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Greenhouse gas efficiency of industrial activities in EU and Non-EU

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Policy Summary

Unilateral measures to reduce the emissions of greenhouse gases, consisting of targets, trading schemes or other measures, have a risk that industries move production capacity to countries not subject to emission restrictions. This process is called carbon leakage, generally defined as an increase in greenhouse gas emissions in third countries where industry would not be subject to comparable carbon constraints. Estimates in the literature of the extent of worldwide carbon leakage as a result of actions by developed countries estimated with models differ considerably. One of the main reasons for this is the assumption on the probability that industries will indeed re-locate their production capacity.

With regard to the EU Emission Allowance Trading Scheme (EU-ETS), several studies have been done on net cost price increases within EU industries to determine whether some industries are more vulnerable than others to auctioning of emission allowances. This report aims to answer the question how the pattern of emissions would change if industries would indeed re-allocate production capacity as a result of the EU-ETS.

The key variable in this discussion is the emission efficiency or the emission intensity (or the amount of emissions per unit of production) of industrial processes. Many international organizations use official statistics to discuss country differences in the emission efficiencies of various industrial sectors. This report demonstrates that due to problems in the statistics, such as definitions and data availability on the appropriate ISIC or NACE level, such an approach does not represent reality and cannot be used to estimate potential carbon leakage. Progress in the compilation and publication of bottom-up inventories by industrial organizations is still insufficient to rely on data from industry. An additional problem with industry data is the confidentiality of the results. Often released data are aggregated over continents.

Although in this report approximations are used to give at least some impression of the differences in emissions efficiencies, this approach is insufficient to arrive at reliable conclusions about the precise extent of carbon leakage in case industries would re-locate. That is because we have used standard characteristics of production processes for producing country comparisons, as knowledge on the spread of technologies over the various countries is lacking. The result is, however, useful for gaining a general insight in the main factors determining greenhouse gas efficiencies.

For most industries the results reflect either the fuel mix in industry in general and/or the fuel mix in electricity generation. As a result countries with a large share of coal in the energy mix have high greenhouse gas emission intensities (e.g. Poland, China, South Africa) and countries with a large share of nuclear or hydropower have low greenhouse gas emission intensities (e.g. France, Switzerland, Brazil).

The question if carbon leakage occurs and the absolute amount of leakage thus strongly depend on the country of origin and the country of destination of a re-allocated industry. Or in other words: industry in the EU is not always more efficient than in the rest of the world. As such, it is not possible to say whether re-location of an industry from the EU to a developing or another OECD-country will lead to carbon leakage. Equally it is not possible to state that a certain amount of carbon leakage is a consequence of the EU-ETS without performing a detailed country specific study (assuming that some industries would indeed re-locate as a consequence of the EU-ETS).

Under an unilateral regime of climate policies, industries with a high share of electricity consumption in countries with electricity generation with high CO_2 emissions/kWh (e.g., coal based electricity), are more exposed to financial burdens than similar industries in countries with “clean” electricity generation. The results of this study suggest that if relocation would happen under the ETS, the movement in the first place would be away from economies that are largely coal based. If that is true, than carbon leakage would be zero or limited.

The influence of the fuel mix used in industrial processes and of the fuel mix for electricity generation on national efficiencies is far larger then the potential efficiency gains by employing Best Available Technology or by any efficiency gains that can be achieved in industrial processes in the coming years. This means that the size of potential carbon leakage is of course influenced by choices in production technology if one considers a given pair of countries (a country of origin and a destination country), but that, as the differences between processes are relatively small, the fuel mix in the country of origin and destination is the main determining factor for the extent of carbon leakage.

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Annexes:

1 Introduction

Mitigation of climate change has cross boundary effects. Generally these are called spillover effects, which are the effects of mitigation policies and measures taken in one country or group of countries on other countries. Spillover effects can have many forms: such as transfer of technologies, often from industrialized to developing countries; effects through reduced oil and gas prices, often expected for oil producing countries; effects on competitiveness, whereby positive effects are expected for countries with energy efficiency policies, and carbon leakage (Barker et al., 2007).

In this report carbon leakage is defined in the general sense as "an increase in greenhouse gas emissions in third countries where industry would not be subject to comparable carbon constraints" (Council, 2009)[1]. An increase in fossil fuel prices resulting from mitigation policies may lead to the re-allocation of production to regions with less stringent mitigation rules, or no mitigation rules at all, leading to higher emissions in those regions and therefore to carbon leakage. Also the amended ETS Directive within the Policy Package on Climate and Energy (Council, 2009) is suspected to lead to higher financial burdens for the industries falling under the ETS and hence to the possibility of carbon leakage.

The amended ETS Directive (Council, 2009) includes rules for auctioning of emission allowances for sectors that can pass on the increased costs, and provisions for free allocation for sectors more exposed to international competition. The amended Directive has led to intensive discussion on the question which sectors would qualify for exemptions from auctioning (at least in the first years).

Until now, several studies have been done on net cost price increases within EU industries to determine whether some industries are more vulnerable than others to auctioning of emission allowances. Such studies have suggested that sectors with substantial net cost price increases include the iron and steel industry, the aluminium industry, the chemical and fertilizer industry and cement production (See e.g. Graichen et al, 2008; Renaud, 2008)

The assumption is that under the pressure of increased production costs some facilities may move to (or loose production to companies) outside the EU. For the balance of global emissions (and to determine the extent of carbon leakage), it is necessary to know the difference in specific emissions for the concerned installations between the EU and the country that would take over production.

For considering the implications of all these cases, and for the discussion on benchmarking of industries, either within the ETS or in possible sectoral agreements that might be part of a post Kyoto agreement, data are needed on the greenhouse gas efficiencies of industries in- and outside the EU. For a proper comparison these efficiencies should be inclusive of the greenhouse gas emissions linked to the consumption of electricity by the industries.

The aim of this study is (1) to assess the availability of greenhouse gas efficiency data for a selection of industries and a selection of countries, taking into account technological developments and the application of these technologies and to (2) to assess the consequences with regard to potential carbon leakage.

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[1] Scientifically carbon leakage can be defined as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries (Barker et al., 2007).

2 Selection of industries and countries

2.1 Selection of industries considered

This study focuses on the industry categories included in the amended ETS Directive Table 2-1 (see Annex 1, Council, 2009). However, the availability of comparable data limits the extent of the analysis. This is largely caused by the limited availability of data on electricity use in industry. Internationally comparable statistics, as gathered by the IEA, use a subdivision of industry as in Table 2-2.

Table 2-1 Activities included in the amended ETS Directive.

Activities [IPCC subcategory]	**Greenhouse gases**
Other Energy activities *[1B1b,1B2a]* – Mineral oil r**efineries** – **Coke ovens**	 Carbon dioxide Carbon dioxide
Production and processing of metals *[2C]* – **Metal ore** (including sulphide ore) roasting or sintering installations – Installations for the production of **pig iron or steel** (primary or secondary production) – Production and processing of **ferrous metals** (including ferro-alloys) – Production of **aluminium** – Production and processing of **non-ferrous metals**	 Carbon dioxide Carbon dioxide Carbon dioxide Perfluorocarbons, Carbon dioxide Carbon dioxide
Mineral industry[2A] – Installations for the production of **cement clinker** – Installations for the production of **lime** – Installations for the manufacture of **glass** including glass fibre – Installations for the manufacture of **ceramic** – Installations for the manufacture of **rock wool or stone wool** – Installations for the drying or calcination of **gypsum** or for the production of plaster boards and other gypsum products,	 Carbon dioxide Carbon dioxide Carbon dioxide Carbon dioxide Carbon dioxide
Chemical industry *[2B, 2A4]* – Production of **carbon black** involving the carbonisation of organic substances such as oils, tars, cracker and distillation residues, – Production of **nitric acid** – Production of **adipic acid** – Production of **glyoxal and glyoxylic acid** – Production of **ammonia** – Production of **basic organic chemicals** by cracking, reforming, partial or full oxidation or by similar processes, – Production of **hydrogen** (H_2) and **synthesis gas** – Production **of soda ash** (Na_2CO_3) and **sodium bicarbonate** ($NaHCO_3$)	 Carbon dioxide Nitrous oxide Nitrous oxide Nitrous oxide Carbon dioxide Carbon dioxide Carbon dioxide Carbon dioxide
Other activities *[2D1]* – Industrial plants for the production of (a) **pulp** from timber or other fibrous materials (b) **paper and board** with a production capacity exceeding 20 tonnes per day	 Carbon dioxide Carbon dioxide

Source: Council, 2009

Table 2-2 IEA flow codes and names for activities included in the amended ETS Directive.

Sector name	ISIC codes	IEA flow code	Notes	IPCC code
Iron and steel	2731	IRONSTL		1.A.2.a
Non-ferrous metals	2732	NONFERR		1.A.2.b
Chemicals and petrochemical	24	CHEMICAL-NECHEM	For emissions: feedstock use in petrochemicals (NECHEM) subtracted from CHEMICAL	1.A.2.c
Pulp, paper and print	21 and 22	PAPERPRO		1.A.2.b
Non-metallic minerals	26	NONMET	Includes glass, ceramic materials, cement, etc.	Part of 1.A.2.f (which is other industry)

It is also on the level of detail of main industrial categories as in Table 2-2 that emissions are available for non-Annex 1 countries, as these are derived from IEA statistics as well.
Hence the subdivision as given in Table 2-2 is the basic activity classification that is used for the statistical comparison of countries. The main headings of Section 4 also follow this classification. Under these headings selected data on subsectors are presented whereby the approach varies per sub-sector according to data availability.

2.2 Country selection

Criteria 1: share of industry in GDP
As the study is on large industries the focus is on industrialized countries. The assumption is that industries will primarily move to countries with an industrial infrastructure that will be able to absorb part of the production nationally. Table 2-3 lists the countries with a relatively high share of industry in GDP. Small and poor countries have been omitted.

Criteria 2: Data availability
Within Europe data availability does not constitute a limitation for the broad industrial sectors. Only for Serbia emission data are incomplete. For the large developed industrial countries and economies in transition the same holds, although data for Ukraine and Belarus are less complete and less detailed with regard to subsectors. Electricity use in the non-ferrous metal industry in the Russian federation is not included in the IEA statistics. Emission data for Singapore are incomplete.
In a number of developing countries a major obstacle is the absence of electricity consumption data per industry branch. Countries without problems are: China, Brazil, S. Korea, Mexico, South Africa, Thailand, Philippines. Countries with data deficiencies with regard to electricity use are India, Indonesia, Argentina, Malaysia, and Columbia. Emission and electricity statistics are lacking for the countries listed in Table 2-3 below the Philippines.

Table 2-3 Share of manufacturing industry in total value added, 2007.

Europe		Other developed countries and EIT		Developing countries	
	%		%		%
Germany	23	United States	13	China, People's Republic of	34
France	13	Japan	20	Brazil	18
Italy	18	Canada	16	India	16
Spain	16	Russian Federation	32	Republic of Korea	28
Netherlands	14	Turkey	21	Mexico	18
Belgium	17	Singapore	25	Indonesia	28
Switzerland	19	Ukraine	23	South Africa	18
Sweden	20	Belarus	32	Thailand	35
Poland	19			Argentina	23
Austria	20			Venezuela	17
Ireland	25			Malaysia	27
Finland	23			Colombia	16
Czech Republic	27			Philippines	22
Romania	23			Egypt	17
Hungary	22			Peru	16
Slovakia	23			Puerto Rico	42
Croatia	19			Viet Nam	21
Slovenia	24			Morocco	16
Lithuania	21			Bangladesh	18
Serbia	18			Dominican Republic	21
Bulgaria	18			Tunisia	18
Estonia	16			Guatemala	19

Note: Only countries with >15% share of manufacturing industry in total value added, and a total value added of more than 30.000 USD in 2007 prices. An exception has been made for the industrialized countries USA, France and The Netherlands that are slightly below the 15% cut-off boundary. Countries listed per grouping according to decreasing size of total value added.

Source: UN Statistical Division, national accounts main aggregates database, Sept. 2008 upload.

Criteria 3: Industrial connections

One could assume that it becomes easier to relocate industries when there are direct ties with other countries for instance through a multinational company or a multinational holding. An internet search of international business and financial pages (such as Hoovers and Yahoo Finance) reveals that the large European companies in metal, chemicals and paper and pulp industries have already ties with many other countries outside Europe. In the paper and pulp industry ties seem especially strong with USA and Canada, but links exist with Russia, Mexico, China, South Korea, and other Asian countries. The iron and steel industry seems to link especially with USA, South Africa, Brazil, China and India. European Chemical companies operate typically worldwide, but subsidiaries are most frequently found in the large industrial countries as listed in Table 2-3 (developing countries in the list generally above Colombia). For all industries it seems that apart from Russia few links exist with other EECCA countries.

In general it is remarkable that industrial linkages are most frequent with the countries mentioned in Table 2-3, without Ukraine and Belarus but adding Australia and New Zealand, and for the top 12 of the developing countries.

Conclusion

Taking into account data availability, the selection of countries for this study is:

Table 2-4 Countries considered in the current study.

EU	**Other developed countries and EIT**	**Developing countries**
Germany	United States	China, People's Republic of
France	Japan	Brazil
Italy	Canada	India
Spain	Switzerland	Republic of Korea
Netherlands	Turkey	Mexico
Belgium	Russian Federation	Indonesia
Sweden	Ukraine	South Africa
Poland		Thailand
Czech Republic		
Romania		
Hungary		

3 Methodology and data availability

This section describes the standard methodology applied for each industrial main sector as well as some important data quality and data availability issues.

3.1 International statistics: data availability

For comparing emission efficiencies of industrial sectors between countries, it is important to have consistency in definitions and coverage. As international official statistics are usually based on agreed conventions, data from recognized international statistics bodies have been used in the first place. Data on energy consumption have been obtained from the IEA Energy Statistics (IEA, 2007b), see Table 3-1 for details. Also the data on electricity consumption in various industrial sectors have been obtained from the IEA Energy Statistics (IEA, 2007b). The CO_2 emission factors used to calculate CO_2 emissions have been taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).
Production data have been obtained from various international statistical databases. These are described in Table 3-1 as well. A major problem with the collection of production data is the incomplete coverage of countries and products. This is mainly a problem for aggregated sectors, such as the chemical industry and the non-metallic minerals. This will be discussed in more detail in the respective Sections of Chapter 4.

