for Canada to –54% for Japan compared to best available technology. For electricity, this remaining improvement potential varied from 2% for Germany to 28% for the United Kingdom.

Canada and the United States are among the countries with the most energy intensive pulp and paper industries in the world. The average technical age of their pulp and paper mills is perhaps the oldest. Both are rich in wood resources and are major virgin pulp producers with the United States the largest chemical pulp producer and Canada the largest mechanical pulp producer.

Canada's pulp production of 25.59 Mt in 2004 is significantly above that of its paper and paperboard production of 20.58 Mt. With a larger portion of its pulp and paper industry focused on the more energy intensive pulp market, Canada is perhaps less able to benefit from energy savings provided by integrated mills which can maximise waste heat recovery systems and hence lower energy consumption.

Unlike Canada, the pulp and paper industry in the United States is dominated more by paper and paperboard production than pulp production. Its pulp production is more than 90% chemical pulp. Chemical pulp production uses both heat and electricity and offers greater opportunity for energy efficiency than mechanical pulp, especially in an integrated mill.

European countries such as Germany, France and Italy are major paper and paperboard producers, but produce relatively little pulp. They have high paper recovery rates and use a significant amount of recovered paper as raw material for their paper production. The pulp and paper industry in these three countries showed significantly better energy efficiency indices than its North American counterparts. This may reflect very high energy prices which have led many European producers to focus on energy efficiency to remain competitive in the market. Of the three European countries, Italy showed the greatest room for improvement in heat consumption which may be due to its high market share of speciality papers which have much higher energy requirements than regular writing and printing papers.

The industry in Finland, Sweden and Norway are large producers of pulp and paper, with about equal share between pulp and paper. Finland and Sweden's pulp production is dominated by chemical pulp, while in Norway pulp production leans more towards mechanical pulping. Although no statistics are available for integrated mills, it is likely that the greater energy efficiency of the Nordic countries could be attributed to a higher degree of integrated plants together with a lower average technical age compared with Canada and the United States. The industry in the Nordic countries appear to have a better match in terms of absolute pulp and paper production which would allow for greater opportunities for integrated mills and hence higher energy efficiency. Finland appears to have the highest energy intensity in the industry of the three Nordic countries. Paper production in the Finnish industry is dominated by high grades of paper which are more energy intensive to produce. This analysis split paper production into seven products, but this may not have sufficiently reflected the energy needs of some of the high paper grades.

The pulp and paper industry in Japan and Korea appear to be the most efficient in terms of heat use with an energy efficiency index above one hundred. As this index compares energy use to best available technology it does not seem logical to have an index greater than one hundred. Possible explanations are that the BAT figures used are too low or energy data are not comparable across countries or are based on different system boundaries. Paper plants in Korea are perhaps among the most modern in the world and benefit from the lowest average technical age. In Japan, efficiency improvements are the result of a successful voluntary action plan by the pulp and paper industry. The high level of integrated pulp and paper mills (90% of all pulp produced in Japan is from integrated mills) could explain Japan's energy efficiency index above one hundred.

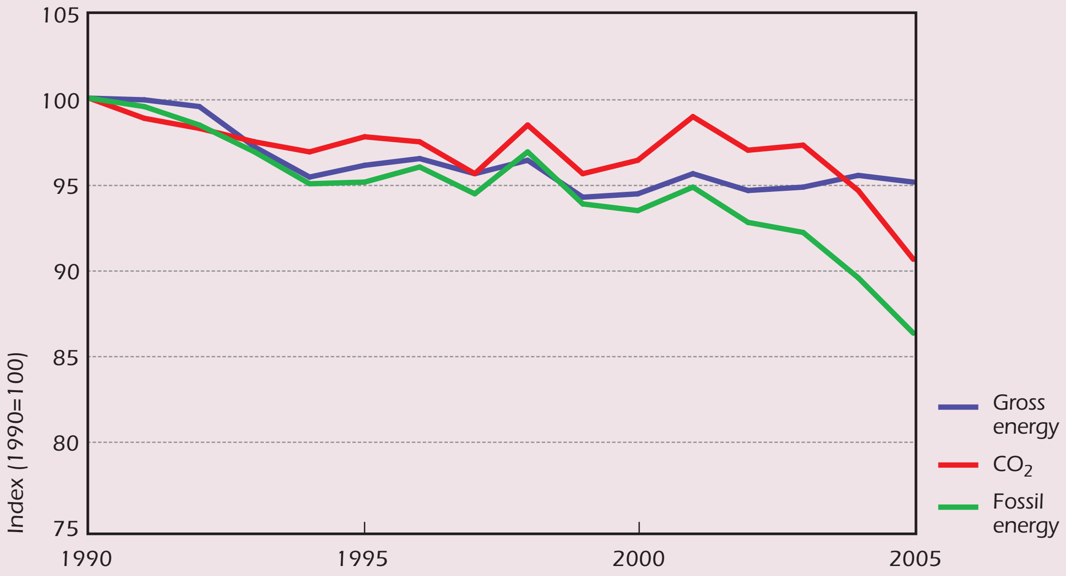
Box 7.3

Pulp and Paper Industry Voluntary Action Plan in Japan

A voluntary action plan was established by the Japanese Paper Association in 1997. At the outset its two main goals were to reduce fossil fuel consumption by 10% per unit of output from 1990 levels and expand forest plantation by 550 000 hectares by 2010. These goals were revised in 2004 and now aim to: reduce fossil fuel consumption by 13% per unit of output from 1990 levels; reduce CO_2 emissions per unit of output by 10% over 1990 levels and expand forest plantation by 600 000 hectares. The plan covers 88% of total paper and paperboard production in Japan.

Figure 7.10 shows that the target for reduced fossil fuel consumption has been met. In 2005, fossil fuel consumption per unit fell 13.5%, while the CO_2 emissions reduction in 2005 was just shy of its 10% goal at 9.2%. An important result of this voluntary action has been the introduction of biomass waste as a fuel to replace fossil fuels and hence a significant decline in both fossil energy and CO_2 emissions per tonne of paper produced. This index was produced by the Japanese Paper Association and is specific to Japan.

Figure 7.10 ▶ *Energy Consumption and CO2 Emissions Index – Japan*



Source: Hayakawa (2006), Japanese Paper Association (2006).

In Japan, the trend towards lighter paper has reduced overall energy and resource needs, but increases the energy need per tonne of product and represents a hurdle for international energy efficiency comparisons. The Japanese industry is applying a life cycle inventory method for assessment of its energy efficiency.

Energy Efficiency Potentials

Energy costs, energy supply and climate change are among the core issues impacting on the future of the pulp and paper industry. They impact on manufacturing costs, as well as allocation of investments around the globe. The increasing focus on biomass as an energy source may on the one hand increase wood prices for existing industries, but on the other hand open new markets to other parts of the forest cluster. Co-production of pulp and other biomass products may result in new business models and high overall energy efficiency.

This analysis of heat and electricity consumption versus best available technology in the main pulp and paper producing countries show that there is significant room for improvement. The market structure for the pulp and paper industry in each country may determine or limit the degree to which these energy efficiency gains can be achieved. The industries in Korea, Japan, Finland, France and Germany have achieved sizable improvements in the efficient use of energy for heat over the last decade. Canada, China, the United Kingdom and the United States seem to have the most to gain from investing in more efficient technologies and systems.

Increased paper recycling and recovered paper use in many countries could help to further reduce energy consumption in pulp and paper production. While Europe, Japan and Korea appear to be close to their practical limits for paper recycling, North America and parts of Asia could benefit from more effective policies on waste disposal to encourage higher recycling rates.

In theory, production of paper from pulp can use close to zero external energy in the case of chemical pulp integrated with paperboard production. Outdated small-scale paper plants in developing countries, notably China and India, use excessive amounts of energy. Larger plants, upgrading of older facilities to best available technology, and higher CHP use could all reduce the energy needs of pulp and paper production.

The results of the indicator analysis show a potential savings of 14% for heat and 16% for electricity if actual energy use was based on best available technology. To calculate a potential savings, these rates have been applied to the 2004 global energy use in the pulp and paper industry. To estimate potential energy savings from higher recycling rates, the current 2010 European target of 66% was applied, which represents an additional 20% in global paper recycling. An assumption could also be made for an appropriate rate of CHP use which could increase savings by an estimated 0.3 – 0.6 EJ. The total energy savings potential in the pulp and paper industry from increased process efficiency and systems/life cycle improvements is estimated to be in the range of 2.1 – 2.4 EJ. The electricity and heat savings only of 1.0 EJ per year translate into 1.3 to 1.5 EJ in primary energy terms, depending on the efficiency for power and steam generation.

Table 7.13 ▶ *Energy Savings Potential in the Pulp and Paper Industry*

	Estimated Savings *EJ/yr*
Electricity	0.3
Heat	0.7
Assuming 66% global recycling rate	0.8
CHP	0.3 – 0.6
Total	**2.1 – 2.4**

Note: Heat, electricity and recycling are expressed in final energy units. CHP refers to the energy content of the saved fuel.

Source: IEA estimates.

NON-FERROUS METALS

Key Findings

- *More than half of the energy used in non-ferrous metals is for primary aluminium production. Aluminium smelters used 1.7 EJ of electricity in 2004, about 3.5% of global electricity consumption.*
- *The electricity use for aluminium smelters is an important indicator for this sub-sector. World average electricity use for primary aluminium production is 15 268 kWh per tonne. This average has declined about 0.4% per year over the last twenty-five years. On a regional basis, the averages range from 14 337 in Africa to 15 613 kWh/t in North America. Africa is the most efficient region due to new production facilities.*
- *The regional average energy use for alumina production ranges from 10 to 12.6 GJ per tonne.*
- *With existing technology, energy use in the key steps of aluminium production can be reduced by 6 to 8% compared with current best practice. The potential energy savings are on the order of 0.3 to 0.4 EJ per year on primary energy equivalent basis.*
- *Energy use for other non-ferrous metals production depends strongly on the ore quality and the metal ore composition. Copper, chromium and manganese each account for more than 0.5 EJ primary energy per tonne of metal. This warrants further indicator analysis. However, there are no detailed statistics available regarding energy use for the production of these metals. More data should be collected and indicators should be developed for these non-ferrous metals.*

Introduction

Various kinds of non-ferrous metals are produced and used in a multitude of applications. This chapter focuses on aluminium, as it has the largest production volume and accounts for more than 50% of energy use in the non-ferrous metals sub-sector. It finds that the global potential of electricity efficiency improvements in primary aluminium production to be 15% compared with current best practice. This chapter also considers copper production in Chile as a case example and provides primary production data for a number of non-ferrous metals, but more data and analysis are needed to determine energy savings opportunities.

Global Importance and Energy Use

Table 8.1 provides an overview of the global primary production of key non-ferrous metals and an estimate of the primary energy used for their production. Primary production data on non-ferrous metals is available from a variety of sources, including governments, trade associations and specialised consulting companies. While the energy intensity of metals such as nickel, gold and silver is extremely high, global production is relatively small. However, in some countries, such metals are a key part of the economy, as well as national energy consumption.

Note that Table 8.1 presents only primary production. For some metals, *e.g.* lead, recycling (or secondary production) represents the largest share of global supply. Recycling is far less energy intensive than primary production due to the often low concentrations of the metals in the exploited ore reserves. However, data on recycled metal production is hard to obtain and energy consumption data is even more difficult to acquire.

Table 8.1 ▶ ***Estimated Energy Consumption in Primary Non-Ferrous Metals Production, 2004***

	Production *Mt/yr*	Final Energy Use *GJ/t*	Primary Energy Intensity *GJ/t*	Primary Energy Use *PJ/yr*
Aluminium	30.2	100	175	5 285
Copper	13.8		93	1 283
Chromium	17		50	850
Manganese	11		50	550
Nickel	1.4		160	224
Zinc	8.5		50	425
Tin	0.264		50	13
Lead	2.95		20	59
Gold	0.0025		52 000	130
Silver	0.020		2 900	58
Total				**8 877**

Source: IEA data.

Aluminium Production

Aluminium is the most relevant non-ferrous metal from an energy perspective. Its production can be split into primary production and recycling. Primary aluminium production is about twenty times as energy intensive as recycling. The steps for primary aluminium production consist of bauxite mining, production of alumina from bauxite, production of carbon anodes, electrolysis and rolling.

Bauxite is found in many parts of the world. Yet, more than 80% of global bauxite production is in Australia, Brazil, Guinea, Jamaica, China and India. Bauxite mining uses about 45 MJ/t of ore. Generally, the ore contains at least 40% alumina. Bauxite is processed to alumina near the bauxite mine, or shipped to alumina plants in other parts of the world.

Virtually all alumina is produced in the Bayer process, a combination of an extraction (digestion with caustic soda) and a calcination process. Most energy consumed in alumina refineries is in the form of steam used in the main refining process. The calcining (drying) of the alumina also requires large amounts of high temperature heat. Because of this high demand for steam, modern plants use combined heat and power (CHP) systems. Electricity accounts for an average of 13% and fuel for 85% of total energy use in alumina production. Fuel consumption of a Bayer plant can vary between 10 – 15 GJ/t of alumina. Average fuel consumption in Australian plants is 11 GJ/t of alumina produced. This could be reduced to 9.5 GJ/t through better heat integration and improved CHP systems (ISR Australia, 2000). The global average was 11.4 GJ/t in 2004, with a range from 10 – 12.6 GJ/t (Table 8.2). Global alumina production in 2004 was 60 Mt and consumed 0.68 EJ of energy.

Best practice electricity use in an alumina plant is about 203 kWh/t of alumina. Energy use for digesting can vary between 6.3 – 12.6 GJ/t alumina, while the fuel consumption for the calcining kiln can vary from 3.4 GJ/t for stationary kilns to 4.2 GJ/t alumina for rotary kilns (Worrell and De Beer, 1991). Compared with best practice, the potential for energy efficiency improvement in alumina production is estimated to be 15%. However, energy efficiency improvements of this magnitude are often found to be not cost effective in the short or medium term.

Table 8.2 ▶ ***Regional Average Energy Use of Metallurgical Alumina Production, 2004***

	GJ/t Alumina
Africa and South Asia	12.6
North America	10.4
Latin America	10.0
East Asia and Oceania	11.9
Europe	12.4
Weighted average	**11.4**

Note: Oceania includes Australia and New Zealand.
Source: World Aluminium, 2006.

Electrolysis is the most energy intensive step in the production of aluminium. The main producers of aluminium are located in China, North America, Latin America, Western Europe, Russia and Australia. Japan has phased-out its primary aluminium production over the last thirty years and now imports most of its aluminium from Australia. The aluminium industry is the single largest industrial consumer of electricity in Australia, accounting for about 15% of industrial consumption (Department of Industry, Science and Resources Australia, 2000). The aluminium industry is of similar importance in other countries with low-cost electricity, such as Norway, Iceland, Canada and Russia. In recent years, several new smelters have been built in Africa, which also take advantage of electricity from hydropower. Table 8.3 provides an overview of primary aluminium production.

Table 8.3 ▶ *Global Primary Aluminium Production, 2004*

	Production *Mt/yr*	Share %	Cumulative Production Share %
China	6.59	22.0	22.0
Russia	3.59	12.0	34.0
Canada	2.59	8.7	42.7
United States	2.52	8.4	51.1
Australia	1.90	6.3	57.5
Brazil	1.46	4.9	62.3
Norway	1.37	4.6	66.9
India	0.88	3.0	69.9
South Africa	0.86	2.9	72.8
Dubai	0.68	2.3	75.0
Germany	0.67	2.2	77.3
Venezuela	0.63	2.1	79.4
Mozambique	0.55	1.8	81.2
Bahrain	0.53	1.8	83.0
France	0.45	1.5	84.5
Spain	0.40	1.3	85.8
United Kingdom	0.36	1.2	87.0
Tajikistan	0.36	1.2	88.2
New Zealand	0.35	1.2	89.4
Netherlands	0.33	1.1	90.5
Other	2.86	9.5	100.0
Total	**29.91**	**100.0**	

Source: US Geological Survey, 2006a.

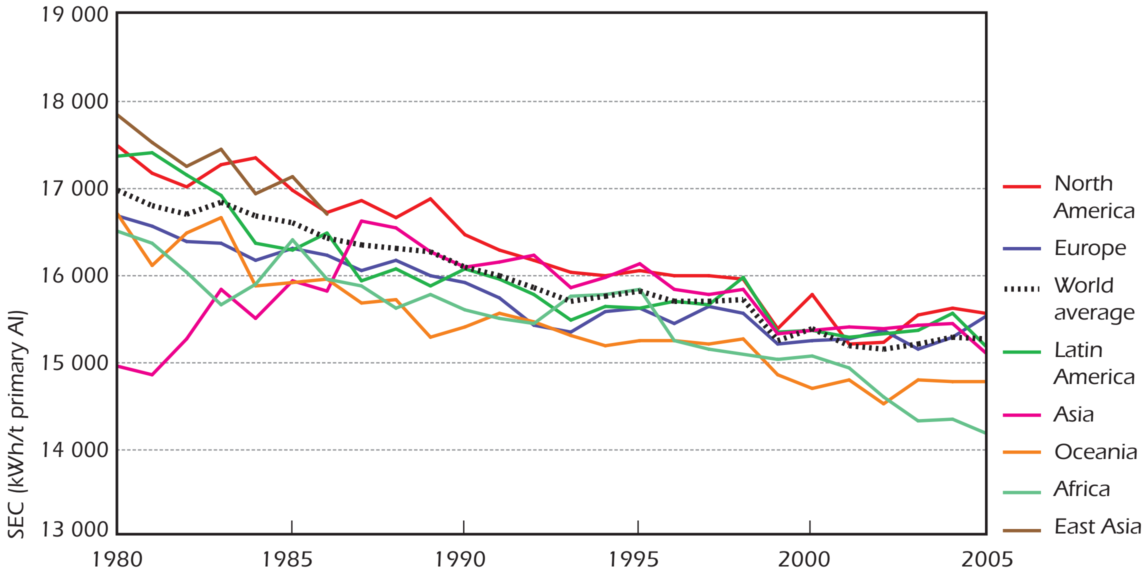
Two main types of smelters are used for the electrolysis: the Hall-Héroult system with pre-baked anodes and the older Søderberg cell with in-situ baked electrodes. The majority of global primary aluminium production uses the pre-baked anodes. It accounted for 71% of global production in 2004, with 19% from Søderberg smelters and 10% from other pre-baked cells. All new smelters use the point-fed pre-baked technology. Electricity consumption for pre-baked smelters is in the range of 13 – 16.5 kWh/kg while Søderberg smelters use about 15 – 18 kWh/kg of aluminium (European Commission, 2001).

The Hall Héroult electrolysis process is a mature technology, but improvements in its productivity and environmental performance are still possible. The difference in efficiency between the best and worst plants is approximately 20% and can be attributed to different cell types and to the size of the smelters, which is generally related to the age of the plants.

Figure 8.1 depicts the specific power consumption for primary aluminium production for various regions. It illustrates that electricity consumption has declined in most regions as new capacity is constructed and old capacity is retrofitted with new cells. This average has declined about 0.4% per year over the last twenty-five years. The range across regions is relatively narrow, compared to the differences in energy efficiency that have been observed in other manufacturing industries. Africa has the most energy efficient smelters in the world. This reflects the relatively young age of the smelters in Africa. New smelters tend to be based on the latest technology and energy efficiency is a key consideration in smelter development.

Figure 8.1 ▶ ***Regional Specific Power Consumption in Aluminium Smelting***

Key point: Africa has the most energy efficient aluminium smelters worldwide.



Note: In this graph, Europe includes EU25 plus Iceland, Norway, Switzerland, Bosnia and Herzegovina, Croatia, Romania, Russian Federation, Ukraine, Serbia and Montenegro.

Source: International Aluminium Institute, 2003.

Primary aluminium production was 30 Mt in 2004 and consumed 1.66 EJ of electricity in smelters, about 3.5% of the world's total electricity use. The global average electricity use for primary aluminium production is 15 268 kWh/t (Table 8.4).

Table 8.4 ▶ ***Regional Average Energy Use of Primary Aluminium Production, 2004***

	kWh/t Aluminium
Africa	14 337
North America	15 613
Latin America	15 551
Asia	15 427
Europe	15 275
Oceania	14 768
Weighted average	**15 268**

Note: Oceania includes Australia and New Zealand.
Source: World Aluminium, 2006.

About 18 GJ of pitch and petroleum coke (petcoke) is needed per tonne of aluminium for the production of the pre-baked anodes. The most efficient smelters consume 400 – 440 kg of anode per tonne of aluminium (European Commission, 2001). Anodes are produced by heating tar pitch or coke from refineries at high temperatures in gas-heated furnaces. Anodes can be produced on-site at the smelter or in plants that specialise in the manufacture of carbon anodes for various industries and applications. The specific energy consumption for anode production is estimated to be 2.45 GJ/t anode (fuel) and 140 kWh/t anode (electricity) (International Aluminium Institute, 2003; Worrell and De Beer, 1991).

In addition, 7.4 GJ of energy is consumed per tonne of aluminium for other uses in the smelters, *e.g.* casting, ingot holding and rolling, which accounts for 0.8 EJ of energy use. This excludes the energy used to process the aluminium to final products, which most often is done at different sites or industries.

In 2005, more than 60% of the electricity consumed by aluminium smelters worldwide was produced from hydropower plants. In addition to being a major electricity user (and hence a potential source of indirect CO$_2$ emissions from power generation), the electrolytic smelting process is also a major source of per fluorocarbons (PFCs), which are potent greenhouse gases. The PFCs are formed due to electrode effects; however, PFC emissions have been successfully reduced by improved process controls. Reductions of more than 70% have been achieved at plants in the United States and Western Europe. The international aluminium industry has pledged a global reduction of 33% of PFC emissions by 2010 from 1990 levels and a reduction in specific electricity consumption of 10% by 2010.

The lowest theoretical energy requirement for electrolysis is 6 360 kWh/t of aluminium. However, no current cell design comes close to the thermodynamic minimum. The current best practice of Hall-Héroult electrolysis cells (using currents of 300 – 315 kilo ampere) is estimated at 12.9 – 13 MWh/t of aluminium.[1] The global potential of electricity efficiency improvement with current technology is estimated to be 15%. The industry plans to retrofit or replace existing smelters in order to reduce energy consumption to 13 kWh/kg (46.8 GJ/t) in the short term and to 11 kWh/kg (39.6 GJ/t) in the longer term, which would be based on the use of inert cathodes and anodes. Over time, electrolysis process designs using aluminium chloride or carbothermic processes could become the most energy efficient way to produce primary aluminium.

Copper Production

Total copper production was 15.8 Mt in 2004, of which primary copper was 10.8 Mt, about 3 Mt was from copper nickel mattes and secondary production was about 1.9 Mt. Worldwide there are 124 smelters in operation. Production of primary copper is concentrated in these key countries: Chile, China, Japan, Russia, Poland, United States, Canada, Kazakhstan and Australia (Table 8.5).

More than half of global copper ore is produced in open cast mines. Rich copper ores have been depleted. Today mined copper ore reserves typically contain less than 1% copper, while some large deposits containing less than 0.3% are commercially mined. The ore concentration and the mine type are of key importance for the energy use in the mining step of copper production.

Most copper ores contain valuable by-products such as molybdenum, gold, silver and nickel. The molybdenum can be separated at the mine during the production of the intermediate product known as concentrate. Gold, silver and nickel follow the process and are recovered during the electrolytic refining step.

About 90% of all copper is produced from sulphidic ores and 10% from oxidic ores. This provides an advantage for the copper smelting process as there is no need for process fuel or carbon as a reduction agent. Instead, smelting and fire refining is fuelled by the energy provided by the sulphur within the ore. There is even an excess of energy which can be used to either melt secondary material (scrap) within the same process or to generate heat or power for other uses.

The Outokumpu flash smelter is the most common with approximately 50% of world production while the reverberatory smelter accounts for 25% and other types of smelters for the remaining 25%. The Outokumpu flash smelting process combines the conventional operations of roasting, smelting and partial converting into one process. Preheated oxygen-enriched air is used to provide heat in such a manner that additional fuel is not required for the reactions to proceed. Copper concentrate (matte) is recovered from the slag and recycled through the smelter. The clean slag is sent for disposal. Heat and dust are recovered from the smelter gases producing dust for recycle to the smelter. The gaseous stream containing 10 – 30% of sulphur dioxide is used for production of sulphuric acid. The matte is further treated in conventional converters to obtain blister copper (98% copper). The blister is then refined in another furnace to 99.6% purity and cast into anodes for electro-refining.

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[1] Losses of rectifiers, auxiliaries and pollution control demand an additional 0.7-1 MWh/t of primary aluminium.

Table 8.5 ▶ *Global Primary Copper Production, 2004*

	Production *Mt/yr*	Share %	Cumulative Production Share %
Chile	1.52	14.1	14.1
China	1.32	12.3	26.4
Japan	1.22	11.3	37.7
Russia	0.66	6.1	43.8
Poland	0.55	5.1	48.9
United States	0.54	5.0	53.9
Canada	0.45	4.1	58.1
Kazakhstan	0.44	4.1	62.2
Australia	0.44	4.1	66.3
Korea	0.38	3.5	69.8
Peru	0.32	3.0	72.8
Mexico	0.30	2.8	75.6
Zambia	0.28	2.6	78.2
Germany	0.28	2.6	80.7
Bulgaria	0.23	2.1	82.9
Spain	0.22	2.1	84.9
Philippines	0.22	2.0	86.9
Indonesia	0.21	2.0	88.9
Brazil	0.21	1.9	90.8
Other	0.99	9.1	100.0
Total	10.78	100.0	

Source: US Geological Survey, 2006b.

Electro-refining removes the remaining impurities in the raw metal, either from the ore or from secondary sources, to achieve the desired copper purity of 99.99%. This is independent of the number of use cycles that the metal has already gone through. Downstream metal processing steps include the fabrication of semi-finished products, such as tube, strip, sheet, rod, wire and bars.

Theoretical energy requirements for copper production are quite low. They are actually negative in the case of sulphide ores whose chemical energy release of output (blister) minus input (copper ore) is approximately 2.2 MJ/kg. However, actual specific energy consumption (SEC) is relatively high, typically 30 MJ/kg of refined copper for pyrometallurgical processes (Table 8.6). The energy use for copper production depends strongly on the ore concentration. The primary energy need for copper production is about 33 GJ/t for the smelting process at 3% copper concentration and 64 GJ/t for the leaching process with 2% ore. Primary energy use rises to 125 GJ/t for ore that contains 0.5% copper (Norgate and Rankin, 2000). The bulk of the electricity use is for crushing and grinding of the ore, while electro-refining consumes between 300 – 400 kWh/t. Declining ore grades will result in a higher energy use for primary copper production. Increased recycling can balance this to some extent.

Statistics on energy use in copper production are scarce. Table 8.6 shows the distribution of energy use over the different production steps, using the copper industry in Chile as an example. Chile is the world's largest copper producer and is responsible for 14% of global primary copper.

Table 8.6 ▶ ***Energy Use for Copper Production in Chile***

	Fuel Use *GJ/t*	**Electricity Use** *kWh/t*
Mining		
Open pit	5.68	
Underground	0.46	
Concentration		2 029
Drying	1.13	
Smelting	9.56	672
Refining		
Electro-refining	1.18	341
Electro-winning	1.08	2 791
Sulphuric acid plant		141
Services	1.05	32
Others	0.38	
Total (open pit mining)	20.06	**6 006**

Note: 1.14% copper ore grade, 30% copper content in the concentrates.
Source: Alvarado, *et al.*, 2002.

Energy use in some of the key steps has improved considerably over time in the copper industry in Chile. For example, fuel use in smelting was reduced by 32% between 1992 and 2000, while power use increased by 31% due to the introduction of new processes, *e.g.* Outukompu flash process, resulting in overall net energy savings of nearly 20%. The savings were partially offset in other production steps by changes in ore type and grades.

Energy Efficiency and CO_2 Reduction Potentials

Further improvement of energy efficiency in the non-ferrous metal industries is possible. With existing technology the energy use in key production steps of aluminium production, *i.e.* the Bayer process and the smelter, can be reduced by 15% compared with current best practice. The aluminium industry has pledged to realise 5 percentage points of this potential by 2010 (in smelting), leaving additional potential available.

In addition to further efficiency improvements, a switch to less CO_2-intensive electricity sources provides emission reduction opportunities for the non-ferrous metal industries, particularly for the aluminium industry. The share of hydropower in the electricity generation mix for the aluminium industry has gradually increased over the past decades. However, in some regions there is still a small share of hydropower in the fuel mix, *e.g.* Asia, Oceania and Africa. The share of oil and coal-fired power has slowly decreased while natural gas-fired power has increased slightly.

In the copper industry, the introduction of more efficient processes to smelt and refine the metal is a key area for efficiency improvement. For Chile, a potential exists to reduce direct CO_2 emissions by nearly 29% by switching to more efficient, virtually energy-neutral process designs (Maldanado, *et al.*, 1998). However, in the future these reductions may be partially offset as reduced ore concentrations result in increased energy needs for mining.

SYSTEMS OPTIMISATION

Key Findings

- *Industrial motor and steam systems can deliver substantial efficiency improvements on the order of up to 9 to 12 EJ of primary energy savings. Barriers to realising these potentials are largely due to a lack of awareness by industry, consultants and suppliers that could be addressed through a combination of policy and educational initiatives.*
- *Motors and boilers can have high efficiencies. Yet today, motor and steam system efficiencies are low in all countries. Based on hundreds of cases studies across many countries, it is estimated that the potential for improvement is 20 to 25% for motor systems and 10 to 15% for steam systems.*
- *In principle it would be possible to develop indicators for systems on a country level. However, currently there are insufficient data available to develop such indicators.*
- *Developing countries with emerging and expanding industrial infrastructures have a particular opportunity to apply systems optimisation best practice in new facilities.*
- *Combined heat and power (CHP) is a proven industrial energy efficiency measure and one of the more attractive greenhouse gas mitigation options for industry. Globally, CHP generates about 10% of all electricity.*
- *CHP capacity is concentrated in a few key sectors: chemicals, forest products and oil refining. Certain barriers exist to greater use of CHP, including the site-specific nature of the technology, rules governing the sale of power to electricity grids and environmental regulations. In order to increase the use of CHP issues such as grid access, interconnection regulations, buy-back tariffs and backup fees need to be adequately addressed.*
- *An agreed methodology to assess the environmental benefits of CHP is lacking. This analysis proposes two indicators: one measuring the current contribution of CHP and another to estimate CHP potential.*
- *Up to 5 EJ per year of primary energy savings potential remain for CHP in manufacturing. This equals about 3 to 4% of global industrial energy use*

Introduction

The first section of this chapter describes motor and steam systems, their energy use and the global energy savings potential from optimising these systems for energy efficiency. The second section examines the current and potential energy savings from combined heat and power (CHP) in manufacturing industry. The barriers that prevent optimal use of industrial systems and CHP are addressed. The motor and steam systems discussion points out the challenges of establishing performance indicators for motor-driven systems and steam systems. The CHP section includes an indicators analysis. Process integration is discussed in Annex A.

Industrial Systems

Industrial systems contribute to production processes, including: pumping, compressed air, and fan systems (referred to collectively as motor systems), steam systems, and process heating systems. These systems are ubiquitous in industry with applications ranging from energy-intensive petroleum refining to less intensive industries such as textiles, or seasonal such as food processing. This analysis focuses on motor and steam systems. The aggregate global savings and CO_2 reduction potential from improving the energy efficiency of process heating systems are also substantial; however, further discussion of these systems is deferred due to the high degree of variability of these systems and limited availability of data. Moreover, they have been dealt with to some extent in the sector chapters.

Industrial systems offer substantial opportunities for improved energy efficiency. Realising this potential is hindered by barriers that are primarily institutional and behavioural, rather than technical. The fundamental problem is lack of awareness of the energy efficiency opportunities by industry, consultants, and suppliers and insufficient training on how to implement them. Even if energy efficient components are applied, this is no assurance of an efficient operating system. A system-wide perspective is needed.

Industrial System Energy Use and Energy Savings Potential

Motor systems are estimated to account for 15% of global final manufacturing energy use and steam systems for 38%. Motor and steam systems globally account for approximately 46 EJ/year in energy use, representing 41% of total industrial energy use. In the United States, detailed studies have resulted in estimates that compare quite favourably, with motor system usage estimated at 12% and steam system usage estimated at 35% of primary manufacturing and mining energy use.

Motor and steam systems offer a large opportunity for energy savings, a potential that has remained largely unrealised worldwide. While the energy efficiency of individual components, such as motors (85 – 96%) and boilers (80 – 85%) can be quite high, when viewed as an entire system, their overall efficiency is quite low. Motor systems lose on average approximately 55% of their input energy before reaching the process or end-use work. For steam systems, the losses are only marginally better, with 45% of the input energy lost before the steam reaches point of use (USDOE, 2004d). Some of these losses are inherent in the energy conversion process; for example, a compressor typically loses 80% of its input energy to low grade waste heat as the incoming air is converted from atmospheric pressure to the desired system pressure (Compressed Air Challenge™, 2003). Other losses are due to system inefficiencies that can be avoided through the application of commercially available technology combined with good engineering practice. These improvements in energy efficiency of existing motor and steam systems are cost-effective, with costs typically recovered in two years or less.

On a global basis, it is estimated that the energy efficiency of motor systems can be improved by 20 – 25% using commercially available technologies and steam systems can be improved by at least 10% (more if steam lines are uninsulated), as documented by programme experiences in the United States, United Kingdom and China. This represents a global final energy savings opportunity of approximately 5.9 EJ/year.

At present, most markets and policy makers tend to focus on individual system components, such as motors or pumps, with an improvement potential of 2 – 5%, instead of optimising systems. Equipment manufacturers have steadily improved the performance of individual system components, *e.g.* motors, boilers, pumps and compressors, but these components only provide a service to the users' production process when operating as part of a system. Even when new technologies emerge at the component level, such as a. 94% efficient boiler currently under development in the United States, their significant energy efficiency advantages can be negated by a poorly configured system. Terms such as "supply side efficiency" that seek to limit the definition of system energy efficiency to the compressor room, boiler room, or pump house are misleading in the context of system optimisation. There is little benefit in producing compressed air, steam, or pumped fluids efficiently only to oversupply plant requirements by a significant margin or to waste the energized medium through leaks or restrictions in the distribution system. System energy efficiency requires attention to the whole production scheme; otherwise the result is often failure to realise a significant proportion of the energy savings potential.