Table 3-1 Overview of energy flows (IEA, 2007b) and other statistical data sources used in this study.

Sector name	IEA flow code	Data sources for production
Iron and steel	IRONSTL	USGS Minerals Yearbooks for steel production (USGS, 2009)
Non-ferrous metals	NONFERR	USGS Minerals Yearbooks for the priority non-ferrous metals: aluminium, copper, lead and zinc (USGS, 2009), http://minerals.usgs.gov/minerals/pubs/country/index.html
Chemicals and petrochemical	CHEMICAL-NECHEM	EUROSTAT PRODCOM data when available for country (Eurostat, 2009); else combination of fertilizer production data from FAOSTAT (FAO, 2009) and other chemical production data from the UNFCCC locator tool (UNFCCC, 2009)
Pulp, paper and print	PAPERPRO	Pulp and paper production from FAOSTAT (FAO, 2009)
Non-metallic minerals	NONMET	USGS Minerals Yearbooks for cement and lime (USGS, 2009); data on glass and ceramic production from UN statistical database where available (UN, 2009)

The data sources, as mentioned in the table, have been selected because of their coverage and completeness. The USGS Minerals Yearbook (USGS, 2009) covers all countries considered in this study and provides production data for the major products in the iron and steel, non-ferrous metals and the non-metallic minerals industries. Regarding alternative datasets, for the iron and steel industry data are also available from the International Iron and Steel Institute (IISI) via www.worldsteel.org. These data are nearly identical to those found in the USGS Minerals Yearbook. Furthermore, UN statistics (UN, 2009) contains statistics on the production of metals and minerals, but the spatial coverage is generally less than in the USGS data. Regarding the paper and pulp industry, FAO statistics includes the only production dataset covering all countries.

The most difficult sector is the chemical industry. For this sector, production data are only scarcely available and the country and product coverage of the available datasets (UN, 2009; Eurostat, 2009; UNFCCC, 2009) is poor.

3.2 Standard statistical methodology

A standard calculation has been applied for all industrial sectors as the first attempt to determine the greenhouse gas efficiencies. This methodology has been consistently applied for all 5 IEA flow categories that are considered in this study (see Table 3-1) and uses the input variables as described in this table. The standard methodology produces the calculated CO_2 efficiency per industrial sector per country, which is defined as the sum of direct and indirect CO_2 emissions divided by the total production rate. This section discusses the calculation procedure in more detail.

The sources of the statistical data used are given in Table 3-1. Direct CO_2 emissions in 2005 have been calculated per fuel by directly multiplying the energy use in the industry (from IEA, 2007b) with the appropriate emission factor provided by the 2006 IPCC Guidelines (IPCC, 2006). Direct CO_2 emissions are the sum of emissions from all fuels (See Annex 1 for outcomes).
Indirect emissions refer to the use of electricity and the associated emissions of CO_2. As for the direct emissions, the indirect emissions are calculated by multiplying the electricity use with an appropriate emission factor. The electricity use for each year and each industrial sector (IEA flow) is available from IEA (2007b). The emission factor for electricity use (e.g. the CO_2 emission per kWh of electricity used) has been calculated using the following steps:

1. The CO_2 emissions from the electricity generation sector have been calculated by multiplying the energy use in this sector (IEA flows MAINELEC, MAINCHP, AUTOELEC and AUTOCHP) with the relevant emission factors for CO_2 from the IPCC Guidelines (IPCC, 2006). These data have been aggregated to total CO_2 emissions per country per year.
2. The total electricity output from the electricity generation sector (IEA flows ELMAINE and ELMAINC) has been extracted from the IEA Energy Statistics (IEA, 2007b) and aggregated to the total electricity output per country per year.
3. The emission factor for electricity use has been defined for each individual country as the total CO_2 emissions from the electricity generation sector divided by the total output from this sector.

The per country emission factors for electricity use and production are given in Table 3-2.

Table 3-2 Average electricity generation CO_2 efficiency per country for 2005.

	CO_2 emission (kton)	**Electricity generated (EJ)**	**CO_2 emission per unit of electricity generated (ton/TJ)**
European Union			
Germany	375 996	7 462	50.4
France	60 009	7 181	8.4
Italy	148 271	3 679	40.3
Spain	127 036	3 290	38.6
Netherlands	61 778	1 100	56.2
Belgium	27 084	1 106	24.5
Sweden	20 507	1 989	10.3
Poland	170 736	1 929	88.5
Czech Rep.	63 555	939	67.7
Romania	35 644	739	48.2
Hungary	21 930	458	47.9
EU27 ***	1 556 868	39 707	39.2
Other developed countries and EIT			
United States	2 609 217	51 924	50.3
Japan	476 645	12 560	37.9
Canada	137 964	7 503	18.4
Switzerland	2 649	703	3.8
Turkey	100 633	1 877	53.6
Russia	637 020	11 740	54.3
Ukraine	73 135	2 292	31.9
Developing countries			
China	2 111 913	31 914	66.2
Brazil	46 563	4 708	9.9
India	704 864	8 089	87.1
South Korea	179 008	4 702	38.1
Mexico	127 734	2 838	45.0
Indonesia	99 759	1 623	61.5
South Africa	282 979	3 022	93.6
Thailand	78 228	1 536	50.9

* 1 EJ = 1000 TJ

Table 3-2 shows a large variation in CO_2 efficiency of the electricity generation. Switzerland emits on average only 3.8 ton CO_2 per TJ of electricity generated, while the emission in South Africa exceeds 93 ton CO_2 per TJ of energy. Countries that rely heavily on nuclear energy (e.g. France) or hydroelectric energy (e.g. Switzerland, Brazil) have relatively low emissions of CO_2 per unit of electricity, while countries that use almost 100% conventional fossil-fuel based power plants (e.g. Poland, South Africa) have relatively high emissions.

Total CO_2 emissions equal the sum of the direct and indirect CO_2 emissions $E_{CO2,direct}$ and $E_{CO2,indirect}$, respectively, while the CO_2 efficiency is calculated as the ratio of the total CO_2 emissions and the total production P in the country.

In formula, the CO_2 efficiency $\eta_{CO2,sector}$ can be written as:

$$\eta_{CO2,sector} = \frac{E_{CO2,direct,sector} + E_{CO2,indirect,sector}}{P_{sector}}$$

where:

$$E_{CO2,direct,sector} = \sum_{fuels} AR_{sector,fuel} \times EF_{CO2,sector,fuel}$$

$$E_{CO2,indirect,sector} = AR_{electricity,sector} \times \frac{\sum_{fuels} AR_{PowerPlants,fuel} \times EF_{CO2,PowerPlants,fuel}}{AR_{electricity,total}}$$

where:

P_{sector} = the total production rate in the sector (ton)
$AR_{sector,fuel}$ = the energy used in the sector per fuel (TJ)
$EF_{CO2,sector,fuel}$ = the CO_2 emission factor (EF) from the sector per fuel (kg/TJ)
$AR_{electricity,sector}$ = the total use of electricity in the sector (TJ)
$AR_{electricity,total}$ = the total amount of electricity generated in the country (TJ)
$AR_{PowerPlants,fuel}$ = the energy used in the electricity generation per fuel (TJ)
$EF_{CO2,PowerPlants,fuel}$ = the EF for CO_2 from electricity generation per fuel (kg/TJ)

3.3 Standard energy efficiencies methodology

As the calculation of greenhouse gas efficiencies based on international statistics for many sectors did not deliver a useful result, in several sections an alternative calculation has been done. This method is based on standard energy efficiencies for industrial processes.
For most industries, data on the energy efficiency of individual processes are available, both for the use of fossil fuels and the use of electricity. Usually these are expressed in MJ/kg of product, or a comparable unit. The efficiencies are described as process characteristics, and assumed to be independent of the country in which the technology is applied. In practice however, differences will exist, but no information on these differences is available.
In several cases we were able to retrieve information on the spread of production technologies over the various countries considered. We could thus allocate (a specific mix of) efficiencies to each country.
From the statistical sources quoted above we have derived average CO_2 emissions per unit of fuel energy in the main industrial sectors according to Table 3-1 per country (see Annex 1), and average CO_2 emissions per unit of electricity for each country. The unit of these is ton CO_2 emissions/MJ, or comparable (see Table 3-2). By multiplying the standard energy efficiencies and electricity efficiencies of the production processes in use, and average CO_2 emissions per unit of energy or electricity respectively, for each country, it is possible to construct a country comparison of CO_2 efficiencies for energy (fuels) and for electricity per ton of product. The sum of these gives the total CO_2 efficiency.

For many industries information on the share in production technologies per country is lacking. In order to demonstrate at least some differences between countries we have done the calculation as explained above for one single technology. That means that the energy efficiencies and electricity efficiencies were assumed to be the same in all countries, which means that the fuel mix in the industrial sectors and in electricity production in the countries concerned determine the outcome.

3.4 Industry initiatives

Little data are available from industry organisations or industry initiatives to support this study.
Data from the International Aluminium Institute are made available on a world region basis and have been used in Section 4.2.8. Publicly available data from the WBCSD sustainable cement initiative have been used in the calculations for Section 4.5.2.
The World Steel Association has only recently completed a common methodology of CO_2 emissions calculation and has started collecting data from steel plants around the world. Data are not yet available, and at the present stage it is unclear if the data will be made available to the public on a country/region basis “due to their politically sensitive aspect”.
A study has been completed by an Australian consultancy on CO_2 emissions from the copper and zinc industry on a mine by mine level[2]. The price of the reports (20,000 US$ each) is however slightly above the budget for the current study and no aggregate results have been released yet. There are various industry study groups for other non-ferrous metals, who are interested in the topic, but no data collection has been undertaken yet.
The European and world pulp and paper industry (gathered in CEPI and ICFPA, respectively) is interested in the carbon efficiencies in their industry, but confidentiality fears among their members have prevented a world wide inventory of greenhouse gas emissions from pulp and paper plants thus far. As the official statistics are giving a misleading picture of the industry’s performance, CEPI is trying to improve European statistics to correctly represent the role of CHP in the industry.
CEFIC, the European Chemical Industry Council, was at the time of writing gathering data as input into the development of benchmarks for the ETS.

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[2] Greenhouse Gas Emissions from World Copper Mining, 2009, and Greenhouse Gas Emissions from World Zinc Mining, 2009. Metalytics Pty Limited and minecost.com. Website: <http://www.minecost.com/GHG_Web.pdf>.

4 Outcomes per branch of industry

4.1 Iron and steel

The production of iron and steel is one of the most energy intensive industries and therefore an important industry to consider in the framework of this study. Global steel production has grown exponentially in the second half of the 20th century to a total of 1330 million tons in 2008. This growth is mainly attributed to non-European countries. Steel production in Europe has grown at a much lower rate. By far the largest producer of steel is China, accounting for almost one third of global steel production in 2008. Other important steel producing countries are Japan (10%), the United States (7%) and Russia (5%).

4.1.1 Analysis of available statistics

This section describes the outcomes by applying the standard methodology as it is described in section 3.2. The data that have been used are, as described in Section 3.1, the IEA energy statistics (IEA, 2007b) for use of fossil fuels and electricity in the iron and steel industry, and CO_2 emission factors from the 2006 IPCC Guidelines to calculate CO_2 emissions. Production figures are taken from USGS Minerals Yearbook for Iron and Steel (production of raw steel by country from USGS (2009)). The value for EU27 indicates the total production and energy use in EU27, and calculates a weighted average CO_2 efficiency for EU27.

The table displays a wide range of CO_2 efficiencies, from around 500 kg CO_2 / ton steel to almost 2700 kg CO_2 / ton steel for South Africa. Switzerland represents an outlier, probably due to the specific character of steel industry with a lot of recycling activities. The average CO_2 efficiency for the EU27 has been calculated to be 722 kg CO_2 per ton steel based on 21 Member States. As indicated in the footnote of the table, six countries have been excluded from the analysis, because either the production data or the energy use / electricity use data were not available.
Although the outcomes are intuitively right, it should be noted that statistical problems might influence some of the outcomes, as illustrated by Switzerland. To get a better understanding of operational differences between the countries, the next section reports a variant calculation, based on process information. Overall results are discussed at the end of Section 4.1.2.

Table 4-1 CO_2 efficiency as calculated for the iron and steel industry derived from international statistics for the year 2005.

IRONSTL	Production (kton)	CO_2 emissions direct (kton)	CO_2 emissions indirect (kton)	CO_2 efficiency direct (kg CO_2/ton product)	CO_2 efficiency indirect (kg CO_2/ton product)	CO_2 efficiency (kg CO_2/ton product)
European Union						
Germany	44 524	30 974	4 897	696	110	810
France	19 500	12 088	474	620	24	640
Italy	28 913	14 434	2 959	499	102	600
Spain	17 800	8 502	2 553	478	143	620
Netherlands	6 919	4 300	551	622	80	700
Belgium	10 422	6 585	529	632	51	680
Sweden	6 000	3 937	199	656	33	690
Poland	8 336	7 424	1 890	891	227	1 120
Czech Republic	6 200	6 981	838	1 126	135	1 260
Romania	5 632	7 949	1 470	1 411	261	1 670
Hungary	1 962	2 029	131	1 034	67	1 100
EU Average*	194 139	122 999	19 483	634	100	730
Other developed countries and EIT						
United States	94 900	36 390	14 430	383	152	540
Japan	112 470	70 830	9 319	630	83	720
Canada	17 000	13 748	710	809	42	850
Switzerland	1 200	202	19	168	16	180
Turkey	20 960	7 152	2 250	341	107	450
Russia	66 186	107 472	29 155	1 624	440	2 060
Ukraine	38 636	58 285	2 978	1 509	77	1 590
Developing countries						
China	353 240	594 761	60 615	1 684	172	1 850
Brazil	31 631	58 722	854	1 856	27	1 880
India	34 000	76 172	N/A **	2 240	N/A **	2 240
South Korea	47 770	24 679	5 923	517	124	640
Mexico	16 195	12 864	1 313	794	81	870
Indonesia	0	3 741	N/A **	N/A ***	N/A **	
South Africa	9 493	18 668	7 060	1 966	744	2 710
Thailand	5 160	1 242	1 180	241	229	470

Notes: Emission figures excluding emissions from the combustion of waste gases.
* Excluding Cyprus, Ireland, Malta, Denmark, Estonia, Lithuania as no full dataset was available.
** Indirect emissions could not be calculated since electricity use is not available for this industrial sector

4.1.2 Different process types

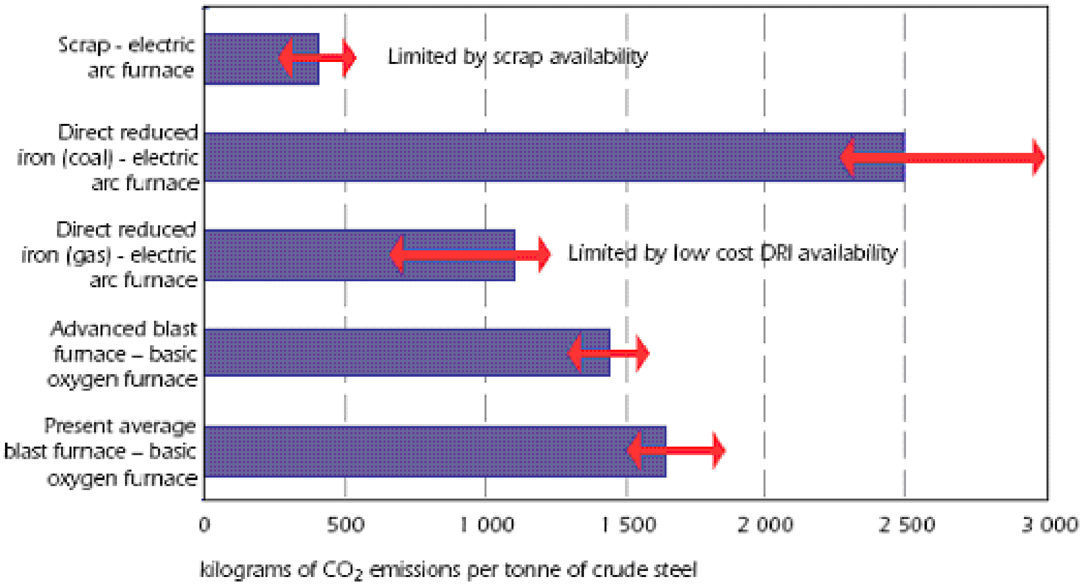
The actual CO_2 emissions per tonne of crude steel produced vary significantly with the process type that was used to produce the steel, as displayed in Table 4-1. The generic approach as applied in Section 4.1.1 may therefore be too coarse and a focus on different pathways to produce steel is necessary for comparing the efficiencies of steel furnaces.

An alternative way of calculating the CO_2 efficiency from the iron and steel industry is therefore by looking at shares of the different steel production ways, with each their CO_2 intensities. The calculation here is performed independently from the data used to calculate the CO_2 efficiencies in Table 4-1.
Present-day steel production uses one of the following two process routes:

1. Integrated Steelworks: production of coke in the coke oven plant, then sintering or pelletisation and iron ore production in a blast furnace. Steel production occurs in a basic oxygen furnace, uses mainly iron ore as input.
2. Electric Arc Furnace: direct melting of steel, uses mainly scrap as input.

A third route is available, that is production of steel in an Open Hearth Furnace. This is an outdated method to produce steel (replaced mainly by the basic oxygen furnace), which is still in place in some Eastern European countries (Russia, Ukraine). These have been excluded from further analysis, because typical energy intensity values are unavailable for both fuel and electricity consumption.

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.

Source: IEA, 2007

Figure 4-1 Variation of CO_2 efficiency in the iron and steel industry.

The result of this exercise to calculate CO2 efficiencies is shown in Table 4-3. The first two columns display the average fuel and electricity intensities in the country. These are calculated by combining country-specific data on the distribution of metal production of the two process routes (IEA, 2007) with average fuel and electricity intensity factors (expressed in GJ/ton steel), as reported in Bergman et al. (2007). These data are given in Table 4-2 and have been assumed to be valid for all countries. In practice however, this will not be the case and differences in both fuel and electricity use will exist between countries which limits the usability of the outcome of this exercise. However, no data are available to get more insight in these differences.

Table 4-2 Energy intensities for the two main process routes in the iron and steel industry. Source: BREF Iron and Steel (Bergman et al., 2007).

		Integrated Steelworks (IS)	**Electric Arc Furnace (EAF)**
Fuel energy intensity (I_{fuel})	GJ/ton	19.4	1
Electricity intensity (I_{elec})	GJ/ton	0.35	1.5

These are then combined with the total production to obtain the total use of fuel and electricity (expressed in GJ). In the same way as described under the standard statistical methodology (Section 0), these data are combined with emission factors to calculate the total emissions. The CO_2 efficiency is again defined as the total emissions divided by the total production, but now for each process route. Box 4-1 describes the procedure in more detail

Box 4-1. Calculation of the CO_2 efficiency

1. The fuel intensity I_{fuel} represents the weighted average fuel intensity in the country, using the relative share of both production processes in Table 4-2. In formula this can be written as:
$$I_{fuel} = \frac{P_{IS}}{P_{total}} I_{fuel,IS} + \frac{P_{EAF}}{P_{total}} I_{fuel,EAF}$$
Here P_{IS}, P_{EAF} and P_{total} represent the production (in tonnes) of the integrated steelworks, electric arc furnace and the total production, respectively. These are available for most countries from IEA (2007). For countries for which this is not available, the average distribution of production over process types of EU25 or the world has been assumed. For Switzerland, Czech Republic, Hungary, the Netherlands and Sweden he EU25 distribution has been assumed, while for Indonesia, Romania and Thailand the world distribution has been used.
The intensities $I_{fuel,IS}$ and $I_{fuel,EAF}$ have been taken from Table 4-2.
2. The electricity intensity has been calculated in the same way, in formula:
$$I_{elec} = \frac{P_{IS}}{P_{total}} I_{elec,IS} + \frac{P_{EAF}}{P_{total}} I_{elec,EAF}$$
3. The average CO_2 emissions from fuel combustion have been calculated for the Iron and Steel sector on a national level from the IEA energy statistics and CO_2 emission factors from the 2006 IPCC Guidelines, as in Table 4-1. The average CO_2 emission factor from fuel (in kg/GJ) is defined as the total CO_2 emissions divided by the total energy use.
4. The average CO_2 emissions from electricity use have been calculated on a national level, as explained in Section 0.
5. The CO_2 efficiencies for both fuel and electricity are calculated by multiplying the intensity with the average CO_2 emission factor. This leads to the CO_2 efficiency for both fuel and electricity, and the overall CO_2 efficiency is then defined as the sum of the CO_2 efficiencies for fuel and electricity, respectively.

Table 4-3 Energy intensity per country for the production of steel, based on the default energy intensities given in Table 4-2.

	Fuel intensity (GJ/ton)	Electricity intensity (GJ/ton)	Average CO_2 from fuel (kg/GJ)	Average CO_2 from electr. (kg/GJ)	CO_2 eff. fuel (kg/ton)	CO_2 eff. electr. (kg/ton)	CO_2 eff. (kg/ton)
European Union (EU27)							
Germany	13.8	0.70	118	50	1618	35	1650
France	12.5	0.78	118	8	1474	6	1480
Italy	8.3	1.04	82	40	685	42	730
Spain	5.5	1.22	85	39	470	47	520
Netherlands	12.3	0.80	123	56	1502	45	1550
Belgium	14.7	0.64	101	24	1490	16	1510
Sweden	12.3	0.80	105	10	1283	8	1290
Poland	11.9	0.82	110	88	1304	73	1380
Czech Republic	12.3	0.80	110	68	1344	54	1400
Romania	12.6	0.73	115	48	1439	35	1470
Hungary	12.3	0.80	118	48	1450	38	1490
Other developed countries and EIT							
United States	9.3	0.98	67	50	618	49	670
Japan	14.7	0.64	114	38	1670	24	1690
Canada	11.8	0.83	96	18	1125	15	1140
Switzerland	12.3	0.80	61	4	753	3	760
Turkey	6.4	1.16	118	54	750	62	810
Russia	12.1	0.46	102	54	1232	25	1260
Ukraine	9.8	0.32	98	33	963	10	970
Developing countries							
China	17.0	0.50	140	66	2377	33	2410
Brazil	15.0	0.60	107	10	1600	5	1600
India	10.6	0.86	131	87	1397	75	1470
South Korea	11.3	0.86	117	38	1324	33	1360
Mexico	6.1	1.18	70	45	429	53	480
Indonesia	12.6	0.73	75	61	948	45	990
South Africa	11.2	0.86	101	92	1135	79	1210
Thailand	12.6	0.73	82	51	1024	37	1060

Note: the columns “fuel intensity” and “ electricity intensity” are based on the default energy intensities given in Table 4-2 weighted for the national mix of the two main production technologies.

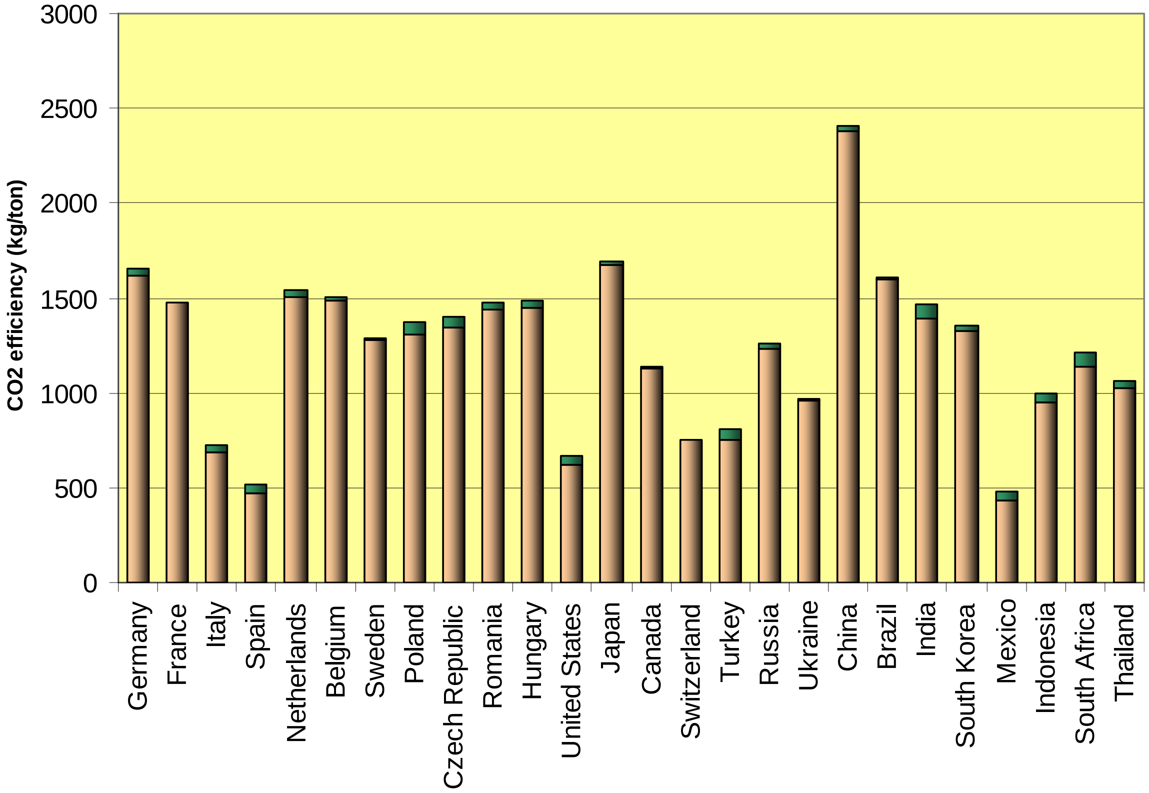


Figure 4-2 CO_2 efficiencies per country from Table 4-3. The lower red bars represent the CO_2 from fuel combustion, the top end green part represents CO_2 from electricity use.

Table 4-3 and Figure 4-2 show the highest CO_2 efficiency for China. This is due to two reasons:

- The high share of the integrated steelworks process (87%), which has a high energy use (Table 4-2).
- The main fuel combusted in Chinese steel plants is coal, which has relatively high emission factors for CO_2 compared to other fuels.

Relatively low CO_2 efficiencies are reported for Italy, Spain, the United States and Mexico. The reason is the relatively high share of electric steel in these countries, which has a dramatically lower energy use than the integrated steelworks through the blast furnace process (see Table 4-2).

Figure 4-3 displays the comparison between the CO_2 efficiencies as calculated in Table 4-1 (top-down from energy statistics and total production) and Table 4-3 (bottom-up using specific energy intensities per process type). It is observed that significant differences exist between both datasets for many countries. This indicates that, since even for a well-defined sector like the iron and steel industry the difference are large, the usability of the input data for calculating CO_2 efficiencies is limited. The uncertainty in the results is determined by the uncertainty in the input factors, which include:

- The uncertainty in the IEA Energy Statistics. Not all countries report in the same way – some energy uses may be included for one country and excluded for the other. We do not have additional information to justify or falsify this conclusion.