Improved energy system efficiency can also contribute to an industrial facility's profitability at the same time as improving the reliability and control. Increased production through better use of equipment assets is frequently a collateral benefit. Maintenance costs may decline because better matching of equipment to demand results in less cycling of equipment operation, thus reducing wear. Optimising the efficiency of steam systems may result in excess steam capacity that can be used for CHP applications. Payback periods for system optimisation projects are typically short – from a few months to three years – and involve commercially available products and accepted engineering practices.

These opportunities are well documented. For example, a study of 41 completed industrial system energy efficiency improvement projects in the United States between 1995 and 2001 resulted in an average 22% reduction in energy use. In aggregate, these projects cost USD 16.8 million and saved USD 7.4 million and 106 million kWh, recovering the cost of implementation in slightly more than two years (Lung, *et al.*, 2003). A more recent series of three-day steam and process heating assessments conducted in 2006 at 200 industrial facilities by the United States Department of Energy (US DOE) through their Save Energy Now initiative, identified a total of USD 485 million dollars in annual energy savings and 52 TBtus (1.31 Mtoe) of annual natural gas savings, which, if implemented, would cut CO_2 emissions by 3.3 Mt. Six months after their assessments, 71 plants had reported almost USD 140 million worth of energy savings recommendations completed, underway or planned.[1]

System energy efficiency improvements can occur with little or no capital expenditure. For example, a Swedish mining company found after analysing a conveyance system that a 450 kW motor could be removed from service, saving

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[1] USDOE, http://www1.eere.energy.gov/industry/saveenergynow/

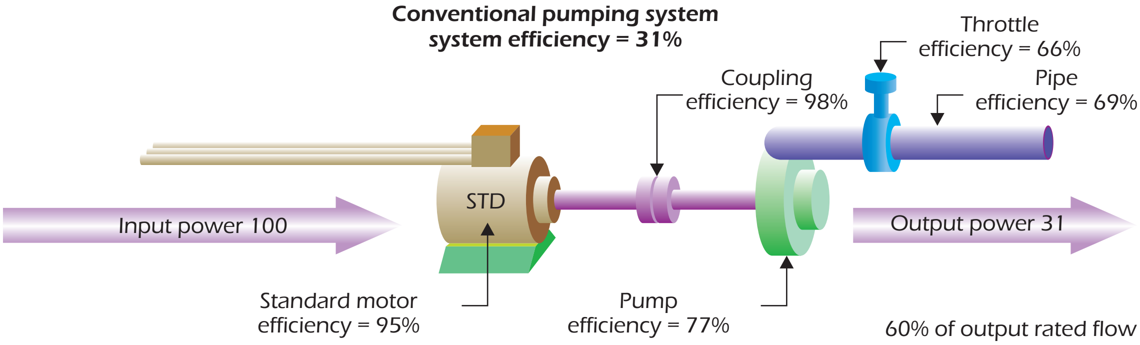
EUR 105 000 annually in energy costs. A European manufacturer trimmed the impeller on a pump, reducing the energy requirements of the pump and allowing for a smaller motor. The project recovered costs in less than four months on an investment of less than EUR 4 000.

Even modern, well maintained industrial systems can benefit from optimisation. As an example, the Canadian utility, Manitoba Hydro, offers industrial facilities system assessments through their PowerSmart programme. System optimisation projects completed and documented in 2004 reduced the energy requirements of compressed air systems at a milk plant and a garment manufacturer by more than 60%. One system was only nine years old with well maintained, energy efficient equipment.[2]

Motor Systems

Motor-driven equipment accounts for approximately 60% of manufacturing final electricity use. Motor systems are made up of a range of components centred on a motor-driven device such as a compressor, pump or fan. Figure 9.1 provides a schematic of a conventional pumping system with a system efficiency of 31%.

Figure 9.1 ▶ ***Conventional Pumping System Schematic***



Source: Almeida, *et al.*, 2005.

The performance of motor systems can be improved by optimising them to meet end-use requirements. The power consumption of the drive varies based on the cube of the motor rotation speed, while the flow varies linearly. As a result, small changes in motor speed can yield large energy savings. Proper matching of the driven load (pumps, fans, compressors) to the system demand is essential to optimising energy efficiency. This may or may not require a speed control device, depending on the variability of the load being served and the existing configuration and load response capabilities of the driven equipment.

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[2] http://www.hydro.mb.ca/power_smart_for_industry

Large savings can often be achieved by analysing and then optimising the complete motor system. Based on worldwide experience, it is estimated that industries can cost-effectively reduce the electricity use of motor systems by 20 – 25%, although the potential will vary from plant to plant. Optimising motor systems could save significant amounts of energy on a continual basis. Programme experience in the United States, Europe and China document commercially achievable system improvement opportunities of 20 – 30% (McKane, *et al.*, 2005) (Xuiying, *et al.*, 2003).

The potential efficiency improvements are well known. They include:

- Matching the scale of the motor service to the work demand.
- Providing efficient control strategies to respond to variations in load, including the ability to incrementally respond to increased loads, as well as speed control devices such as adjustable speed drives (ASDs).
- Reducing demand for energy services (*e.g.* substituting a blower for compressed air or turning off steam supplied to inactive equipment).
- High efficiency motors.
- Improved maintenance practices, with focus on filters, valves, system leaks, and equipment lubricants.
- High efficiency transmission systems.
- Reduced system losses (pipeline systems with lower friction that require less pumping energy).
- Re-design of the equipment that is driven by the motor.

Energy Efficient Motors

High efficiency motors use better quality materials, are made more precisely and are about 85 – 96% efficient, depending on size. Premium efficiency motors are the most energy efficient motors widely available today. Although the cost of a high efficiency motor is 10 – 25% more than a standard motor, motor losses decrease by 20 – 30%. Depending on the hours of operation, these additional costs can be recovered in less than three years. A motor that costs USD 2 000 may use USD 50 000 of electricity during its life span. In France in the early 1990s, for example, 88% of industrial compressors, 75% of pumps and 70% of fans ran for more than 4 000 hours per year, a rate typical for most regions (De Almeida, *et al.*, 1998). In the United States, the average operating hours for industrial motors across all sectors is approximately 5 000 hours, with motors larger than 150 kW operating 6 000 hours or more, on average (US DOE, 1998). While the distribution of motor sizes may vary across sectors and regions; it is generally true that larger motors use a high proportion of the industrial electricity while more numerous smaller motors offer greater component level opportunities for improvements in energy efficiency. New motor technologies, such superconductive motors, improved permanent magnet motors, copper rotor motors, switched reluctance drives and written pole motors offer additional energy efficiency opportunities.

When a motor fails, it is usually due to stress on the equipment, which can include overloading, voltage fluctuations, poor maintenance practices or environmental conditions. Motors are frequently repaired at failure instead of replaced, with the typical industrial motor repaired 3 – 5 times over its useful life. The quality of the repair is the most important factor in maintaining the efficiency of the repaired motor. In general, quality repairs can yield 0.5% or less reduction in energy efficiency, while poor repairs can result in an efficiency degradation of 3% or more. It is usually more cost effective to replace standard motors of 30 kW or less with more energy efficient ones rather than repair them. For larger motors, the repair/replace decision should address life cycle cost, which includes future operating costs. Replacing an operating motor with a more energy efficient one can also be cost effective under certain conditions (Nadel, *et al.*, 2002).

The most effective policy for improving the energy efficiency of motors as a component has been shown to be minimum efficiency performance standards, commonly known as MEPS. Where standards for high efficiency motors have been mandatory for some time, such as in the United States and Canada, the proportion of high efficiency motors is significant at about 70%. Where they are not mandatory, such as in the European Union, more than 90% of all industrial motors operate at or below standard efficiency (Table 9.1). Additionally, benchmarking of electric motors in Asia has shown that Australia's MEPS for electric motors has helped to protect its market from a flood of lower efficiency imported motors from Asian suppliers (Ryan, *et al.*, 2005).

Table 9.1 presents a comparison of the current status of international minimum efficiency performance standards. While further efforts are needed to harmonise international standards, it is possible to draw such a rough international comparison based on current practice.

Speed Control

Systems with varying demand loads need a method of responding effectively to maintain energy efficiency. Depending on the characteristics of the demand and the driven equipment (compressor, fan or pump), an adjustable speed drive (ASD) may be an appropriate solution. An ASD is a device that controls the rotational speed of motor driven equipment. Variable frequency drives (VFDs), the most common type of ASD, efficiently meet varying process requirements by adjusting the frequency and voltage of the power supplied to an AC motor to enable it to operate over a wide speed range.

ASDs are not the only method of controlling speed and should be applied with attention to issues such as the quality of the motor insulation, the typical loading pattern for the motor (a motor/drive combination will use about 3% more energy than a motor alone at full load and torque requirements). The savings potential for an ASD application needs to be assessed for each individual motor system. In general, savings of 10 – 20% can be achieved, but savings up to 60% are possible for specific systems if an ASD is applied as an alternative to a poor practice such as throttling.

Motor-driven Loads

The application part of the motor system offers by far the largest savings potential. After the motor and drive, energy is transmitted to the driven load. A third of all motor systems use belt-drive systems. Energy efficiency can be improved by up to 4%

Table 9.1 *Motor Efficiency Performance Standards and the Market Penetration of Energy Efficient Motors*

Efficiency Level*	Designations based on Test Method		Minimum Energy Performance Standards *(estimated in-country % market share)***	
	IEC 34 – 2	IEEE / CSA	Mandatory	Voluntary
Premium		NEMA Premium		Australia (10%) Canada, US (16%) China – 2010
High	EFF 1	EPAct, the Level, JIS C 4212	Australia – 2006 Brazil – 2009 Canada, US (54%) China – 2010 Mexico	Australia (32%) Brazil (15%) China (1%) EU (7%) India (2%) Japan (1%)
Standard	EFF 2	Standard	Australia (58%) Brazil (85% >20 after 2009) China (99%) Canada, US ~30% exempt	EU (66 non-CEMEP, 85 of CEMEP agreement members) India (48%) Japan (99%)
Below Standard	EFF 3			EU (28% non-CEMEP, 8 CEMEP) India (50%)

*Normalised, taking differences in test methods and frequencies into account.
** Based on information from standards workshop and EEMODS, September 2005.
Note: NEMA – National Electrical Manufacturers Association; CEMEP – European Committee of Manufacturers of Electrical Machines and Power Electronics; CSA – Canadian Standards Association, EPAct – Energy Policy Act; EEF – European efficiency levels; IEC – International Electrotechnical Commission; IEEE – Institute of Electrical and Electronics Engineers; JIS – Japanese Test Standard.
Source: Brunner and Niederberger, 2006.

by replacing the belts in belt-drive systems with energy efficient belts. Care must be taken to ensure that the belt-driven processes can tolerate reduced slippage.

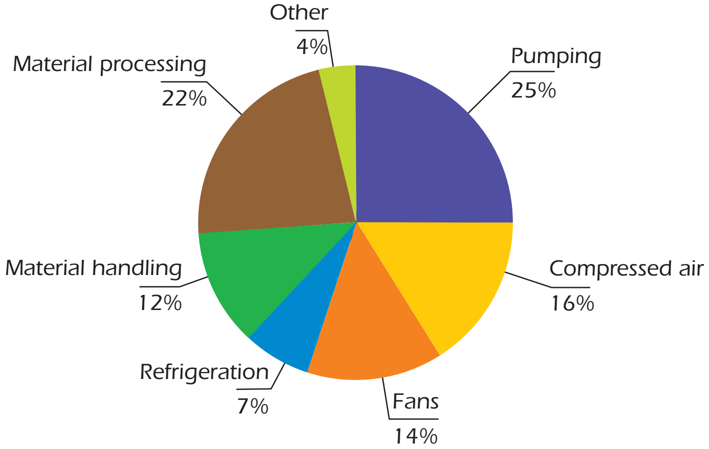
Air compressors, pumps and fans are the main energy consumers among industrial motor applications (Figure 9.2)

Pumping System Energy Efficiency Opportunities

Pumps are very important in the chemical industry, where they use 37 – 76% of motor power, but compressor consumption varies widely from 3 – 55% (Cheek, *et al.*, 1997). Pump systems, compressor systems and fans are often over-sized for the work requirements. As a consequence, the driven equipment (compressors, fans, pumps) either operates at significantly less than its peak performance efficiency or is subject to inefficient practices such as throttling, bypass or blow-off that waste the energized fluid or gas. This results in significant efficiency losses. In industrial pumping systems, the system energy efficiency can vary 10 – 70%, depending on the design and how closely the supply (amount of pumped fluid) is matched with the demand (US DOE, 2006).

Figure 9.2 ▶ *Estimated Industrial Motor Use by Application*

Key point: Air compressors, pumps and fans use more than half of the total energy consumed by motors.



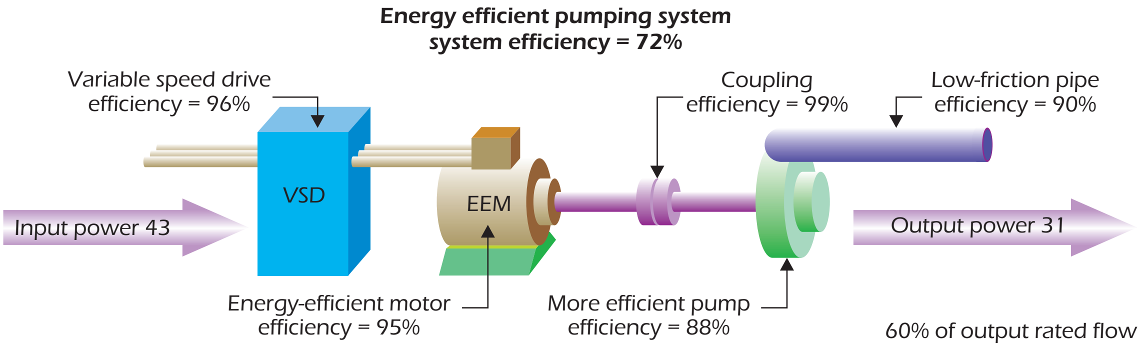
Source: USDOE, 1998.

Pumping systems are the most common of the motor systems and have a wide variety of applications in industry. Because many plants have hundreds or even thousands of pumping *systems*, the initial step in increasing energy efficiency is to determine which systems merit further attention.

- ▷ Pre-screen pumping systems to identify those with the greatest opportunity for improvement (indicators include: large size, long hours of operation, maintenance or operational issues).
- ▷ Conduct a more detailed assessment of identified pumping systems.
- ▷ Shut down unnecessary pumps; use pressure switches to control the number of pumps in service when flow rates vary.
- ▷ Restore internal equipment clearances.
- ▷ Replace or modify over-sized pumps:
  - install new properly sized pumps,
  - install a pony pump to handle lower flow requirements,
  - trim or change pump impellers to match the output to system requirements when pumping head exceeds those requirements.
- ▷ Meet variable flow rate requirements with an ASD or multiple pump arrangement instead of throttling or bypassing excess flow.
- ▷ Replace standard efficiency pump drive motors with high or premium efficiency motors.
- ▷ Fix leaks, damaged seals and packing.
- ▷ Repair or replace valves with more energy efficient designs.
- ▷ Establish a predictive maintenance program (USDOE, 2006).

Figure 9.3 depicts an energy efficient pumping system performing the same work as the system shown in Figure 9.1, but with an input power of 43 rather than 100, yielding an efficiency of 72%.

Figure 9.3 ▶ ***Energy Efficient Pumping System Schematic***



Source: Almeida, *et al.*, 2005.

Compressed Air System Energy Efficiency Opportunities

Of all motor systems, compressed air systems are typically the least energy efficient, with 80% of the input energy lost to the heat of compression (assuming no recovery of the resulting low grade heat, which is typically not done). Up to half of the remaining energy is often lost to leaks and inappropriate end uses, resulting in a net system efficiency of 10 – 15% (CAC, 2003). These systems also require the most sophisticated control schemes due to the dynamic nature of compressed air. Because the operation of these systems is often poorly understood, system designers and operators focus on reliability, disregarding energy efficiency. Ironically, this frequently results in over-sized and poorly controlled systems, unstable air pressures and excess equipment wear. Frequently, system components downstream of the compressor room are poorly maintained and further contribute to poor operating efficiencies. The use of ASDs in compressed air systems has become increasingly popular in recent years, but misapplications are common, particularly improper sizing.

The first step in optimising the operation of a compressed air system is to identify and determine the load patterns of existing compressors. Once that is completed and a baseline of energy usage established, maintenance issues (worn or clogged filters, inoperable regulators, lubricators, and drains, cracked hoses, and system leaks) should be addressed. Compressed air is energy intensive to produce and it is a piped service readily available to production processes. Misapplications are common and should be discontinued or replaced by more energy efficient options such as blowers, mechanical drivers or vacuum pumps. Once demand has been reduced, compressor controls require adjustment by a qualified professional. Failure to adjust controls often reduces energy savings, sometimes substantially (Compressed Air Challenge™, 2004).

An evaluation of the Compressed Air Challenge training for US DOE identified participants taking the energy efficiency actions listed in Table 9.2.

Table 9.2 ▶ *Percent Energy Savings Potential by Compressed Air Improvement*

Compressed Air System Improvement Option	Potential Energy Savings %
Replace current compressor with more efficient model	2
Reconfigure piping to reduce pressure loss	20
Add compressed air storage	20
Add small compressor for off-peak loads	2
Add, restore, upgrade compressor controls	30
Install or upgrade distribution control system	20
Rework or correct header piping	20
Add, upgrade or reconfigure air dryers	1
Replace or repair air filters	10
Replace or upgrade condensate drains	5
Modify or replace regulators (controls at the process)	20
Improve compressor room ventilation	1
Install or upgrade (ball) valves in distribution system	10

Note: Does not account for interactions or inappropriate use.
Source: US DOE, 2004.

Fan System Energy Efficiency Opportunities

Fan systems have similar issues with over-sizing and poor maintenance practices as pumping and compressed air systems. They include problems with the fan/motor assembly and those associated with the system itself. The build-up of contaminants on or corrosion of fan surfaces and problems with belt drives and bearings are common concerns for the fan/motor assembly. System improvements for energy efficiency include:

- Correct poor airflow conditions at fan inlets and outlets.
- Repair or replace inefficient belt drives.
- Fix leaks and damaged seals.
- Replace or modify over-sized fans.
- Meet variable flow rate requirements with an ASD, variable inlet vanes or multiple fan arrangements rather than with dampers.
- Replace standard efficiency fan drive motors with high or premium efficiency motors, and
- Establish a predictive maintenance programme (US DOE, 2003).

Motor System Opportunities

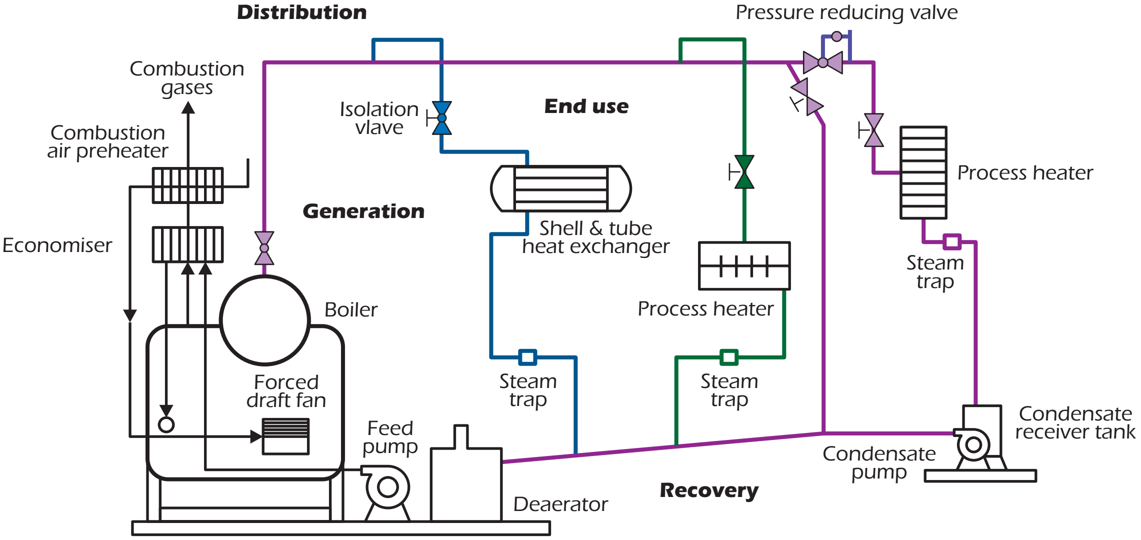
Optimisation of motor systems to save energy has received only limited attention. In countries where government programmes on energy efficient motors have been in place, *e.g.* Canada and the United States, the prevalence of energy efficient motors has substantially increased, but the potential increase in motor system efficiency remains largely unrealised due to the lack of national standards and policies that encourage companies to integrate energy efficiency into their management practices. The US programme has been partially successful in building awareness through voluntary approaches such as training, case studies, publications and technical assistance, but these are time intensive, plant-by-plant efforts that fall far short of the total savings potential (McKane, *et al.*, 2005). Given the 5 – 10% savings potential on total electricity use, a much more comprehensive approach is warranted.

The energy efficiency of motor-driven equipment, such as pumps, fans and compressors, can be improved through variable speed controls capability, use of premium lubricants, system design optimisation, and improved management practices such as engineering for energy efficiency, proper sizing and operational best practices. Improvements can also be made to the controls on existing systems, for example, for compressed air systems by combining pressure/flow controllers, dedicated storage and master controls. Sensor-based controls and advanced adjustable speed drives with improvements like regenerative braking, active power factor correction and better torque/speed control can contribute to greater overall efficiency.

Steam Systems

Steam is used extensively as a means of delivering energy to industrial processes (Figure 9.4). Steam holds a significant amount of energy on a unit mass basis that can be extracted as mechanical work through a turbine or as heat for process use. This latent heat can be transferred efficiently at a constant temperature, an

Figure 9.4 ▶ ***Steam System Schematic***



Source: US DOE, 2002.

attractive quality for process heating applications. Steam is also used to control temperatures and pressures during chemical processes, strip contaminants from process fluids, dry paper products and as a source of hydrogen for steam methane reforming in chemical and petroleum refining applications.

Steam can either be generated on-site at an industrial facility or purchased from a supplier. The share of purchased steam varies widely, *e.g.* in the United States from 2% or less for pulp and paper to nearly 25% for inorganic pigments. Similarly, the total use of steam in industry also varies widely, with the top five industries in the United States by steam use given in Table 9.3.

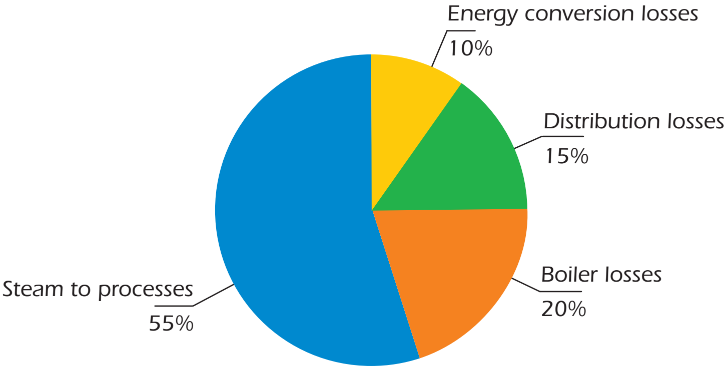
Table 9.3 ▶ ***Percentage Steam Use by Sector – Top Five US Steam-Using Industrial Sectors***

		Total Energy %
1	Forest products	84
2	Chemicals	47
3	Petroleum refining	51
4	Food and beverage	52
5	Textiles	29

Sources: US DOE, 2004d.

The efficiency of steam boilers varies with design and fuel type. A well designed boiler fired by coal is typically about 84% efficient, but a boiler fired with spent liquor will have an efficiency of approximately 65% (Giraldo, et al., 1995). Average boiler efficiency in China is approximately 65%. The boiler is only one part of an industrial steam supply system; distribution losses from can be quite important as well. While there are no detailed statistics regarding global system efficiencies, the estimated overall system efficiency in the United States is 55% (Figure 9.5).

Figure 9.5 ▶ ***Steam System Use and Losses***



Source: US DOE, 2004d.

The best option for improving the energy efficiency of a steam system is through a combined heat and power system (CHP). The efficiency of a steam system can also be increased through the application of best practices or by replacing the steam boiler with a heat pump in case low temperature heat is needed. Higher efficiency boilers currently under development offer the promise of higher efficiencies. Sometimes other processes can be used in lieu of steam to perform the same work, for example, in recent decades the chemical industry has successfully developed new catalysts and process routes that reduce the need for steam. The application of steam system best practices provides a very cost effective near-term path to improved energy efficiency regardless of site configuration, including either avoiding excess production of steam or finding alternative uses for it, such as onsite electricity generation. Steam demand may decline considerably over time as new, more efficient, process equipment is introduced. As a consequence, the boiler capacity may exceed the plant needs, usually in low efficiencies.

The relevance of each measure depends on the specifics of a particular steam system. Table 9.4 indicates the savings potentials for steam systems only and do not include any possible measures related to reducing steam demand.

Experience with well managed industrial facilities in OECD countries indicates that there is an energy efficiency improvement opportunity on the order of 10%. This potential is related to lack of adjustment of steam system supply to demand as production needs

Table 9.4 ► ***Steam System Efficiency Improvements***

	Typical Savings %	Typical Investment *USD/GJ Steam/yr*	Use in OECD Countries %	Use in Non-OECD Countries %
Steam traps	5	1	50	25
Insulation pipelines	5	1	75	25
Feed-water economisers	5	10	75	50
Reduced excess air	2	5	100	50
Heat transfer	–	–	75	50
Return condensate	10	10	75	50
Improved blow down	2 – 5	20	25	10
Vapour recompression	0 – 20	30	10	0
Flash condensate	0 – 10	10	50	25
Vent condenser	1 – 5	40	25	10
Minimise short cycling	0 – 5	20	75	50
Insulate valves & fittings	1 – 3	5	50	25

Source: IEA, 2006.

change over time and inadequate attention to routine maintenance of steam traps, valves and heat transfer surfaces. In many developing countries, the losses from steam supply systems are substantial. For example, pipeline insulation is often non-existent in Russia. In China, many small-scale boilers operate with considerable excess air and incomplete combustion of coal. In countries with a high reliance on poor quality coal, this can be a major contributor to poor steam system efficiency. Poor coal quality is the main cause for the low efficiency of Chinese boilers (Box 9.1).

Box 9.1

Coal-fired Boilers in China

There were 526 300 industrial boilers in China in 2001. The vast majority (90%) of the capacity burn coal as fuel, which use 400 Mt of coal per year. Of the newly installed boilers in 1999, 79% were coal-fired, 16% oil and gas-fired (Energy Foundation).

Some 47% of industrial boilers are 4 t/h or smaller in size, with approximately 16% at 6 t/h, 22% at 10 t/h, and the remainder 20 t/h or larger (Zhehang, 2006). The mix of boilers from greater to lowest frequency includes: chain boilers – 60%; reciprocating – 21%; stock – 14%; fluid bed – 4%; and other – 1%. Actual tests of boiler efficiency seem to support an average boiler efficiency of 60 – 65%.

Overall demand for steam in China is about 5.7 EJ per year. The boilers fall into three groups, those with:

- average efficiency of 59%, which account for 47% of the boilers;
- average efficiency of 65 – 70%, which account for 28%;
- average efficiency more than 70%, which account for 25%.

Boiler efficiency in China is lower than the 80% efficiency level common in western countries for a number of reasons:

- Use of low quality coal in certain regions, e.g. boilers in Shanxi, have an efficiency 4 – 5% below the national average because of low quality coal use.
- High excess-air.
- High coal content in the slag (27.4%) and fly-ash (49.7%) as the result of using untreated coal.

Reducing the fraction of coal fines from 50 – 28% by coal washing would increase efficiency by 14%. However, this is not feasible in the short term. It is considered feasible to increase average efficiency from below 65% to between 70 – 73% by improved boiler operation practices. The cost would be USD 3 000 per boiler, or USD 0.25 – 0.35 per GJ saved. Increasing the efficiency from 73 – 80% would require re-building the boilers.

Chinese efficiency standards set in 1999 differentiate boilers by coal quality and boiler capacity. The minimum efficiency ranges from 55 – 63% (for a capacity of less than 0.5 t/h) to 72 – 79% for boilers with a capacity of more than 20 t/h (Xiuying, 2002). A project under the framework of the Global Environment Facility to work with Chinese boiler manufacturers to improve efficiency has been funded at USD 100 million, but has had mixed results. The new boilers achieve 80 – 85% efficiency under test conditions, but the efficiencies are much lower under normal conditions. Coal quality remains a critical issue. Private sector involvement, the removal of market barriers, transfer of knowledge and local participation are vital to success to improve boiler efficiency in China (Philibert and Podkanski, 2005).

Barriers to Industrial System Energy Efficiency

There are several factors that contribute to a widespread global failure to recognise and realise the energy efficiency potential of optimising motor and steam systems. These include the complexity of the systems and the institutional structures within which they operate. These systems are ubiquitous in manufacturing, but their applications are highly varied. They are supporting systems, so facility engineers are usually responsible for their operation, but production practices on the plant floor (over which the facility engineer may have little influence) can have a significant impact on their operational efficiency. Operational budgets are typically segregated from capital budgets in industrial organisations, so that energy use, typically the single largest element of system equipment life cycle cost, does not influence purchase. Without energy efficient procurement practices, lowest cost purchase of elements in the distribution system such as tool quick-connects and steam or condensate drain traps can result in on-going energy losses that could be avoided with a small premium at initial purchase. Without well documented maintenance procedures, the energy efficiency advantages of high efficiency components can be negated by clogged filters, failed traps and malfunctioning valves.

System optimisation cannot be achieved through simplistic "one size fits all" approaches. Unlike equipment components (motors and drives, compressors, pumps, boilers), which can be seen, touched and rated, optimisation of systems requires engineering and measurement. Further, since matching supply with demand is a critical element of optimisation, production changes over time can degrade the energy efficiency of a system if procedures are not in place to adapt to the changes. The presence of energy efficient components, while important, provides no assurance that an industrial system will be energy efficient. Misapplication of energy efficient equipment, such as variable speed drives, in these systems is common. System optimisation requires taking a step back to determine what work needs to be performed. Only when these objectives have been identified can analysis be conducted to determine how best to achieve them in the most energy efficient and cost effective manner (Williams, *et al.*, 2006).

Effective Policies and Programmes

The challenge of industrial system optimisation is that it requires a new way of looking at systems and corresponding changes in the behaviour of those that supply and manage them. Industrial energy efficiency policy and programmes should aim to change traditional operational practices and to integrate best practices into the institutional culture of industrial companies. Effective policies to promote industrial system optimisation include energy management standards and related training, system assessment protocols, capacity building of system experts through specialised training initiatives, training to raise awareness of plant engineers and managers, tools for assessment and documentation of system energy efficiency, case studies and technical materials.

Experience in Canada, Germany, the United Kingdom and United States has shown that the involvement of equipment suppliers in programmes to promote greater industrial system energy efficiency can be a highly effective strategy. Industrial facilities typically develop very close relationships with their supply chain. Suppliers can have an important role in introducing system optimisation concepts through their interactions with customers. Conversely, if suppliers do not identify any benefit or value from an industrial energy efficiency programme or policy, they can have a significant negative impact (McKane, 2007).

Energy service companies (ESCOs) have experienced limited success in industrial markets worldwide. With a few exceptions, such as industrial purchased steam or CHP, ESCOs have had little impact on the development of energy efficiency projects that involve industrial systems. There are many reasons for this, including the high cost of opportunity identification, limited replicability site-to-site and lack of expertise in specific industries (Elliott, 2002). ESCOs typically enter industrial markets with experience from the commercial sector and tend to concentrate on measures such as lighting and heating, ventilating and air conditioning that are found in commercial buildings, which miss most of the energy savings at industrial sites. In recent years, suppliers of industrial system equipment have begun providing value-added services that may include everything from a broader range of product offerings to complete management of the industrial system as an outsourced provider. Their success appears to be attributable to their specialised level of systems skill and familiarity with their industrial customers' plant operations and needs (Elliott, 2002).

Programmes to promote energy efficient industrial systems can be highly cost effective. In 2004, the US DOE, through educational policies promoting system optimisation (Best Practices), generated energy savings of 21.4 PJ equal to about USD 112 million/yr. These savings resulted from a programme investment of USD 8.1 million, which yielded about USD 14 in benefits annually for each programme dollar spent that year, during a period of relatively low energy prices. Cumulative programme energy savings from 1995 – 2004, with the last few years including both motor and steam systems, are 0.7 EJ per year and USD 1.4 billion in annual energy cost savings (US DOE, 2005).

The Canadian Industry Program for Energy Conservation (CIPEC) provides technical assistance to assist manufacturing and mining companies to attain an energy efficiency improvement target of 1% per year. [3]

An estimated investment for an extensive motor system programme in the European Union is about USD 500 million, with projected annual savings of USD 10 billion (Keulenaer, et al., 2004). A program in Germany, Druckluft Effizient, identified average savings opportunities of 20 – 30% from a sample of more than 100 compressed air assessments, depending on system size (Radgen, 2003). The European Commission offers technical assistance to companies seeking to improve the energy efficiency of their electric motor driven systems (Motor Challenge Programme).

China has begun offering technical support to improve energy efficiency at its 1 000 most energy-intensive plants as part a national effort to reduce energy consumption per unit of GDP by 20% by 2010.

A pilot programme conducted by the United Nations Industrial Development Organization trained twenty-two engineers in system optimisation techniques. Within two years after completing training, these experts conducted 38 industrial plant assessments and identified nearly 40 million kWh in energy savings (Williams, *et al*., 2005).

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3. http://cetc-varennes.nrcan.gc.ca

Box 9.2

Indicators of System Energy Efficiency

Measuring the energy efficiency of motors as a component is reasonably straightforward and well documented. Although differences in the treatment of some losses in the measurement process still exist, these differences are relatively small and have narrowed in recent years as measurement techniques have begun to become more standardised. The same is not true in the measurement of motor system energy efficiency, where most of the energy efficiency potential exists. Few industrial facilities can quantify the energy efficiency of motor systems without the assistance of a systems expert. Even system experts can fail to identify large savings potentials if variations in loading patterns are not adequately considered in the assessment measurement plan. If permanently installed instrumentation such as flow meters and pressure gauges are present, they are often non-functioning or inaccurate. It is not uncommon to find orifice plates or other devices designed to measure flow actually restricting flow as they age.