- The uncertainty in the production statistics. We have compared the steel production figures used in this study (USGS, 2007) with figures from the International Iron and Steel Institute website (www.worldsteel.org) and found that data are generally very similar. For some countries differences do exist. This indicates that the uncertainty in the production volumes may be relatively small.
- The uncertainty in the default energy intensities (Table 4-2). This may vary significantly between facilities. For instance, the draft revised BREF document for Iron and Steel (JRC, 2008) reports for the electric arc process a fuel use of 50-1500 MJ/ton liquid steel and an electricity consumption of 1584-2693 MJ/ton liquid steel. Another issue may be the on-site production of electricity and heat in a CHP plant, which may not be reflected correctly in the energy balances.

For Germany, France, Netherlands, Belgium, Sweden and also Switzerland there is a consistent difference between the higher figure from Table 4-3, and the lower statistical figure from Table 4-1. The share of recycling leading to an overestimate through the process route calculation may be the cause.

Another main reason for the differences may be that the process specific intensities as supplied by Table 4-2 may not be realistic for all countries. These are based on the BREF document for Iron and Steel production and may therefore be unrealistic for countries outside the EU. This may explain the lower intensity in the bottom-up approach for e.g. Russia, India and South Africa.

The figure clearly shows that the usability of the figures is limited, since the two methods can show up to a factor 2 difference. In some cases the top-down approach leads to a higher efficiency, while in some other cases the bottom-up approach leads to a higher efficiency.

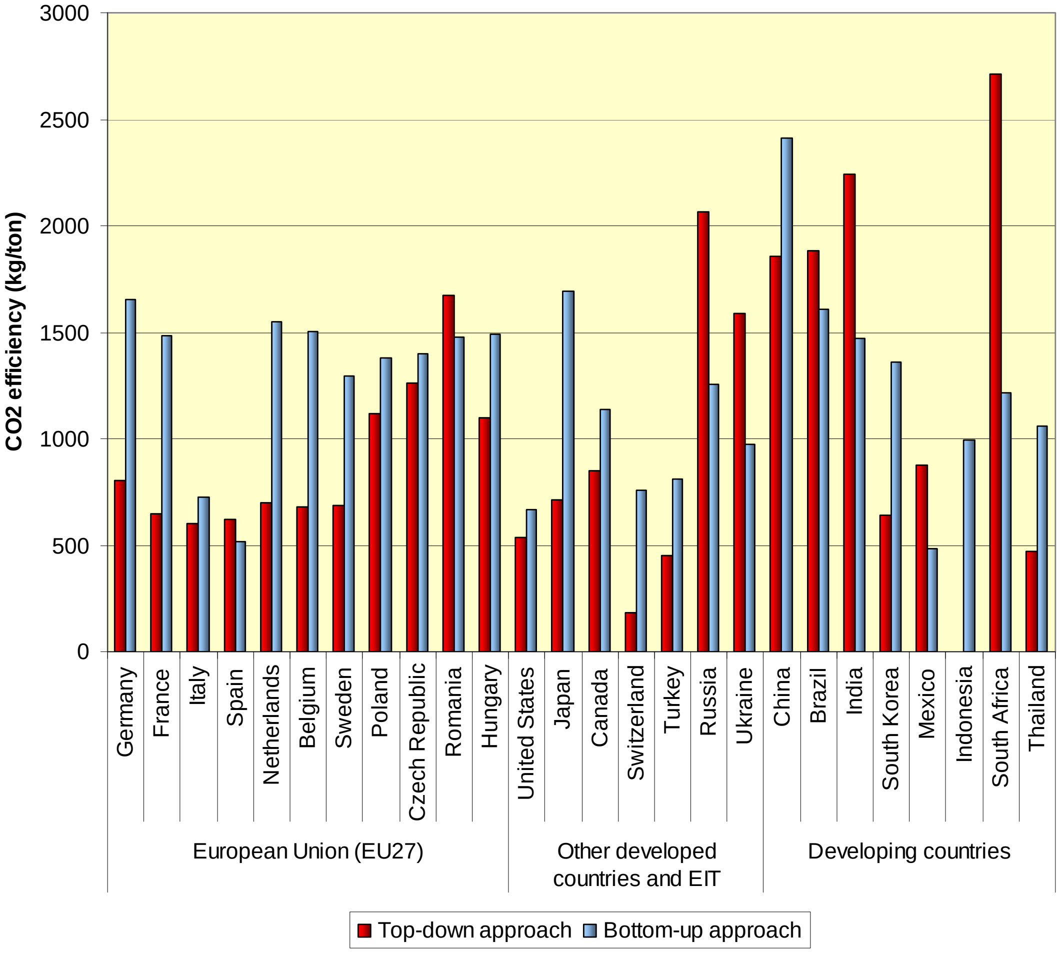


Figure 4-3 Comparison between the top-down and bottom-up CO_2 efficiencies for the iron and steel industry, as calculated in this section (kgCO_2/ton steel).

With regard to potential carbon leakage these results lead to the following conclusions:

- A movement from “clean EU” (which we can roughly define as ca 700 kg CO_2/ton steel) to the USA (ca 500 kg CO_2/ton) would not result in an increase in global emissions. It would give a reduction of almost 30 % per ton steel instead.
- A movement from “clean EU” to China (ca 1800 kg CO_2/ton steel) would result in a carbon leakage of almost 1100 kg CO_2/ton steel. For an integrated steelwork with a production of 2 million ton year that would mean 2.2 Mton CO_2 emissions (0.04 % of EU27 greenhouse gas emissions in 2007, or 3.3 % of the greenhouse gas emissions of Denmark).
- A movement from “dirty EU” which we can define as ca 1100 kg CO_2/ton steel, to China (ca 1800 kg CO_2/ton steel) would result in a more restricted carbon leakage of about 700 kg CO_2/ton steel. For an integrated steelwork with a production of 2 million ton of steel per year that would mean 1.4 Mton CO_2 emissions per year.

In general: if carbon leakage due to relocation of steel mills occurs and to which extent, depends on both the country of origin and of destination. From the statistical data it seems that movements from the new member countries in this sample lead to less carbon leakage than a comparable move from more efficient EU countries.

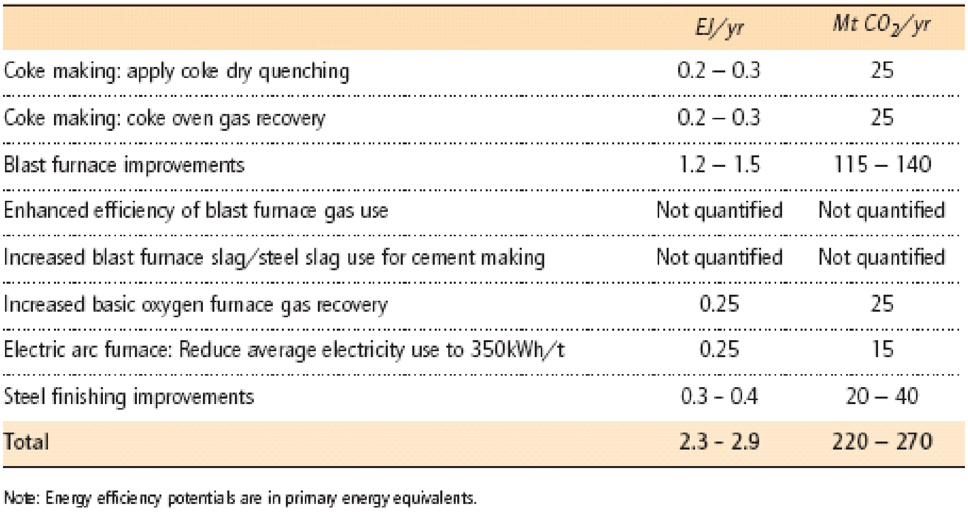
4.1.3 Industrial sources

Data from the industry as collected from individual plants by the World Steel Association are not yet available, and at the present stage it is unclear if the data will be made available to the public on a country/region basis.

4.1.4 BAT, future efficiencies and its effect on carbon leakage

IEA (2007) has listed theoretical or technological potentials for future CO_2 efficiencies in the iron and steel industry. These take into account technologies applied elsewhere in the world today, assuming that this technology could be applied globally in the future. The analysis as such does not include factors such as economic feasibility, transition rates and regulatory and social factors. The overview is given in Table 4-4.

Table 4-4 Overview of the expected energy reduction potential and associated reduction in CO_2 emissions from the 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.

Source: IEA, 2007.

The total reduction potential is 220 – 270 Mton CO_2 per year on a global basis. The total global emissions from the iron and steel industry (direct and indirect) equal around 1420 Mton (calculated using the methodology described in section 0). The global reduction potential for CO_2 emissions from this industry using currently available technologies is therefore 15-20%.

These figures do not include enhanced recovery of residual gases and a higher efficiency of residual gas use for power generation. In combination with the closure of remaining outdated plants (open hearth furnace, ignot casting), more efficient operation of coke ovens and waste heat recovery from sintering plants the total energy savings could be as high as 4.5 EJ of primary energy per year (IEA, 2007). The full range of CO_2 emission reduction is therefore estimated to be between 220 and 360 Mton per year, or (equivalently) 15-25%. Additionally, it must be mentioned that the developing technique of CO_2 capture and storage (CCS) is not included in this analysis. ULCOS (Ultra-Low CO_2 Steel making), a consortium of 48 European Companies and organisations has evaluated an emission reduction potential of 500 to 1500 kgCO_2/t steel, but this includes the use of CCS, which is not foreseen in the short term (Birat, 2005).

Even if 15-25% emission reduction through applying BAT to China would be achieved, then a considerable amount of carbon leakage would still occur in case of relocation from the EU to China. This is mainly due to the coal based energy provision of steel mills in China.

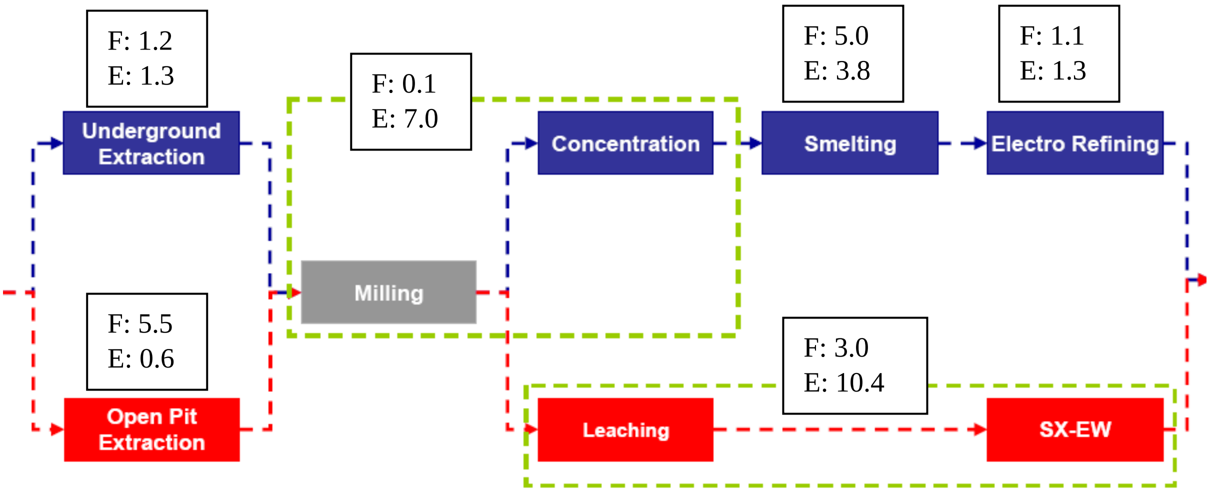
4.2 Non-ferrous metals

4.2.1 Analysis of available statistics

International statistics on CO_2 emissions and electricity use are available for the Non-ferrous metal industry as a group only. For a calculation of greenhouse gas efficiencies we have retrieved the production of aluminium, refined copper, lead and zinc (all primary and secondary outputs) and considered the sum of production data a proxy for the total production in the non-ferrous metal industry. These four metals are the most widely used non-ferrous metals and constitute most of the production of the non-ferrous metal industry. The resulting CO_2 efficiencies, however, showed a wide spread and seemed rather useless for international comparisons.
A major difficulty in the analysis is that the non-ferrous metal industry consists of the production of refined metal and of semi manufactures. The last includes metal and metal allow cast ingots or wrought shapes, foil, strips, rods, etc. The semi manufacture production has a much lower energy use than primary and secondary metal production. For a proper analysis it is therefore necessary to consider the production of individual metals, whereby we will focus on the energy intensive part of producing refined metal.

4.2.2 Subbranches: Copper

The energy and electricity use figures found in the literature depend on a number of factors. Figure 4-4 illustrates for Chile average energy requirements of the different production routes. An important determinant of energy consumption in the extraction, milling and concentration phase is the copper content in the ore. IEA (2007) reports a primary energy use of up to 125 GJ/ton for ore that contains 0.5% copper.
As electricity is the main source of energy (Figure 4-4), the CO_2 emissions of copper production depend to a high degree on the (indirect) emissions from electricity production. The more recently applied hydro-metallurgical process uses more electricity than the conventional smelting and electro-refining process. It can however be applied on ores (and recycled material) that contain copper that is more difficult to extract.



Note: the upper process line is the traditional pyrometallurgical process, the lower line the more recent hydrometallurgical process. SX-EW stands for Solvent Extraction and Electro Winning.
Source: based on : Vargas, 2008, with data from Cochilco.

Figure 4-4 Energy consumption in copper production in Chile (F=Fuel, E=Electricity use, unit: GJ/ton copper).

The resulting greenhouse gas emissions have a wide spread. Research by Minecost and Metalytics on emissions from the production of primary copper by mines in 19 main copper producing countries resulted in a range from very little to 7300 kgCO_2-eq/tCu, with most of the production in the range 2000-3500 kgCO_2-eq/tCu[3]. These data include mining operations, and include fuel and electricity emissions.

The widely cited figures for energy use in copper production (36 GJ/ton Cu, or 42.1 GJ/ton Cu including mining) in IEA (2007) are derived from data from Chile (Alvarado et al., 2002), which is at the high side of the range. The BREF document for non ferrous metals does not provide detailed data. It gives a range from 14-20 GJ/ton Cu total energy consumption from concentration to the refined product (JRC, 2001, p214). Grimes et al. (2008) give a range based on several studies (33-57.3 GJ/ton Cu) for energy use from copper ore to the product “copper cathode”. The range is partly based on differences in Cu content of the ore. Unfortunately no specification is given in fuel and electricity use. Norgate and Rankin (2000) summarise various studies, their CO_2 emissions are based on coal fired power plants.

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[3] Data from leaflet on Minecost website < http://www.minecost.com/GHG_Web.pdf>. The full report with data per country and per mine is priced at US$20,000.

Table 4-5 Energy and CO_2 intensity of copper production.

	fuel intensity (GJ/ton met)	electricity intensity (GJ/ton met)	energy intensity (GJ/ton met)	CO_2-intensity (kg/ton met)
primary copper production (pyrometallurgical process)[a)]	14.4 24.4 [c)]	21.6 8.6 [c)]	36.0 (33-57) [b)] 33 [c)]	3500 3300 [c)]
primary copper production (hydrometallurgical process)[c)]	45.1	18.9	64	6200
secondary copper production (hydrometallurgical process)[b)]		6.3	6.3	440

Note: primary copper production refers to concentrating, smelting and refining from copper ore to the product “copper cathode”,
Source: a) IEA, 2007 (IEA figures are derived from data from Chile (Alvarado et al, 2002)); b) Grimes et al., 2008; c) Norgate and Rankin, 2000.

Combining the figures from Table 4-5 with statistics on the CO_2 intensity of fuel use in the non-ferrous metal industry and the CO_2 intensity of electricity production in the various countries, a total CO_2 intensity of copper production can be calculated (Table 4-6). We have use the specific energy use of the pyrometallurgical process by IEA, as we did not have information on the spread of the different production processes over countries. Although we have used the relatively high energy consumption figures from IEA, these outcomes are on average lower than those reported by Minecost and Metalytics, because 1) a significant share of production uses the more energy-intensive hydrometallurgical process; 2) the selection of countries in the current report includes countries without mines and countries with less polluting electricity generation.
As could be expected, the electricity component has a large influence on the outcome. Countries with a coal based industry, such as Poland, Czech Republic, China, have high overall intensities.

The potential carbon leakage depends on the country of origin and of destination. Relocation from most EU countries to a country like Brazil will decrease global CO_2 emissions. Relocation from EU countries to China (with the probable exception of Poland) would lead to carbon leakage.
With regard to the potential carbon leakage is should be noted that those countries or industries with a high electricity CO_2 intensity are also indirectly vulnerable to price increases of electricity due to climate policies. That means that a possible relocation would start in countries with high intensities. The effect of a relocation of these very CO_2 intensive copper industries to another country would then be either carbon neutral or could even be beneficial for total world emissions.

Table 4-6 CO_2 intensity of copper production by country.

	fuel CO_2 intensity	electricity CO_2 intensity	total CO_2 intensity
	$kgCO_2$/ton met		
EU			
Germany	964	1088	2050
France	873	180	1050
Italia	854	870	1720
Spain	1039	834	1870
Belgium	952	529	1480
Sweden	1184	223	1410
Poland	1212	1912	3120
Czech republic	808	1462	2270
Romania	n/a	1042	n/a
Hungary	813	1034	1850
Other developed countries and EIT			
USA	830	1085	1910
Japan	1381	820	2200
Canada	911	81	990
Turkey	981	1158	2140
Russia	n/a	1172	n/a
Developing countries			
China	1288	1429	2720
Brazil	1151	214	1360
India	1312	n/a	n/a
South Korea	1225	822	2050
Mexico	811	972	1780
Indonesia	n/a	n/a	n/a
South Africa	n/a	2023	n/a
Thailand	n/a	1100	n/a

Notes: based on IEA energy data (fuel use and its CO_2 intensity in the non-ferrous metal industry per country) and standard fuel and electricity efficiency factors and energy efficiencies of the pyrometallurgical process. The last are the same for all countries. The outcomes are relevant for a relative country comparison, but absolute numbers may differ considerably from reality. Switzerland, the Netherlands and Ukraine have been excluded as these currently do not have copper production. An EU average figure is hence not possible and useful. The rather high fuel intensity in the non-ferrous metal industry in Japan is probably due to statistical causes such as a deviating sector definition.

4.2.3 *Copper: BAT, future efficiencies and its effect on carbon leakage*

In the pyrometallurgical process efficiency gains are possible by using bath smelting with continuous smelters/converters (JRC, 2001), in the hydrometallurgical process efforts are ongoing to improve the electrical efficiency of the electro winning process with about 40% (Dresher 2001). However, far larger gains are possible by increasing the amount of recycled copper. As recycled copper has only electricity requirements, greenhouse gas emission can be reduced considerably in countries with low indirect (electricity linked) emissions. With regard to the discussion on carbon leakage, we may assume that in Europe copper recycling will still increase, which would lead to a larger loss of CO_2 emissions to the rest of the world in case of a relocation of industries.

4.2.4 Subbranches: Zinc

Zinc is produced from zinc sulphide ores containing between 2 and 30% zinc. Based on general process data carbon intensities for various processes in zinc production can be calculated (see Table 4-7). Depending on the process and the grade of the ore the energy use and the emissions vary considerably.

Table 4-7 Energy and CO_2 intensity of zinc production.

	process	energy intensity (GJ/ton met)	CO_2-intensity (kg/ton met)
primary zinc production	electrolysis	14 – 50	1800 – 4600
	imperial smelting furnace + New Jersey distillation	42 (36-45)	4100 (of which 430 process emissions)
secondary zinc production	Waelz kiln process	50	5000 (of which 3700 process emissions)

Source: JRC, 2001, IPCC 2006, Grimes et al., 2008.

Also zinc casting is energy intensive. Die casting with electric heating consumes 1,4-1.6 GJ/ton met (Energetics, 1999).
As fuel and electricity intensity have not been split out, a country analysis, similar to copper, has not been undertaken. Not all countries in the EU produce refined zinc. Zinc producing countries are: Belgium, Bulgaria, Finland, France, Germany, Italy, Netherlands, Norway, Poland, Romania, Spain and United Kingdom.
Also for zinc production Minecost and Metalytics have produced a report with country information but aggregate figures have not been released yet[4].

4.2.5 Subbranches: Lead

The energy requirements for the production of lead depend on the lead concentration in the ore. Lead sulphide ores usually contain less than 10% of lead per weight. The metal is concentrated to around 50-70% before processing in either a blast furnace process or the Imperial smelting process. The last is designed to recover both zinc and lead from ores. It has, however, higher energy intensity for lead alone.
Secondary lead production uses scrap from old vehicle batteries as a source, which is melted in two steps to separate the metal.

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[4] Brochure on: http://metalytics.info/yahoo_site_admin/assets/docs/ZnGHG_Brochure.109215806.pdf, also this report has a unit price of US$20,000.

Table 4-8 Energy and CO_2 intensity of lead production.

	process	**energy intensity (GJ/ton met)**	**CO_2-intensity (kg/ton met)**
primary lead production	blast furnace	20	2100
	imperial smelting furnace	32	3200
secondary (recycled) lead production	disaggregation, smelting, refining	9.1	

Note: energy consumption for the full lifecycle including mining and concentration.
Source: Grimes et al., 2008.

As fuel and electricity intensity have not been split out, a country analysis, similar to zinc, has not been undertaken. Not all countries in the EU produce refined lead. Lead producing countries in the EU are: Austria, Belgium, Bulgaria, Czech Rep., Estonia, France, Germany, Greece, Ireland, Italy, The Netherlands, Poland, Portugal, Romania, Slovenia, Spain, Sweden, and the United Kingdom.

4.2.6 Subbranches: Nickel

The energy requirements for nickel production depend on the type of ore (and therewith with the process required for refining) and on the nickel content of the ore. A reduction of the ore grade from e.g. 2.4% to 0.3% results in a tripling of the energy requirements (Grimes et al., 2008). Nickel mining occurs in Europe in Finland, Greece and Norway. Additional countries with nickel processing industry are Austria, France, Poland and the UK.

Table 4-9 Energy and CO_2 intensity of nickel production.

	process	fuel intensity (GJ/ton met)	electricity intensity (GJ/ton met)	energy intensity (GJ/ton met)	CO_2-intensity (kg/ton met)
primary nickel production	from sulphide ore (2.4%) in flash furnace with Sherritt-Gordon refining	96	18	114 (100-200)	11400
	from laterite ore (1%) by pressure acid leaching, solvent extraction and electrowinning	165	29	194	16100
	from laterite ore by ammonia leaching, solvent extraction, reduction and sintering			340-800	
secondary (recycled) nickel production	disaggregation, smelting, refining			15.4-15.8	

Note: energy consumption for the full lifecycle including mining and concentration. CO_2 intensities calculated for 100% coal based electricity.

Source: Grimes et al., 2008, Norgate and Rankin, 2000.

For a country comparison the data on the CO_2 intensity of fuel use in the non-ferrous metal industry and the CO_2 intensity of electricity production in the various countries have been combined with the fuel en electricity efficiencies listen Annex 1 and Table 3-1. As we did not have information on the spread of the different production processes over countries (and even some countries currently do not have nickel mining or nickel processing industry), efficiencies for production from sulphide ore (2.4%) in flash furnace with Sherritt-Gordon refining have been used for all countries. This leads, of course, to an underestimate of real emission efficiencies, but is useful to get a rough impression of the differences in intensity between countries.

Production of nickel is more CO_2-intensive than producing copper. Per ton of product there is comparably more use of fuels than of electricity, which means that in the calculation CO_2 emissions from the use of electricity have less weight than emissions from fuel use. Consequently the range in outcomes of the total CO_2 intensity is less extreme than for electricity intensive processes like Aluminium and Copper production (See Table 4-10).

Still, coal based economies like Poland and China top the list.

Table 4-10 CO_2 intensity of nickel production by country.

	fuel CO_2 intensity	**electricity CO_2 intensity**	**total CO_2 intensity**
	kgCO$_2$/ton met		
EU			
Germany	6426	907	7330
France	5820	150	5970
Italia	5696	725	6420
Spain	6929	695	7620
The Netherlands	5386	1011	6400
Belgium	6346	441	6790
Sweden	7894	186	8080
Poland	8079	1594	9670
Czech republic	5386	1218	6600
Other developed countries and EIT			
USA	5533	905	6440
Japan	9209	683	9890
Canada	6850	331	7180
Switzerland	6075	68	6140
Turkey	6539	965	7500
Russia	n/a	977	n/a
Ukraine	5723	574	6300
Developing countries			
China	8583	1191	9780
Brazil	7673	178	7850
India	8744	n/a	n/a
South Korea	8164	685	8850
Mexico	5409	810	6220
Indonesia	n/a	n/a	n/a
South Africa	n/a	1686	n/a
Thailand	n/a	917	n/a

Notes: based on IEA energy data (fuel use and its CO_2 intensity in the non-ferrous metal industry per country) and standard fuel and electricity efficiency factors and energy efficiencies of production from sulphide ore (2.4%) in flash furnace with Sherritt-Gordon refining. The last are the same for all countries. The outcomes are relevant for a relative country comparison, but absolute numbers may differ considerably from reality. Romania and Hungary have been excluded from the table as they currently do not have nickel production. The rather high fuel intensity in the non-ferrous metal industry in Japan is probably due to statistical causes such as a deviating sector definition.

4.2.7 Subbranches: Tin

Tin ore is mined from hard rock and from alluvial deposits. The grade in alluvial deposits is higher and that explains the lower energy intensity (Table 4-11). Tin producing countries in Europe are Portugal and Spain, their production is, however, limited compared to large producers like China, Indonesia and Peru.

Table 4-11 Energy and CO_2 intensity of tin production.

	process	energy intensity (GJ/ton met)
primary tin production	from alluvial deposits, roasting, reduction and refining	19.6
	from hard rock ore, roasting, reduction and refining	127
secondary (recycled) tin production	disaggregation, smelting, refining	0.2

Note: energy consumption for the full lifecycle including mining and concentration.
Source: Grimes et al., 2008.

As fuel and electricity intensity have not been split out, a country analysis, similar to zinc, has not been undertaken. On average tin production generates 15650 kg CO_2/ton tin (based on 0.1% tin in crude ore and electro-refining).

4.2.8 Subbranches: Aluminium

Primary aluminium is produced in three steps: bauxite mining, alumina refining and aluminium smelting.
The International Aluminium Institute provides data on energy use in refining and aluminium smelting per world region (Table 4-12). These data, however, do not include the Chinese alumina production, with an energy consumption that is twice the level reported in Table 4-12 (IEA, 2008).

Table 4-12 Regional average energy use in aluminium production.

	Alumina production[a)]	Aluminium smelting		Total
	GJ/ton aluminium	kWh/ton aluminium	GJ/ton aluminium	GJ/ton aluminium
Africa and South Asia	29.0	14 622[b)]	52.6 [b)]	81.6
North America	23.8	15 452	55.6	79.4
Latin America	22.4	15 030	54.1	76.5
East Asia and Oceania	23.6	15 103[c)]	54.4 [c)]	78.0
Oceania		14 854	53.5	
Europe	26.2	15 387	55.4	81.6
World weighted average	24.0	15 194	54.7	78.7

Notes: a) based on 1 kg aluminium from 2 kg of alumina; b) Africa only; c) whole of Asia only
Source: World Aluminium, 2007.

General process data give carbon intensities for various processes in aluminium production as in Table 4-13. These figures include also other energy use in the smelting process.

Table 4-13 Energy and CO_2 intensity of aluminium production.

	fuel intensity (GJ/ton Al)	electricity intensity (GJ/ton Al)	energy intensity (GJ/ton Al)	CO_2-intensity (kg/ton Al)
primary aluminium production	36.8	56.6	93.3	7700 – 18400[a)]
secondary aluminium production	7.1	-	7.1	500

Notes: a) lowest value corresponding to the energy mix in European aluminium electrolysis industry, highest value corresponding to CO_2 intensity of coal fired power plants

Source: JRC, 2001, IPCC 2006

The resulting CO_2 emissions depend heavily on the source of the electricity. About half of aluminium production in the world relies on hydro-electricity, but there are large regional differences (Table 4-14)

Table 4-14 Smelting electricity fuel source (percentages per continent), 2007.