Measuring the combustion efficiency of boilers is well defined, although the efficacy of testing techniques, especially for existing boilers, can vary substantially. Measuring steam system energy efficiency has many of the same problems described for motor system efficiency. In addition, steam system efficiency must take into consideration the mix of purchased steam and steam generated on-site.

For indicators of system energy efficiency, reasonably reliable proxies are available. These proxies include a set of “best practices” that have proven to be fairly accurate indicators of the relative energy efficiency of these systems. A body of literature, primarily from Canada, the United Kingdom and United States has been developed in the past fifteen years to identify these best practices. The US DOE has established “energy scorecards” as a method for industrial facilities to roughly estimate their system energy efficiency improvement potential and is working on standardised system assessment protocols that will provide a finer grain of accuracy to these estimates. China has published a voluntary standard *Economical Operation of Fan (Pump, Compressed Air) Systems GB/T 13466 – 2006* based on best practice principles.

Best practices that contribute to optimisation are system specific, but generally include:

- ▷ Evaluating work requirements and matching system supply.
- ▷ Eliminating or reconfiguring inefficient uses and practices (throttling, open blowing).
- ▷ Changing or supplementing existing equipment (motors, fans, pumps, boilers, compressors) to better match work requirements and increase operating efficiency.
- ▷ Applying sophisticated control strategies and speed control devices that allow greater flexibility to match supply with demand.
- ▷ Identifying and correcting maintenance problems.
- ▷ Upgrading on-going maintenance practices and documenting these practices.

The presence of an overall energy management plan at a facility or corporate level based on continuous improvement principles provides an excellent platform for system optimisation to occur and is a strong indicator energy efficient performance. Yet, the presence of an energy management plan is no guarantee that every system in a facility will be energy efficient. To accomplish this, the plan must be combined with awareness of system opportunities, which can be achieved through training and technical assistance. An effective plan should include specific system performance improvement goals based on incremental implementation of recommendations identified in system assessments.

Performance Indicators

Data on global motor and steam system energy use and energy savings opportunities is based on detailed studies conducted in the United States, some data from the EU and China, and expert opinion applied to existing information on global industrial energy consumption. Table 9.5 provides an estimate of motor system energy savings.

Table 9.5 ▶ ***Motor System Energy Savings Potential***

(Final Energy in EJ/yr)

Country	Manufacturing Electricity Use *EJ/yr*	Motor System Electricity Use *EJ/yr*[1]	Motor Systems Savings Potential *EJ/yr*[2]
Argentina	0.15	0.09	0.02
Australia	0.32	0.19	0.04
Brazil	0.62	0.37	0.07
Canada	0.73	0.44	0.09
China	4.16	2.50	0.50
Chinese Taipei	0.38	0.23	0.05
France	0.48	0.29	0.06
Germany	0.84	0.50	0.10
India	0.71	0.43	0.09
Iran	0.16	0.10	0.02
Italy	0.52	0.31	0.06
Japan	1.42	0.85	0.17
Korea	0.64	0.38	0.08
Mexico	0.37	0.22	0.04
Netherlands	0.15	0.09	0.02
Norway	0.18	0.11	0.02
Poland	0.15	0.09	0.02
Russia	1.20	0.72	0.14
Spain	0.37	022	0.04
South Africa	0.40	0.24	0.05
Sweden	0.21	0.13	0.03
Thailand	0.19	0.11	0.02
Turkey	0.21	0.13	0.03
Ukraine	0.24	0.14	0.03
United Kingdom	0.42	0.25	0.05
World	**21.48**	**12.89**	**2.58**

Note: This is an estimate depicting magnitudes of use and opportunity and is not suited for target setting.

[1] Estimated at 60% of manufacturing electricity use.

[2] Estimated at 20% energy savings fraction.

Sources: LBNL 2006; IEA data.

Table 9.6 ▶ *Steam System Energy Savings Potential*

(Final Energy in EJ/yr)

Country	Manufacturing Fossil Electricity Use *EJ/yr*	Steam System Energy Use *EJ/yr*[1]	Steam Systems Savings Potential *EJ/yr*[2]
Argentina	0.50	0.18	0.02
Australia	0.96	0.34	0.03
Brazil	2.85	1.14	0.11
Canada	2.35	0.94	0.09
China	17.94	7.18	0.72
Chinese Taipei	0.93	0.37	0.04
France	1.55	0.62	0.06
Germany	2.22	0.84	0.09
India	4.00	1.60	0.16
Iran	1.08	0.43	0.04
Italy	1.64	0.66	0.07
Japan	4.29	1.72	0.17
Korea	1.59	0.56	0.06
Mexico	1.14	0.46	0.05
Netherlands	0.56	0.20	0.02
Norway	0.28	0.10	0.01
Poland	0.70	0.25	0.02
Russia	5.32	2.13	0.21
Spain	1.24	0.43	0.04
South Africa	0.99	0.40	0.04
Sweden	0.53	0.19	0.02
Thailand	0.90	0.32	0.03
Turkey	0.84	0.34	0.03
Ukraine	1.40	0.49	0.05
United Kingdom	1.37	0.48	0.05
United States	12.57	5.03	0.50
OECD	36.80	13.98	1.40
Non-OECD	49.38	18.76	1.88
World	**86.18**	**32.75**	**3.27**

Note: This is an estimate depicting magnitudes of use and opportunity and is not suited for target setting. Figures are in final energy units.

[1] Steam system use is highly varied among industrial sectors. For countries with steam-intensive industries (forest products, chemicals, petroleum refining, food and tobacco, textiles, transport equipment, iron and steel), the steam system use is calculated at 40% of manufacturing energy use, while for other countries the use is calculated at 35%. This is a conservative estimate.

[2] Estimated at 10% energy savings fraction.

Source: IEA data.

Accurate estimates for steam systems are further complicated by the use of purchased steam, which effectively transfers about two-thirds of the overall system losses to an off-site steam generation facility. Industrial facilities that purchase steam continue to have opportunities to improve steam system energy efficiency, but they are limited to the distribution system. Since many countries that rely heavily on purchased steam for industrial use also have greater than average distribution losses due to lack of insulation and leakage, the estimate provided conservatively assumes a potential 10% system improvement opportunity.

Improving Available Data

A better data set for system energy consumption should be developed. A series of "Energy Footprints" developed for US DOE may provide a good starting point to elicit expert opinion (US DOE, 2004b). The resulting data could then be enhanced at the national or regional level by information such as the percentage of purchased steam and the prevalence of "efficiency indicators" such as the sale of VSDs, controls and other energy efficient components. The involvement of industrial equipment manufacturers, many of whom have global operations, as well as universities and government and non-governmental organisations would yield a more accurate result.

An opportunity exists to ensure that industrial facilities, particularly in rapidly growing economies, have system energy efficiency designed in from the start, rather than requiring more costly retrofit actions. Current design practices offer no assurance of energy efficiency for systems in new industrial facilities. Absent effective intervention, this new industrial infrastructure will be substantially less energy efficient than it need be, a situation that will persist for years to come.

Combined Heat and Power

Combined heat and power (CHP), also known as cogeneration, has been used for more than a century at industrial and municipal sites around the world. It was the foundation of the early electric power industry in some countries. CHP is used in industries that have high and relatively constant steam and electric demand, as well as access to by-product or waste fuels.

CHP is the sequential or simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system. CHP systems consist of a number of individual components – prime mover (heat engine), generator, heat recovery and electrical interconnection. The type of equipment that drives the overall system typically identifies the CHP system. Prime movers for industrial CHP systems include steam turbines, gas turbines, combined-cycle systems and reciprocating engines, as well as micro turbines and fuel cells for smaller systems. These prime movers are capable of burning a variety of fuels including natural gas, coal, oil and biomass or waste fuels to produce shaft power or mechanical energy. Although mechanical energy from the prime mover is most often used to drive a generator to produce electricity, it can also be used to drive rotating equipment such as compressors. Thermal energy from the system can be used in direct process applications, *e.g.* process heating, drying, or indirectly to produce steam, hot water, hot air for drying or chilled water for process cooling.

CHP micro-turbines and fuel cells offer promise for small-scale industrial applications that have not previously used CHP. For traditional CHP using sectors, research is contributing to increased efficiencies and new applications. Table 9.7 provides a summary of the key cost and performance characteristics of the leading CHP technologies.

Table 9.7 ▶ ***Summary of CHP Technologies***

CHP System	Advantages	Disadvantages	Available Sizes
Gas turbine	High reliability. Low emissions. High grade heat available. No cooling required.	Require high pressure gas or in-house gas compressor. Poor efficiency at low loading. Output falls as ambient temperature rises.	500 kW to 40 MW
Micro turbine	Small number of moving parts. Compact size and light weight. Low emissions. No cooling required.	High costs. Relatively low mechanical efficiency. Limited to lower temperature CHP applications.	30 kW to 350 kW
Spark ignition (SI) reciprocating engine	High power efficiency with part-load operational flexibility. Fast start-up. Relatively low investment cost. Can be used in island mode and have good load following capability. Can be overhauled on-site with normal operators. Operate on low-pressure gas.	High maintenance costs. Limited to lower temperature CHP applications. Relatively high air emissions. Must be cooled even if recovered heat is not used. High levels of low frequency noise.	< 5 MW
Diesel/compression ignition (CI) reciprocating engine			High speed (1 200 RPM) ≤ 4 MW Low speed (60 to 275 RPM) ≤ 65 MW
Steam turbine	High overall efficiency. Any type of fuel may be used. Ability to meet more than one site heat grade requirement. Long working life and high reliability. Power to heat ratio can be varied.	Slow start up. Low power to heat ratio.	50 kW to 250 MW
Fuel cells	Low emissions and low noise. High efficiency over load range. Modular design.	High costs. Low durability and power density. Fuels requiring processing unless pure hydrogen is used.	200 kW to 250 kW

Source: US Environmental Protection Agency, 2005.

Benefits of CHP

CHP can offer industrial plants several benefits over electric-only and thermal-only systems. CHP typically requires only three-quarters of the primary energy required by separate heat and power systems. The advantages of CHP include:

- The simultaneous production of useful thermal and electrical energy in CHP systems leads to increased fuel efficiency, resulting in cost savings and reduced fuel combustion. CHP is a key industrial CO_2 emissions reduction strategy.
- CHP units can be strategically located at the point of energy use. Such on-site generation avoids grid transmission and distribution losses and can offer relief in areas where the power system is congested.
- CHP is versatile and can be combined with existing and planned technologies for a variety of different industrial.
- CHP offers attractive energy cost savings where the spread between the costs of purchased natural gas (or other fuel) and electricity is sufficiently large.

Total CHP efficiency is a composite measure of the fuel conversion capability and is usually expressed as the ratio of total useful energy output to fuel consumed. The total CHP efficiency for gas turbine-based systems between 1 and 40 MW, ranges from 70 – 75% for power-to-heat ratios between 0.5 – 1. In smaller industrial applications, micro turbines typically achieve between 65 – 75% total CHP efficiency for a range of power-to-heat ratios, while natural gas spark engines ranging between 100 kW to 5 MW are likely to have total CHP efficiency between 75 – 80%. While steam engine performance will vary depending on the input fuel, they are likely to achieve close to 80% efficiency over a range of sizes and power-to-heat ratios. Fuel cell technologies can achieve total CHP efficiency in the 65 – 75% range.

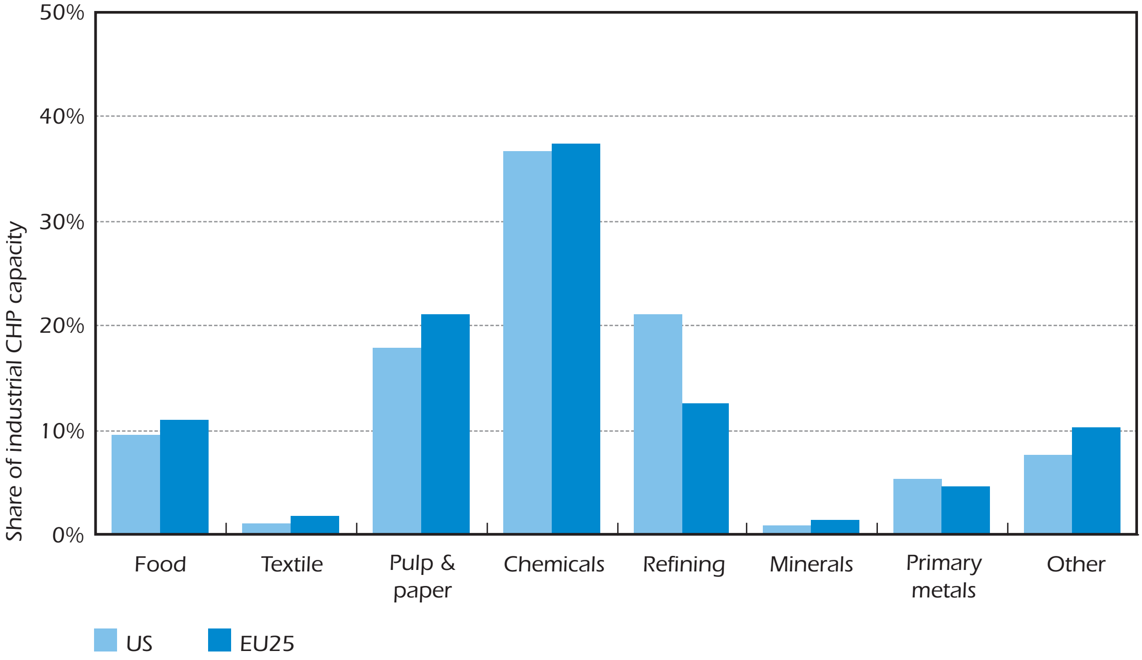
Existing CHP capacity is concentrated in a few industries where there is a high demand for steam and power. While CHP facilities can be found in almost all manufacturing industries, the food, pulp and paper, chemical, and petroleum refining sub-sectors represent more than 80% of the total electric capacities at existing CHP installations. Figure 9.6 shows the distribution of CHP capacity in the European Union and United States.

While there is large variation in electrical capacity at industrial CHP facilities, large systems still account for the vast majority. For example, in the United States, more than 85% of existing capacity is 50 MW and larger systems. Reciprocating engines and smaller gas turbines dominate in the small industrial CHP applications, *e.g.* food processing, fabrication and equipment industries, while combined-cycle and steam turbine systems dominate the larger systems.

Natural gas fuels 40% of CHP generated electricity in the EU and 72% of capacity in the United States, but coal, wood and process wastes are used extensively in many industries, especially in large CHP systems. As a result, combustion turbines are the dominant technology, representing 38% of CHP-based power in the EU and 67% of installed capacity in the United States. Boilers and steam turbines represent 50% of power generated by CHP in the EU and 32% of installed CHP capacity in the United States.

Figure 9.6 ▶ ***Distribution of Industrial CHP Capacity in the European Union and United States***

Key point: Industrial CHP use is concentrated in three sub-sectors: chemicals, pulp and paper, and oil refining.



Note: In Eurostat statistics, utility-owned CHP units at industrial sites are classified as public supply. This may affect the distribution of capacity.

Source: IEA data and statistics.

Barriers to CHP Adoption

Denmark, Finland and the Netherlands already have high penetration CHP rates, but most countries have significant potential to expand the use of CHP. The adoption of industrial CHP systems is typically limited by a handful of key factors, including:

- ▷ Power grid access/interconnection regulations and utility practices (buy-back tariffs, exit fees, backup fees).
- ▷ Environmental permitting regulations and lack of an agreed methodology to assess the environmental benefits of CHP.
- ▷ Increases in natural gas prices relative to electricity prices extend payback periods and make them less attractive investments.

Regardless of whether industrial CHP systems want to sell power to the local electricity grid, they must meet the procedural and technical requirements of the local utility and negotiate back-up and stand-by power service. The technical requirements are to ensure grid stability and safety. Typically, utilities establish the conditions that CHP systems must meet. A handful of jurisdictions have regulatory oversight. These conditions include requirements that the CHP system install safeguards or undertake grid upgrades to enable the project to interconnect. Utilities often impose operating restrictions, and/or require interconnection application procedures that may create barriers for some CHP projects, particularly small systems.

If interconnection procedures are overly expensive in proportion to the size of the project, they can make it uneconomic. It is for these and other reasons that some jurisdictions are developing standardised interconnection requirements for non-traditional generation types, including CHP.

Typically regulatory authorities do not offer credit for regional emission reductions that can result if a more efficient CHP system replaces electricity produced from less-efficient fossil-fuel plants and transported via the electricity grid. Further, the combined heat and power aspects have presented difficulties as CHP projects attempt to receive favourable treatment under greenhouse gas emissions trading schemes, since there is no agreed upon methodology to determine the environmental benefits of CHP.

The recent trend toward relatively higher natural gas prices has made some industrial CHP systems – typically those that seek to replace older, less efficient coal-fired boilers with a gas-fired CHP system – less economically attractive. Industrial plants are addressing these issues by investigating the viability of expanding the use of waste fuels in CHP systems and by exploring coal-fired CHP systems.

CHP Statistics

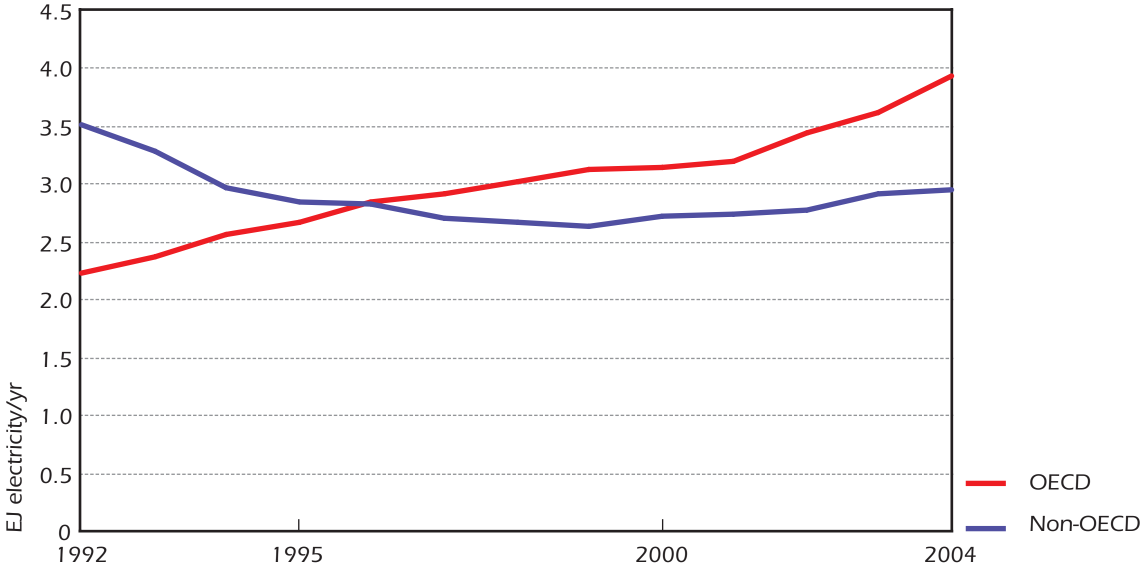
Countries have incorporated CHP in various ways in energy statistics, making it difficult to compare trends in capacity, power and heat production. The amount of electricity that is produced from CHP has been increasing gradually and is now more than 6 EJ per year, more than 10% of total global electricity production. The amount of heat that is co-generated is not exactly known, but it is in the range of 5 – 15 EJ per year, which represents an important share of industrial heat supply. If the heat is not sold, but used by the producer, part of the fuel use of the CHP plant is reported under industrial fuel use, rather than as CHP. Most of the growth in electricity production from CHP since the early 1990s is in OECD countries, which account for half of CHP electricity production (Figure 9.7).

Table 9.8 provides key data on installed CHP capacity. Together, the selected countries generate about 80% of total global electricity. It also provides estimates of the total CHP contribution to power generation in those countries. It is evident that the contribution of CHP to capacity and total generation varies widely. Moreover, the share of industrial CHP within the total CHP capacity varies, due to differences in a country's economic structure, *e.g.* energy intensive sectors, climate, role of district heating, and the history of barriers and policies to promote CHP.

Table 9.8 shows the variability in CHP contribution to energy efficiency today in different nations. Only a few countries have a CHP contribution to power generation larger than 20%. China, the EU countries, Japan, Korea, Russia and the United States show the highest estimated fuel savings from CHP. The data also show that the vast majority of CHP capacity is at industrial sites. The exceptions are in countries such as Poland or Russia, which have large district heating systems powered by CHP.

Figure 9.7 ▶ *Global CHP Capacity, 1992 – 2004*

Key point: Global CHP use has not increased significantly in recent decades.



Source: IEA data.

The estimated savings from the use of existing CHP are 4.5 EJ and CO_2 emission reductions of 252 Mt per year.

Fuel and CO_2 emission savings are estimates. For the calculation of the current savings from CHP, data on industrial CHP energy electricity production were used. For each country an estimate was made regarding the share of back-pressure turbines and steam turbines in one category with an assumed electric efficiency of 18%; and simple-cycle turbines, combined-cycle and gas engines in a second category with 32% efficiency. The country average power/heat ratio across both categories was set at 0.31. Assuming an equal share in both categories, the average overall efficiency, for electricity and heat is 80%. This was used to calculate the primary energy use for CHP and the energy production from CHP.

The country average efficiency of the reference electricity production was taken from the IEA energy statistics (average for centralised power production). For stand-alone steam boilers, the efficiency was set at 78%. This information was used to calculate the amount of fuel needed for a situation where electricity and steam were generated separately. The difference in fuel use for the CHP system and the stand-alone generation represents the energy savings. The world average fuel saving is 36% and savings from CHP account for 5.4 EJ. For the calculation of the CO_2 benefits, it was assumed that all steam cycles use coal and all gas turbines use natural gas, because of a lack of better data. The average CO_2 intensity of the centralised electricity production was used to estimate the savings for electricity. In this approach, CHP accounts for 326 Mt of CO_2 savings today.

Table 9.8 ▶ *CHP Use in Selected Countries*

Country	Installed CHP Capacity			Share of Generation		Estimated Savings from Existing CHP	
	Total	Industry	Total	Total	Industry	Fuel	CO_2
	GW	*GW*	*%*	*%*	*%*	*PJ*	*Mt*
Australia	2.5	2.5	5.6	5.5	5.5	111	9.4
Brazil	3.9	3.9	4.4	3.9	3.9	112	3.9
Canada	6.8	5.1	6.0	4.7	3.5	134	4.6
China	56.0	13.4	12.7	12.7	3.0	267	20.6
Denmark	5.4	0.6	42.1	50.2	6.8	14	0.9
EU25	91.6	34.1	12.2	9.9	4.6	1 129	50.8
Finland	5.8	1.7	35.1	38.0	12.8	57	2.5
France	6.5	2.8	5.6	4.0	2.0	131	2.0
Germany	26.4	13.4	20.9	9.8	4.0	207	12.1
Italy	4.4	2.2	5.6	7.4	4.1	98	6.0
Japan	9.6	7.0	3.5	5.0	3.6	316	15.7
Korea	6.1	3.9	9.4	9.0	7.1	214	11.2
Mexico	1.7	1.7	3.3	3.9	4.0	68	3.7
Netherlands	6.7	1.0	33.3	29.9	9.5	89	5.7
Poland	6.3	3.8	20.0	16.0	5.3	23	2.8
Russia	65.1	39.5	31.3	20.2	12.2	384	22.4
Spain	3.3	3.3	5.2	7.8	7.2	203	10.1
Sweden	3.2	0.9	9.6	6.8	2.9	10	0.0
Turkey	4.3	4.3	11.7	11.7	11.7	75	5.4
United Kingdom	6.3	2.7	7.9	5.4	5.0	215	12.1
United States	76.5	58.1	7.2	4.6	3.9	1 721	103.4
TOTAL	324.1	173.6	10.3	8.1	5.5	4 507	252.2

Note: Figures are from various sources and are for 2002 for EU countries and 2004 for other countries. Industry excludes the transformation sector. Ownership may vary, making the distinction between industrial and other CHP capacity sometimes difficult, *e.g.* in the Netherlands part of the other CHP capacity is operated by power companies at industrial sites, artificially reducing the share of industrial cogeneration.

Indicators for CHP Energy Efficiency Benefits

There are two types of indicators to calculate energy efficiency gains attributable to CHP:

▷ Current CHP capacity and associated energy savings and CO_2 benefits.

▷ Forecasts of additional CHP potential.

Current CHP use can be measured in terms of installed power generation capacity, steam generation capacity, electricity production or heat production. Data on installed generation capacity generally are available, while actual production data are less so.

Total CHP electricity production can be tracked on a country level in IEA statistics. However, it is not possible to tell which sector uses CHP from the statistics or to track the total heat generated by CHP systems. Therefore, it is not possible to calculate average efficiencies of CHP systems.

The energy efficiency benefits of CHP depend on the type and performance of the CHP prime mover and on the characteristics of the reference energy system. The type of CHP technology determines the ratio of electricity and heat that is produced, and the quality of the heat. The heat quality will depend on its anticipated use: low temperature heat, low, medium or high temperature steam, or high-temperature off-gases, *e.g.* for pre-heated furnace inlet air.

The efficiency gains of installing CHP are highest if a process is replaced where fossil fuels are used to generate low-temperature heat (below 100°C). The energy efficiency gains are limited if high temperature heat is needed, as this allows for less power production.

The reference system is the alternatives of heat and electricity production that are used for comparison. The reference electricity production efficiency can vary significantly depending on the fuel. If a gas-fired CHP system replaces a coal-fired boiler and coal-fired power plant, the efficiency gains and CO_2 reductions can be substantial. However, if the reference is an efficient gas-fired combined cycle, energy savings are less. Typical gains for a gas-fired CHP system are 10%, compared to an energy efficient combined-cycle, and 30% compared to an existing coal-fired power plant.

The actual share of CHP in power production is not a good measure of energy efficiency. Instead, the gap between actual CHP use and maximum CHP potentials, divided by the CHP potentials, is a better estimate of remaining energy efficiency potential from CHP. However, undertaking a CHP potential analysis requires detailed, sector-specific data on heat demand, as well as assumptions about the technology that will be applied. Typically, data for fuel consumption are available, but heat demand need to be estimated. Analyses of the potential for CHP should also focus beyond traditional CHP systems, *e.g.* a gas turbine with a waste heat recovery boiler, in order not to underestimate additional potential. This is because more advanced technologies or technologies with a higher power-to-heat ratio are available that lead to additional CHP installation potential.

Global estimates for the potential for CHP do not exist, though there are studies for some countries and regions. They may not be comparable due to differences in definitions, methodologies, system boundaries and technology assumptions. Most studies only include conventional CHP systems, *i.e.* generation of power and steam or hot water, and do not include the more advanced processes. Hence, the estimates of CHP potentials discussed are limited to these conventional applications.

In the United States, estimates for the additional CHP potential vary from 48 – 88 GW. The lower estimate only includes large-scale conventional systems. The CHP potential in Europe is about twice the installed CHP capacity. Some studies estimate a maximum potential of 252 GW in 2020, of which nearly 200 GW is in the EU, including district heating and advanced small-scale technologies (Whiteley, 2001). Other studies estimate about 150 GW of remaining CHP potential in Europe, about half of which is in manufacturing industry (Minett, 2004).

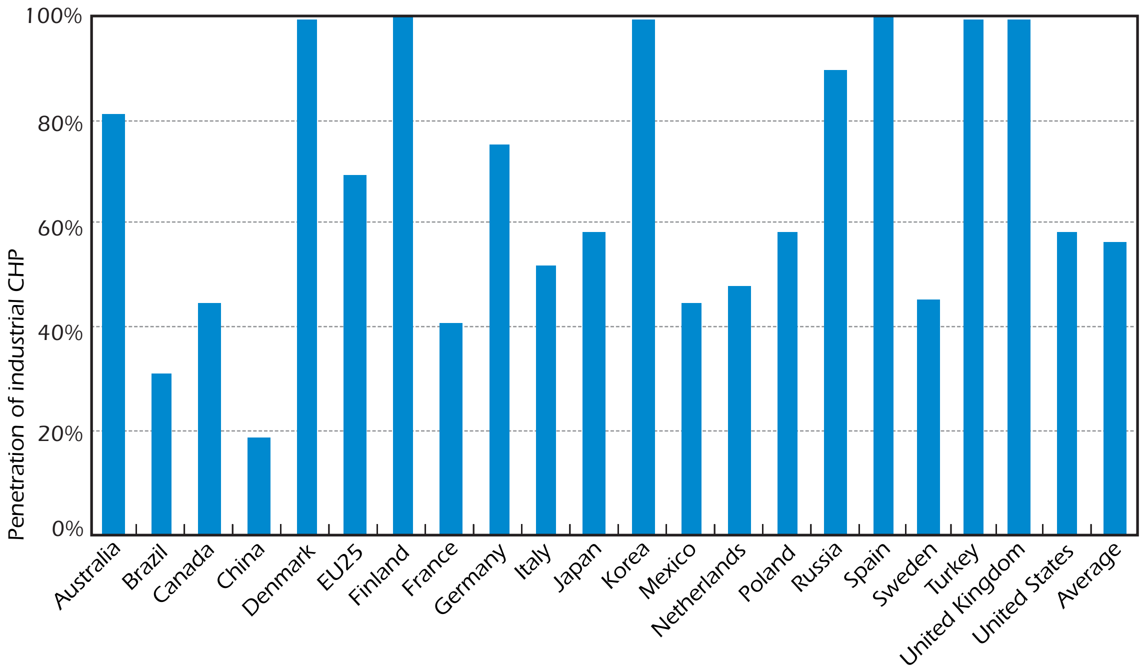
CHP potential in this analysis was calculated using an estimate for heat demand by sector (percentage of total fuel use) based on estimates of maximum shares of CHP for a variety of sub-sectors for US industry. The power-to-heat ratios by sub-sector were taken from actual US experience. The savings were calculated following the approach for Table 9.8. Using similar assumptions on share of heat demand in key industrial sub-sectors, maximum penetration and technology characteristics, global technical potential for new CHP in industry is estimated to be nearly 160 GW, generating about 500 TWh of electricity.

The net energy savings are estimated at 4.5 EJ. The key countries and regions in which this potential is found are China (200 TWh), United States (108 TWh), EU (60 TWh), Brazil (30 TWh), Japan (25 TWh) and Canada (24 TWh). Figure 9.8 shows the current CHP power production as a share of the estimated potential for CHP,

Figure 9.8 ▶ *Current Penetration of Industrial CHP*

(Share of Estimated Potential)

Key point: Many large countries have significant potential to expand industrial CHP.



Source: IEA data and statistics.

using the calculation method described. A high share means that already a large part of the conventional CHP potential has been used, while a low share indicates a large potential remaining.

These estimates are influenced by many factors. A key factor is the reliability of the energy balances and data on heat use in the industrial sub-sectors. Data are more reliable for IEA countries than for others Different assumptions on efficiencies, power-to-heat ratio, and technology would result in varying estimates of CHP potential. Hence, the indicator should be interpreted with care. It does give, however, a first indication of the differences among countries.

There are additional caveats, particularly regarding data on industrial fuel use. For example, data for some countries suggest that there is no additional potential for CHP; other studies suggest that there is further potential. IEA expects additional data collection and analysis in this area would uncover additional CHP potential for these and other countries and recently launched an initiative to address this. In addition, classification of CHP plants as either industrial or other/public, e.g. district heating, may affect the results. For example, the Netherlands has a very high degree of CHP at industrial sites, but as they are owned (or in joint ventures) with utilities, they are classified as public CHP capacity. This shows a low penetration rate for CHP in the Netherlands when in reality, the current use is much higher than the indicator suggests.

LIFE CYCLE IMPROVEMENT OPTIONS

Key Findings

- *Industrial energy use is different from other end-use sectors as significant quantities of energy and carbon are stored in products. Moreover, materials choice affects product energy use. Therefore, it is particularly important to consider efficiency improvement options on a life cycle basis.*
- *The consumption of materials for a given level of per capita GDP differs widely between countries. This suggests that important efficiency gains in materials use are possible.*
- *It is difficult to apply indicators to assess the efficiency of materials use because of wide product diversity and the variations in materials choice, lifestyle and natural resource endowments.*
- *Materials recycling and energy recovery can reduce industrial energy use substantially. Today there are large variations in recycling practices and energy recovery from waste materials among countries. Substantial amounts of waste materials are still disposed of in land fills.*
- *Additional energy efficiency potential in increased recycling is 3.3 to 5.1 EJ per year and 3 to 4.5 EJ per year in energy recovery in primary energy terms. Realising this potential could reduce CO_2 emissions by 0.16 to 0.42 Gt CO_2 per year, if gas or coal were replaced on a thermal par basis. The potential for increased recovery of used materials should be analysed in more detail.*

Introduction

A significant share of industrial energy use is related to the production of energy-intensive materials. Improving the efficiency with which the economy uses these materials will reduce industrial energy consumption and CO_2 emissions. Ways to improve material efficiency include material recycling, product re-use, re-design and substitution.

The full life cycle and energy and materials systems impacts need to be taken into account. This chapter looks at the efficiency trends in materials and product use such as cars and packaging. It also looks at opportunities to recycle and reuse plastics, paper, aluminium and steel, and at energy recovery from the incineration of used materials. It identifies additional recycling potential in the range of 3.3 – 5.1 EJ per year and energy recovery potential of 3 – 4.5 EJ per year. Realising this potential could reduce emissions by 0.16 – 0.42 Gt CO_2 per year, if gas or coal were replaced on a thermal par basis.

Indicator Issues

Two types of measures are discussed in this chapter. The first one relates to the efficiency of materials and product use. The second one relates to the efficiency of recovery of used materials, both recycling and energy recovery.

A Product Efficiency Indicator (PEI) may be relatively easy to apply, but the simplification ignores many important aspects that influence the results. Practical constraints make it difficult to use PEIs to identify single numbers that can be used to justify favouring one type of product over another or to inform the consumer. For example, the European Commission (EC) concludes that it currently seems neither possible nor appropriate to propose harmonised measures to encourage reusable consumer beverage packaging at the Community level (EC, 2006).

Life cycle analysis (LCA) is a widely applied tool to compare products that facilitates the analysis of different types of materials and product use. This type of comparison focuses on very specific product services, which means the method is less suited to make country comparisons in terms of their efficiency of materials use. In fact, comparative assertion is not allowed by the ISO standard for life cycle analysis. Therefore, it is not discussed further in this analysis.