	Africa	North America	Latin America	Asia	Europe	Oceania	world average
	%						
Hydro	51	74	92	11	64	23	57
Coal	49	25	0	33	20	77	29
Oil	0	0	0	3	1	0	1
Natural gas	0	0	8	53	5	0	9
Nuclear	0	1	0	0	10	0	4
Total	100	100	100	100	100	100	100

Source: IAI

Combining the efficiencies for primary aluminium production from Table 4-13 with carbon intensities of fuel use in the non-ferrous metal industry and of national electricity generation[5], results in Table 4-15.
As with the other metals the outcome is heavily determined by the electricity intensity. Countries with a large share of hydro or nuclear electricity (France, Belgium, Sweden, Canada, Switzerland and Brazil) have a good score, while coal dominated countries (such as Poland, China, Czech Republic, and to a lesser extent USA, Turkey and Hungary) have high intensities.

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[5] The split in electricity fuel source from Table 4-14 has not been used for this calculation, because (1) it is not split by country, (2) the national average split in fuels for power plants might be more close to reality for some countries than a continental average.

Table 4-15 CO_2 intensity of aluminium production by country.

countries (between brackets nr of smelters)	fuel CO_2 intensity	electricity CO_2 intensity	total CO_2 intensity
	kgCO_2/ton met		
EU			
Germany (6)	2463	2852	5310
France (4)	2231	473	2700
Italia (3)	2184	2281	4460
Spain (3)	2656	2185	4840
The Netherlands (2)	2064	3180	5240
Belgium[a)]	2433	1386	3820
Sweden (1)	3026	584	3610
Poland (1)	3097	5011	8110
Czech republic [a)]	2064	3831	589
Romania (1)	n/a	2730	n/a
Hungary (1)	2078	2710	4790
Other developed countries and EIT			
USA (23)	2121	2844	4960
Canada (12)	2626	1041	3670
Switzerland (1)	2329	213	2540
Turkey (1)	2507	3034	5540
Russia (13)	n/a	3071	n/a
Ukraine (2)	2194	1806	4000
Developing countries			
China (20)	3290	3745	7040
Brazil (7)	2941	560	3500
India (7)	3352	n/a	n/a
Mexico (1)	2073	2548	4620
Indonesia (1)	n/a	n/a	n/a
South Africa (2)	n/a	5301	n/a

Notes: based on IEA energy data (fuel use and its CO_2 intensity in the non-ferrous metal industry per country) and standard fuel and electricity efficiency factors; the outcomes are relevant for a relative country comparison; absolute numbers may differ from reality. Between brackets the number of smelters per country. Japan, South Korea and Thailand have been omitted from the table as these countries currently do not have aluminium production. a) currently only secondary aluminium production.

Apart from emissions of CO_2, the aluminium industry is an important source of PFC emissions. These are formed in the aluminium smelting process during brief upset conditions known as “anode effects”. By reducing the frequency of anode effects, emissions can be reduced. The age of the facilities is a crucial variable in this: new facilities with the most modern controls have the lowest emissions. The performance of OECD and non-OECD countries in PFC emissions is more or less comparable. In 2006 the world average emission of PFC was 700 kg CO_2-eq/ton of aluminium produced (IAI, 2008).

The conclusion with regard to carbon leakage is similar to that for the equally energy intensive copper industry. With the exception of France, relocation from the EU to Brazil would lead to lower emissions. Relocation from the EU to China would lead to higher global emissions (with Poland as the probable exception). For the rest the carbon leakage is very much dependent on the country of origin and destination.

4.2.9 Aluminium: BAT and future efficiencies and its effect on carbon leakage

New world class smelters consume 13 000 kWh (48.6 GJ) per ton of aluminium. It is expected that in the next decade the strive to further reduce energy consumption will lead to another efficiency improvement of 10%, giving an efficiency of the smelter alone of ca 44 GJ/ton Al (Moors, 2006).
This is still somewhat away from a theoretical minimum total energy use, which would be 20 GJ for the smelter, 18 GJ of petroleum coke for production of the anodes and 7.4 for other energy use in the smelter, totalling 45.4 GJ/ton (IEA, 2008).
It is important to note that producing recycled aluminium requires only 5% of the energy that is needed for producing “new” aluminium (see Table 4-13). Large efficiency improvements are thus possible by increasing the share of recycled aluminium. Currently it is 30% in the world, expected to grow to 40-50% in the coming decade.
Future efficiency improvements in primary aluminium production are, however, still of minor importance compared to the choice of fuel and the source of electricity. An overview of plans for new installations in India for instance, reveals that most of the electricity would come from coal based powerplants[6]. Also the Chinese aluminium production continues to rely on electricity from coal. Relocation of production to these countries will almost certainly lead to carbon leakage.

4.3 Chemicals and petrochemicals

4.3.1 Analysis of available statistics

Due to the absence of production data is was not possible to calculate greenhouse gas efficiencies based on international statistics, as in the previous Sections. Only the production of fertilizers worldwide is available from FAO (2009). Scattered production data are available from Eurostat for EU countries, and from UNFCCC (2009) for some of the Annex 1 countries. However, the coverage of the variety of chemical products is not enough to calculate efficiencies.
For the discussion in this section we have selected those branches within chemical industry that have a large share in greenhouse gas emissions in the Annex I countries (UNFCCC data), that is: the production of ammonia, nitric acid, adipic acid, carbon black, ethylene and methanol. Most data are available for ammonia production, which is dealt with in more detail. For other processes only general emission intensities are listed as energy and greenhouse gas emission data are unavailable at country level. It should be noted that there is often an overlap between chemical industries. For instance, ammonia is a precursor of the nitrogen chemicals nitric acid and adipic acid. For the sake of simplicity, the energy and CO_2 intensities of those production processes are presented separately.

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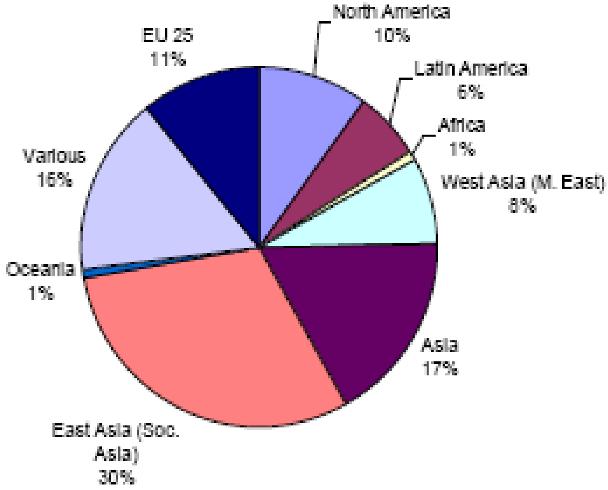
[6] Metalworld, January 2008. <http://www.metalworld.co.in/report0108.pdf>

4.3.2 Subbranches: Ammonia production

The ammonia industry is an important chemical industrial branch. Ammonia (NH_3) gas is used for the production of fertilizers, nitric acid, nitrates and organic nitro compounds (e.g. amides, amines, and urea).
In 2005, the worldwide ammonia production amounted to about 145 Mt. More than half of the production was manufactured in Asia (see Figure 4-5).



Source: International Fertiliser Association

Figure 4-5 Ammonia production by region, 2005.

Ammonia manufacturing requires a nitrogen (N) and hydrogen (H) source. Nitrogen (N_2) is mostly obtained from air through liquid air distillation. Hydrogen is mostly obtained from natural gas by means of steam reforming (77%). Coal gasification is also applied but this way of production is of minor importance (14%). Additionally, other hydrocarbons are used as H sources, such as naphtha and fuel oil via partial oxidation. This process accounts for only 9% of the ammonia production. The choice of feedstock has a major influence on the energy use (see Table 4-16) and hence on CO_2 emissions by the ammonia industry.

Table 4-16 Energy intensity of ammonia production.

Region	Production	Energy intensity			
		GJ/t NH_3			
	Mt NH_3	Gas based	Oil based	Coal based	Average
Western Europe	12.2	35			35
North America	14.4	37.9			37.9
CIS	20.9	39.9			39.9
Central European Countries	6.2	43.6			43.6
China	43.7	34	42	54	48.8
India	12.2	36.5	50		43.3
Other Asia	13.3	37			37
Latin America	9	36			36
Africa	4	36			36
Middle East	8.5	36			36
Oceania	1.2	36			36

Source: International Fertiliser Association and IEA.

China and India have the highest energy intensities because of the use of oil and coal based feedstocks in ammonia plants. According to Worrel et al. (2007), the US energy use in ammonia plants amounts 37,1 GJ/tonne NH_3, which is in correspondence with the value in the previous table.
Apart from feedstocks also the choice of process influences energy use and CO_2 emissions (see Table 4-17).

Table 4-17 Default total fuel requirements (fuel plus feedstock) and emission factors for ammonia production in Europe.

Production process	Total fuel requirement in GJ (NCV[a])/tonne NH_3	CO_2 emission factor (kg CO_2/tonne NH_3)
Modern plants-Europe Conventional reforming-natural gas	30.2	1700
Excess air reforming-natural gas	29.7	1700
Autothermal reforming-natural gas	30.2	1700
Partial oxidation (hydrocarbons)	36	2800
Partial oxidation (coal)	48	> 2800
Derived from European average values for specific energy consumption (mix of modern and older plants) Average value-natural gas	37.5	2100
Average value-partial oxidation	42.5	3300

Note: a) NCV stands for Net Calorific Value.
Source: IPCC, 2006.

Compared to CO_2 the emissions of other greenhouse gases from ammonia production are negligible. See table 4-18.

Table 4-18 Greenhouse gas emissions NH_3 production.

	GHG emissions steam reforming		GHG emissions partial oxidation	
	kg/t NH_3	kg CO_2-eq/t NH_3	kg/t NH_3	kg CO_2-eq/t NH_3
N_2O	0.0148	4.58	0.0549	1.15
CH_4	0.012	3.72	0.022	0.46
CO_2	1460	1460	2340	2340

Source: Althaus et al., 2007.

From the country reports to the UNFCCC some data can be derived on the emission intensity of ammonia manufacturing in the Annex I countries (Table 4-19). The emission intensities from UNFCCC data are generally in line with the CO_2 emission intensities in Table 4-17. Intensities in non-European countries are in the same order of magnitude as in European countries. However, some countries, like France, Italy and Spain report lower than average emission intensities. The high intensities in the Czech Republic, Hungary and in the Ukraine can probably be explained by the use of coal as feedstock.

Table 4-19 Reported emissions from ammonia production.

Country	Production (kton)	CO_2 emissions (kton)	Implied emission factor (kg CO_2/ton product)
EU			
Germany	2894	5253	1800
France	1444	2068	1400
Italy	607	705	1200
Spain	542	612	1100
Netherlands		3105	
Belgium	388	1330	3400
Poland	2524	4448	1800
Czech Republic	254	609	2400
Hungary	336	822	2400
Non-EU			
USA	10143	12817	1300
Japan	1309	2155	1600
Canada	4025	6330	1900
Russia	12473	18709	1500
Ukraine	5213	10859	2100

Source: UNFCCC, 2009

In the absence of information on the distribution of technologies over the various countries it is impossible to produce a country comparison data based on energy use and standard emissions factors per process, like in previous sections. However, using the reported values, industry information on energy intensity per continent and the default emission factors a rough guesstimate of the CO_2 emission intensity of ammonia production can be made (Table 4-20). Some tentative conclusions: Carbon leakage would occur in case of relocation from a western European country (probably apart from Belgium) to a developing country. In case of relocation from Eastern Europe to a developing country it would probably be carbon neutral. Movements from Western Europe to other OECD countries would probably be also carbon neutral. Within these broad conclusions, the situation may differ from country to country.

Table 4-20 Guesstimate of CO_2 emission intensities.

countries	**total CO_2 intensity**
EU	
Germany [a)]	1800
France [a)]	1400
Italia [a)]	1200
Spain [a)]	1100
The Netherlands	1700
Belgium [a)]	3400
Sweden [a)]	1800
Poland	3400
Czech republic [a)]	2400
Romania	3400
Hungary [a)]	2400
Other developed countries and EIT	
USA [a)]	1300
Japan [a)]	1600
Canada [a)]	1900
Switzerland	1700
Turkey	
Russia [a)]	1500
Ukraine [a)]	2100
Developing countries	
China	3700
Brazil	2800
India	3400
South Korea	2850
Mexico	2800
Indonesia	2850
South Africa	2800
Thailand	2800

Notes: a) derived from UNFCCC, 2009; all other figures derived from defaults in Table 4-17.

BAT ammonia production and carbon leakage

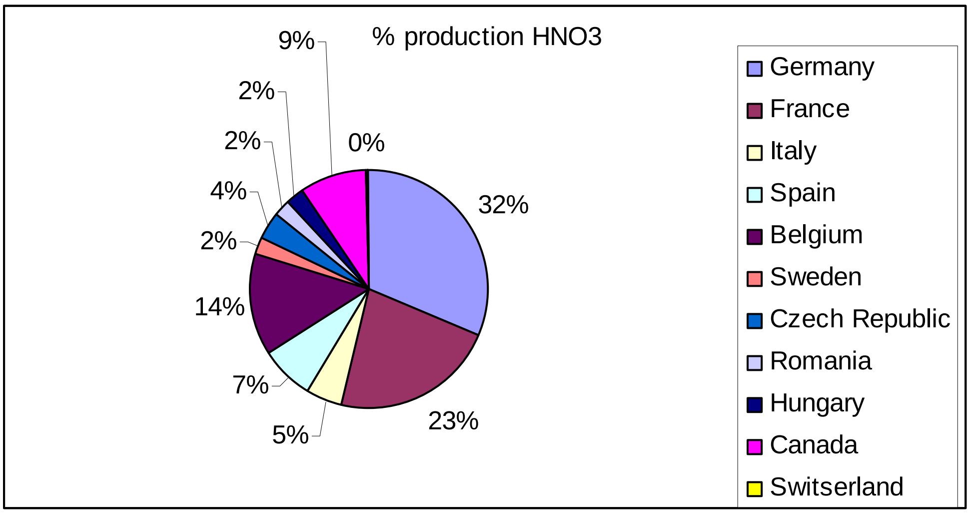
Current operated units have an energy demand of about 30 GJ/ton NH_3. BAT processes are at about 28-29 GJ/ton NH_3 (SenterNovem, 2008). Other sources (Bergmann et al., 2007, Althaus et al. et al., 2007) mention this BAT energy intensity value as well.