Materials flow analysis (MFA) is another approach that looks at the materials throughput of countries. This type of indicator is of higher relevance for measuring the indirect energy and CO_2 intensity of countries related to materials consumption. However, the method as it is applied today is not specifically designed for this purpose, *e.g.* Matthews, *et al.* (2000). As a consequence, the existing MFA approaches are not suited for the purpose of this study. However, general concepts of LCA and MFA such as systems approaches and allocation procedures may apply.

A more general analysis looks at the materials intensity of economic activity to provide some insight regarding the efficiency of materials use in an economy. The energy use for materials production is a function of the materials volume that is produced. Certain limitations apply. For example, the analysis is usually based on materials consumption data that do not account for the trade of materials in the form of products. For certain (usually small) countries, this trade can be substantial and can distort the materials intensity analysis. This type of indicator does not credit recycling or energy recovery from waste.

Also countries rely on various materials depending on their natural resource endowments. The most notable difference is the choice of building materials. Wood is widely used in countries with large forests and relatively low population densities, while concrete dominates in Asian countries with high population densities. Compared on such a basis, countries will look more or less materials efficient because of different product characteristics. One way to overcome this matter is to aggregate materials based on average energy use and CO_2 emissions not only during their production, but also during their use phase.

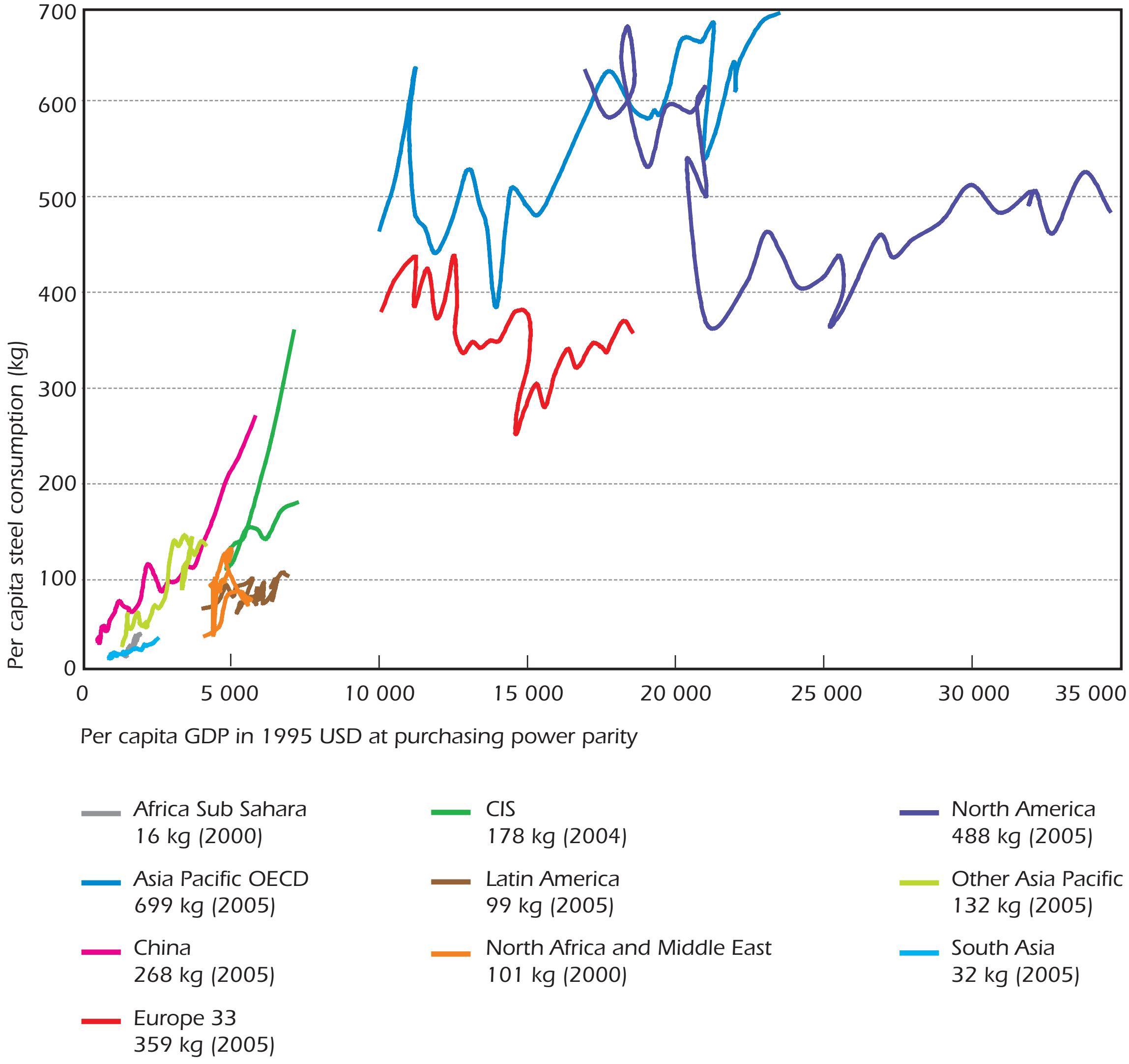
Setting targets and enforcing them can pose problems. Compared to materials efficiency, an assessment of recycling and energy recovery rates is more straightforward. Recycling rates can be calculated in different ways. The best estimate calculates the amount of recycled material as a share of the total release of used materials. In the case of pulp and paper and petrochemicals, recycling and energy recovery represent alternative, but not equal options. An aggregate indicator that credits both options appropriately provides the best estimate of recovery efficiency. The energy recovery efficiency differs substantially depending upon whether the waste heat is put to productive use. Ideally, this should be accounted for in the indicator analysis.

Trends in the Efficiency of Materials and Product Use

Despite the opportunities for material efficiency improvement, consumption of energy-intensive materials in almost all economies grows over time and may eventually stabilise (saturate) at a certain high per capita income level. These patterns can be observed for steel (Figure 10.1), cement (Figure 10.2), but are not yet evident for plastics, paper (Figure 10.3) and aluminium. If GDP were the only explanatory factor, curves for different countries would overlay each other. This

Figure 10.1 ▶ *Apparent Steel Consumption Trends per capita, 1971 – 2005*

Key point: Per capita steel demand stabilises in the 400 – 600 kg range.



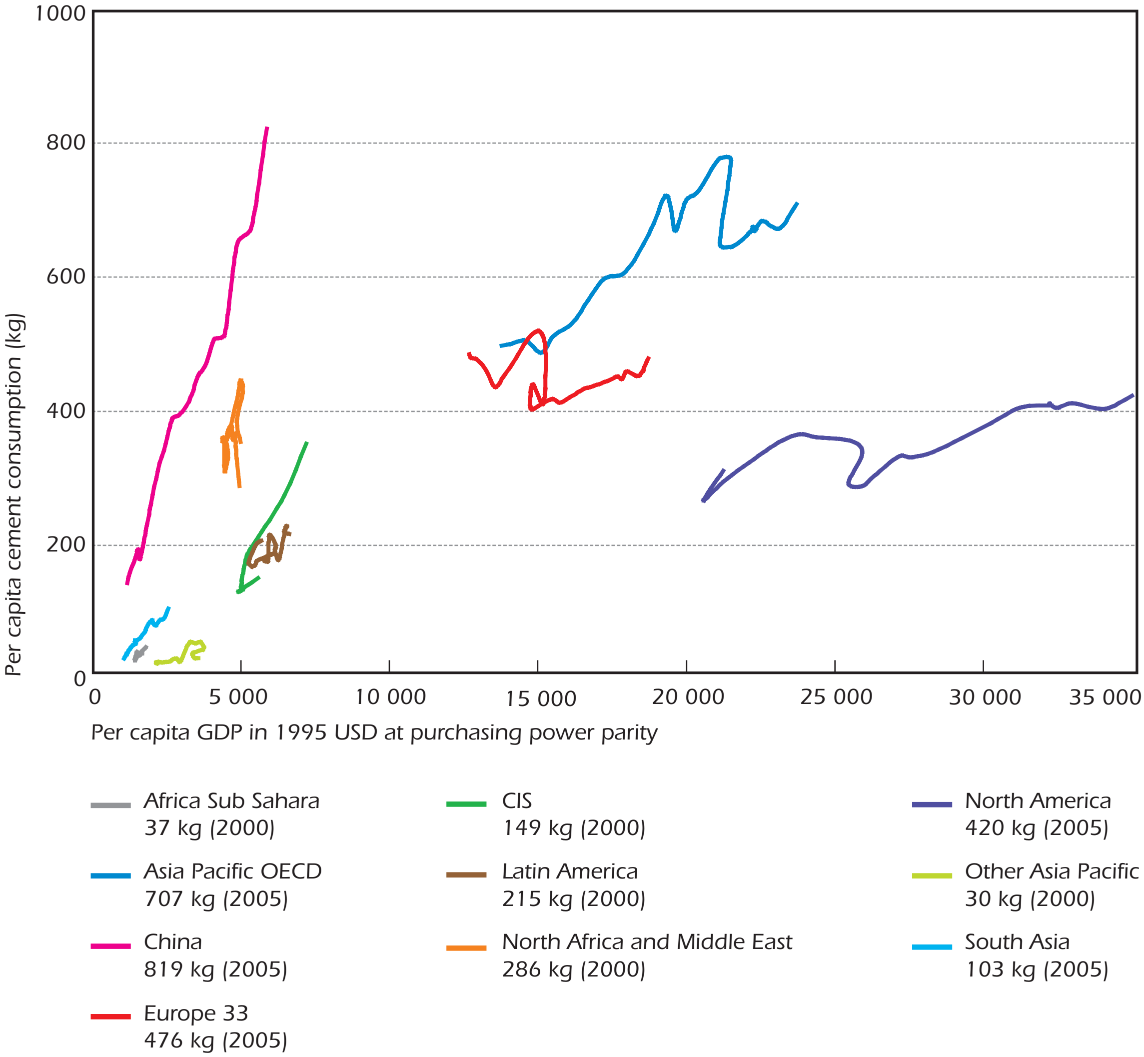
Note: Apparent consumption is production plus imports minus exports.
Europe-33 consists of EU27 excluding three Baltic States, and including Albania, Bosnia, Croatia, Iceland, Former Yugoslav Republic of Macedonia, Norway, Serbia, Switzerland and Turkey.

Source: Lysen, 2006.

seems to be the case for plastics, paper and maybe aluminium. For steel, cement and ammonia, the intensity levels differ considerably at a given GDP level. This intensity of GDP levels can be explained by different material choices, consumption patterns and efficiency of materials use. Trade also affects the pattern and generally is not included in the apparent consumption figures of materials in products. For example, it is estimated that the United States imported about 16.9 Mt of steel in products, which is equal to about 50 kg/capita, on top of the 500 kg/capita (Figure 10.1) (AISI, 2006). Material use and choice is also a function of domestic resource availability, affluence, culture and other factors.

Figure 10.2 ▶ ***Apparent Cement Consumption Trends per capita, 1971 – 2005***

Key point: Per capita cement demand and growth in China is exceptionally high compared to per capita GDP.



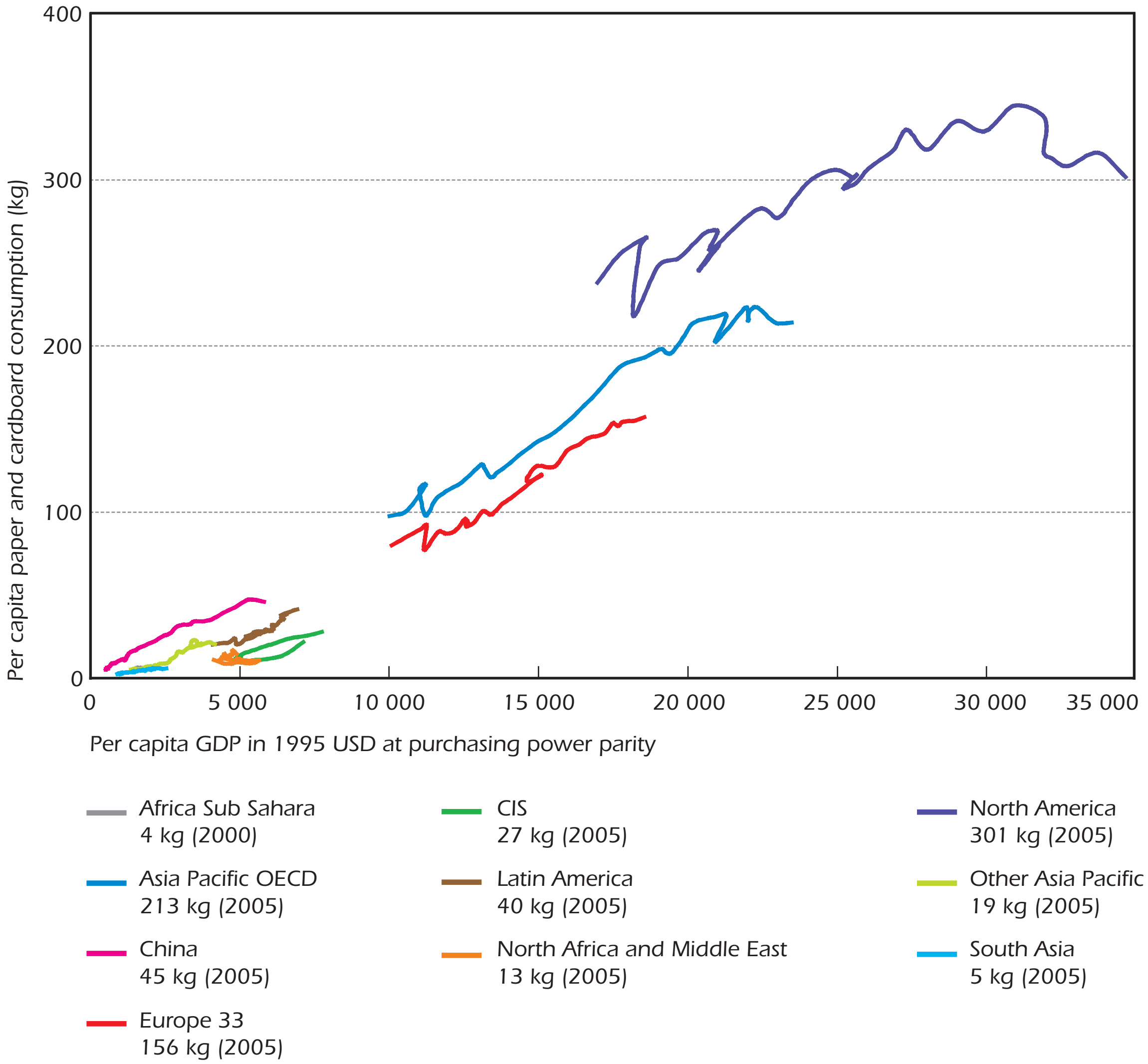
Note: Apparent consumption is production plus imports minus exports.
Europe-33 consists of EU27 excluding three Baltic States, and including Albania, Bosnia, Croatia, Iceland, Former Yugoslav Republic of Macedonia, Norway, Serbia, Switzerland and Turkey.

Source: Lysen, 2006.

The efficiency of materials and product use is a function of the product life span and the materials use per unit of product. Both factors are, in turn, influenced by many variables. Hence, it is hard to establish a clear indicator for material efficiency. Comprehensive studies that compare the efficiency of materials and product use in a bottom-up fashion have not been encountered. Nevertheless, various studies have demonstrated the potential for further material efficiency improvement. In most cases, increased materials efficiency will reduce CO_2 emissions. However, in certain applications the use of

Figure 10.3 ▶ *Apparent Paper and Paperboard Consumption Trends per capita, 1971 – 2005*

Key point: Paper and paperboard demand is closely connected with GDP, but tends to stagnate in recent years as digital media gain importance.



Note: Apparent consumption is production plus imports minus exports.
Europe-33 consists of EU27 excluding three Baltic States, and including Albania, Bosnia, Croatia, Iceland, Former Yugoslav Republic of Macedonia, Norway, Serbia, Switzerland and Turkey.

Source: Lysen, 2006.

materials affects the energy demand when the product is being used. This is particularly the case in applications where emissions over the life of a product dwarf those of the material and product production and increased material use may result in net life cycle emission reductions. Only a life cycle approach would be able to determine the trade-offs between the two and, hence, the net impact on energy use and CO_2 emissions. Yet, the variations in country materials intensity of GDP suggests that important efficiency gains in materials use are possible.

Three categories are of key importance for total materials consumption: buildings, packaging and transportation equipment.

Buildings

Buildings are a primary consumer of energy-intensive materials such as cement, steel, glass and bricks. Residential and other kinds of buildings each account for about half of the material inputs. This analysis focuses on housing.

Residential building area in OECD countries grew about 50% between 1980 and 2004, which required a very significant increase in the use of materials. It is the increase of the stock that drives materials demand rather than replacements. Assuming a low estimate of 500 kg of material per square metre, the growth in housing represents an increased stock of 6 000 Mt, or 250 Mt of materials per year. Figure 10.4 shows the trend of the building area per unit of GDP. Note that the range of housing intensities of economic activity has narrowed, measured as square metres of dwelling area per USD 1 000 on a purchasing power parity basis (Figure 10.4). In most countries, the floor area is growing at a slightly lower rate than GDP and the average intensity has declined from around 2.2 – 1.8 square metres per USD 1 000 over the last twenty-four years.

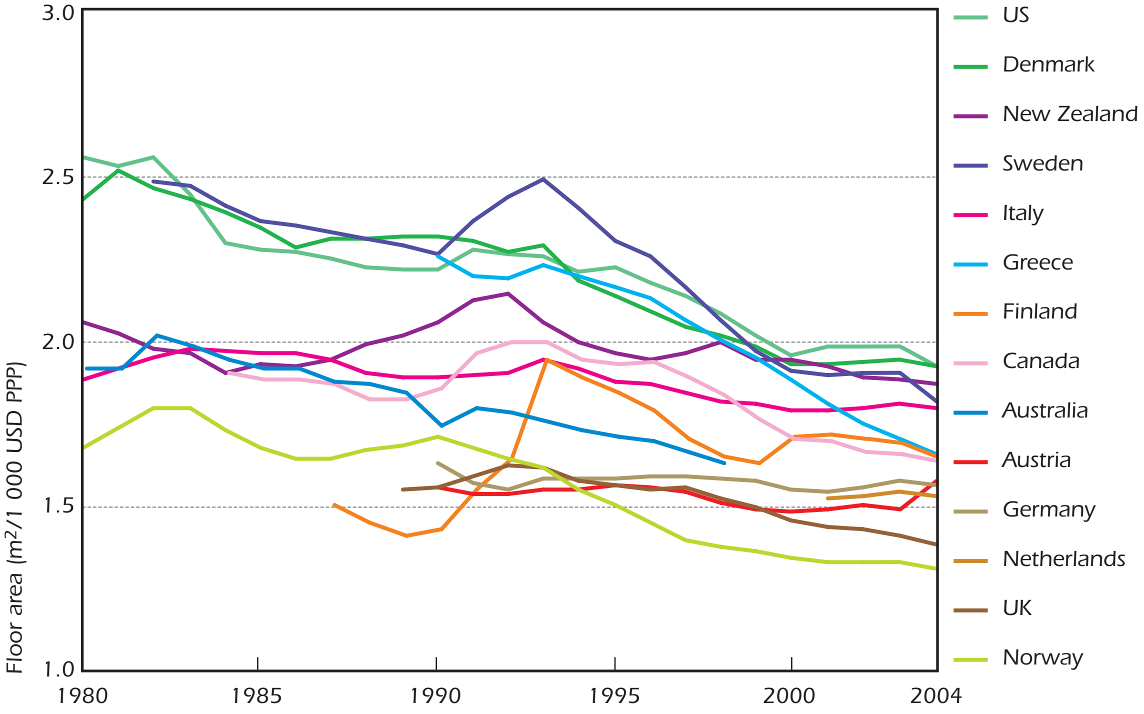
The production of construction materials has increased very rapidly in China due to the development of buildings and infrastructure. Today, China is the world's largest producer of steel, cement and bricks, and the specific per capita consumption of cement in China is above that of OECD countries.

Packaging

Packaging is ubiquitous in today's society. It has many applications and uses many different materials, *e.g.* steel, aluminium, glass, paper and plastics. Worldwide the consumer packaging market is estimated to be worth about USD 460 billion with 5% annual growth rates. Packaging demand has grown with GDP across a wide range of income levels and regions. Europe represents the largest packaging market (30%), followed by North America (28%) and Asia (27%). Food and beverage, commercial and industrial packaging are the three largest market segments and account for more than 70% of the total (Figure 10.5). While the materials intensity varies for packaging types, these market shares in monetary terms provide a first indication of the relevance of different packaging types from a CO_2 and energy perspective.

Figure 10.4 ▶ *Floor Area per unit of GDP for OECD Countries*

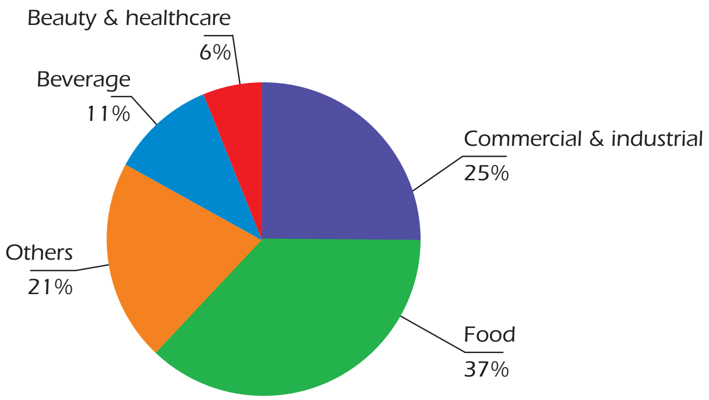
Key point: Housing floor area is closely related to GDP and tends to converge in the range of 1.5 – 2 m² per USD 1 000.



Source: IEA data.

Figure 10.5 ▶ *Packaging by Market Segment*

Key point: Food and beverage, commercial and industrial packaging account for 73% of the total packaging market.



Source: Packaging Federation, 2005.

Packaging is a relatively small, but still significant product and material stream. It represents about 5% of total solid waste and 17% of municipal waste by weight and 20 – 30% by volume for the EU15.[1] The greenhouse gas emissions related to packaging consumption in the EU15 are estimated to be 80 Mt of CO_2 equivalent per year. This equals around 2% of total EU15 greenhouse gas emissions in 2005.

Various studies of the potential for energy savings and CO_2 emission reduction through material efficiency improvement have identified a wide array of opportunities including re-use, recycling and product re-design. Most studies found reusable packaging to be more environmentally beneficial in situations where transport distances were small and return rates high, while one-way packaging performed better in situations with generally high transport distances and low return rates. Relatively large technical potentials, up to 40%, for material efficiency improvement have been identified in the studies. Realising these potentials, however, is a function of many factors, which can be hard to influence.

Transportation Equipment

Transportation equipment is a major consumer of steel, aluminium and plastics. About 55 million cars were sold worldwide in 2005, of which more than 80% were in OECD countries.[2] Figure 10.6 shows car ownership as a function of GDP per capita. Clearly both are closely related. Note the very low ownership rates in India and China. The ownership rates in OECD Europe, Japan and the United States are similar, at almost one car for every two inhabitants.

Global car sales have doubled since 1980 (Figure 10.7). In recent years, sales are growing even more rapidly in the emerging economies including China and India. Clearly this is the main driving factor for increased materials demand for transportation equipment.

Along with growing sales, vehicle weight and performance features have also increased. The trend to larger cars has offset efficiency gains from using lighter steel and lightweight materials such as aluminium and plastics. In fact, this development has slowed fuel efficiency improvements in the United States and other industrialised countries. Increased car weight has also resulted in increased material demand for car manufacturing (Figure 10.8). Today, total steel consumption for car manufacturing amounts to approximately 100 Mt, or almost 10% of global steel production.

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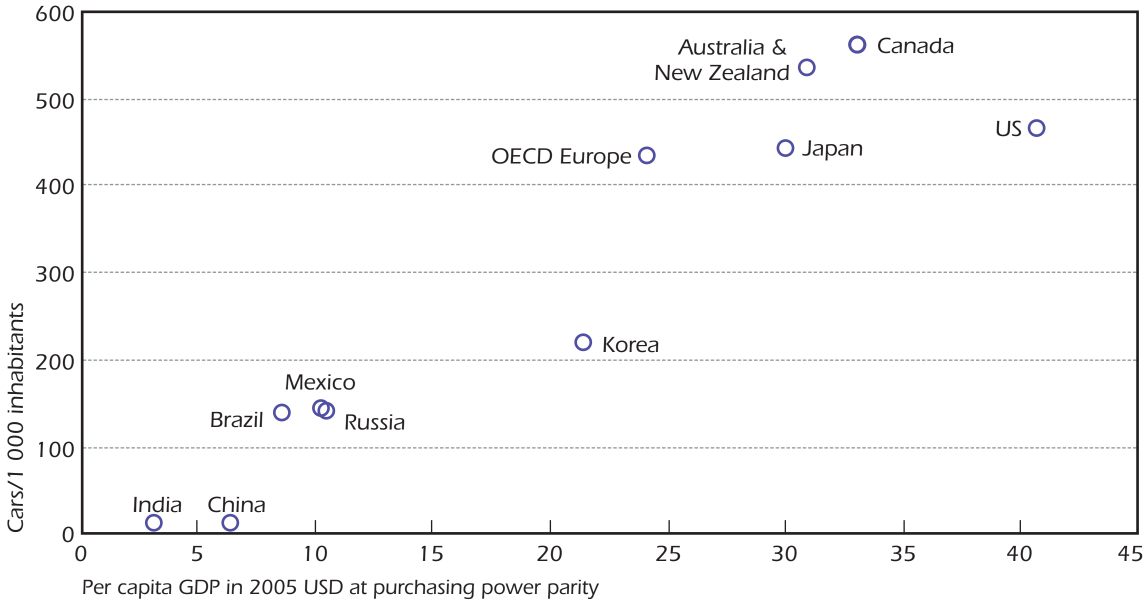
[1] The EU15 includes: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom. Ten additional countries joined the European Union on 1 May 2004.

[2] Cars in this study refer to light-duty vehicles which include cars, minivans, sport-utility vehicles and personal use pick-up trucks.

Figure 10.6 ▶ *Global Car Ownership Rates as a Function of per capita GDP, 2005*

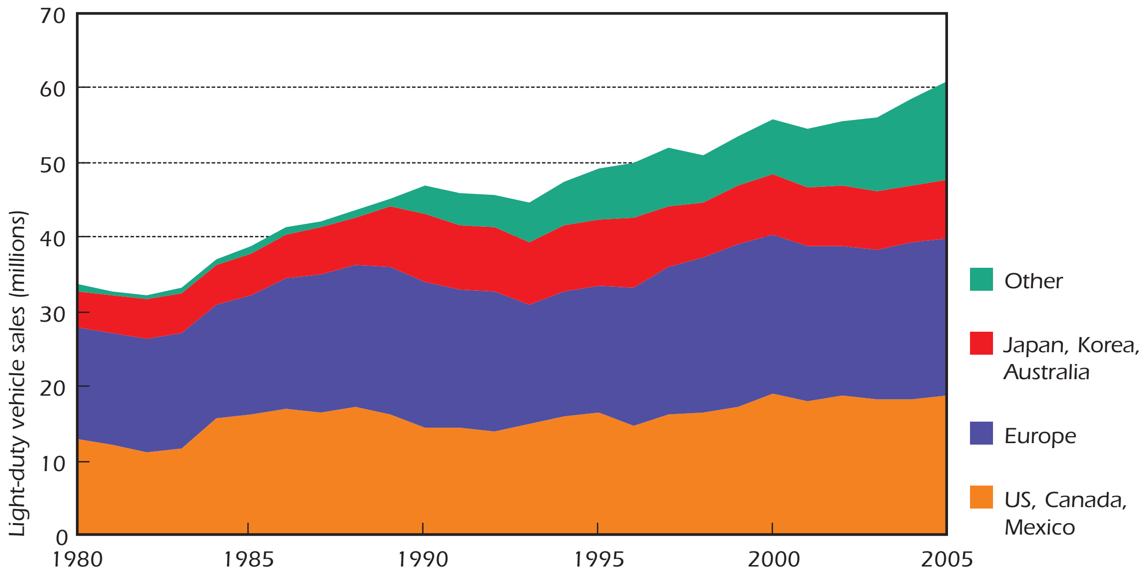
Key point: Car ownership rates are closely related to income levels.



Source: IEA data.

Figure 10.7 ▶ *Global Car Sales, 1980 – 2005*

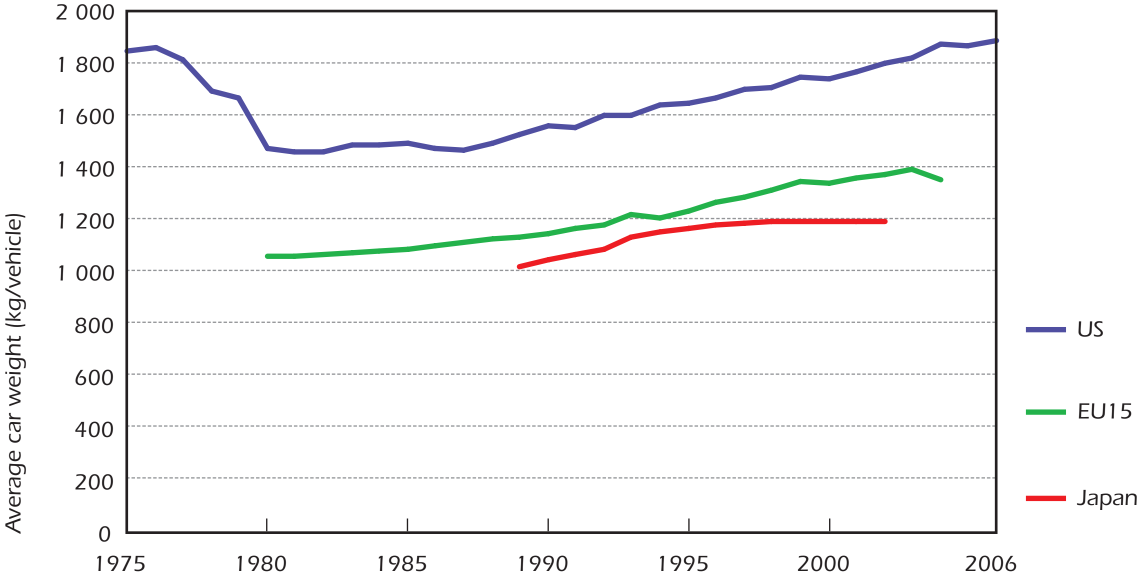
Key point: Car sales have almost doubled in the past twenty-five years, which has considerably increased the demand for materials.



Source: IEA data.

Figure 10.8 ▶ *Car Weight Trends, 1975 – 2005*

Key point: Car weights have increased by 20 to 30% in the past twenty-five years, which has contributed to increased global demand for materials such as steel.



Source: IEA data.

Recycling and Reuse

Obviously, recycling of materials and reusing products translates into lower demand for primary materials, whose production is generally much more energy intensive. The main materials where recycling makes sense are metals, synthetic and natural organic materials. Recyclable materials can be recovered from three main streams: internal in the plant that produces the material (home scrap); production residues from processing industries; and post-consumer wastes.

Various indicators can be used to estimate the life cycle efficiency of materials. A Japanese study distinguished six indicators to measure the "metabolism" of society, of which three relate to the opportunities to reuse or recycle products and materials:

- Use of recovered product – a potential indicator being the recycled content in total production;
- Amount of recovered material – recovery rate for used materials that are released, *i.e.* percentage of total material that is recycled, also called the recycling rate;
- Material use efficiency – use of materials and by-products in production.

The recovery rate is the most useful indicator to express the recycling efficiency in a given economy as recycled material may be imported or exported. The recovery rate expresses the amount of material that is recovered from all streams as a share of the total spent material released. Since many materials may be used in products with a long life, it is difficult to estimate the total amount of available material for recovery. Yet there are various methods to calculate the recovery rate. The volume of available material in the total stream can be estimated on the basis of models (material flow analysis), statistical data and sampling of streams to determine the material composition. Depending on the method used, results may vary. For example, a study of the European copper streams determined a recovery rate of 63 – 67%, depending on the method used to establish the amount of available copper for recovery (Ruhrberg, 2006). Similar differences are found in other estimates of recycling rates for steel, paper and glass. Recycling and recovery rates in the literature need to be carefully interpreted.

There are data for most countries on quantities and types of materials that are recycled, or for the amount of recycled materials that go into producing new products. What is lacking in the statistics is how much material is available from post-consumer waste. An accurate estimate of this amount is needed because the gap between the material that could be available and the amount that is recycled reveals the untapped recycling potential and consequently the energy and CO_2 reduction opportunities.

Reliable statistical data exist for the apparent consumption of materials, which is defined as the production plus imports minus exports. Taking the apparent consumption and subtracting the amount of processing residues, the stock changes and the material degradation estimates the amount of available post-consumer material. Stock change and the material degradation factors are often not known precisely. Moreover, materials are traded in the form of parts and finished products, on which where are no reliable statistics. The relevance of this issue varies by materials category.

As the number of houses, cars and other products grows, the materials stock expands. The boundary between stock increase and those materials becoming available for reuse is somewhat fluid and depends on the economic value of spent materials. A disused industrial installation that has not been dismantled is an example.

Another way to consider the material available for reuse is that it equals the amount of products that reach the end of their life span, multiplied by their materials content. This approach is widely used to estimate material availability. The impact of stock changes is most significant for products with a long life span. For example, most plastics are used in packaging and have a life span of less than one year. If the amount of packaging in use grows by 2% per year, the stock change explains at most a 2% difference between apparent consumption and spent material available. But in the case of buildings and infrastructure, the life span may be 50 years or more. In case the buildings and infrastructure stock grows by 1% per year, the material arising for this product category equals only 60% of the apparent consumption. As a consequence recycling can not exceed 60% of total supply in this product category.

The amount of material that is recycled is not equal to the amount of new material that is produced due to material loss in recycling processes. Waste paper, for example, may contain plastic, fillers and water that must be removed. Steel scrap may contain paint and zinc coatings that are removed during recycling. Important amounts of aluminium scrap end up in the dross (solid impurities), although this is recycled to some extent.

Table 10.1 compares the apparent consumption and the amounts of used materials released (home scrap, processing and post-consumer flows). The total amount of used materials available is considerably lower than the apparent consumption due to the increasing product stock. The recovery rate for many materials is therefore considerably higher than the recycling content. The remaining potential includes spent materials that are not, but could be, recycled. This is translated into an energy savings estimate by multiplying the remaining potential and the energy savings per tonne.

The additional recycling potential for plastics, paper and wood is limited by the spent material quality. Moreover, incinerating used materials to produce energy is a competing option. The potential for increased recovery of used materials should be analysed in more detail, notably for steel and aluminium because of considerable uncertainties in the spent material availability data.

Table 10.1 ▶ ***Global Recycling Rates and Additional Recycling Potential***

	Year	Apparent Consumption *Mt/yr*	Post-Consumer Flows *Mt/yr*	Total Material Available *Mt/yr*	Additional Recycling Potential *Mt/yr*	Primary Energy Saving Potential *EJ/yr*
Crude steel	2005	1 129	261	446	20 – 50	0.2 – 0.5
Aluminium	2004	44.1	7.3	13	6.7	0.9 – 1.2
Copper	2004	14.5	9	10.4	3	0.1
Plastics	2004	235	115	120	20 – 40	0.8 – 1.5
Paper & paperboard	2004	354	254	274	50 – 75	0.5 – 0.8
Wood	2004	600	284	344	50	0.5 – 1
Glass	2004	100	77	87	23	0.0
Total						**3.3 – 5.1**

Note: Wood materials value at heating value, which is not generally accounted for in energy statistics.

Sources: IEA data; International Iron and Steel Institute; International Aluminium Institute.

Preliminary results suggest that the additional energy efficiency potential from increased recycling is 3.3 – 5.1 EJ per year (Table 10.1). This does not account for future increases in available materials. About 2 – 4% of all industrial energy use could be saved if the full amount of used materials available were recycled. Aluminium, plastics, paper, paperboard and wood, in particular, show additional potential. Note that this analysis does not consider the economic costs of recycling. Most of the potential is related to municipal solid waste and packaging. Recovery of materials from this waste stream is often not economic. For paper and paperboard, note that the biomass feedstock for primary products is not accounted for in energy statistics, so the energy saving potential is statistically smaller than indicated in the table. However, recycling of natural fibre materials results in a surplus of primary biomass that can be used for energy purposes and can reduce CO_2 emissions, *i.e.* if it substitutes for coal.

Data regarding waste release, calculated from the materials consumption information, can be compared to the data on waste quantities and their composition. Global municipal solid waste amounts to 1.2 – 1.4 Gt per year (wet weight) (IEA data; Lacoste and Chalmin, 2006). Food waste accounts for half the weight and glass, paper, paperboard, textiles, wood and synthetic organic materials account for the remainder.

The OECD countries account for roughly half of municipal solid waste (MSW). China accounts for a quarter, but is very different because its MSW contains substantial amounts of coal ash. MSW represents only part of total post-consumer waste. About 1 200 – 3 000 Mt of non-hazardous industrial waste are released each year, including construction and demolition debris most of which is concrete, bricks and other inorganic materials (Lacoste and Chalmin, 2006). Blast furnace slag, fly-ash, etc. are often included in this category. Note that the boundary and definition between waste and by-products is blurred for some industrial streams. For example, blast furnace slag is a co-product with a market price that is widely used as an efficient raw material for cement production.

As materials represent an important cost component for processing industries, they try to minimise waste. For most energy-intensive materials, the amount of industrial waste is comparatively small. For plastics and paper it is typically less than 10% of the total amount of post-consumer waste.

Construction and demolition and shredder waste (from shredding used cars and the like) are also important waste categories. While metals are recovered and recycled, this is usually not the case for plastic and wood waste. Reliable statistics for construction and demolition waste are not available for most countries.

Petrochemical Products

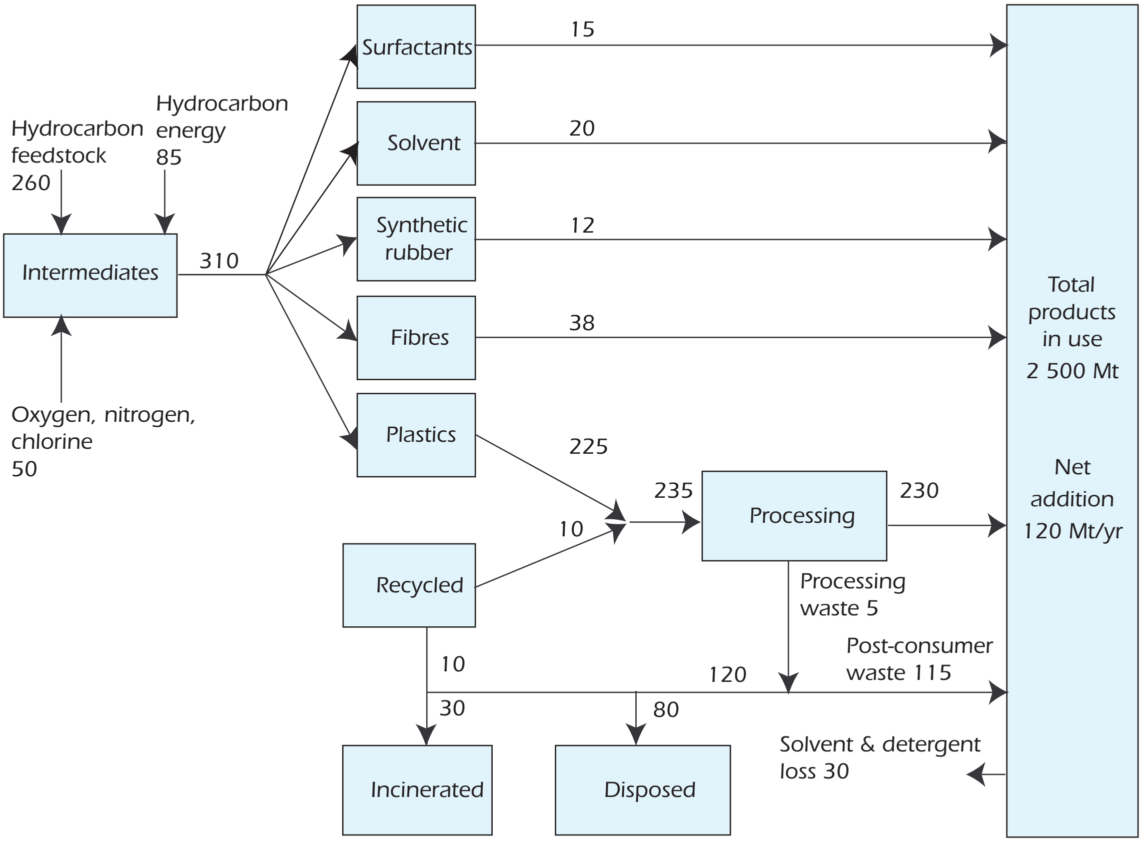
Recycling is often costly, whereas disposal via land fills and incineration are comparatively cheap. As well, not all recycling is advantageous from an energy and CO_2 perspective. That is because some recycling processes are energy intensive and the energy used in waste collection must be taken into account. Optimal recycling rates, in energy efficiency and CO_2 emissions terms, differ depending upon each material, waste flow and region. This complex evaluation is especially needed for the diverse category of used plastic.

Figure 10.9 shows the global petrochemical mass balance. In 2004, 345 Mt of hydrocarbons (about 16 EJ heating values) were converted into 310 Mt of petrochemical products. Plastics represented 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents and synthetic rubber. About 120 Mt were stored in increasing product stock, the remainder was released into the atmosphere or as solid and liquid waste. Across the globe, the majority of this waste was disposed of in land fills.

Figure 10.9 ▶ *World Petrochemical Mass Balance, 2004*

(Mt/yr)

Key point: Recycling of petrochemical products is small compared to primary production.



Note: Excludes methanol, ammonia, carbon black.

Sources: Freedonia, 2003; Plastics Europe 2006, Rubber Study, 2006; Industrievereinigung Chemiefaser, 2006.

Plastic is a material where recycling could have a substantial impact in terms of energy and CO_2 emissions. Figure 10.9 shows that about 30 Mt of plastic waste is incinerated with energy recovery and about 10 Mt of plastic waste is recycled. Compared with a waste availability of about 120 Mt/yr, this represents a global average recycling rate of 8%.

Several options exist for plastic waste recovery:

- ▷ Back-to-polymer;
- ▷ Back-to-monomer;
- ▷ Back-to-feedstock;
- ▷ Energy recovery.

Some technology options can be categorised either as energy recovery or feedstock recycling. This is, for example, the case if plastic waste is used for coke or methanol production or injection in blast furnaces.

Plastics can be divided into thermoplastics and thermo sets. The thermoplastics can be recycled though mechanical recycling, but thermo sets can not. All plastics can be recycled via back-to-polymer and back-to-feedstock technologies. Other recovery methods can be applied for the remaining plastic waste fraction. This includes energy recovery, back-to-monomer and back-to-feedstock technologies.

The quality of recycled plastic depends on the quality of the waste input. If the input waste is of low quality, costly upgrading is needed and/or the quality of the recycled plastic is not equal to the quality of primary plastic. If certain plastic products such as bottles are separated in collection or sorted, post-consumer waste can be mechanically recycled. Mechanical recycling is less suited for plastics from mixed MSW.

In Europe and Japan, the countries with the most advanced recycling policies, mechanical recycling rates for post-consumer plastics range from 20 – 30%. It seems unlikely that these rates can increase much above this level. There are many countries where mechanical recycling rates are quite low.

Plastic and paper waste can be jointly processed into a fuel with a high calorific value, although PVC must be removed in the fuel preparation to avoid boiler corrosion and dioxin emissions. Known as refused derived fuel, it is used in the Netherlands and Germany for co-combustion in coal-fired power plants. Such fuel can also be used in other boilers and kilns, *e.g.* in the cement and pulp and paper industries. If the plastic-based fuel substitutes for coal on a thermal par basis, it is more efficient than MSW incineration and CO_2 emissions will be reduced on the whole.

Table 10.2 compares the CO_2 impacts of post-consumer plastic waste recovery options versus a reference case of disposal in land fills. It considers recycling, energy recovery in cement kilns, coal-fired power plants and incineration in MSW incinerators that produce electricity only. The CO_2 impact varies for different plastic types, but in all cases the order of preference is recycling, energy recovery in cement kilns or power plants and MSW incinerators. MSW incinerators in fact increase CO_2 emissions compared to land fill disposal, but they may offset fossil fuel use. It should be noted that the main driver for a switch from land fill disposal to incineration is the scarcity of land fill space, not energy or GHG policies.

Table 10.2 ▶ ***CO_2 Impacts of Plastic Waste Recovery Options versus Land Fill Disposal***

	Mechanical Recycling *t CO_2/t waste*	Incineration Cement Kiln or Coal-Fired Power Plant *t CO_2/t waste*	Incineration (18% efficiency) *t CO_2/t waste*
High density polyethylene	–1.50	–0.82	0.84
Low density polyethylene	–1.98	–0.82	0.84
Polyethylene terephthalate	–2.49	–0.58	0.95

Note: United States power generation reference.

Sources: USEPA, 1998; EPIC, 2002.

The net CO_2 benefit of recycling and waste incineration depends also on the energy needed for waste collection and for the recycling process, and the efficiency of energy recovery in the case of incineration. Typically, the net CO_2 benefit ranges from 50 – 80% compared with the energy use and CO_2 emissions in primary production.

Product quality is also a consideration. Comparing a recycled plastic on a per-tonne basis with primary product may be deceptive. Recycled plastic can directly substitute for primary plastic in some applications, however, the amount of materials needed may be higher to make up for reduced materials performance. In other applications, *e.g.* plastic lumber, the use of waste plastic is a new market, so comparison with primary plastics suggests a saving that does not exist.

Table 10.3 shows plastic waste recycling data for some OECD countries.

Europe is the region with the longest experience with plastic waste recycling policies. Production of primary plastics in Western Europe was 53.5 Mt in 2004 and 19.1 Mt of plastic waste was generated. The gap between the two is due to exports and increasing product stock. For the plastic waste, 53% (10.1 Mt) was disposed of and 47% (8.9 Mt) was recovered for recycling or energy purposes. Use of the plastic waste for energy recovery (5.6 Mt) took place in municipal waste incinerators (92%), cement kilns (~75 kt) and other installations such as power plants (380 kt). For the plastics recovered for recycling, about 3 Mt was mechanically recycled and 0.35 Mt was recycled as feedstock (Plastics Europe, 2006). Mechanical recycling for plastic waste has increased rapidly in the last decade and energy recovery has doubled. The increase in mechanical recycling has reduced the need for primary plastic production by 2 Mt over the past ten years, an energy saving of about 125 PJ, or 2.5% of the total energy used in the European chemical and petrochemical industry.

Japan produced 14.5 Mt of plastic resins in 2004 and 10.1 Mt of plastic waste was generated. More than 90% is post-consumer waste: 60% is used for recovery, while 40% is land filled or incinerated without energy recovery. The recovery includes 18% material recycling, 3% recycling via liquefaction and blast furnaces, 5% use as solid fuel (refuse derived fuel) and 34% incineration with energy recovery (Ida, 2006).

The United States generated 28.9 Mt of plastic waste in MSW in 2005 (US EPA, 2006). Of this amount, 1.65 Mt (5%) was recovered and 14% was incinerated. The recycling of plastic bottles amounted to 0.87 Mt in 2004 (American Plastics Council, 2004). Plastic waste recovery in the United States has stabilised over the past ten years.

Paper

In 2004, paper consumption was 354 Mt, of which about 150 Mt were recovered (Figure 10.10). Paper recycling rates (waste paper used divided by total paper produced) are already high in many countries, varying between 30% in the Russian Federation to 64% in China. In 2005, the European paper and paperboard industry recycled 59% of all paper consumed.

Yet opportunities for increased paper recycling and energy savings are still attractive. The recovery rate in most non-OECD countries is 15 – 30 percentage points lower than in OECD countries. However, the rate at which paper is actually recycled in developing countries is higher than the recovery rate suggests. Large amounts of waste paper are imported from OECD countries. Between 10 – 20 GJ can be saved per tonne of paper recycled, depending on the type of pulp and the efficiency of the pulp production it replaces. The net effect on CO_2 emissions is less clear, as some pulp mills use significant amounts of bioenergy, while recycling mills may use fossil fuels. Biomass that is not used for paper production could potentially be used for dedicated power generation.

Table 10.3 ▶ *Plastic Waste Recycling by Country*

	Year	Total *kt/yr*	Packaging Households *kt/yr*	Total Plastic Waste %
Austria	2004			18
Belgium	2003		50	14
Denmark	2004			6
Finland	2004		13	8
France	2004		184	8
Germany	2004		633	30
Greece	2004			1
Ireland	2004			3
Italy	2003		480	17
Netherlands	2004			14
Norway	2004		26	20
Portugal	2003		24	5
Spain	2003	335	285	17
Sweden	2004			4
Switzerland	2004			8
United Kingdom	2002	350	305	7
United States	2004	1.65	1 500	6
Canada	2002	85	2	2
Japan	2004	2 110	515	21
Australia	2004	191	100	13
Total			**3 685**	

Sources: EPRO, 2006; PWMI, 2006; Simmons, *et al.*, 2006; US EPA, 2006.

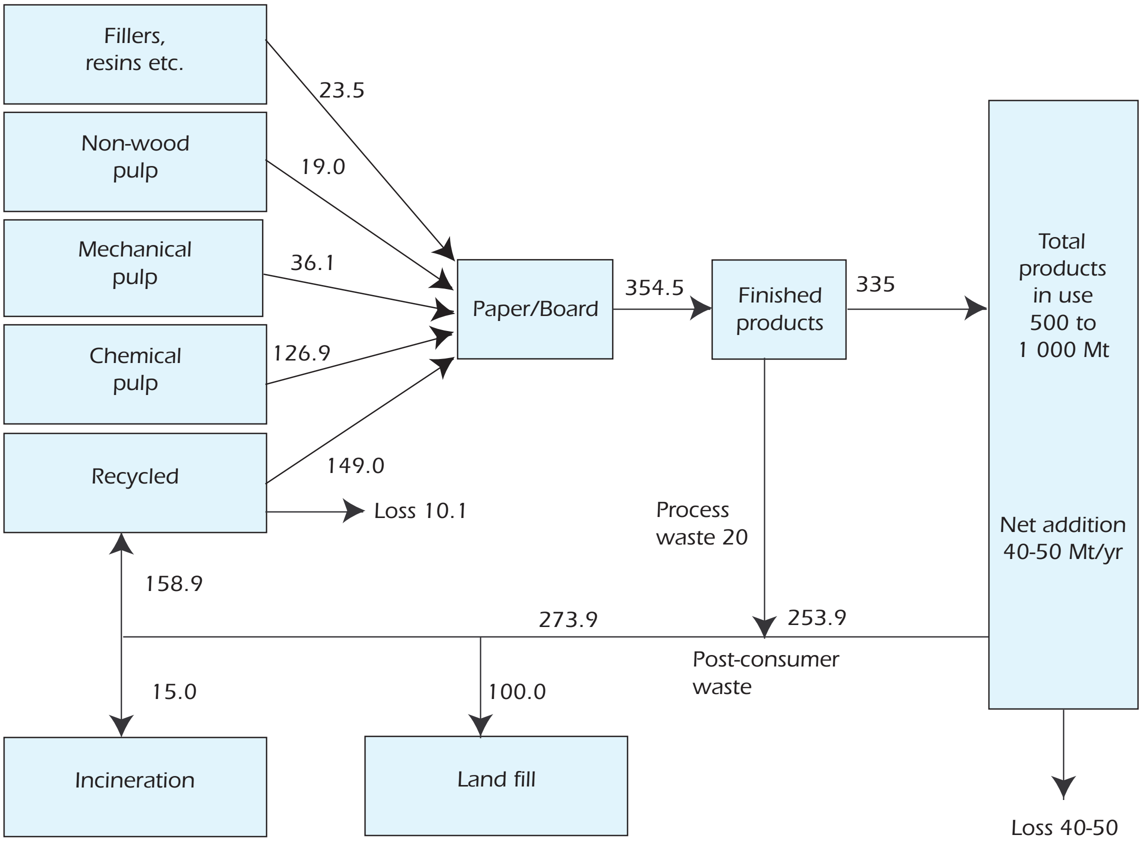
Paper can be recycled into a wide variety of paper and other cellulose products. As fibres degrade during recycling, paper is generally "down graded". Strength and quality considerations limit the recycling potential. On average, the fibre becomes too short after six recycling steps. Certain paper categories can not be recycled.

The additional paper recycling potential is approximately 50 – 75 Mt. The energy saving potential is 0.5 – 0.8 EJ. Note that paper recycling competes with its use for energy recovery.

Figure 10.10 ▶ *World Pulp and Paper Mass Balance, 2004*

(Mt/year)

Key point: Paper recycling rates are high.



Sources: UN FAO; IEA data.

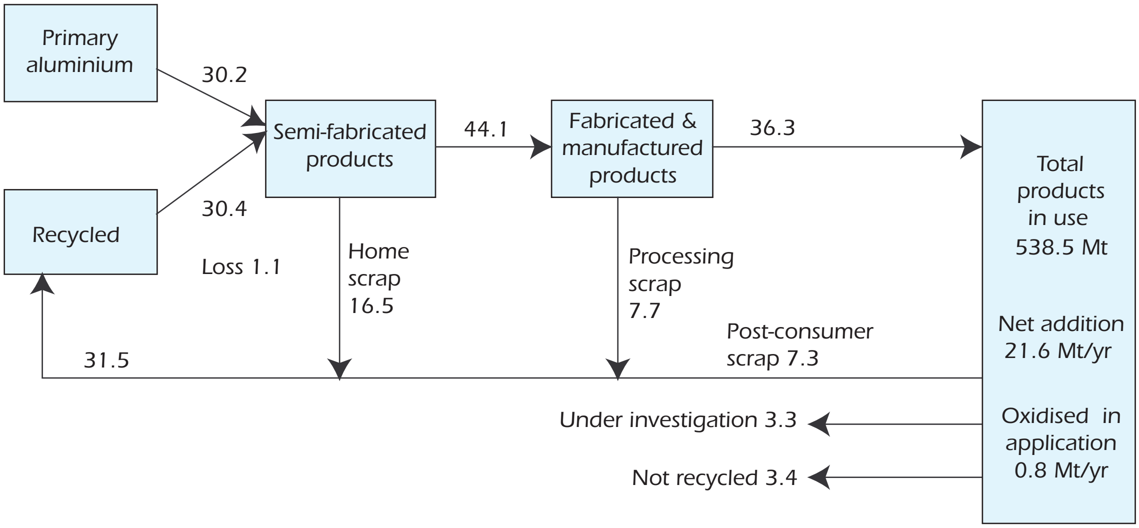
Aluminium

Figure 10.11 shows the world aluminium mass balance. More than half of aluminium metal comes from recycling, most of which is from home scrap and processing. The amount of finished product is about 60% of the ingot metal consumption. The product stock is still rapidly increasing and about three-quarters of all aluminium that is consumed remains stored in products.

Figure 10.11 ▶ *World Aluminium Mass Balance, 2004*

(Mt/year)

Key point: The availability of aluminium scrap is much lower than the consumption because of the increasing stock.



Sources: International Aluminium Institute.

Aluminium collection rates vary by region and by product category. For instance, collection rates from building and transport are high (80 – 90%), while collection rates for flexible packaging are low.

It is not clear where about 3.3 Mt of used aluminium ends up. Part of this scrap may end up in land fills or other sites. If this scrap could be recovered, it would allow additional energy savings. If the total remaining recycling potential amounts to 6.7 Mt, the energy saving potential is 0.9 – 1.2 EJ per year. Further analysis is recommended.

The aluminium recovery rate in the smelting process is about 96%, except for foils where the recovery amounts to only 30%. Because of the energy intensity of primary aluminium production, increased recycling of even small amounts can have significant energy benefits.

Steel

Steel is the most widely recycled material in the world. In 2005, about 450 Mt of scrap was recycled by the steel industry, compared to an apparent final steel consumption of 1 059 Mt (IISI, 2005). In addition, about 50 Mt of scrap is used to produce cast iron.

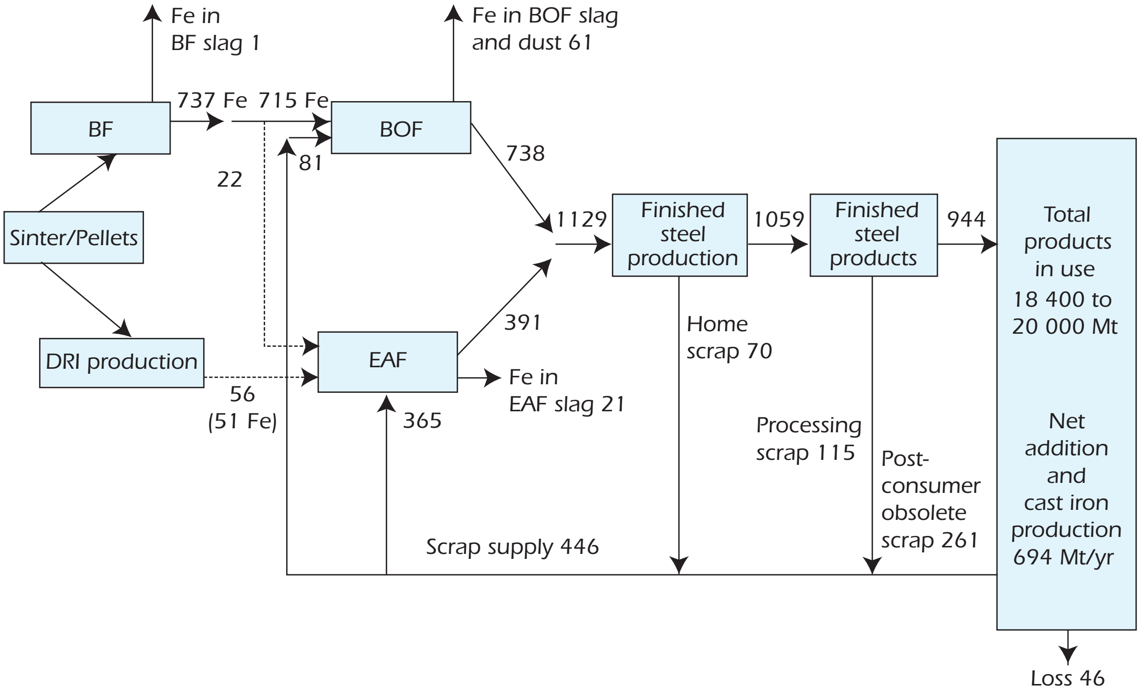
A better understanding of the global steel materials balance is needed in order to assess the additional recycling potentials. There are no detailed statistics. Estimates for the United States indicate that 9 Mt of steel scrap are lost as part of MSW (US EPA, 2006). Most of this loss is due to steel being a part of products that are not easily recyclable, such as discarded mattresses (springs), furniture (variety of steel products from hinges to support arms) and other miscellaneous steel components such as nails and small appliances (US EPA, 2006).

Almost 29 Mt of steel scrap is lost in Europe (Moll, *et al.*, 2005). The total for the US and Europe implies a lower estimate of 38 Mt loss in 2005. This is in line with the estimates of the International Iron and Steel Institute that estimates a historical recovery rate for obsolete (post-consumer scrap) scrap of 85%, and 46 Mt per year of loss worldwide (Hayashi, *et al.*, 2007). Another recent source estimates a lower recovery rate for obsolete scrap in the range of 50 – 70% (Neelis and Patel, 2006). The gap between the two estimates may be due to different definitions and approaches, such as the somewhat vague boundary between product use and waste release for steel. For example, considerable amounts of steel are used for building foundations that are not recovered but will be mostly reused when the building is replaced. Such steel could still be recovered at a later stage, so its classification as steel stock or loss is not evident. In the International Iron and Steel Institute terms that are used for Figure 10.12, products in use, net addition and loss figures are based on a definition of steel in use that includes all material that is potentially recoverable at a later stage as the location of the steel is known.

Figure 10.12 ▶ ***World Steel Mass Balance, 2005***

(Mt/yr)

Key point: Losses from the life cycle of steel are small; net additions to the stock constitute a major materials sink



Note: BF– blast furnace; BOF – basic oxygen furnace; DRI – direct reduced iron; EAF – electric arc furnace.

Source: Hayashi, *et al.*, 2007.

Total scrap recovery in steel production has increased from about 325 – 450 Mt from 1970 to 2005 (Figure 10.13). There are three types of scrap:

▷ Home scrap – arising in steel plants;

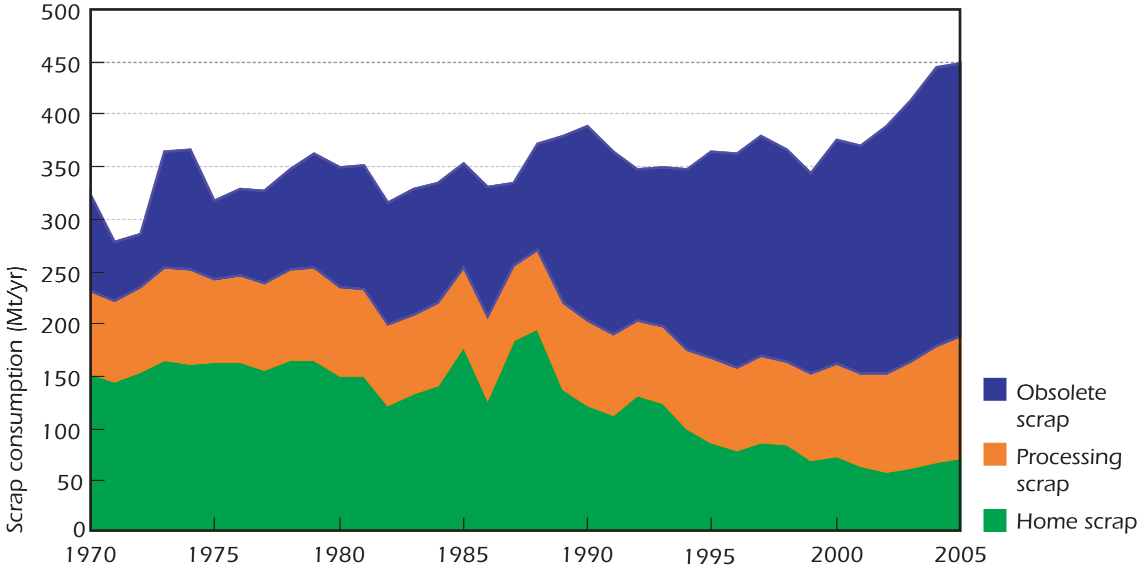
▷ Processing scrap – arising during the processing of finished steel into final products;

▷ Obsolete scrap – arising after product use (post-consumer).

This increase is the net result of a decreasing amount of home scrap and an increasing amount of obsolete scrap. It should be noted that the total crude steel production is roughly twice as high as the scrap arising. This results from an expanding economy where important amounts of steel are stored in the product stock.

Figure 10.13 ▶ ***Global Steel Scrap Recovery, 1970 – 2005***

Key point: Obsolete scrap has grown from a quarter to more than 40% of total scrap.



Source: International Iron and Steel Institute.

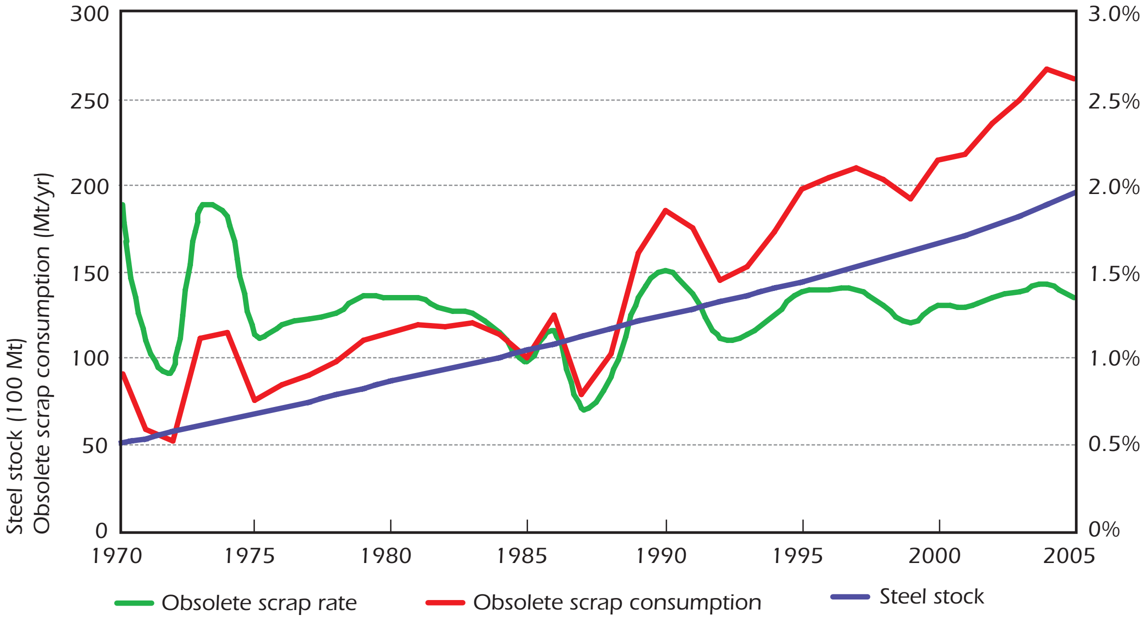
The decline in the amount of home scrap represents an important efficiency gain with fewer losses in the conversion of crude steel into finished steel products. Part of this reduction can be attributed to the shift from ingot casting to continuous steel casting and to the improvements in quality control that have reduced the need for re-melting of certain products.

The home scrap ratio has declined from 24 – 6.5%. This ratio measures the amount of in-house scrap as a share of total finished steel production. The remaining potentials to reduce home scrap are concentrated in a few countries, *e.g.* Russia, Ukraine, South Africa (Neelis and Patel, 2006).

Figure 10.14 shows a calculated recovery rate for obsolete scrap, based on a materials balance for crude steel production, finished steel products and scrap consumption. The difference between crude steel and finished steel products gives the amount of home scrap and processing scrap is calculated. The processing scrap rate was about 10% in 2005. The amount of obsolete scrap recovered is calculated as the difference between total scrap usage and the recovery of home and processing scrap. The steel stock is calculated based on the cumulative difference between the past amounts of steel material in new final products minus the amount of obsolete scrap. The figure suggests a roughly constant obsolete scrap recovery rate of 1 – 1.5% of the total steel stock for the period 1970 – 2005. It is not possible to measure the loss directly. Some reports estimate the obsolete scrap arising based on assumptions of average life span, which results in somewhat different figures (Neelis and Patel, 2006). As this is a derived coefficient that cannot be directly measured, the quality of the data can not be validated.

Figure 10.14 ▶ *Global Steel Obsolete Scrap Recovery Rate, 1970 – 2005*

Key point: Obsolete scrap recovery has been about 1 – 1.5% of total steel stock in the past twenty-five years.



Source: International Iron and Steel Institute.

While the stock of steel is increasing it seems unlikely that there is a store of obsolete steel that can be released in the short term. Recently steel scrap prices worldwide have increased dramatically, but scrap recovery has not increased significantly. More analysis is needed regarding the increasing steel product stock in the economy, the steel losses during use and the amount of obsolete scrap that is recovered.

Energy Recovery

Table 10.4 provides an overview of current energy recovery rates and remaining potentials. The savings potential is calculated based on the energy content of the waste. In fact, the energy recovery efficiency depends on the combustion technology

Table 10.4 ▶ *Global Incineration Rates and Additional Potential, 2004*

	Apparent Consumption *Mt/yr*	Post-consumer Waste *Mt/yr*	Total Waste Available *Mt/yr*	Incineration Rate *%*	Remaining Incineration Potential *Mt/yr*	Energy Saving Potential *EJ/yr*
Plastics and rubber	235	115	120	25	30 – 70	1 – 2.2
Paper and paperboard	354	254	274	8	25 – 50	0.4 – 0.8
Wood	600	284	344	25	100	1.5
Total						**3 – 4.5**

Source: IEA data.

and may be somewhat lower. Still, the savings potential is in the range of 2 – 3% of total manufacturing industry energy use, or 3 – 4.5 EJ per year in terms of energy content of the waste materials.

Municipal solid waste (MSW) incinerators represent the bulk of global waste incineration. But some waste is incinerated in other installations such as cement kilns and power plants.