Neelis et al. (2006), however, mentions reductions in the final energy consumption of 20% to 40%, depending on the feedstock. Assuming that the pessimistic value is closer to reality, the use of BAT would not change much to the conclusions regarding carbon leakage. Although the ammonia industry might be an early applicant of Carbon Capture and Storage (CCS) this has not been taken into consideration, as technologies still are in an early phase of development.

4.3.3 Subbranches: Nitric acid production

As stated in the previous subsection, ammonia is an important raw material for the production of other nitrogen compounds, like nitric acid. Nitric acid is mainly used as a raw material for the production of nitrogenous fertilizers, adipic acid and explosives (e.g. dynamite). Moreover, this acid has applications in metal etching and in the processing of ferrous metals. Nitric acid is manufactured through a high temperature catalytic oxidation of ammonia.

In 2003, 12,1 million tonnes of nitric acid were produced in the Annex I countries. Germany and France were the major HNO_3 producing countries, followed by Belgium. No data have been found for HNO_3 production in other parts of the world.



Source: JRC, 2006.

Figure 4-6 Nitric acid production shares Annex I countries, 2003.

Nitric acid is produced from ammonia in a few nitrogen oxidation steps, at which NO and NO_2 are intermediates. Those nitrogen oxidation steps are important N_2O sources. NO decomposes to N_2O and NO_2 at high pressures for a temperature range of 30 to 50 ^{0}C. The amount of N_2O that is released depends on the reaction conditions, such as the pressure, temperature, catalyst composition and also the age and design of the plant play a role. Concentrated nitric acid can be manufactured in both single pressure plants and in dual pressure plants (IPCC, 2006). In single pressure plants the oxidation and absorption occur at the same pressure. In dual pressure plants, absorption occurs at a higher pressure than the oxidation stage.

If not abated, the by-product nitrous oxide (N_2O) is undesired because it is a strong greenhouse gas. Furthermore, formation of N_2O or N_2 decreases the conversion efficiency of NH_3 and reduces the yield of NO. Abatement of N_2O emissions is possible by means of catalytic reduction or N_2O destruction, which is discussed at the end of this subsection. The N_2O emission factors for various nitric acid production processes are given in Table 4-21.

Table 4-21 N2O emission factors for various production processes.

Production process	kg N2O/tonne nitric acid	kg CO_2-eq/tonne nitric acid
Atmospheric pressure plants (low pressure)	5	1550
Medium pressure plants	7	2170
High pressure plants	9	2790

Source: IPCC, 2006

Table 4-22 integrates both CO_2 and N_2O emission intensities.

Table 4-22 Energy and CO_2 and N_2O intensities of nitric acid production.

Process route	Energy intensity (GJ/tonne HNO_3)	CO_2 intensity (kg CO_2/tonne HNO_3)	Greenhouse gas intensity (kg CO_2 eq. /tonne HNO_3)
Integrated, NH_3 from air/steam reforming, natural gas	6.7	500	2500
Integrated, NH_3 partial oxidation, heavy hydrocarbons	9.3	800	2800

Note: The CO_2 intensity is calculated as the net result of the exothermal nitric acid production process (-1,6 tonnes CO_2/tonne HNO_3) and the proportionate share of the NH_3 production process. The total greenhouse gas intensities include for N_2O emissions the average of 2 tonnes CO_2 eq./tonne HNO_3.

Source: Bergmann et al., 2007.

BAT nitric acid production and carbon leakage

N_2O emissions can be reduced by means of some abatement measures, such as NSCR (Non-selective catalytic reduction) and SCR (Selective catalytic reduction), which are end-of-pipe solutions. Additionally, process-integrated or tail gas N_2O destruction are possible and adjustment of reaction and gas absorption circumstances. HNO_3 plants provided with the N_2O abatement measures NSCR, process-integrated or tail gas N_2O destruction give rise to significant N_2O emission reductions, compared to plants without N_2O abatement. The N_2O emission factors associated with these BAT processes are given in Table 4-23.

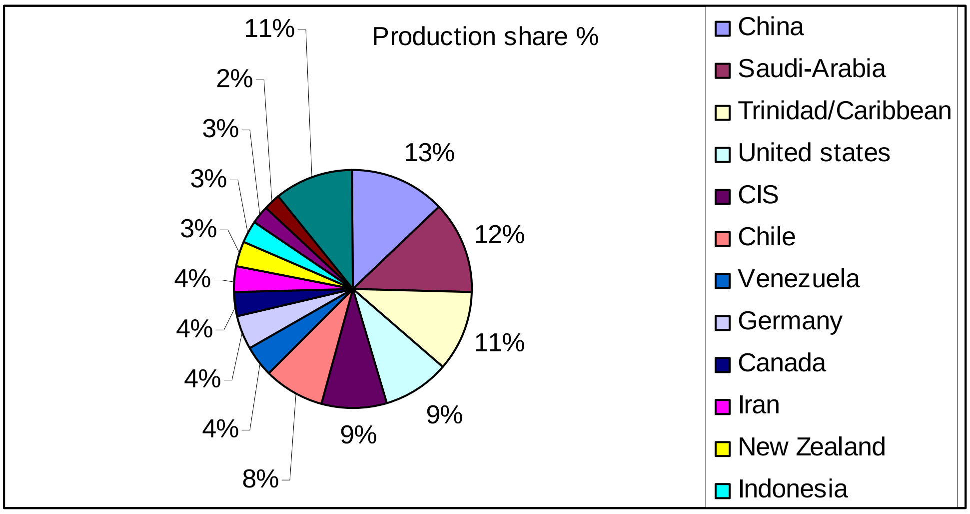
Table 4-23 N_2O emission factors for BAT production processes.

BAT process	N_2O emission factor	
	kg N_2O/tonne nitric acid	kg CO_2-eq/tonne nitric acid
Plants with NSCR (Non-Selective Reduction; all processes)	2	620
Plants with process-integrated or tail gas N_2O destruction	2.5	775

In the absence of information on the distribution of production processes over countries, no country comparison table has been made. The huge reductions of N_2O emissions by applying BAT, which potentially more than halve the emission intensity, highlight however that the technology applied is a very important factor in determining carbon leakage for relocation of nitric acid production.

4.3.4 Subbranches: Methanol production

Most of the methanol (about 70%) that is produced worldwide is used in chemical synthesis of various organic compounds, such as formaldehyde, MTBE (methyl tertiary butyl ether), acetic acid, MMA (methyl methacrylate) en DMT (dimethyl terephtalate). Only a small share of the methanol production is used for energy production.



Source: IEA, 2007.

Figure 4-7 Methanol production shares by main producing countries (IEA, 2007).

China is the biggest methanol producer, very closely followed by Saudi Arabia and Trinidad/the Caribbean (Figure 4-7). The main resource for global methanol production is natural gas, which is both feedstock and fuel. About 80% of the global methanol production is gas based. The remainder is coal based, particularly in China (EIA, 2007). Nearly all methanol in the world is produced by means of conventional steam reforming (JRC, 2003). In this process, methane and steam are converted into synthesis gas (CO, and H_2). CO reacts with H_2O to CO_2 and H_2. Methanol is produced in the reaction between CO and H_2.

Methanol can also be produced from renewable resources as well, e.g. biomass (IPCC Guidelines 2006), which is probably the case for much of the ethanol from the Caribbean, but information on the total share is lacking.

The conventional reforming process can include a single reformer unit or both a primary reformer unit and a secondary reformer. Lurgi developed a two-step combination (combined reforming process) for large methanol synthesis plants. Partial oxidation is hardly applied.

Table 4-24 Methanol production CO_2 intensities for various process feedstock combinations.

	Natural gas	Natural gas + CO_2	Oil	Coal	Lignite
Process configuration	kg CO_2/tonne methanol produced				
Conventional Steam Reforming, without primary reformer (Default Process and Natural Gas Default Feedstock)	670				
Conventional Steam Reforming, with primary reformer	497	267			
Partial oxidation process			1376	5285	5020

Note: based on the average of emission data from methanol plants in New Zealand, Chile, Canada and the Netherlands using the conventional steam reforming process with natural gas feedstock, applied to energy use of the other processes.
Source: IPCC, 2006

In the mid 1990’s, methane emissions were determined by Methanex for two methanol production plants in Canada (IPCC, 2006). Methane emissions arise from reformers, package boilers, methanol distillation units and crude methanol storage tanks. CH_4 emissions from those methanol plants accounted for 0.5-1.0% of the total greenhouse gas emissions from those plants. The average CH_4 emission factor amounts 2.3 kg CH_4/tonne CH_3OH, corresponding with 48.3 kg CO_2-eq/tonne CH_3OH.

BAT methanol production and carbon leakage

Neelis et al. (2006) report BAT energy intensities for Western European methanol production plants. According to their study, the total final energy consumption of BAT processes is 9.4 GJ/tonne methanol. The total final average energy consumption of current methanol plants in Western Europe is 12,5 GJ/tonne methanol. Both values apply to the feedstock natural gas. A reduction of energy use by 25% would probably translate in an equal CO_2 emission reduction.
Lurgi introduced several methanol production processes with lower energy intensities resulting in emission reductions of about 50% (Table 4-25).

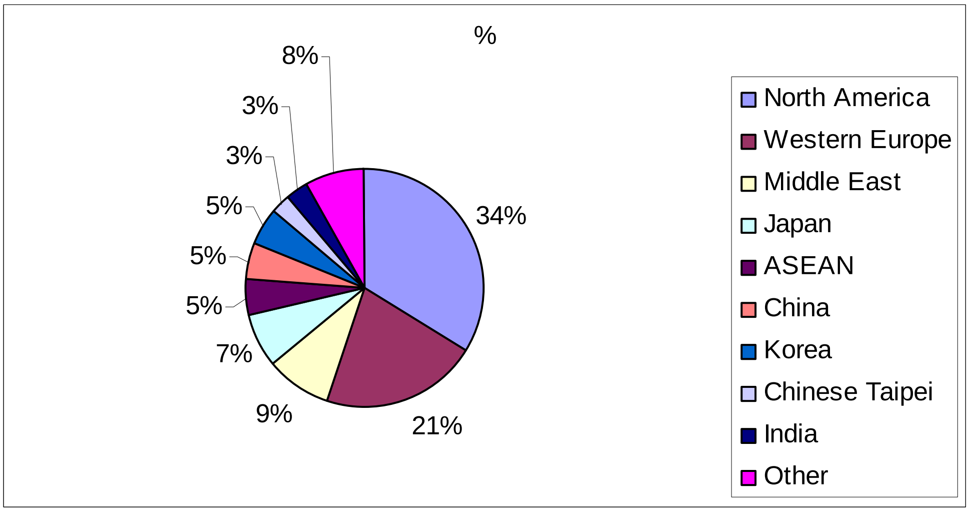
Table 4-25 Lurgi methanol production processes with their CO_2 emission factors for the Lurgi with the feedstock natural gas.

Process configuration	kg CO_2/tonne methanol produced
Conventional Steam Reforming, Lurgi Conventional Process	385
Conventional Steam Reforming, Lurgi Low Pressure Process	267
Combined Steam Reforming, Lurgi Combined Process	396
Conventional Steam Reforming, Lurgi Mega Methanol Process	310

In the absence of country specific information on production processes no country comparison has been made. From the available information it can be concluded that any relocation to a country with coal as feedstock would lead to huge carbon leakage (a tenfold increase of emissions per ton of methanol). The effect of relocations between countries using gas as feedstock depends on the technologies in use in the various countries.

4.3.5 Subbranches: Ethylene production

Ethylene is primarily used for polymer synthesis. More than half of the globally produced ethylene is used for the production of polystyrene (via ethylbenzene and styrene), glycol (via ethylene oxide), vinyl acetate and PVC. The global production capacity was approximately 112.6 million tones in 2004 (Bergmann et al, 2007). North America and Western Europe are major production areas of ethylene (Figure 4-8).



Note : ASEAN = association of South East Asian Nations
Source: METI, 2006, Bergmann et al., 2007.

Figure 4-8 Ethylene production shares by region.

Ethylene is mainly produced by means of steam cracking of various petrochemical feedstocks, such as ethane, propane, butane, naphta, gas oil etc., varying by region (IPCC, 2006). In this thermal process, such hydrocarbons are heated to very high temperatures in the presence of steam (JRC, 2003). The product yield depends on the kind of feedstock that is used. In the USA, ethylene is mainly manufactured from steam cracking of ethane. In Europe and Asian countries like Korea and Japan, ethylene is predominantly produced from steam cracking of naphtha (from crude oil refining). Steam cracking also yields some valuable by-products such as propylene, butadiene and aromatic compounds. The by-products hydrogen, methane and C4+ hydrocarbons are generally burned for energy recovery within the process. However, some methane is emitted. Furthermore, the boilers emit carbon dioxide.
The energy intensities of ethylene production in Europe are on average higher than the American values (Table 4-26). Plants that are provided with the feedstock gasoil have the highest energy consumption, in Europe as well as in the USA.

Table 4-26 Energy intensities of ethylene production from various feedstocks.

Feedstock	**Europe GJ/tonne ethylene**	**USA GJ/tonne ethylene**
Ethane	15-25	14
Naphtha 15	25-14	20-27
Gas oil 25	40-20	20-27

Source: Worrel et al, 2000.