In the United States, 246 Mt of MSW were generated and 33 Mt were incinerated in 2005 (US EPA, 2006). About 2.8 Mt of MSW were combusted in cement kilns, utility boilers, pulp and paper mills, industrial boilers and dedicated scrap tire-to-energy facilities, with tires contributing a majority of the total. The electricity generating capacity of MSW incinerators was 2.7 GW in 2004 (Themelis, 2006). In 2005, there were 88 waste-to-energy facilities in the United States, down from 102 in 2000 (US EPA, 2006).

In Europe, 52.6 Mt of MSW were incinerated in 2003. Efficiency of European waste incinerators is shown in Table 10.5. In Japan, virtually all MSW is incinerated, about 45 Mt per year. The electricity generating capacity of MSW incinerators is 1.5 GW and the average electricity generation efficiency is 10.5%. About 7.1 TWh electricity were generated in 2004, which equals about 0.7% of all power generation. No data are available regarding heat generation efficiency. In China, total MSW incineration capacity amounted to 7 Mt in 2003, only 1.5% of all waste is incinerated (Solenthaler and Bunge, 2003).[3]

In recent years, methane emissions from land fills have gained increasing attention. The methane emissions originate from biodegradable materials, mainly kitchen scrap and waste paper. As methane is a potent greenhouse gas, incineration reduces emissions more significantly than energy data would suggest, if it replaces land fill disposal.

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[3] Chinese MSW has a LHV of only 5 GJ/t, versus 10 – 12 GJ/t in OECD countries. This heating value is so low that coal must be co-combusted in special fluid-bed incinerators. However, the heating value is increasing in cities as the coal ash share declines and more plastic waste is generated.

Table 10.5 ▶ *Efficiency of European Waste Incinerators*

	Heat %	Electricity %	Total %
Sweden	97.7	1.7	99.4
Austria	65.1	3.4	68.6
Switzerland	51.4	13.7	65.1
Norway	58.3	1.7	60.0
Denmark	37.7	13.7	51.4
Average	*27.4*	*10.3*	*37.7*
France	27.4	1.7	29.1
Germany	20.6	6.9	27.4
Italy	13.7	10.3	24.0
Netherlands	0.0	17.1	17.1
Spain	0.0	17.1	17.1
United Kingdom	0.0	16.5	16.5
Portugal	0.0	16.1	16.1
Hungary	0.0	9.6	9.6

Source: Profu, 2004.

The biomass fraction (kitchen waste, paper, paperboard and wood) of MSW accounts for about half of the energy content, the other half is plastic and rubber. According to IEA statistics, 409 PJ of non-renewable MSW and 441 PJ of renewable MSW were incinerated with energy recovery in 2004, 97% of which in OECD countries. The average gross electric efficiency was 20%, and the average heat efficiency was 17%. A bottom-up estimate based on waste volumes and composition results in slightly higher values, about 1 013 PJ (Table 10.6). Given an average energy content of about 10 GJ/t MSW, about 80 Mt of waste was incinerated with energy recovery. The total amount of MSW incinerated worldwide was 150 Mt in 2004, which suggests that about half of all waste is incinerated with energy recovery (Themelis, 2003; IEA data).

The potential to use waste heat from MSW incineration depends on the proximity of appropriate applications. In the Nordic countries, most heat is used for district heating. Heat integration with industrial plants been successful in some cases. The fact that waste incinerator siting is often contentious means that heat integration potentials are often limited.

Table 10.6 ▶ *MSW Incineration with Energy Recovery, 2004*

	Food Waste *PJ/yr*	Paper/ Paperboard *PJ/yr*	Wood *PJ/yr*	Textiles *PJ/yr*	Rubber/ Leather *PJ/yr*	Plastic *PJ/yr*	Total *PJ/yr*
Eastern Asia	153.4	48.0	30.6	19.2	19.8	93.2	364.2
South-Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South-East Asia	20.3	13.5	11.0	2.8	2.0	18.4	68.0
Africa	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Europe	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eastern Europe	8.8	14.3	5.2	3.1	1.9	9.9	43.2
Northern Europe	4.7	13.5	4.7	0.9	11.9	7.5	43.2
Southern Europe	6.1	6.4	4.2	0.7	10.1	6.4	33.9
Western Europe	28.6	73.2	31.1	5.3	71.5	45.3	255.0
Caribbean	2.9	2.4	0.4	0.7	0.6	3.4	10.4
North America	38.1	58.6	16.6	9.9	7.3	52.2	182.7
Central America	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South America	3.4	2.9	0.8	0.4	0.2	4.4	12.2
Total	**266.3**	**232.8**	**104.7**	**43.1**	**125.2**	**240.7**	**1 012.8**

Source: IPCC, 2006; IEA data.

Petrochemical Products

In cement kiln incineration, plastic waste replaces coal on a thermal par basis. The CO_2 effect depends on the assumed baseline use of plastic waste. Compared with land fill disposal, where the carbon would be stored, the CO_2 reduction effect of incineration in cement kilns is the difference in CO_2 content between coal and plastic, about 21 kg/GJ. The CO_2 reduction effect is 0.7 t CO_2/t plastic waste. For incineration without energy recovery, the CO_2 saving effect is 94 kg/GJ, or about 3.3 t CO_2/t of plastic waste. These are two extremes.

Waste tire combustion in cement kilns is an established option. The use of plastic waste is often more limited. The kiln technology and local opposition often pose constraints for waste fuel use.

Some plastic waste is combusted in power plants. In 2004, about 380 kt of plastics waste was used as alternative fuel for power generation in Europe, with the Netherlands (96 kt) and Germany (92 kt) being the largest users (Plastics Europe, 2006). In the case of co-combustion in coal plants, the equivalent of about 14% of the energy content is needed for fuel preparation of the plastics (Table 10.7).

Table 10.7 ▶ *Energy Needs for Fuel Preparation for Plastics Co-combustion in Coal-Fired Power Plants*

	%
Mechanical separation	0.7
Pellet production	9.1
Road transportation	0.8
Pulverisation/injection	3.3
Fuel Product	100.0

Source: Schoen, *et al.* (n.d.).

Based on waste amounts there is potential for an additional 80 Mt of plastic waste incineration, however, 30 – 70 Mt seems realistic and is the basis for the estimate of 1 – 2.2 EJ per year remaining potential. Moreover, the efficiency of the current incineration processes can be improved by diverting high-calorific waste from MSW incinerators. Worldwide, the energy saving potential of improved energy recovery from plastic waste is between 3 – 4 EJ per year.

Box 10.1

Rubber Waste

About 9 Mt of natural rubber and 12 Mt of synthetic rubber were produced and consumed in 2005 (Rubber Study, 2006). Given losses during use about 8 – 10 Mt of waste rubber are released every year, equal to 0.35 EJ.

The United States represents 30% of the global rubber market (5 Mt rubber consumption per year, 4 Mt waste rubber). In 2003 in the United Sates, 40% of all waste tires were recycled and 45% of all scrap tires were incinerated. Of the 130 million tires that are incinerated, 53 million were incinerated in cement kilns, 26 million in pulp and paper mills, 24 million in power plants and 27 million in other kilns (US EPA, 2006b).

Europe represents a quarter of the global rubber market. In the EU25, 3.2 Mt of waste tires were released in 2005: 20% were exported or retreaded; 31% were used for materials recycling; 33% were incinerated with energy recovery, mainly in cement kilns; and 16% were disposed of in land fills (ETRMA, 2006).

In Japan, 1.02 Mt of waste tires were released in 2005: 15% were recycled; 52% were incinerated with energy recovery, mainly in cement kilns and pulp and paper mills; 21% were exported and 12% were stocked or reclaimed (JATMA, 2006).

While recycling and energy recovery rates in other parts of the world may be less favourable, the available data suggest that the potential for additional energy savings and CO_2 reductions through waste tire treatment is limited.

Paper

About 190 Mt (wet weight) of paper waste is disposed of in land fills per year. Assuming 50% moisture content, this equals about 100 Mt air dry weight with a 25 – 50% recovery rate of about 25 – 50 Mt. The lower heating value of paper waste ranges from 12 – 16 GJ/t. This waste could replace coal on a thermal par basis, *e.g.* in power plants. Overall, the energy saving potential is approximately 0.4 – 0.8 EJ per year. However, if the paper waste is incinerated in MSW incinerators, the energy saving effect is lower. Improved separation techniques can provide more paper waste for paper recycling and material use, this option therefore competes with increased waste paper incineration for energy recovery.

Wood

About 220 Mt of used wood comes from construction and demolition waste and an estimated 80 Mt from MSW. Because of treatment with paint, pesticides and other compounds a significant share of this wood can only be combusted in special waste incinerators. The estimated energy savings potential is 1.5 EJ per year, although there are large uncertainties in this estimate.

ANNEX A: Process Integration

Introduction

Integration of processes in industry has been used since the late 1970s. These days new tools and methods identify more efficient measures and system solutions from an energy and environmental point of view. Using process integration concepts, energy savings on the order of 10 – 40% can be achieved. This means that system solutions are as important as new technologies for reducing energy use in industry. Unlike new technology solutions, however, process integration measures vary from case to case in terms of technical solutions and energy savings. Therefore, it is more difficult to identify where and to what extent process integration tools have been used and how much they have contributed to energy savings.

This annex presents principles and benefits of process integration, energy savings in general terms, and experiences with process integration in some countries and of industries. It partly based on A *Briefing Package on Process Integration* prepared as part of Annex 1 of the IEA Process Integration Implementing Agreement.[1] A very rough first estimate is that process integration can save 2 – 5 EJ of primary energy per year, or 5 – 10% of all fuel use in the process industries.

Definition of Process Integration

An expert meeting in Berlin (1993) defined *process integration* to be:

"Systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects." Its scope is much wider than just heat recovery.

This definition points to design methods, but the term "process integration" is also used to describe physical arrangements such as the interconnection of equipment and process streams in an industrial plant. While some are concerned that process integration may cause problems for plant operation, it is a fact that many industrial processes today are highly integrated in order to reduce operating cost (energy and raw materials).

Process Integration Benefits and Applications

The initial focus of process integration from the early 1980s was to reduce energy consumption. Methods were further developed during the 1990s to address

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[1] IEA Process Integration Implementing Agreement, (2002), *A Briefing Package on Process Integration*, http://www.tev.ntnu.no/iea/pi/

objectives such as total annualised cost, plant operability and flexibility. More recently, measures such as environment and sustainability have become integral parts of process integration.

The benefits from process integration arise from using a systems approach. Most of the plants in the process industries are highly complex interconnections of advanced equipment and objectives related to economy, operability and environment across the structure of the overall plant.

Since process integration primarily is a systems oriented methodology, the largest benefits and savings are expected for complex processes or plants, *e.g.* oil refineries, chemical and petrochemical factories, pulp and paper mills. However, even apparently small and simple processes in the food and drink industry are sufficiently complex to make process integration methods interesting and valuable. Other industries, where process integration has been successfully applied, include pharmaceutical and metal industries.

Process integration is primarily used for design (original and retrofits), but certain aspects of planning and operation can also be addressed. The methods are general in nature and (at least some) apply to continuous, semi-batch and batch processes. The relationship between design, planning (long term) and operation (short term) is particularly strong in batch processes.

Process integration can be used for:

- ***Heat integration*** – identify the economically optimal level of heat recovery and to design a corresponding heat exchanger network with minimum equipment cost.
- ***Heat and power*** – identify economically optimal loads and levels for steam consumption and/or production, and to identify opportunities for combined heat and power systems. Thermodynamically “correct” and economically optimal use of heat pumps can also be easily identified by using the systematic methods of process integration.
- ***Plant productivity*** – remove bottlenecks for production throughput, *e.g.* where the energy system is limiting the mass flow through the process. This is certainly the case in many oil refineries where furnaces operate at maximum capacity.
- ***Environment and sustainable development*** – minimise the investments required to comply with regulations and societal expectations, *e.g.* reduce emissions and water use.

Process Integration Methodologies

The three major features of process integration methods are the use of:

- Heuristics (rules of thumb);
- Thermodynamics;
- Optimisation techniques.

There is significant overlap between the various methods and the trend today is strongly towards methods using all three features. The large number of structural alternatives in process design and integration is significantly reduced by the use of insight, heuristics and thermodynamics, and it then becomes feasible to address the remaining matters and the multiple economic trade-offs with optimisation techniques.

Despite this merging trend, it is still valid to say that *Pinch Analysis* and *Exergy Analysis* are methods with a particular focus on thermodynamics. *Hierarchical Analysis* and *Knowledge Based Systems* are rule-based approaches with the ability to handle qualitative knowledge. Optimisation techniques can be divided into deterministic (mathematical programming) and non-deterministic methods (stochastic search methods such as simulated annealing and genetic algorithms).

Use of Process Integration in Some Countries and Industries

A large survey on use and experience with process integration was carried out in seven countries as part of the IEA Process Integration Implementing Agreement, Annex 1, in 1997. (There are not more recent data.) A total of 92 completed questionnaires were received and the breakdown by country together with the number of respondents in each country who are using process integration (PI) techniques are shown in Table A.1.

Table A.1 ► *Process Integration Survey Results*

Country	Number of Completed Questionnaires	Number Using PI Techniques
United Kingdom	22	19
Finland	18	13
Sweden	13	9
Switzerland	13	9
Denmark	12	11
Portugal	9	4
Norway	5	4
Total	**92**	**69**

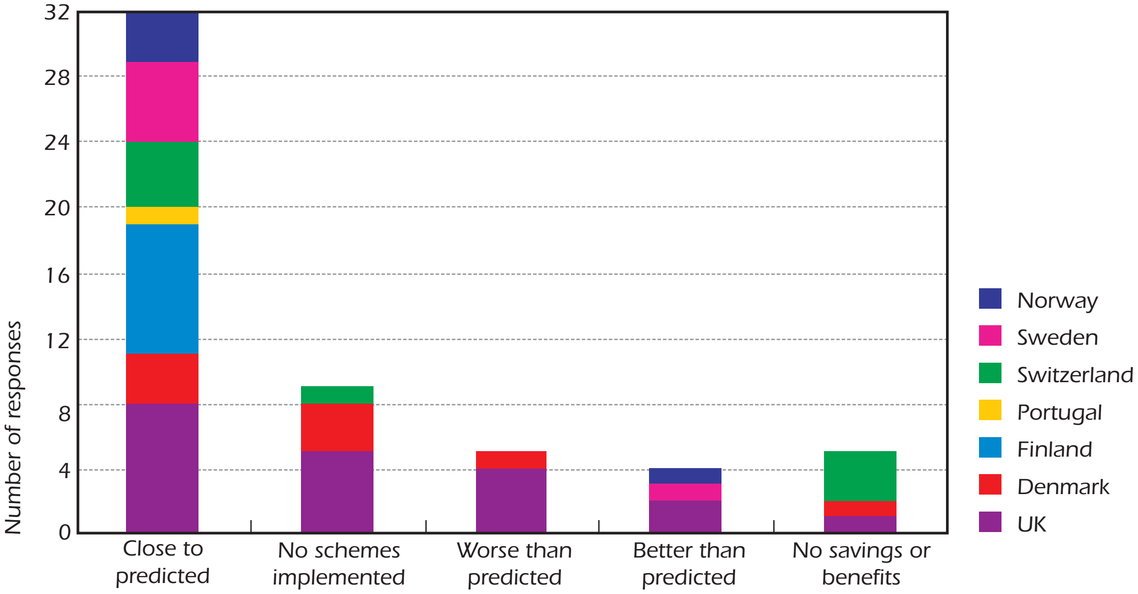
Source: IEA Process Integration Implementing Agreement, 2002.

Most of the responses to the questionnaire contained positive statements about process integration methods, including:

- ▷ Software is easy to use with straightforward data entry.
- ▷ Results are easy to understand and to explain to customers.
- ▷ Complex problems are simplified resulting in a better understanding of the process(es).
- ▷ Methods are structured and systematic.

Of those companies that have implemented the findings from process integration studies, most indicate that the savings have been close to predicted (Figure A.1). The figure shows that, in a number of cases, process integration schemes have not progressed beyond the feasibility stage. This is due to a prevailing climate of low capital investment in many companies. This suggests that important potential savings are available.

Figure A.1 ▶ *Results/Savings from Process Integration Schemes*

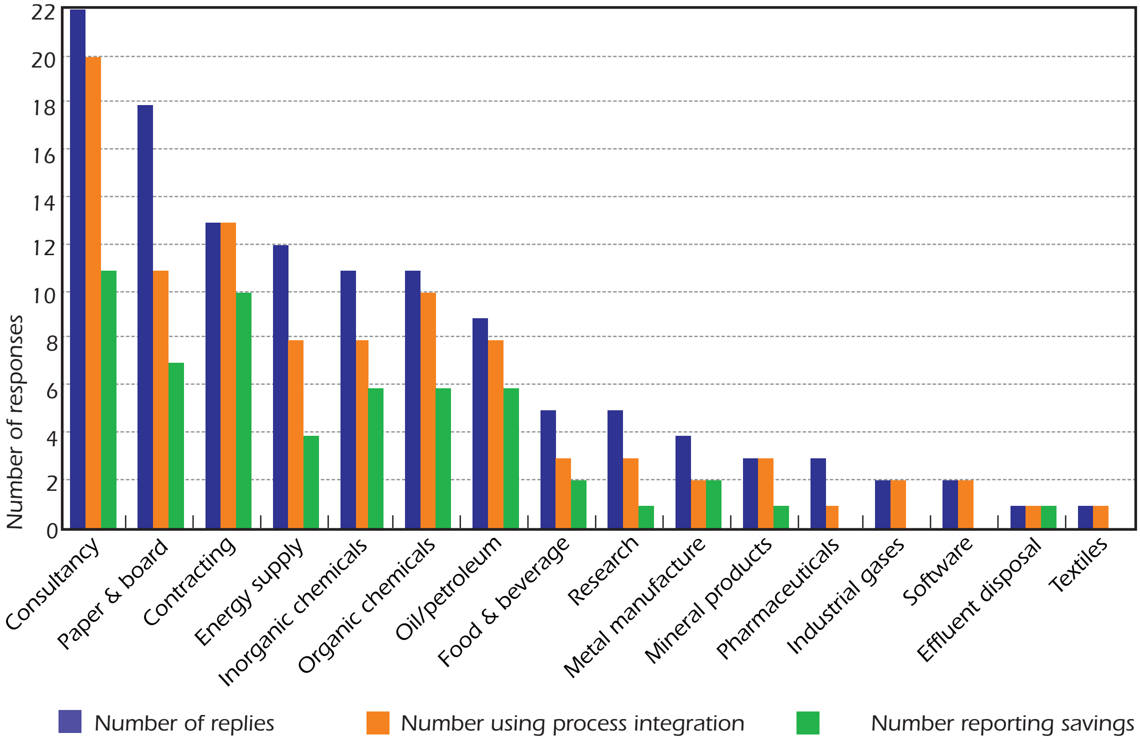


Source: IEA Process Integration Implementing Agreement, 2002.

Figure A.2 illustrates the extent to which process integration is being used in different industries and the level of reported success.

Pinch technology has been used in all of the cases illustrated in Figure A.2. The column indicating the number of companies reporting savings does not include studies that are at the feasibility stage. Hence, this number has the potential to increase significantly as companies increase their level of capital investment.

Figure A.2 ▶ *Savings from Process Integration Schemes by Industry*



Source: IEA Process Integration Implementing Agreement, 2002.

Experiences from Industry

Petrochemical Industry

Process integration technology has its origins in the petrochemical industry. It has been applied successfully at many oil refineries and offshore installations. In general, the aim in the petrochemical sector is to reduce energy requirements. Some of the schemes implemented to achieve energy savings include:

- Heat recovery from product streams, particularly from distillation columns.
- Boiler water and feed preheating using waste heat.
- Installation of additional levels of refrigeration.

Typical savings are a 20% reduction in energy consumption with some reports of savings as high as 50%. Payback periods are generally less than two years and can be as low as several months.

Chemical Industry

Process integration in the chemical industry has been used successfully for many years. Typical savings on the order of 20 – 50% have been reported.

An example from the United Kingdom is the use of water pinch analysis at a speciality chemicals site. The objective of the survey was to reduce water use and minimise the volume of wastewater requiring treatment. A number of opportunities were identified:

- Re-using water within processes,
- Water re-use in other processes, *e.g.* supplying cooling towers and water for washing down purposes from used process water,
- Segregating and treating effluent streams separately.

Implementation of these schemes has led to a reduction in fresh water and wastewater volumes of 30% with a 76% reduction in the chemical oxygen demand of the effluent. In addition, the introduction of segregated effluent treatment means that only 25% of the site's effluent requires secondary treatment. This has resulted in substantial cost savings compared with the centralised biological effluent treatment plant being considered before the study was carried out.

Fertilizer Industry

During ammonia production significant amounts of waste heat are generated that can be used for other processes. As well, ammonia is further processed into various types of nitrogen fertilizers, during which more heat is generated than can be used. While off-site use may be possible in some cases, important on-site opportunities remain. For example, a recent case study for nitric acid plants suggests that better process integration can result in 30% electricity savings.[2]

Iron and Steel Industry

In the iron and steel industry, process integration tools have been used since 1991 in Sweden, especially at SSAB. These integrated steel plants show a complex network of energy carriers, which also include energy exchange with heat and power plants and district heating networks in the surrounding community. Due to the complexity at SSAB Tunnplåt, mathematical programming was identified as a powerful methodology.

A tailor-made tool for this industry was developed and has been used frequently by SSAB. When the coke oven plant had to work on 60% production rate due to revamping, the tool was used to identify a system solution so that imbalances in the steel plant and the CHP plant were avoided. Another example is that the tool was used for decision making in a situation when revamping blast furnace plants or finding another solution. These uses of the process integration tool are difficult to quantify but have substantially contributed to energy savings and rational resource use.

In 2006 a centre of excellence for process integration in steel production (PRISMA) was founded in Sweden.

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[2] Nielsen, J.S. (2007), *Energy Efficiency Measures in Fertilizer Sites*. Paper presented at the IFA-IEA workshop on Energy Efficiency and CO$_2$ Reduction Prospects in Ammonia Production, Ho-Chi Minh City, 13 March.
http://www.fertilizer.org/ifa/technical_2007_hcmc/2007_tech_hcmc_papers.asp

Pulp and Paper Industry

Studies in the United States, Canada, Finland and Sweden have identified large potentials for energy savings in the pulp and paper industry. The results from process integration studies (mainly pinch analyses) have been implemented in more than 100 mills worldwide (IEA, Process Integration Implementing Agreement, Annex 3). In chemical pulp mills with relatively high energy consumption, more efficient heat exchanger networks lead to energy savings on the order of 10 – 40 %. In energy efficient mills, novel system solutions, *e.g.* integration of the evaporation plant and the secondary heat system, can lead to energy savings of 15 – 30%. In addition to energy saving in existing mills, this tool has also proven to be powerful for analysis in connection with development of new processes or mill concepts.

Food Industry

The process integration schemes that have been proposed and partly implemented in a brewing industry case study include:

- ▷ Optimisation of the wort vapour condenser.
- ▷ Installation of additional heat transfer area in the wort cooler and adjustment of its operating conditions.
- ▷ Improved use of hot water storage.
- ▷ Heat recovery on the keg cleaning operation.

Fossil fuel savings of 25% have been achieved with a payback period of three years averaged over the various retrofit projects.

In a large Swedish study in the meat industry, process integration tools have been used to identify energy saving opportunities.3 For example, in a case study a shaft work targeting method identified opportunities for reducing electricity demand by 10%. Process integrated heat pumps or CHP plants in the meat industry can be profitable and environmentally good solutions.

Textile Industry

A process integration study for a textile company in Portugal has identified the following energy saving opportunities:

- ▷ Use warm air from the compressors and cogeneration system instead of preheating fresh air.
- ▷ Increase the hot water production from the cogeneration unit and using it directly in the leaching and washing processes.
- ▷ Use hot water from the cogeneration unit for boiler make-up water.

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3. Fritzon, A., *Energy Efficiency in the Meat Processing Industry*, Chalmers University, Sweden.

ANNEX B: Industry Benchmark Initiatives

Iron and Steel

For iron and steel, the Asia Pacific Partnership (APP) proposes to develop separate indicators for steel production from basic oxygen furnaces and electric arc furnaces. There is no further breakdown of energy use by individual processes. The approach includes energy consumption and CO_2 emission from energy conversion and material preparation in upstream processes off-site from the steel plant, but does not include mining and transportation. Credits for energy sold to third parties are included in the calculation.

Cement

The APP is developing energy efficiency and CO_2 emission indicators for the cement industry. These indicators for cement are aligned with the Cement Sustainability Initiative (CSI) Protocol and will be used to help set benchmarks and estimate the potential for CO_2 emissions reductions. Possible energy and CO_2 emissions indicators being considered include:

- Heat intensity of clinker (gross & net [MJ/t clinker]).
- Power intensity of clinker (production pre clinker silo inlet [kWh/t clinker]).
- Total energy intensity of clinker (gross & net* [MJ/t clinker]).
- Power intensity of cement (processes after clinker silo outlet [kWh/t cement]).
- CO_2 intensity of cement (gross & net* [kg CO_2/t cement product]).

Cement Sustainability Initiative

Under the umbrella of the Cement Sustainability Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), a number of major cement companies have agreed on a methodology for calculating and reporting CO_2 emissions. The latest edition of the Cement CO_2 Protocol was published in June 2005 and is aligned with the March 2004 edition of the overarching greenhouse gas protocol developed under a joint initiative of the WBCSD and the World Resources Institute.

The Protocol provides a harmonised methodology for calculating CO_2 emissions, with a view to reporting these emissions for various purposes. It addresses all direct and the main indirect sources of CO_2 emissions related to the cement manufacturing process in absolute as well as specific or unit-based terms. The basic calculation methods used in the Protocol are compatible with the latest guidelines for national greenhouse gas inventories issued by the Intergovernmental Panel on Climate Change (IPCC), and with the revised WRI / WBCSD Protocol. Default emission factors suggested in these documents are used, except where more recent, industry specific data has become available.

However, one area where the recommendations of the Cement Protocol differ from the IPCC guidelines is in allowing credits for indirect emission reductions related to the use of wastes as alternative fuels and for waste heat exports. The premise for this crediting is that the combination of direct emissions impacts, indirect emission reductions and resource efficiency makes the substitution of alternative fuels for conventional fossil fuels an effective way to reduce global greenhouse gas emissions and the cement industry should be able to account for these wider benefits.

Petrochemicals and Chemicals

Solomon Associates Inc. (SAI) set up the first widely used international benchmarking system for ethylene crackers in the 1990s. Companies that participate in the benchmark are requested to fill a detailed survey on the performance of their units, including energy consumption on a semi-annual basis. More than half of all world crackers participate in the survey, representing more than two-thirds of the total production capacity. SAI acts as a clearing house and provides to individual participants a comparison between their units and a distribution of the other plants participating in the survey, accounting for feedstock use and operating conditions. More than 150 plants worldwide are tracked.

http://www.solomononline.com/data/xyli/olefins.pdf

Process Design Center

Process Design Center (PDC) has set up 50 energy benchmarks around world for petrochemical products. The petrochemical industry is very diverse and as a result needs a wide range of benchmarks. Short questionnaires are used and only anonymous overall energy efficiency performances are disclosed. Benchmarking for certain petrochemical products is difficult as only a couple of producers exist and each have their own process design. PDC is providing benchmarking services to the Dutch and Flemish energy efficiency initiatives.

http://www.process-design-center.com/4.2-enbenchprogr.htm

Philip Townsend Associates

Philip Townsend Associates (PTAI) performs various consulting and benchmarking in services for the plastics industry. PTAI is working with the Dutch and Flemish governments on their energy efficiency initiatives. PTAI is well known in the industry for its Performance and Cost Metrics Programs.

http://www.ptai.com/external_benchmarking/industry/index.asp

International Fertilizer Industry Association – Ammonia Benchmarking

The International Fertilizer Industry Association has a benchmarking activity for ammonia plants. The first round of benchmarking was in 2002 – 2003. Sixty-six ammonia plants participated in the effort. The next energy benchmarking survey is planned for 2007, based on 2005 – 2006 operating data. The analysis is done by Plant Survey Inc., a US company.

http://www.fertilizer.org/ifa/technical_2007_hcmc/PDF/2007_tech_hcmc_al_ansari.pdf

Pulp, Paper and Printing

Paprican Benchmark

In 2002, Paprican completed an analysis of energy use in the pulp and paper industry in Canada. This project surveyed 50 Canadian mills of which 45 are in operation today. The best performing mill was two times better than the worst mill (of the 45 still in operation). The other five mills which have since closed were 3 – 4 times less efficient. Higher energy prices in recent years made these mills unprofitable. Where possible, mills with multiple production lines were included in the analysis.

The best mills are not always the newest mills. There are new mills with heat recovery systems that were badly managed that performed worse then older well managed mills. Some of the older mills were better managed and more careful with energy use than newer mills which, although were designed with more energy efficient technology, suffered from poor energy management. Therefore, technology data alone do not suffice to assess the energy efficiency of pulp and paper plants.

Industrial Energy-Related Technologies and Systems Benchmark

The Industrial Energy-Related Technologies and Systems (IETS) Implementing Agreement is working on an energy benchmarking project in the pulp and paper industry. The goal is to provide a consistent reporting methodology across jurisdictions. The project defines: what to measure, data requirements, process areas and product grades. It is recommended that data be collected on energy and fibre produced and consumed. Energy is then allocated to different areas and products. The IETS project aims to provide a consistent measurement and reporting method for existing mills, not set a standard for mills to meet. Canada, Finland, Norway, Sweden and the United States are involved in this project, as well as the Confederation of European Paper Industries.

Poyry Consulting

Poyry has a database for benchmarking individual plants and paper machines. In order to compare energy efficiency across regions and countries, there is a need to include differences in the production profiles of countries. This task is further complicated by the fact that there is no one reliable source of energy data for the industry. Poyry Consulting uses technical age as a tool to evaluate (not measure) energy efficiency across countries and regions. As older technology will no longer keep up with best available technology, this tool provides a good indicator for comparing energy efficiency of plants and countries. It showed that the average technical age of printing and writing paper plants is 18 years in North America;

15 years in Latin America and 12 – 13 years in Europe. The lower the technical age, the higher the expected energy efficiency of the region.

Aluminium

International Aluminium Association

The International Aluminium Institute benchmarks the aluminium smelters of its members on an annual basis, covering about 80% of world primary aluminium production. The electricity use of primary aluminium smelters and the energy use for alumina production are monitored separately. Results are publicly available on the level of six world regions.

http://www.world-aluminium.org/iai/stats/index.asp

ANNEX C: Definitions, Acronyms and Units

Chapter 1 – 3 ▶

Asia Pacific Partnership

Asia Pacific Partnership comprising Australia, China, India, Japan, Korea, and the United States.

Best Available Technology

Best available technology is taken to mean the latest stage of development (state-of-the-art) of processes, facilities or of methods of operation which include considerations regarding the practical suitability of a particular measure for enhancing energy efficiency.

Biomass

Biomass includes solid biomass such as wood, animal products, gas and liquids derived from biomass, industrial waste and municipal waste.

Blast Furnace Gas

Blast furnace gas is produced in blast furnaces in the iron and steel industry. It is recovered and used as a fuel partly within the plant and partly in other steel industry processes or in power stations equipped to burn it.

Clean Coal Technologies (CCT)

Technologies designed to enhance the efficiency and the environmental acceptability of coal extraction, preparation, combustion and use.

Coal

A solid fuel with a high carbon content. In the IEA statistics, unless stated otherwise, coal includes all coal types and coal products: both coal primary products, including hard coal and lignite (brown coal), and derived fuels, including patent fuel, coke-oven coke, gas coke, coke-oven gas and blast-furnace gas. Peat is also included in this category.

Coking Coal

In IEA statistics, coking coal refers to coal with a quality that allows the production of a coke suitable to support a blast furnace charge. Its gross calorific value is greater than 23 865 kJ/kg (5 700 kcal/kg) on an ash-free but moist basis.

Coke-oven Coke

The solid product obtained from carbonisation of coal, principally coking coal, at high temperature. In IEA statistics semi-coke, the solid product obtained from the carbonisation of coal at low temperatures is also included along with coke and semi-coke.

Combined Heat and Power (CHP)

Combined heat and power, also called cogeneration, is a technology where electricity and steam or electricity and hot water are produced jointly. This increases the efficiency compared to separate electricity and heat generation.

Energy Intensity

Energy intensity is a measure of total primary energy use per unit of gross domestic product or per unit of physical product.

Hard Coal

Coal of gross calorific value greater than 5 700 kcal/kg on an ash-free but moist basis and with a mean random reflectance of vitrinite of at least 0.6. Hard coal is further disaggregated into coking coal and steam coal.

Heat

In the IEA energy statistics, heat refers to heat produced for sale only. Most heat included in this category comes from the combustion of fuels, although some small amounts are produced from geothermal sources, electrically-powered heat pumps and boilers.

Natural Gas

Comprises gases occurring in underground deposits whether liquefied or gaseous, consisting mainly of methane. In IEA statistics, it includes natural gas, both associated and non-associated as well as methane recovered from coal mines.

Naphtha

Naphtha is a feedstock destined either for the petrochemical industry, *e.g.* ethylene manufacture or aromatics production, or for gasoline production by reforming or isomerisation within the refinery.

Nuclear

Nuclear refers to the primary heat equivalent of electricity produced by a nuclear plant with an assumed average thermal efficiency of 33%.

Oil

Oil includes crude oil, natural gas liquids, refinery feedstocks and additives, other hydrocarbons, and petroleum products (refinery gas, ethane, liquefied petroleum gas, aviation gasoline, motor gasoline, jet fuel, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, paraffin waxes, petroleum coke and other petroleum products).

Other Asia Pacific

Afghanistan, Brunei, Cambodia, North Korea, Hong Kong, Fiji Islands, Indonesia, Kiribati, Lao, Macao, Malaysia, Mongolia, Myanmar, Philippines, PNG, Salomon, Samoa, Singapore, Taiwan, Thailand, Tonga, Vanuatu, Vietnam.

Other Petroleum Products

Other petroleum products include refinery gas, ethane, lubricants, bitumen, petroleum coke and waxes.

Other Renewables

Other renewables include geothermal, solar, wind, tide and wave energy for electricity generation. The direct use of geothermal and solar heat is also included in this category.

Other Transformation, Own Use and Losses

Other transformation, own use and losses covers the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes energy use and loss by gas works, petroleum refineries, coal and gas transformation and liquefaction. It also includes energy used in coal mines, oil and gas extraction and electricity and heat production. Transfers and statistical differences are also included in this category.

Power Generation

Power generation refers to fuel use in electricity plants, heat plants and combined heat and power plants. Both public plants and small plants that produce electricity for their own use (autoproducers) are included.

Renewables

Renewables refer to energy resources, where energy is derived from natural processes that are replenished constantly. In the IEA statistics, they include geothermal, solar, wind, tide, wave, hydropower, biomass and liquid biofuels.

Purchasing Power Parity (PPP)

The rate of currency conversion that equalises the purchasing power of different currencies, *i.e.* makes allowance for the differences in price levels and spending patterns between different countries.

Steam Coal

All other hard coal not classified as coking coal. Also included are recovered slurries, middlings and other low-grade coal products not further classified by type. Coal of this quality is also commonly known as thermal coal.

Synthetic Fuels

Synthetic fuel, or synfuel, is any liquid fuel obtained from coal or natural gas. The best known process is the Fischer-Tropsch synthesis. An intermediate step in the production of synthetic fuel is often syngas, a mixture of carbon monoxide and hydrogen produced from coal which is sometimes directly used as an industrial fuel.

Traditional Biomass

Traditional biomass refers mainly to non-commercial biomass use.

Total Final Consumption

Total final consumption (TFC) is the sum of consumption by the different end-use sectors. TFC is broken down into energy demand in the following sectors: industry, transport, other (includes agriculture, residential, commercial and public services) and non-energy use. Industry includes manufacturing, construction and mining industries.

Total Primary Energy Equivalent

An energy measure that accounts for losses in the production of final energy carriers.

Total Primary Energy Supply

Total primary energy supply is equivalent to primary energy demand. This represents inland demand only and, except for world energy demand, excludes international marine bunkers.

Chapter 4 ▶ **Aromatics**

Type of petrochemicals characterised by a ring structure, that are produced in refinery reformers and petrochemical plants. The most common are benzene, toluene and xylenes.

Catalytic Reforming

Process where a chemical component is converted into another chemical component, using a catalyst.

Diaphragm Process

Process for chlorine and sodium hydroxide production where two compartments of the electrolysis cell are separated by a permeable diaphragm.

Distillation Columns

Process equipment (usually a tall cylinder) used for separation of liquid chemical components based on different boiling points.

Intermediates

Chemical components that are converted into other chemical components.

Membrane Process

Process for chlorine and sodium hydroxide production where two compartments of the electrolysis cell are separated by an ion-exchange membrane, allowing only sodium ions and small water quantities to pass through it.

Mercury Process

Process for chlorine and sodium hydroxide production using a liquid mercury cathode.

Monomers

A monomer is a small hydrocarbon molecule with a double bond between carbon atoms that may become chemically bonded to other monomers to form a polymer.

Olefin

Class of unsaturated open-chain hydrocarbons that have the general chemical formula C_nH_{2n}. The simplest olefins, ethylene, propylene and butylene are gases.

Polymerisation

Process of transforming a combination of monomers into a polymer using a chemical reaction.

Pyrolysis Furnace Section

The high-temperature section of a steam cracker for ethylene production where the main chemical reaction takes place.

Pyrolysis Gasoline

A naphtha-range product with a high aromatic content, used either for gasoline blending or as a feedstock for a BTX extraction unit. Pyrolysis gasoline is produced in an ethylene plant that processes butane, naphtha or gasoil.

Reformate

Product from a petroleum-refinery reforming process (thermal or catalytic reforming).

Steam Cracking

A petrochemical process in which saturated hydrocarbons are broken down into smaller hydrocarbons. It is the principal industrial method for producing the olefins (ethylene, propylene, butadiene).

Chapter 5

Basic Oxygen Furnace

Process where liquid hot iron metal is converted into steel, using oxygen injection.

Blast Furnace

A blast furnace is a type of metallurgical furnace used for smelting. Fuel and ore are continuously supplied through the top of the furnace, while air (oxygen) is blown into the bottom of the chamber, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace. This type of furnace is typically used for smelting iron ore to produce hot metal (pig iron), an intermediate material used in the production of commercial iron and steel.

Coke Oven

Pyrolysis process for conversion of coal into coke.

Coke Oven Gas

Gaseous by-product of coke making.

Direct Reduced Iron

Product made through chemical reduction of iron ore pellets in their solid state.

Electric Arc Furnace

Furnace for smelting of iron scrap and other metals using electricity.

Iron, Pig iron and Hot Metal

Iron, pig iron and hot metal refers to various mineral aggregates from which the steel metal is obtained by the conversion of various iron ores by reduction either into pig iron (hot metal) or into a solid spongy form (sponge iron or direct reduced iron) or into lumps by various direct reduction processes.

Quenching

Quenching is the rapid cooling of a solid to lock it into a metastable crystal structure rather than allow it to cool slowly and revert to a softer structure. It is most commonly used to harden steel.

Sintering

Sintering involves the heating of fine ore, causing it to agglomerate into larger granules.

Chapter 6 ▶

Blast Furnace Slag

A by-product from the blast furnace iron production process.

Dry Kiln

A kiln that produces cement clinker using dry limestone feedstock.

Fly-Ash

A residue from coal fired power plants that can be used for cement making.

Intermittent Kilns

Kilns that operate in batch mode.

Lime Kilns

Kilns that convert limestone and dolomite into burned lime.

Oxy Fuel Furnaces

A furnace that uses oxygen or enriched air.

Portland Cement

The most common cement type that contains a high share of clinker.

Portland Fly-ash Cement

A cement type that contains fly-ash and cement clinker.

Roller Kiln

A specialty type of kiln, common in tableware and tile manufacture, is the Roller-hearth Kiln, in which ware placed on bats is carried through the kiln on rollers.

Shaft Kilns

Vertical kilns for cement making.

Tunnel Kilns

A continuously operated brick kiln in the shape of a tunnel.

Wet Kiln

A kiln that produces cement clinker using wet limestone feedstock.

Chapter 7 ▶

Black Liquor

This is a recycled by-product formed during the chemical pulping of wood in the pulp and paper industry. In this process, lignin in the wood is separated from cellulose, with the latter forming the paper fibres. Black liquor is the combination of the lignin residue with water and the chemicals used for the extraction of the lignin and are burned in a recovery boiler. The boiler produces steam and electricity and recovers the inorganic chemicals for recycling throughout the process.

Chemical Pulp

This is a thermo-chemical process in which chips are combined with strong solvents and heated under pressure to separate fibres from lignin. Spent liquor (black liquor) can be concentrated and burned for process heat.

Mechanical Pulp

Grinding and sharing of wood chips. Primarily used for low-grade papers. Mechanical pulping has a high yield but results in a pulp that contains substantial impurities that limit its use.

Chapter 8 ▶

Bayer Process

Process for production of alumina from bauxite ore.

Electrolysis

Process for chemical conversion that uses electricity for a chemical reaction.

PFC

Perfluorocarbons, a group of potent greenhouse gases.

Chapter 9 ▶

Exergy Analysis

Method to increase the energy efficiency of complex systems, based on thermodynamic principles.

Motor Systems

A motor system is a machine, *e.g.* pump, fan, compressor, that is driven by a rotating electrical machine (motor).

Pinch Analysis

A methodology for minimising energy consumption of chemical processes by optimising heat exchange between various flows that need heating and cooling.

Steam Systems

A combination of equipment that provides heat using steam.

Chapter 10 ▶

Apparent Consumption

Apparent consumption is production plus imports minus exports.

Back-to-polymer Recycling

Process where used plastics are used for the production of plastics.

Back-to-monomer Recycling

Process where used plastics are used for the production of olefins and other monomers.

Back-to-feedstock Recycling

Process where waste plastics are used for the production of oil-type products.

Regional Definitions

Africa

Comprises: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo, the Democratic Republic of Congo, Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, the United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe.

Central and South America

Comprises: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts-Nevis-Anguilla, Saint Lucia, St. Vincent-Grenadines and Suriname, Trinidad and Tobago, Uruguay and Venezuela.

China

Refers to the People's Republic of China.

CIS

Commonwealth of Independent States which includes: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Ukraine, Uzbekistan and Tajikistan.

Developing Countries

Comprises: China, India and other developing Asia, Central and South America, Africa and the Middle East.

EU15

Refers to the fifteen member countries of the European Union prior to the accession of ten candidate countries on 1 May 2004. The EU15 includes: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the United Kingdom.

EU25

Comprises: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Spain, Slovakia, Slovenia, Sweden and the United Kingdom.

Europe-33

Albania, Austria, Belgium, Bosnia, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland, Turkey and United Kingdom.

Former Soviet Union (FSU)

Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Ukraine, Uzbekistan, Tajikistan and Turkmenistan.

G8

Canada, France, Germany, Italy, Japan, Russia, United Kingdom and United States.

Annex I Parties to the Kyoto Protocol

Australia, Austria, Belarus, Belgium, Bulgaria, Canada Croatia, the Czech Republic, Denmark, Estonia, the European Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States.

Middle East

Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen.

OECD Europe

Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Organization of Petroleum Exporting Countries (OPEC)

Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates and Venezuela.

Other Developing Asia

Afghanistan, Bangladesh, Bhutan, Brunei, Chinese Taipei, Fiji, French Polynesia, Indonesia, Kiribati, Democratic People's Republic of Korea, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, the Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Vietnam and Vanuatu.

Western Europe

Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey and United Kingdom.

Acronyms

ADS	Adjustable speed drive
Al	Aluminium
Al_2O_3	Alumina
APME	Association of Plastic Manufacturers in Europe
APP	Asia Pacific Partnership
ASU	Air separation units
BAT	Best Available Technology
BF-BOF	Blast furnace-blast oxygen furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
BP	British Petroleum
BREF	Best Available Techniques reference document
BTF	Back-to-feedstock
BTM	Back-to-monomer
BTX	Benzene, toulene, xylene
CAC	Compressed Air Challenge
$CaCO_3$	Calcium carbonate (limestone)
CaO	Calcium oxide

CDM	Clean Development Mechanism
CDQ	Coke dry quenching
CEN	European Committee for Standardisation
CEPI	Confederation of European Paper Industries
CH_4N_2O	Urea
CHP	Combined heat and power
CI	Compression ignition
CIEEDAC	Canadian Industrial Energy end-Use Data and Analysis Centre
CO	Carbon monoxide
CO_2	Carbon dioxide
COG	Coke oven gas
CRI	Coke reactivity index
CSI	Cement Sustainability Initiative
CSR	Coke strength after reaction
CTCC	Combustion turbine combined cycle
CTL	Coal-to-liquids
DRI	Direct reduced iron
DTI	Department of Trade and Industry (UK)
EAF	Electric arc furnace
EEA	Environment and Energy Agency
EEI	Energy efficiency index
EIA	Energy Information Agency (US)
EMFA	European Fertilizer Manufacturing Association
EPIC	Environment and Plastics Industry Council Canada
EPRO	European Association of Plastics Recycling and Recovery Organisations
ERPC	European Recovered Paper Council
ESCO	Energy service companies
ETRMA	European Tyre and Rubber Manufacturers
EuLA	European Lime Association
F&B	Food and beverage sub-sector

FAO	Food and Agriculture Organization
FCC	Fluidized catalytic crackers
FCC	Fluid catalytic cracker
Fe	Iron metal
Fe_2O_3	Hematite
FeO	Iron oxide
G8	Group of 8
GBFS	Granulated blast furnace slag
GE	General Electric
GEF	Global Environment Facility
GGBFS	Ground granulated blast furnace slag
GHG	Greenhouse gases
GHR	Gas heated reformers
GTL	Gas-to-liquids
H_2	Hydrogen
HBI	Hot briquetted iron
HDA	Hydrodealkylation
HDPE	High density polyethylene
HVC	High value chemicals
IETS	Industrial Energy-related Technologies and Systems (IEA Implementing Agreement)
IFA	International Fertilizer Industry Association
IGCC	Integrated Gasification Combined Cycle
IISI	International Iron and Steel Institute
IPCC	Intergovenmental Panel on Climate Change
ISO	International Organization for Standardization
ISP	Inline strip production
JATMA	Tyre Industry of Japan
JCA	Japanese Cement Association
JISF	Japan Iron and Steel Federation
LCA	Life cycle analysis

LDPE	Low density polyethylene
LDV	Light duty vehicles
LHV	Low heat value
LLDPE	Linear low density polyethylene
LT heat	Low temperature heat
MECS	Manufacturing Energy Consumption Survey
MEPS	Minimum efficiency performance standards
METI	Ministry of Economy, Trade and Industry (Japan)
MFA	Materials flow analysis
MHI	Mitsubishi Heavy Industries
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
NAFTA	North American Free Trade Agreement
NaOH	Sodium hydroxide
NEAT	Non-energy emission accounting tables
NGCC	Natural gas combined cycle
NH_3	Ammonia
NOx	Nitrogen oxides
NRCAN	Natural Resources Canada
NSC	Nippon Steel Corporation
OCT	Olefin conversion technology
OGJ	Oil and Gas Journal
PCI	Pulverised-coal injection
PEI	Product efficiency indicator
PET	Polyethylene terephthalate
PFC	PerFluoroCarbons
PI	Process integration
PO	Polyolefins
PP	Polypropylene
PSA	Pressure swing absorption
PVC	Polyvinylchloride

PWMI	Plastics Waste Management Institute
R& D	Research and development
SCORE	Selective cracking optimum recovery
SEC	Specific energy consumption
SG	Spheroidal graphite
SI	Spark ignition
STDP	Selective toluene disproportionation process
Tcs	Tonne of crude steel
TDP	Toluene disproportionation
tHM	Tonne of hot metal
TPES	Total primary energy supply
TRT	Top pressure recovery turbines
UEC	Unit energy consumption
US DoE	United States Department of Energy
USC	Ultra selective coil design
USGS	United States Geological Survey
VCM	VinylChlorideMonomer
VFDs	Variable frequency drive
VPSA	Vacuum pressure swing adsorption
VSA	Vacuum swing adsorption
WBCSD	World Business Council on Sustainable Development
WRI	World Resources Institute

Units

MJ	Megajoule = 10^6 joules
GJ	Gigajoule = 10^9 joules
PJ	Petajoule = 10^{15} joules
EJ	Exajoule = 10^{18} joules
t	Tonne = metric ton = 1 000 kilogrammes
Mt	Megatonne = 10^3 tonnes

Gt	Gigatonne = 10^9 tonnes
W	Watt
kW	Kilowatt = 10^3 watts
MW	Megawatt = 10^6 watts
GW	Gigawatt = 10^9 watts
TW	Terawatt = 10^{12} watts
kW_{th}	Kilowatt thermal capacity
kW_{el}	Kilowatt electric capacity
bar	A unit of pressure nearly identical to an atmosphere unit. 1 bar = 0.9869 atm (normal atmospheric pressure is defined as 1 atmosphere).
bbl	Barrel
BOE	Barrels of oil equivalent. 1 BOE = 159 litres
°C	Degrees Celsius
kWh	Kilowatt-hour
Nm^3	Normal cubic metre. Measured at 0 degrees Celsius and a pressure of 1.013 bar.
ppm	Parts per million
Pa	Pascal
A	Ampère
V	Volt

ANNEX D: References

Chapter 1 – 2 ▶ Asia Pacific Energy Research Centre (APERC) (2000), *Energy Efficiency Indicators for Industry in the APEC Region*, Tokyo, Japan.

Canadian Industrial Energy End-Use Data & Analysis Centre (CIEEDAC) (2002), *Development of Energy Intensity Indicators for Canadian Industry: 1990 to 2000*, Burnaby, BC, Canada.

Energy Information Administration (EIA) (1995), *Changes in Energy Intensity in the Manufacturing Sector 1985-1991: Manufacturing Energy Consumption Survey*. Washington, D.C., United States.

EIA (1995), *Measuring Energy Efficiency in the United States' Economy: A Beginning.* DOE/EIA-0555(95)/2.US Energy Information Administration. Washington, D.C., United States.

Farla, J. and K. Blok (2000), *The Use of Physical Indicators for the Monitoring of Energy Intensity Developments in the Netherlands, 1980-1995, Energy* 25 (7-9), pp. 609-638.

Freeman, S.L., M.J. Niefer and J.M. Roop (1996), *Measuring Industrial Energy Efficiency: Physical Volume Versus Economic Value.* Pacific Northwest National Laboratory (PNNL-11435).

G8 (2005), *The Gleneagles Communiqué*, http://www.g8.gov.uk/.

International Energy Agency (IEA) (2004), *Oil Crises and Climate Challenges: 30 Years of Energy Use in IEA Countries*, IEA/OECD, Paris, France.

IEA (2005), *G8 and Governing Board Follow-Up*, IEA/SLT/CERT(2005)16. 4 October 2005.

IEA (2006a), *Energy Technology Perspectives: Scenarios & Strategies to 2050*, IEA/OECD, Paris.

IEA (2006b), *Industrial Motor Systems Efficiency: Towards a Plan of Action*, Proceedings of a workshop 15–16 May 2006, IEA, Paris, France.
http://www.iea.org/Textbase/work/2006/motor/proceedings.pdf.

IEA/CEFIC (2007), *Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products*, Workshop Proceedings, 12-13 December 2006. IEA, Paris, France.
http://www.iea.org/Textbase/work/2006/petrochemicals/proceedings.pdf.

IEA/WBCSD (2006a), *Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry: Towards a Plan of Action*, Workshop Proceedings, 4–5 September 2006. IEA, Paris, France.
http://www.iea.org/Textbase/work/2006/cement/proceedings.pdf

IEA/WBCSD (2006b), *Energy Efficient Technologies and CO_2 Reduction Potentials in the Pulp and Paper Industry*, Workshop Proceedings, 9 October 2006. IEA, Paris.
http://www.iea.org/Textbase/work/2006/pulppaper/proceedings.pdf.

Martin, N., *et al.* (1994), *International Comparisons of Energy Efficiency*, Workshop Proceedings, March 6-9, Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Nanduri, M., J. Nyboer and M. Jaccard (2002), *Aggregating Physical Intensity Indicators: Results of Applying the Composite Indicator Approach to the Canadian Industrial Sector*, *Energy Policy* 30, pp. 151-163.

Natural Resources Canada, Office of Energy Efficiency (NRCAN) (2000), *Energy Efficiency Trends in Canada: An Update: Indicators of Energy Use, Energy Efficiency and Emissions,* Ottawa.

Phylipsen, G.J.M., *et al.* (1997), *International Comparisons of Energy Efficiency: Methodologies for the Manufacturing Industry*, Energy Policy 25(7-9), pp. 715-725.

Phylipsen, G.J.M. (2000), *International Comparisons & National Commitments: Analyzing Energy and Technology Differences in the Climate Debate,* PhD Thesis, Utrecht University, Utrecht, Netherlands.

Worrell, E., L. *et al.* (1997), *Energy Intensity in the Iron and Steel Industry: A Comparison of Physical and Economic Indicators*, Energy Policy, 25 (7-9).

Chapter 3 ▶ International Energy Agency (IEA) (1997), *Indicators of Energy Use and Efficiency, Understanding the Link between Energy and Human Activity*, OECD/IEA, Paris, France.

IEA (2004), *Oil Crises and Climate Challenges. 30 Years of Energy Use on IEA Countries*, OECD/IEA, Paris, France.
http://www.iea.org/textbase/nppdf/free/2004/30years.pdf.

IEA (2005), *Energy Statistics Manual*, OECD/IEA, Paris, France. http://www.iea.org/textbase/nppdf/free/2005/statistics_manual.pdf.

Ono, T. (2006), *Boundary Definitions*. The Asia-Pacific Partnership on Clean Development and Climate 2nd Steel Task Force Meeting and 1st Workshop, 27 September, Tokyo, Japan.

Chapter 4 ▶ American Chemistry Council (2005), *The Ethylene Chain*.
www.americanchemistry.com, posted 18-Sept-2005.

Business Communications Company Research Inc. (BCC) (2003), *The Global Industrial Gas Business*. Wellesley, United States.

Berra, C. and J. Wu (2005), *ABB Lummus Global Propylene Production via Olefins Conversion Technology*, in Meyers, R.A. (ed.) *Handbook of Petrochemical Production Processes*. McGraw-Hill, New York, United States .

Bowen, C. P. (2006), *Development Trends for Ethylene Crackers: Existing Technologies and RD&D*, IEA/CEFIC Workshop Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Cagnolatti, A.A. (2005), *Global Ethylene Plant Performance Comparisons*. Paper presented at the 2005 AIChE Spring National Meeting. 17th Annual Ethylene Producers Conference, April 11-14, Atlanta, Georgia, United States.

Conseil Européen de l'Industrie Chimique (CEFIC) (2004), *IPPC BAT Reference Document – Large Volume Solid Inorganic Chemical Family – Process Bref for Soda Ash* – European Soda Ash Producers Association (ESAPA), Brussels, Belgium.

DiZanno, P. (2004), *Mega Projects Deserve Large and Proven Technologies*, Energy Frontiers International, Gas-to-Market Conference, September.

Energetics (2000), *Energy and Environmental Profile in the US Chemical Industry*, prepared for the DOE/OIT, May 2000, http://www.eere.energy.gov/industry/chemicals/tools_profile.html.

Energy Environmental Analysis Inc. (EEA) (2004), *Sector Profiles of Significant Large CHP Market*, submitted to Oak Ridge National Laboratory, March 9. Washington, D.C., United States.

Euro Chlor (2006), *Chlorine Industry Review*. Brussels, Belgium.

http://www.eurochlor.org/index.asp?page=696.

European Association of Plastics Recycling and Recovery Organisations (EPRO) (2006), *Statistics on Plastic Waste Management in Europe.* Brussels, Belgium.

http://www.epro-plasticsrecycling.org/c_81_1.html.

European Fertilizers Manufacturers Association (EFMA) (2000), *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*, Booklet 1-8, European Fertilizer Manufacturing Association, Brussels, Belgium.

European Union (EU) (2003), *IPPC Reference Document on BAT for Large Volume Organic Chemical Industry*, February 2003, Brussels, Belgium.

Freedonia Market Research Group (2006), *World Carbon Black to 2008.* http://www.freedoniagroup.com/.

Frostbyte (2005), http://www.cryoindservice.com/downloads/frostbyte_05summer.pdf.

Gielen, D. (1997), *Technology Characterization for Ceramic and Inorganic Materials*, Report ECN-C-97-064. Netherlands Energy Research Foundation ECN, Petten.

Gielen, D., K. Bennaceur and C. Tam (2006), *IEA Petrochemical Scenarios for 2030-2050*: *Energy Technology Perspectives*, IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris.

Hedman, B. (2005), *CHP Market Status*, presented at the Gulf Coast Road-mapping Workshop, April. http://files.harc.edu/Sites/GulfCoastCHP/News/RoadmapWorkshop2005/GulfCoastCHPOverview.pdf.

Heinen, R. and E. Johnson (2006), *Efficient Technology and CO_2 Reduction for Petrochemical Products,* IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Ida, H. (2006), *Current Status of Plastics Recycling in Japan,* IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Ingham, J. (2006), *Improving Markets for Waste Plastics,* Chapter 3 in Improving Recycling Markets, OECD, Paris, France.

Integrated Pollution, Prevention and Control (IPPC) (2006), *Integrated Pollution, Prevention and Control: Reference Document on Best Available Techniques for the Manufacture of Large Volume of Inorganic Chemicals – Ammonia, Acids, and Fertilizers*, December 2006.

International Energy Agency (IEA) (2006), *Energy Technology Perspectives, Scenarios & Strategies to 2050*, OECD/IEA, Paris, France.

International Fertilizer Industry Association (IFA) (2006), *Energy Efficiency in Ammonia Production: Executive Summary for Policy Makers.*
www.fertilizer.org.

Kapur, S. (2005), *ABB Lummus Global SRT Cracking Technology for the Production of Ethylene,* in Meyers, R.A. (ed.) Handbook of Petrochemical Production Processes. McGraw-Hill, New York, United States.

Karangle, H.S. (2007), "*Energy Efficiency and CO_2 Emissions in the Indian Ammonia Sector*", IFA-IEA Workshop on Energy Efficiency and CO_2 Reduction Prospects in Ammonia Production, 13 March, Ho Chi Minh City, Vietnam.
http://www.fertilizer.org/ifa/technical_2007_hcmc/2007_tech_hcmc_papers.asp

Keuken (2006), *Benchmarking of Energy Efficiency and CO_2 Emissions in the Petrochemical Sector*, IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Leendertse, A. and J. van Veen (2002), *Dutch Notes on BAT for the Carbon Black Industry*. http://www.infomil.nl/legsys/bref/nl-carbon.pdf.

Lurgi (2006), *Lurgi MegaMethanol*.
http://www.lurgi.com/website/fileadmin/pdfs/brochures/Br_MegaMethanol.pdf.

Meidel, R. (2006), *Cogeneration, Opportunities in Today's Power Markets,* ExxonMobil Dow Chemical, IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Mills, R. (2006), *Energy in Petrochemicals: Dow Chemical*, IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Ministry of Economy, Trade and Industry (METI) (2006), *World Production Capacity of Key Petrochemicals, 2004*, Chemical Division, Tokyo, Japan.

Neelis, M., M. Patel and M.D. Feber (2003), *Improvement of CO_2 Emission Estimation from the Non-Energy Use of Fossil-Fuels in the Netherlands*, NW&S E-2003-10, Utrecht University, Netherlands.

Neelis, M., *et al.* (2005), *Modelling CO_2 Emissions from Non-Energy Use with the Non-Energy Use Emission Accounting Tables (NEAT) Model,* Resources, Conservation and Recycling, (45): 226-250.

Nexant (2005), *PERP Program – Ethylene* – October 2005.

Oil and Gas Journal Survey (2006), *Industry Survey of Ethylene from Steam Crackers*, March 27, 2006.

Patel, M (2003), *Cumulative Energy Demand and Cumulative CO_2 Emissions for Products of the Organic Chemical Industry*, Energy Volume 28 (7), pp. 721-740.

Phillips, R. (2006), *Propylene Emerges from Ethylene's Shadow,* Technon OrbiChem seminar at APIC. Bangkok, Thailand, May.

Plastics Europe (2004), *Plastics in Europe: An Analysis of Plastics Consumption and Recovery in Europe*, Plastics Europe Association of Plastics Manufacturers. www.plasticseurope.org.

Plastics Europe (2006), *An Analysis of Plastics Production, Demand and Recovery in Europe,* Plastics Europe Association of Plastics Manufacturers, Brussels, Belgium. www.plasticseurope.org.

Rafiqul, I., C. Weber, B. Lehmann and A. Voss (2005), *Energy Efficiency Improvements in Ammonia Production – Perspectives and Uncertainties*, Energy 30 (13), pp. 2487-2504.

Ren, T., M. Patel and Blok (2005), *Olefins from Conventional and Heavy Feedstocks: Energy in Steam Cracking and Alternative Processes*, Energy 31 (4), pp. 425-451.

Schyns, V. (2006), *Feedstock Substitutes, Energy Efficient Technologies and CO_2 Reductions in Petrochemical Products*, Presentation at the IEA/CEFIC workshop Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Tam, C. and D. Gielen (2006), *Petrochemical Indicators*, IEA/CEFIC Workshop Proceedings: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Thomasson, A. (2006), *CMAI Completes 2007 World Methanol Analysis.* http://www.cmaiglobal.com/WorldAnalysis/pdf/WMAPressRelease.pdf.

United States Geological Survey (USGS) (2005), *Soda Ash Statistics and Information.* http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/.

USGS (2006), *Mineral Commodity Summaries.*
http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/sodaamcs06.pdf.

Y. Zunhong, G. Xin, W. Fuchen (2005), *Coal Gasification Technology in China: Application and Development.* Presentation Shanghai, January 2005.
http://gcep.stanford.edu/pdfs/wR5MezrJ2SJ6NfFl5sb5Jg/9_china_wangfuchen.pdf

Chapter 5 ▶ ABM (2004), *Anais do XXV Seminário de Balanços Energéticos e Utilidades.* Brazilian Association of Metals and Materials (ABM). Florianópolis, Brazil.

Bajay, S.V., *et. al.* (2007), *Energy Efficiency and CO_2 Emissions in the Brazilian Iron and Steel Industry.* April 23. Interdisciplinary Center for Energy Planning, State University of Campinas, Brazil.

Beer, J. de, E. Worrell and K. Blok (1998), *Future Technologies for Energy-efficient Iron and Steel Making,* Ann. Rev. Energy Environm 23, pp. 123-205.

Bistrow, N. and B. Wilson (2002), *The Coking Coal Market – an Australian Perspective*, 44th Canadian Conference on Coal, 8-10 September, British Columbia, Canada.
http://www.coal.ca/events/44cconf/conf/speakers/wilsonnotes.pdf.

Caffrey, R. (2005), *Global Slag Conference*.
http://www.propubs.com/gs2006/gs05reviewed.html.

Celissen, T. and E. v/d Haak (2004), *Heat Recovery for Hot Blast Stove*. AISTech 2004 Proceedings. American Iron and Steel Institute, Washington, DC.

China Iron and Steel Association (CISA) (2005), *2005 China Steel Industry Analysis Report*, ISBN 7-5017-7016-6, China Economic Publishing House, Beijing, China.

CISA (2005b), *Iron and Steel Yearbook 2005*, ISBN 1003-9368, Beijing, China.

CISA (2005c), *Investigation Report on Energy Conservation and Environmental Protection in Iron and Steel Sector,* Beijing, China.

Cui, Y.-S. and X. Wang (2006), *The State of the Chinese Cement Industry in 2005 and Its Future Prospects*, Cement International 4, pp. 36-43.

Debruxelles, J.P, (2006), *European Perspective Towards the CO_2 Challenge*, DSTI/SU/SC(2006)67, OECD Steel Committee, 7-8 November, Paris, France.

Diemer, P., *et al.* (2004), *Potentials for Utilisation of Coke Oven Gas in Integrated Iron and Steel Works*, Stahl und Eisen 124, no. 7, pp. 21-30.

Euroslag (2006), http://www.euroslag.org/pages/use.html.

Hilding, T. (2005), *Evolution of Coke Properties while Descending through a Blast Furnace*. http://epubl.ltu.se/1402-1757/2005/19/LTU-LIC-0519-SE.pdf.

Honeyands, T. and J. Truelove (1999), *Performance of HBI in Pre-heating Systems*. Presented at Scanmet I, Lulea, Sweden.
http://hbia.org/Technical/openpdf.cfm?filename=Steel-ElectricArc/1999-1SE.pdf.

Institute of Energy Economics Japan (IEEJ) (2006), *The New Energy and Industrial Technology Development Organization* (NEDO), FY 2005 Report, (Ref No. 05002231-0), Tokyo, Japan.

International Energy Agency (IEA) (2005), *Coal Statistics,* OECD/IEA, Paris, France.

IEA (2006), *Energy Technology Perspectives. Scenarios and Strategies to 2050,* OECD/IEA, Paris, France.

International Iron and Steel Institute (IISI) (1998), *Energy Use in the Steel Industry*, Committee on Technology, Brussels, Belgium.

IISI (2000), *EAF Technology*. International Iron and Steel Institute, Brussels, Belgium.

IISI (2005), *World Steel in Figures.* International Iron and Steel Institute, Brussels, Belgium.

IISI (2006), *World Steel in Figures.* International Iron and Steel Institute, Brussels, Belgium.

Japan Cement Association (JCA) (2006), *Cement Industry's Status and Activities for GHG Emissions Reduction in Japan*, IEA-WBCSD Workshop on Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry, 4-5 September, Paris, France.

Japan Iron and Steel Federation (JISF) (2006), *Handbook for Iron and Steel Statistics 2006*.

JP Steel plantech (2002), http://www.steelplantech.co.jp/cont_products/iron4.html.

Köhle, S. (2002), *Recent Improvements in Modelling Energy Usage of Electric Arc Furnaces*.
http://www.bfi.de/de/publikationen/doc/BFI32_EAF_Energy_7EEC_2002.pdf.

Komori, T., N. Yamagami and H. Hara (n.d.), *Design for Blast Furnace Gas Firing Gas Turbine*. Mitsubishi Heavy Industries.
http://www.mhi.co.jp/power/topics/2004/nov_04b.pdf

Lacroix, P., G. Dauwels, P. Dufresne, R. Godijn, P.G. Perini, K.P. Stricker and J. Virtala. (2001*), High Blast Furnaces Productivity Operations with Low Coke Rates in the European Union*, La Revue de Metallurgie – CIT, March, pp. 259-268.

MIDREX (2005), *2005 World Direct Reduction Statistics,* MIDREX, Charlotte, North Carolina, United States. www.midrex.com.

Ministério de Minas e Energia (MME) (2006a), *Brazilian Metallurgical Industry, Statistical Yearbook.* Secretaria de Geologia, Mineração e Transformação Mineral / Ministério de Minas e Energia, Brasília, Brazil.

MME (2006b), *Sinopse – Mineração & Transformação Mineral (Metálicos e Não-Metálicos)*, Secretaria de Geologia, Mineração e Transformação Mineral / Ministério de Minas e Energia (MME), Brasília, Brazil.

Nakano, N. (2006), *Technology-base and Sector-base Approach in the Case of Japan's Steel Industry*, OECD Steel Committee, 7-8 November, Paris, France.

Natural Resources Canada (NRCAN) / Canadian Steel Producers Association (CSPA) (2007), *Benchmarking Energy Intensity in the Canadian Steel Industry,* Ottawa, Canada.

Nippon Slag Association (2006), *Production and Uses of Blast Furnace Slag and Steel Slag*. http://www.slg.jp/e/index.htm.

Nippon Steel (2004), *The Latest Trend of Iron- making Technology in Japan. Relining Oita no. 2 BF.* September.

Ono, T. (2007), *Challenges for GHG Reduction in Japan*, 2007 RITE International Symposium, 18 January 2007.
http://www.rite.or.jp/Japanese/kicho/sympo07/3_ono.pdf.

Pandey, P. (2006), *Monney ISPAT – Striding Ahead in Sponge Iron*.
http://www.simaindia.org/monnet_art.cfm.

Pandit, A., *et al.* (2006), *Coal Based Sponge Iron Industry. A Prime Mover to Enhance Steel Making Capacities in India?*
http://www.steelworld.com/coal.htm.

Perkins, S. (2000), *CemStar Technology Offers Increased Productivity and Environmental Benefits*.
http://www.hatch.ca/Sustainable_Development/Projects/World%20Cement%20Paper.pdf.

Kai Q., *et al.* (2004), *"Production of Shougang BF after Deterioration of Coke Quality"*, AISTech, vol. 1, pp. 269-275, American Iron and Steel Institute.

Radikha, K. and M. Mitra (2006), *Sponge Iron Industry are Killing Fields*. http://www.freeindiamedia.com/environment/18_sep_06.html.

Schoenberger, H. (2000), *BREF on the Production of Iron and Steel – Conclusion on BAT*. http://www.ecologic-events.de/sevilla1/en/documents/Schoenberger_en.PDF.

Sindwani, A. (2006), *DRI (D)estined for (R)apid (I)ncrease*.
http://www.simaindia.org/dri_art.cfm.

Stahl Institut VDEh (2006), *Blast Furnace Reducing Agents Consumption in Selected Regions and Countries in the World, 2005.* Düsseldorf, Germany.

Stanlay, R. (2003), *PCI – Current Status and Prospectus for Growth*. Paper Presented at Asia Steel International Conference, Jamshedpur, India.

Stoppa, H., *et al.* (1999), *Costs and Environmental Impact of Dry and Wet Quenching,* Cokemaking International no. 1/99, pp. 65-70.

Tata Sponge (2006),
http://www.tatasponge.com/Download/TSIL_shareholders_pres_160606.ppt#325,1,Slide 1.

United Nations (UN) (2002), *International Standard Industrial Classification of All Economic Activities (ISIC) Revision 3.1.* Department of Economic and Social Affairs, Statistics Division, Statistical Papers Series M no. 4, rev. 3.1, ST/ESA/STAT/SER.M/4/Rev.3.1. New York, United States.

United States Geological Survey (USGS) (2005a), *Iron Ore*.
http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/.

USGS (2005b), *Iron and Steel Slag End-Use Statistics*.
http://minerals.usgs.gov/ds/2005/140/ironsteelslag-use.xls.

Utsi, A. (2006), *Research Needs on Waste – the Eurofer Perspective*. Workshop on Research in the Waste Area – Towards FP7, February, Internet.

Valia, H.S., Y. Jiying and S. Weijie (2004), *Production of Super Strength Coke from Non-recovery Coke Making at Shanxi Sanjia, Jixiu, Shanxi Province, China*, AISTech proceedings, Vol. 1, pp. 633-636.

Veld, L. de (2006), *Review of the Market for Metallurgical Coal.* Presentation at the McKloskey Coal Conference, Nice, France.

Wei, J. (2006), *Practices of Lowing Energy Use for Iron Making System*, Energy Conservation and Environmental Protection, no. 5.

Yu, F. (2003), *Technology of Mill Run Development and its Impacts on Iron Making*, Proceedings of 2003 China Iron & Steel Annual Conference.

Zhen, W. (2005), *Present Situation, Problem and Countermeasures for Coke-making Production in Our Country*, Proceedings of 2005 China Iron & Steel Annual Conference, Vol. 2. pgs 131-134.

Chapter 6 ▶ American Coal Ash Association (ACAA) (2003), *Coal Combustion Product Production Use Survey*, Aurora, Co, United States.

Associazione Italiana Tecnico Economica Cemento (AITEC) (2000 to 2005), *Annual Report*, AITEC, Rome, Italy.

Battelle (2002), *Toward a Sustainable Cement Industry. Climate Change,* WBCSD, Geneva. http://www.wbcsd.org.

Beerkens, R.G.C., and J. van Limpt (2001), *Energy Efficiency Benchmarking of Glass Furnaces*, Paper presented at the 62nd Conference on Glass Problems. University of Illinois at Urbana-Champaign, Illinois, United States.

Brasilian Institute of Geography and Statistics (IBGE) (2006), *Annual Survey of Mining and Manufacturing Industries.*
www.ibge.gov.br.

Canadian Industrial Energy End Use Data and Analysis Centre (CIEEDAC) (2004), *Development of Energy Efficiency Indicators for Canadian Industry, 1990 -2002*, Burnaby, BC.

CEMBUREAU (2006), *Use of Alternative Fuels and Materials in the European Cement Industry*, presentation to the IEA-WBCSD Workshop "Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry", Paris, France, September 2006. Also personal communication 16 February, 2006.

Ceramic World Review (2001), *World Production and Consumption of Ceramic Tiles.* http://www.ceramicworldweb.it/.

Comité Européen de Normalisation (CEN) (2000), *Cement – Part 1: Compositions, Specifications and Conformity Criteria for Common Cements*, EN 197-1:2000, Brussels, Belgium.

Cui, Y.-S. and X. Wang (2006), *The State of the Chinese Cement Industry in 2005 and Its Future Prospects*, Cement International 4/2006, pp. 36-43.

Cui, Y.-S. (2007), *Estimation of Energy Consumption and CO_2 Emission in Chinese Building Materials Industry in 2006*, Institute of Technical Information for the Building Materials Industry of China (ITIBMIC), Beijing, China.

Cui, Y.-S. (2007), Personal Communication.

Dong-Woon, H. (2006), *Energy Efficiency Improvement Potential in the Korean Cement Industry*, Korean Energy Economics Institute, KEEI/KREA Seoul Conference, September, Korea.

European Commission (EC) (2001), Refe*rence Document on Best Available Techniques in the Cement and Lime Manufacturing Industries*.
http://www.infomil.nl/legsys/bref/cement.pdf.

EC (2006), *Annual European Community Greenhouse Gas Inventory 1990–2004 and Inventory Report 2006*, EEA Technical Report No 6/2006, EC DG Environment, European Environment Authority, Brussels, Belgium.

EC (2006) *Draft Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry*. European Commission, DG JRC.
http://www.epa.ie/.

FLSMidth (2006), *Cement Plant Pyro-technology*, presentation to the IEA-WBCSD Workshop "Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry", IEA, Paris, France, September 2006.

Gielen, D. (1997), *Technology Characterization for Ceramic and Inorganic Materials*, Report ECN-C-97-064. Netherlands Energy Research Foundation ECN, Petten, Netherlands.

Harder, J. (2006), *Development of Slag Use in the Cement Industry*, Global Slag Magazine, Issue 6, Epsom, Surrey, United States.

International Energy Agency (IEA) (2006a), *Energy Technology Perspectives. Scenarios & Strategies to 2050*, IEA/OECD, Paris, France.

IEA (2006b), *Optimising Russian Natural Gas*, IEA/OECD, Paris, France.

Japan Cement Association (JCA) (2006), *Cement Industry's Status and Activities for GHG Emissions Reduction in Japan,* presentation to the IEA-WBCSD Workshop "Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry", IEA, Paris, France, September.

Levine, E., M. Greenman and K. Jamison (2004), *The Development of a Next Generation Melting System for Glass Production: Opportunities and Progress*. ACEEE Summer Study on Energy Efficiency in Industry 2003. American Council for an Energy Efficiency Economy, Washington, D.C., United States.

Miller, M. M. (2003), *Lime*, 2003 Minerals Yearbook. United States Geological Survey, Reston, Virgina, United States.

Miner R. and B. Upton (2002), *Methods for Estimating Greenhouse Gas Emissions from Lime Kilns at Kraft Pulp Mills*. *Energy, the International. Journal* 8 27 pp.729-738 (2002).

Natural Resources Canada (NRCAN) (2006), *Energy Consumption Benchmark Guide: Cement Clinker Production*, Office of Energy Efficiency, NRCAN, Ottawa, Canada.

NRCAN (various years), *Canadian Minerals Yearbook*. Minerals and Metals Sector, NRCAN, Ottawa, Canada.

Observatoire de l'Energie (2003), *Consommation de Combustibles de Substituion dans l' Industrie Cimentiére en 2001*, Ministere de l'Économie des Finances et de l'Industrie, Paris, France.

OFICEMEN (2007), *Statistics of the Spanish Cement Industry*.
www.oficemen.com.

Pilkington (2005), *Flat Glass Industry – Summary*.
http://www.pilkington.com/.

Portland Cement Association (PCA) (2005), *North American Cement Industry Annual Yearbook 2005.* Skokie, Illinois, United States.

Price, L (2006), *Prospects for Efficiency Improvements in China's Cement Sector*, Lawrence Berkeley National Laboratory (LBNL), presentation to the IEA-WBCSD Workshop "Energy Efficiency and CO_2 Emission Reduction Potentials and Policies in the Cement Industry", IEA, Paris, France, September.

Raina, S. J. (2002), *Energy Efficiency Improvement in Indian Cement Industry*, National Council for Cement & Building Materials, paper prepared for IIPEC Programme.

Sathaye, J., *et al.* (2005), *Assessment of Energy Use and Energy Savings Potential in Selected Industrial Sectors in India*, Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Shi Wei (2007), *Potentials and Strategies for Energy-saving and CO_2 Emission Reduction in the Chinese Lime Industry*, Institute of Technical Information for the Building Materials Industry of China (ITIBMIC), Beijing, China.

Siam Cement Company Ltd. (2005), *Sustainable Development Report 2005*, Siam Cement Company Ltd., Bangkok, Thailand.

Smith, I.M. (2005), *Cement and Concrete – Benefits and Barriers in Coal Ash Utilisation*, IEA Clean Coal Centre, London, United Kingdom.

Soares, J.B. and M.T. Tolmasquim (2000), "Energy Efficiency and Reduction of CO_2 Emissions

Through 2015: The Brazilian Cement Industry", *Mitigation and Adaptation Strategies for Global Change* 5, pp. 297–318, Netherlands.

Statistics Canada, *Cement Statistics*, various issues, catalogue number 44-001-XIB, Ottawa, Canada.

United States Geological Survey (USGS) (2004). *Minerals Yearbook – 2004*.
www.usgs.gov.

USGS (various years), *Minerals Yearbook*, USGS, Reston, Virginia, United States.

Vaccari, G., *et al.* (2005), *Overview of the Environmental Problems in Beet Sugar Processing: Possible Solutions*, Journal of Cleaner Production 13, pp.499-507.

Verein Deutscher Zementwerke e.V., Forschungsinstitut der Zementindustrie (VDZ) (2006), *Verminderung der CO_2-Emissionen*, VDZ, Düsseldorf.

Xinchun, W. (2007), *China Float Glass Sector Energy Efficiency Survey*. Glass Performance Days.
www.gpd.fi.

Whittemore, O.J. (1999), *Energy Use and Efficiencies in Firing Ceramics, Melting Glass*. American Ceramic Society Bulletin, July. pp. 69-71.

World Business Council on Sustainable Development (WBCSD) (2005), *CO_2 Accounting Protocol: Calculating CO_2 Emissions from the Production of Cement.*
http://www.wbcsd.org/.

Worrell, E., *et al.* (2001), *Carbon Dioxide Emissions from the Global Cement Industry*, Annual Review of Energy and Environment, Vol 26, 2001.

Zaiyin, Y. (2007), *Energy Saving and Emission Reductions Potentials and Measures in the Chinese Brick & Tile Industry*, Institute of Technical Information for the Building Materials Industry of China (ITIBMIC), Beijing, China.

Chapter 7 ▶ Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC) (2006), *A Review of Energy Consumption and Related Data Canadian Paper Manufacturing Industries: 1990, 1995 to 2003,* Prepared for Forest Products Association of Canada. Simon Fraser University, Burnaby, British Columba, Canada.

CIEEDAC (2006), *Development of Energy Intensity Indicators for Canadian Industry 1990 to 2004,* Simon Fraser University, Burnaby, British Columba, Canada.

Confederation of European Paper Industries (CEPI) (2001), *Special Recycling Statistics.* Brussels, Belgium.

CEPI (2006), *Europe Global Champion in Paper Recycling: Paper Industries Meet Ambitious Target,* Press Release July. Brussels, Belgium.

China State Statistical Bureau (various years), *China Energy Statistical Yearbook*, China Statistical Publishing House, Beijing, China.

COGEN Europe (2005), *CHP Statistics in European Member States 2003 Data*, Brussels, Belgium.

Energy Information Administration (EIA) (various years), *US MECS Survey,* Washington, D.C., United States.

European Commission (EC) (2001), *Integrated Pollution Prevention and Control* (IPPC), Reference Document on Best Available Techniques in the Pulp and Paper Industry. http://www.infomil.nl/legsys/bref/papier.pdf.

European Recovered Paper Council (ERPC) (2006), *European Declaration on Paper Recycling 2006-2010*, Brussels, Belgium.

FAOSTAT (United Nations Food and Agricultural Organization Statistics) (2006), FAO Statistics Division, Rome, Italy.
http://faostat.fao.org/site/381/DesktopDefault.aspx?PageID=381.

Finnish Forest Industries Federation (2002), *Possibilities of Reducing CO_2 Emissions in the Finnish Forest Industry*, Helsinki.

Francis, *et al.* (2002), *Energy Cost Reduction in the Pulp and Paper Industry – An Energy Benchmarking Perspective,* Natural Resources Canada, Ottawa, Canada.

Francis, D.W. and T.C. Browne (2004), *Method for Benchmarking Energy Use in Pulp and Paper Operations,* 2004 TAPPI Fall Tech. Conf., Atlanta, Georgia, United States.

Hayakawa, Y. (2006), *Voluntary Efforts against Global Warming by the Japanese Pulp and Paper Industry*, presented at IEA-WBCSD Workshop on Energy Efficient Technologies and CO_2 Reduction Potentials in the Pulp and Paper Industry, 9 October, Paris, France.

International Energy Agency (IEA) (2006), *Energy Technology Perspectives: Scenarios & Strategies to 2050,* IEA/OECD, Paris, France.

IEA / IETS (1999), *Recommended Methods for Energy Reporting in Pulp and Paper Industry, Summary Report*, Annex XII: Assessment of Life-Cycle-Wide Energy-Related Environmental Impacts in the Pulp and Paper Industry, IEA Programme for Advanced Energy-Efficient Technologies in the Pulp and Paper Industry.

Japanese Paper Association (2006), *The 9th Follow-up Survey of JPA's Voluntary Action Plan on Environment* , Tokyo, Japan.

Jochem, E., *et al.* (2004), *Werkstoffeffizienz. Einsparpotentiale bei Herstellung und Verwendung Energieintensiver Grundstoffe,* Fraunhofer Informationszentrum Raum und Bau, Stuttgart, Germany.

PA Consulting (2002), *Supply Channel Study – Phase 1 Evaluation Report, State of Wisconsin* prepared by M. Rosenberg.

Paprican (2002), *Energy Cost Reductions in the Pulp and Paper Industry,* An Energy Benchmarking Perspective, Natural Resources Canada, Ottawa, Canada.

STFI-Packforsk (2005), *The Future Resource Adapted Pulp Mill*, FRAM Final Report Model Mills, Report No 70, STFI-Packforsk, Stockholm, Sweden.

Whiteman, A. (2005), *Recent Trends and Developments in Global Markets for Pulp and Paper*, United Nations Food and Agricultural Organization, Rome, Italy.

Worrell, *et al.* (2001), *Opportunities to Improve Energy Efficiency in the US Pulp and Paper Industry*, Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Zhuodan, L. (2006), *Current Energy Efficiency in the Pulp and Paper Industry of China,* paper presented at IEA-WBCSD Workshop on Energy Efficient Technologies and CO_2 Reduction Potentials in the Pulp and Paper Industry, 9 October, Paris, France.

Chapter 8 ▶ Alvarado, S., P. Maldonado, A. Barrios and I. Jaques (2002*), Long Term Energy-related Environmental Issues Related to Copper Production*, Energy 27, pp. 183-196.

Department of Industry Science and Resources (ISR) (2000), *Energy Efficiency Best Practices in the Australian Aluminium Industry*. ISBN 0 642 72041 X, Canberra, Australia.

European Commission (EC) (2001), *IPPC Reference Document on Best Available Techniques in the Non-Ferrous Metals Industry,* European Commission, Brussels/Seville, December 2001.

International Aluminium Institute (IAI) (2003), *Life Cycle Assessment of Aluminium: Inventory Data for the Worldwide Primary Aluminium Industry*, IAI, London, United Kingdom.

IAI, *IAI Statistics*.
http://www.world-aluminium.org/iai/stats.

Maldanado, P., S. Alvarado and I. Jaques (1998), *The Chilean Copper Industry and Energy-related Greenhouse Gases Emissions*, Proceedings 17th World Energy Council Congress, Houston, Texas, United States.

Norgate, T.E. and W.J. Rankin (2000), *Life Cycle Assessment of Copper and Nickel Production*, MINPREX 2000, Melbourne, pp. 133-138. The Australian institute of Mining, Carlton South, Victoria, Australia.

United States Geological Survey (USGS) (2006a), *Aluminium.* 2005 Minerals Handbook.
http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/alumimyb05.pdf

USGS (2006b), *Copper*. 2004 Minerals Handbook*.*
http://minerals.usgs.gov/minerals/pubs/commodity/copper/coppemyb04.pdf.

World Aluminium (2006), *Electrical Power Used in Primary Aluminium Production*.
http://www.world-aluminium.org/iai/stats/formServer.asp?form=7.

Worrell, E. and J.G. de Beer (1991), *Energiekentallen in Relatie Tot Preventie en Hergebruik van Afvalstromen: Deelrapport Aluminium* (Energy Requirements in Realtion to Prevention and Re-Use of Waste Streams: Report on Aluminium, in Dutch), Nationaal Onderzoeks Programma Hergebruik van Afvalstoffen, Utrecht/Bilthoven, Netherlands.

Chapter 9 ▶ Almeida, A., F. Ferreira and D. Both (2005), *Technical and Economical Considerations to Improve the Penetration of Variable Speed Drives for Electric Motor Systems*, IEEE Transactions on Industry Applications, January/February 2005.

Brunner, C. and A. Niederberger (2006), *Motor System Model*: *A Tool to Support Efficient Industrial Motor System Policies & Programs.* A+B International, Zürich, Switzerland

Canmet Energy Technology Centre, Natural Resources Canada.
http://cetc-varennes.nrcan.gc.ca/en/indus.htm.

Cheek, K.F. and P. Pillay (1997), *Impact of Energy Efficient Motors in the Petrochemical Industry*, Electric Power Systems Research 42, pp. 11-15.

Compressed Air Challenge (CAC) (2004) *Fundamentals of Compressed Air Systems Training, 7-Step Action Plan.*
http://www.compressedairchallenge.org/.

Compressed Air Challenge and the US Department of Energy (2003), *Improving Compressed Air System Performance: A Sourcebook for Industry*, prepared by Lawrence Berkeley National Laboratory and Resource Dynamics Corporation, Washington, D.C., United States, DOE/GO-102003-1822.
http://www1.eere.energy.gov/industry/bestpractices/techpubs_compressed_air.html

De Almeida, A. and E.L. Fagundes (1998), *Energy Efficiency and the Limits of Market Forces: The Example of the Electric Motor Market in France*, Energy Policy, Vol. 26, No 8, pp 643-653.

Elliott, R. N. (2002), *Vendors as Industrial Energy Service Providers*, American Council for an Energy Efficient Economy, Washington, D.C., United States.

Energy Foundation, (2002), *Energy Conservation Potential Analysis for Energy Intensive Products in China*, Project G-0202-6173.

Giraldo, L. and B. Hyman (1995), *Energy End-Use Models for Pulp, Paper, and Paperboard. Mills*, Department of Mechanical Engineering, University of Washington, Seattle, Washington, United States.

International Energy Agency (IEA) (2006), *Energy Technology Perspectives. Scenarios and Strategies to 2050,* IEA/OECD, Paris, France.

Keulenaer H. de, R. Belmans, E. Blaustein, D. Chapman, A. De Almeida, B. Wachter and P. Radgen (2004), *Energy Efficient Motor Driven Systems.* European Copper Institute, Brussels, Belgium.

Lawrence Berkeley National Laboratory (LBNL) (2004, updated 2006), *Alliance to Save Energy, and Energetics,* Analysis conducted for US Department of Energy on Global Motor System Energy Use and Savings Opportunities.

Lung, R.B., A. McKane and M. Olszewski (2003*), Industrial Motor System Optimization Projects in the US: An Impact Study*, Proceedings of the 2003 ACEEE Summer Study on Energy Efficiency in Industry, Rye Brook, NY LBNL-53053, ACEEE, Washington, D.C., United States.

McKane, A. (2005), *Industrial Standards Framework Overview,* Presentation at UNIDO/DIP Experts Group Meeting, Phattaya City, Thailand.

McKane, A., (2007), forthcoming, *Chapter 17: Industrial Energy Efficiency, Regulation and Sustainable Energy in Africa*, United Nations Industrial Development Organization and the Renewable Energy and Energy Efficiency Partnership, Vienna, Austria.

McKane, A., *et al*. (2005), *Creating a Standards Framework for Sustainable Industrial Energy Efficiency*, Proceedings of EEMODS 05, Heidelberg, Germany, LBNL-58501.
http://industrial-energy.lbl.gov/node/147.

Minett, S. (2004), *Chapnet CHP Strategy*.
http://www.chp-research.com/.

Nadel, S., *et al.* (2005), *Energy-Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities, Second Edition,* American Council for an Energy-Efficient Economy, Washington, D.C., United States.

Philibert, C. and J. Podkanski (2005), *International Energy Technology Collaboration and Climate Change Mitigation Case Study: Clean Coal Technologies*, International Energy Agency COM/ENV/EPOC/IEA/SLT (2005)4.

Radgen, P. (2003), *Compressed Air System Audits and Benchmarking: Results from the German Compressed Air Campaign "Druckluft Effizient*", Fraunhofer ISI, Karhlsruhe, Germany.

Ryan, P., S. Holt, and B. Watkins (2005), *Motor MEPS in Australia: Future Directions and Lessons*, Proceedings of EEMODS 05, Heidelberg, Germany.

United States Department of Energy (US DOE) (1998), *United States Industrial Electric Motor Systems Market Assessment Opportunities*, prepared by Xenergy, Inc, Washington, D.C., United States.

US DOE (2002), *Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries*, prepared by Resource Dynamics Corporation, Washington, D.C., United States, DOE/GO 102002-1639.

US DOE (2003), *Improving Fan System Performance: A Sourcebook for Industry*, prepared by Lawrence Berkeley National Laboratory and Resource Dynamics Corporation, Washington, D.C., United States, DOE/GO-102003-1294. http://www1.eere.energy.gov/industry/bestpractices/techpubs_motors.html.

US DOE (2004a), *Improving Steam System Performance: A Sourcebook for Industry,* prepared by Lawrence Berkeley National Laboratory and Resource Dynamics Corporation, Washington, D.C., United States, DOE/GO-102004-1868. http://www1.eere.energy.gov/industry/bestpractices/techpubs_steam.html.

US DOE (2004b), *Energy Use and Loss Footprints*, prepared by Energetics, Inc.
http://www.eere.energy.gov/industry/energy_systems/footprints.html.

US DOE (2004c), *Energy Loss Reduction and Recovery in Industrial Energy Systems,* prepared by Energetics, Washington, D.C., United States.
http://www.eere.energy.gov/industry/energy_systems/analysis.html.

US DOE (2004d), *Energy Use, Loss, and Opportunities Analysis: U.S. Manufacturing & Mining,* prepared by Energetics and E3M, Washington, D.C., United States.
http://www.eere.energy.gov/industry/energy_systems/analysis.html.

US DOE (2004e), *Evaluation of the Compressed Air Challenge® Training Program*, prepared by Lawrence Berkeley National Laboratory and XENERGY, Inc, Washington, D.C., United States, DOE/GO-102004-1836.
http://www1.eere.energy.gov/industry/bestpractices/techpubs_compressed_air.html.

US DOE (2005), *Estimation of Energy Savings Outcomes from Best Practices Activities*, Fiscal Year 2004 prepared by Oak Ridge National Laboratory (internal report), United States.

US DOE (2006), *Improving Pump System Performance: A Sourcebook for Industry, Second Edition*, prepared by Lawrence Berkeley National Laboratory, Resource Dynamics Corporation, and the Alliance to Save Energy, Washington, D.C., United States. http://www1.eere.energy.gov/industry/bestpractices/techpubs_motors.html.

U.S. Environmental Protection Agency (USEPA) (2005), *Catalogue of CHP Technologies*, Combined Heat and Power Partnership.
http://www.epa.gov/chp.

Whiteley, M. (2001), *The Future of CHP in the European Market - The European Cogeneration Study*. Report XVII/4.1031/P/99-169. Future Cogen/Cogen Europe, Brussels, Belgium.

Williams, R., *et al.* (2005), *The Chinese Motor System Optimization Experience: Developing a Template for a National Program*, Proceedings of EEMODS 05, Heidelberg, Germany. LBNL-58504.
http://industrial-energy.lbl.gov/node/294.

Williams, R., A. McKane and R. Papar (2006), *Energy Management Standards: an Incentive for Industrial System Energy Efficiency?*, Co-generation and On-Site Power Production, Nov-Dec 2006, Volume 7, Number 6, pp.83-91.

Xiuying, L., *et al.* (2003), *Energy Saving Potential from New Industrial Equipment Efficiency Standards in China*, Proceedings from the 2003 ACEEE Summer Study for Industry. ACEEE, Washington, D.C., United States.

Zhehang, J. (2006), *Enterprises Energy Conservation Technology*, ISBN7-5025-8507-9.

Chapter 10 ▶ American Iron and Steel Institute (AISI) (2006), *Report on US Indirect Steel Trade, 1999-2005.* http://www.steel.org.

American Plastics Council (2004), *2004 National Post-Consumer Plastics Recycling Report*.

Environment and Plastics Industry Council Canada (EPIC) (2002), *Opportunities for Reducing Greenhouse Gas Emissions through Residential Waste Management.*

European Association of Plastics Recycling and Recovery Organisations (EPRO) (2006), *Statistics on Plastic Waste Management in Europe.* Brussels, Belgium.
http://www.epro-plasticsrecycling.org/c_81_1.html.

European Commission (EC) (2006), *Report from the Commission to the Council and the European Parliament on the Implementation of Directive 94/62/EC on Packaging and Packaging Waste and its Impact on the Environment, as well as on the Functioning of the Internal Market*, publication no. COM (2006) 767 final. Brussels, Belgium.

European Tyre and Rubber Manufacturers Association (ETRMA) (2006), *Scrap Tyre Statistics*. http://www.etrma.org/.

Freedonia (2003), *World Solvents to 2007*.
http://www.freedoniagroup.com.

Hayashi, S., *et al.* (2007), *Steel Recycling Circuit in the World,* International Iron and Steel Institute internal presentation, February.

Ida, H. (2006), *Current Status of Plastics Recycling in Japan,* Presentation at the IEA/CEFIC Workshop: Feedstock Substitutes, Energy Efficient Technology and CO_2 Reduction for Petrochemical Products, 12-13 December, Paris, France.

Industrievereinigung Chemiefaser (2006), *World Production of Man-Made Fibres by Region*. http://www.ivc-ev.de/live/index.php?page_id=87.

Intergovernmental Panel on Climate Change (IPCC) (2006), *Waste Generation, Composition and Management Data*.
http://www.ipcc-nggip.iges.or.jp.

International Aluminium Institute (IAI) (2003), *Life Cycle Assessment of Aluminium: Inventory Data for the Worldwide Primary Aluminium Industry*, London, United Kingdom.

International Iron and Steel Institute (IISI) (2006), *World Steel in Figures*, Brussels, Belgium.

Japan Automobile Tire Manufacturers Association (JATMA) (2006), *Tire Industry of Japan 2006*. http://www.jatma.or.jp/kankou/pdf/Tyre_industry_2006.pdf.

Lacoste, E. and P. Chalmin (2006), *2006 World Waste Survey: From Waste to Resources,* Economica Editions, Paris, France, ISBN 2-7178-5310-3.

Lysen, E. (ed.) (2006), *Assessment of the Interaction between Economic and Physical Growth,* Report UCE-34, Utrecht Centre for Energy Research, Utrecht, Netherlands.

Matthews, E., *et .al.* (2000), *The Weight of Nations: Material Outflows from Industrial Economies,* World Resources Institute, Washington, D.C., United States.

Moll, S., J. Acosta and H. Schütz (2005), *Iron and Steel - a Materials System Analysis,* Pilot Study Examining the Material Flows related to the Production and Consumption of Steel in the European Union. ETC/RWM Working Paper 2005/3. Prepared by the European Topic Centre on Waste and Material Flows, European Environment Agency, Copenhagen, Denmark. http://waste.eionet.europa.eu/wp/wp3_2005.

Neelis. M. and M. Patel (2006), *Long-term Production, Energy Consumption and CO_2 Emission Scenarios for the Worldwide Iron and Steel Industry*. Utrecht University, Copernicus Institute, Utrecht, Netherlands.

Packaging Federation (2005), *Packaging – a Very Productive Resource*.
http://www.packagingfedn.co.uk/who_we_are/reports/PF_report_4.pdf.

Plastics Europe (2006), *An Analysis of Plastics Production, Demand and Recovery in Europe,* Plastics Europe Association of Plastics Manufacturers, Brussels.
http://www.plasticseurope.org.

Plastic Waste Management Insitute (PWMI) (2006), *Plastic Products, Plastic Waste and Resource Recovery,* PWMI newsletter no. 32, Tokyo, Japan.
http://pwmi.or.jp.

Projektinriktad forskning och Utveckling (Profu) (2004), *Evaluating Waste Incineration as a Treatment and Energy Recovery Method from an Environmental Point of View,* Study conducted for the Confederation of European Waste-to-Energy Plants. http://www.cewep.com/storage/med/media/press/28_profuslides.pdf

Rubber Study (2006), *Statistical Summary of World Rubber Situation*.
http://www.rubberstudy.com/statistics-quarstat.aspx.

Ruhrberg, M. (2006), *Assessing the Recycling Efficiency of Copper from End-of-Life Products in Western Europe,* Resources, Conservation & Recycling 48, pp.141-165.

Schoen, L.A.A., *et al.* (not dated), *Mechanical Separation of Mixed Plastics from Household Waste and Energy Recovery in a Pulverised Coal-fired Power Station,* APME, Brussels, Belgium.

Simmons, P., N. Goldstein, S.M. Kaufman, N.J. Themelis and J. Thompson (2006), *The State of Garbage*, Biocycle April, pp. 26-43.

Solenthaler, B. and R. Bunge (2003), *Waste Incineration in China,* Hochschule fuer Technik Rapperswil, Switzerland.
http://www.umtec.ch/dokumente/dokumente/downloads/publikationen/Waste_Incineration_China.pdf

Themelis, N. (2003), *An Overview of the Global Waste-to-Energy Industry*.
http://www.seas.columbia.edu/earth/papers/global_waste_to_energy.html.

Themelis, N. (2006), *The Role of Waste-to-Energy in the USA*.
http://www.cewep.com/storage/med/media/wastepol/85_ThemelisPresentation.pdf.

United Nations Food and Agricultural Organization (UN FAO) (2007) FAOSTAT – Forestry.
http://faostat.fao.org/.

United States Environmental Protection Agency (US EPA) (1998), *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste,* EPA530-R-98-013, September, US Environmental Protection Agency.

US EPA (2006), *Municipal Solid Waste in the United States,* 2005 Facts and Figures.
http://www.epa.gov.

US EPA (2006b), *Tire Derived Fuel.* http://www.epa.gov/garbage/tires/tdf.htm.

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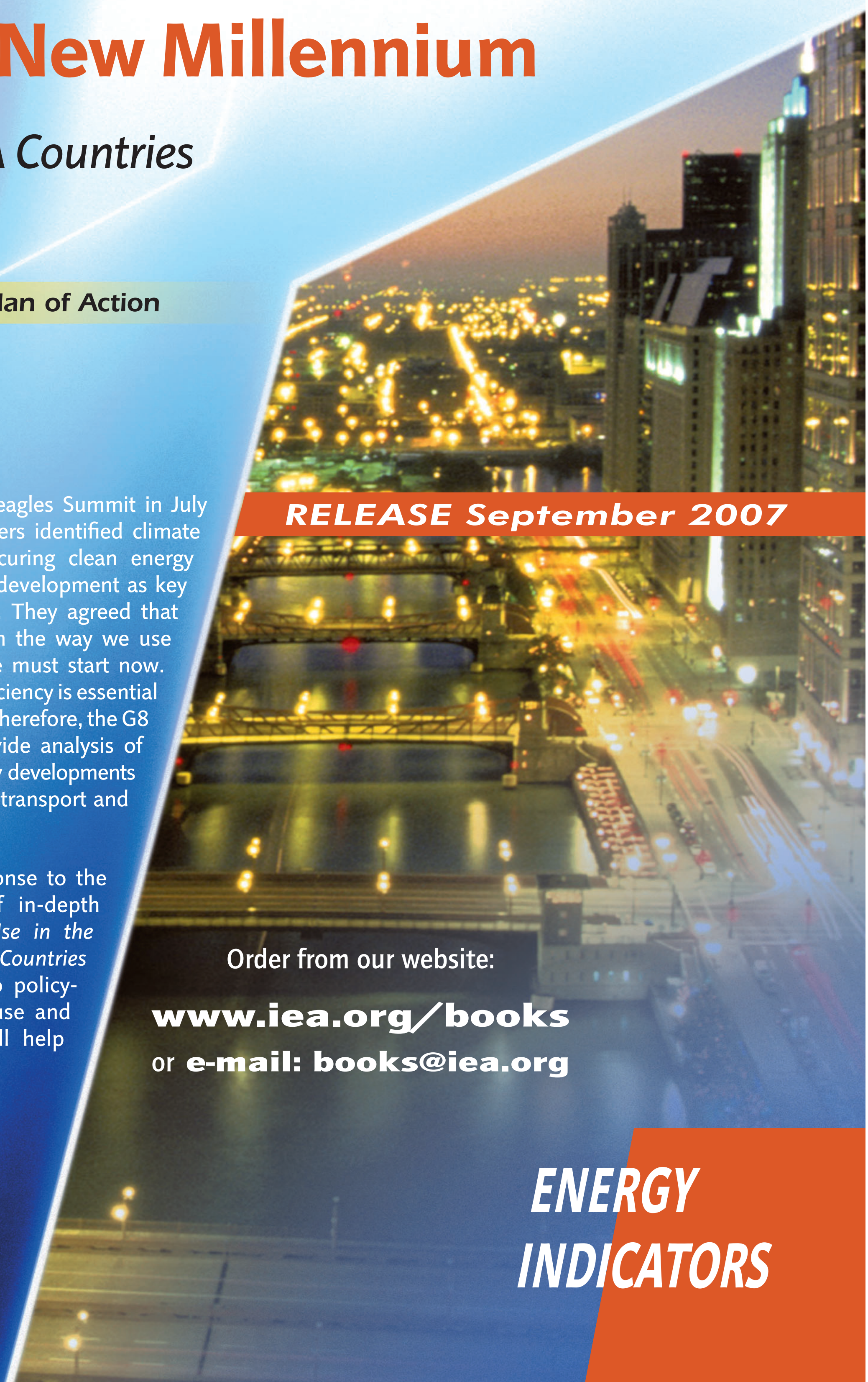

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