As a result gasoil derived ethylene has the highest CO_2 emission intensity (Table 4-27). The methane emissions add relatively little to the total: for the feedstock ethane 126 kg CO_2-eq/ton ethylene, for naphtha and other feedstocks 63 CO_2-eq/ton ethylene (IPCC, 2006).

Table 4-27 CO_2 emission intensity of ethylene production.

Feedstock	**Naphtha**	**Gas oil**	**Ethane**	**Propane**	**Butane**	**Other**
	kg CO_2/tonne ethylene produced					
Ethylene, total process and energy feedstock use	1730	2290	950	1040	1070	1730
Process Feedstock Use	1730	2170	760	1040	1070	1730
Supplemental Fuel (Energy Feedstock) Use	0	120	190	0	0	0

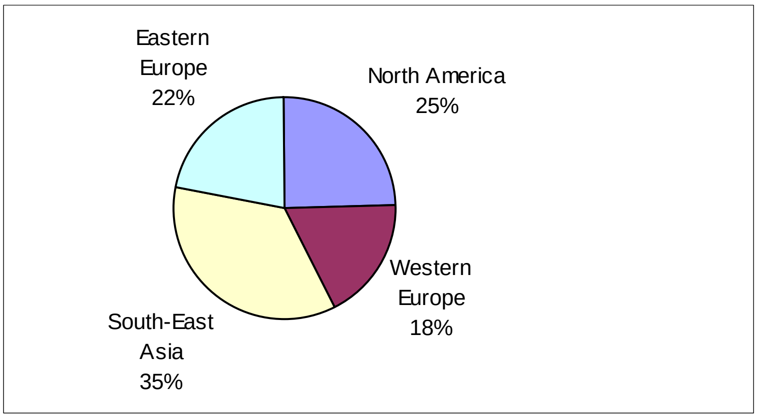
Source: IPCC, 2006.

BAT ethylene production and carbon leakage
Depending on the feedstock reductions of energy use are possible in the order of 25% for propane and natural gas, 37% for ethane and more than 40% for naphtha and gasoil (Neelis et al., 2006).
In the absence of country specific information, the only conclusion with regard to carbon leakage is that that relocation of ethylene production from the EU to the USA probably would not lead to carbon leakage. Feedstock appears to be a crucial variable in discussing carbon leakage, but the influence of the use of (best available) technology is also large.

4.3.6 *Subbranches: Carbon black production*

Carbon black is an important inorganic chemical, particularly in the tire and rubber industry. A minor part (only 10%) is used for the production of inks and pigments. The production of carbon black is spread over the world (Figure 4-9).

Carbon black is not a petrochemical but for its production petrochemical feedstocks are needed . Nearly all carbon black in the world is produced from petroleum-based or coal-based feedstocks in the furnace black process, in which the primary feedstock is injected into a furnace that is heated by a secondary feedstock, usually natural gas or oil. The primary feedstock is thermally decomposed in the absence of oxygen. In addition to the furnace black process, the thermal black process and the acetylene black process are in used but they are of minor importance. These processes resemble the furnace black process but the primary feedstocks are different: gaseous hydrocarbons in the former and acetylene in the latter process.
However, a tiny part of the carbon black may be produced from renewable sources, like animal black and bone black (IPCC Guidelines, 2006). This biogenic share has not been found. In addition, some of the carbon black may be produced in refineries, which are beyond the scope of the chemical industries under study in this report.



Source: Althaus et al., 2007.

Figure 4-9 Shares in the world production of carbon black.

The energy intensity of the thermal black process is approximately 280 MJ/kg carbon black produced (IPCC Guidelines 2006). Emission factors are specified for the production processes furnace black process (default process), the thermal black process and the acetylene black process (Table 4-29).

Table 4-29 CO_2 emission factors for plants in Europe.

Process Configuration	**Primary feedstock**	**Secondary feedstock**	**Total feedstock**
	kg CO_2/tonne carbon black produced		
Furnace black process (default process)	1960	660	2620
Thermal black process	4590	660	5250
Acetylene black process	120	660	780

Source: IPCC, 2006.

In the absence of any further information no conclusions on potential carbon leakage can be drawn.

4.4 Pulp and paper industry

The pulp and paper industry is one of the largest energy consumers (5.7% of the global total industrial energy use). Most of this energy is used for mechanical pulping and paper drying. The need for large amounts of steam here makes it attractive to use on-site CHP (combined heat and power) plants and consequently most modern plants have their own CHP unit. Additionally, chemical pulp mills produce black liquor which is used to generate electricity. IEA estimates the total black liquor use in the pulp and paper sector in 2004 at 2.4 EJ (IEA, 2007), which means that more than one third of all energy use is biomass. This heavy reliance on bio energy means that the CO_2 intensity of the industry is not very high and that CO_2 reduction potentials are limited.

4.4.1 Analysis of available statistics

Seen the relative homogeneity of the sector it was expected that the analysis based on official statistics would provide some relevant outcomes. For applying standard methodology as described in Section 0., production data are available from FAOSTAT (FAO, 2009). Production data include pulp for paper (consists of chemical wood pulp, semi-chemical wood pulp, mechanical wood pulp and other fibre pulp) and recovered paper.

CO_2 emissions can be calculated based on energy use as reported in the statistics. And here lies one of the main problems: Pulp and paper plants have in many cases own CHP plants to provide for the electricity. They are fired with the feed material residues, such as bark, and with process waste and are essentially CO_2 free. The energy balance of a pulp and paper plant with CHP consists of fuel and electricity bought minus electricity sold. However, in official statistics CHP is accounted for separately and not linked anymore to the paper and pulp industry. National statistics also differ in the level of detail provided for the energy consumption, which causes differences in the accounting of the use of wood and wood wastes for energy use. As a result the energy and electricity consumption is not comparable across countries, and hence CO_2 emissions as calculated are not comparable. In general CO_2 efficiencies are too high due to not counting onsite CHP plants. These statistical issues blur the other differences between countries, such as the type of paper produced (based on wood or on recycled materials), and production processes.

4.4.2 Paper and pulp production types

When considering specific production processes, there are different technologies in use. Some operate only for pulp production, others are combined in integrated paper mills, in which pulp is directly processed into paper. Main processes are: the sulphate (Kraft) process, the sulphite process, the groundwood process only used for producing pulp for newsprint, the thermo mechanical pulping process used for producing pulp for newsprint, but also used in integrated paper mills; the chemi-thermo-mechanical process for producing pulp. Some of the chemical pulp mills are energy self-sufficient. Typical European efficiencies of paper production are provided in Table 4-30.

Table 4-30 Energy and CO_2 related data for paper production in European integrated paper mills.

	Fuel intensity (GJ / ton paper)	**Electricity intensity (GJ / ton paper)**	**Energy Intensity (GJ / ton paper)**	**CO_2intensity a) (kg CO_2 / ton paper)**
Sulphate (Kraft) uncoated fine paper	17.5	4.4	21.9	1500/900
Sulphite uncoated fine paper	21.0	4.9	25.9	1800/1100
Thermomechanical pulping TMP-paper	5.5	10.7	16.2	1600/1100
Recycled fibre RCF-paper	9.2	1.9	11.1	500/450

Note: a) first figure: thermal energy assumed to come from natural gas and electricity assumed to correspond to the EU average electricity energy mix; last column: thermal energy and electricity assumed to be produced according to the average energy mix of the European paper industry in 2005 (49.4% biomass (could be accounted as zero CO_2), 38.9% natural gas, 5.7% fuel oil, 4.3% coal).

Source: Bergman et al., 2007, JRC, 2001d.

The fuel and electricity intensities per pulp and paper production technology in Table 4-30 have been combined with available production data from FAO (2009) to calculate the fuel use per country for each production technology. Production data taken into account include bleached/unbleached sulphate and sulphite pulping, mechanical pulping and recycled paper production. Other fibre pulp is not taken into account in this analysis because fuel and electricity intensity are not available, therefore the total production figures are slightly lower compared to the standard statistical methodology. The total fuel use in GJ has been distributed over the countries by taking the relative share of each fuel in the overall pulp and paper industry from the IEA Energy Statistics (IEA, 2007b), assuming that the same fuel mix is used for each production technology. The fuel use per fuel and the electricity use have subsequently been combined with CO_2 emission factors for fuel use and electricity use, similarly to the standard statistical methodology (see Section 0) to obtain total emissions. The CO_2 efficiency is calculated as the emissions divided by the production, for both direct and indirect emissions. The final CO_2 efficiency is the sum of the direct and indirect emissions.

The results are given in Table 4-31, whereby the exhaust emissions from the combustion of biomass are accounted for as CO_2 emissions. The differences that occur from accounting the biomass burning emissions as zero emissions are shown in Figure 4-10 and Figure 4-11.
In Table 4-31, the observed differences between countries are generally smaller which indicates that the CO_2 efficiencies may be closer to reality. However, the differences may in fact be larger due to different fuel mixes per production technology, on which no data are available to us.

Table 4-31 CO_2 efficiency in the pulp and paper industry in 2005 calculated using the fuel and electricity efficiencies in Table 4-30, including non-zero emissions from biomass.

	Production (kton)	**Direct emissions (kton)**	**Indirect emissions (kton)**	**Direct efficiency (kg/ton)**	**Indirect efficiency (kg/ton)**	**CO_2 efficiency (kg/ton)**
European Union						
Germany	17 292	10 017	2 504	579	145	720
France	8 204	6 517	213	794	26	820
Italy	5 907	3 122	591	529	100	630
Spain	6 269	5 236	671	835	107	940
Netherlands	2 579	1 306	333	507	129	640
Belgium	2 647	2 495	179	943	68	1010
Sweden	13 239	19 036	788	1 438	59	1500
Poland	2 151	2 617	606	1 217	282	1500
Czech Republic	1 233	1 661	331	1 347	269	1620
Romania	428	383	63	896	147	1040
Hungary	368	212	33	575	91	670
EU Average	88 093	83 797	13 016	951	148	1100
Other developed countries and EIT						
United States	95 515	113 284	16 805	1 186	176	1360
Japan	33 008	35 809	3 682	1 085	112	1200
Canada	27 472	31 736	3 493	1 155	127	1280
Switzerland	1 462	1 206	16	825	11	840
Turkey	1 241	953	171	768	138	900
Russia	8 548	8 583	2 218	1 004	260	1260
Ukraine	339	189	21	557	61	620
Developing countries						
China	24 079	21 694	3 653	901	152	1050
Brazil	13 649	21 115	540	1 547	40	1590
India	2 736	3 354	1 128	1 226	412	1640
South Korea	7 597	6 449	622	849	82	930
Mexico	1 104	732	126	663	114	780
Indonesia	6 368	9 629	1 543	1 512	242	1750
South Africa	2 316	1 313	900	567	389	960
Thailand	2 318	2 181	333	941	144	1080

The table shows CO_2 efficiencies varying between 640 kg/ton for the Netherlands to 1750 kg/ton for Indonesia. The difference may be explained mainly by differences in technology. In the Netherlands, papermaking from recycled paper is the most used technology, while for instance in Scandinavian countries paper is mostly made directly from wood, which is more energy intensive.

The results from the table are also displayed in Figure 4-10 and Figure 4-11, where Figure 4-10 presents the actual outcomes from Table 4-31, while Figure 4-11 presents the outcomes assuming biomass emissions have net zero CO_2 emissions.

As a result of accounting biomass emissions as zero CO_2, countries like Sweden, Canada and Brazil show a much lower CO_2 efficiency, because their pulp and paper industry relies heavily on biomass as a fuel. Countries as India and Indonesia, that do not use biomass-fuelled paper and pulp production facilities, do not show any difference.

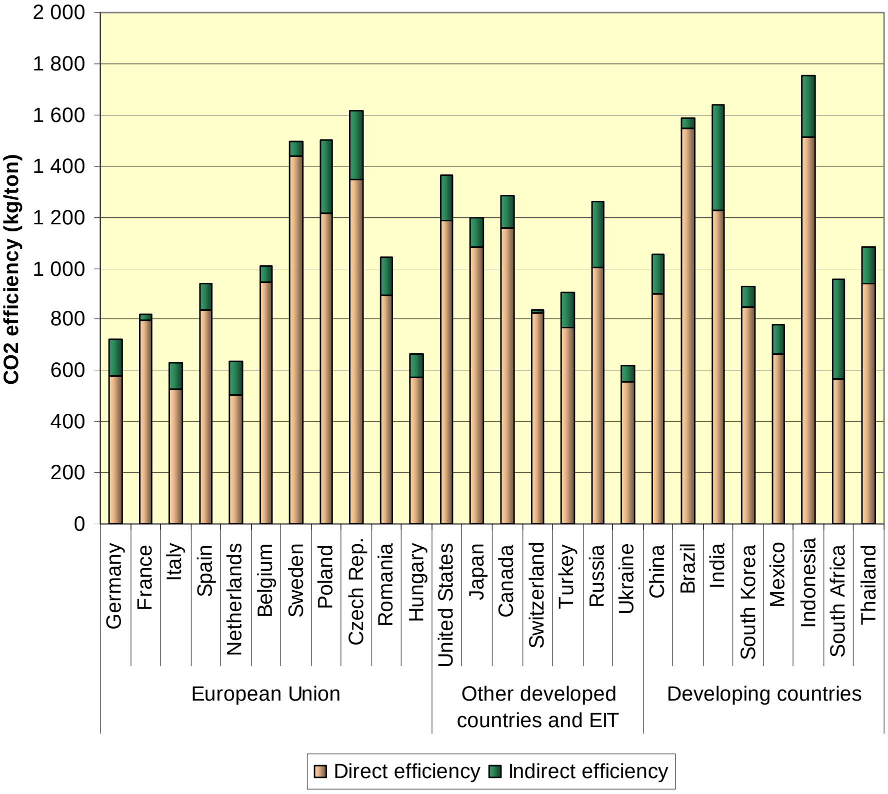


Figure 4-10 CO_2 efficiencies in the paper and pulp industry for the year 2005, accounting biomass emissions as direct emissions

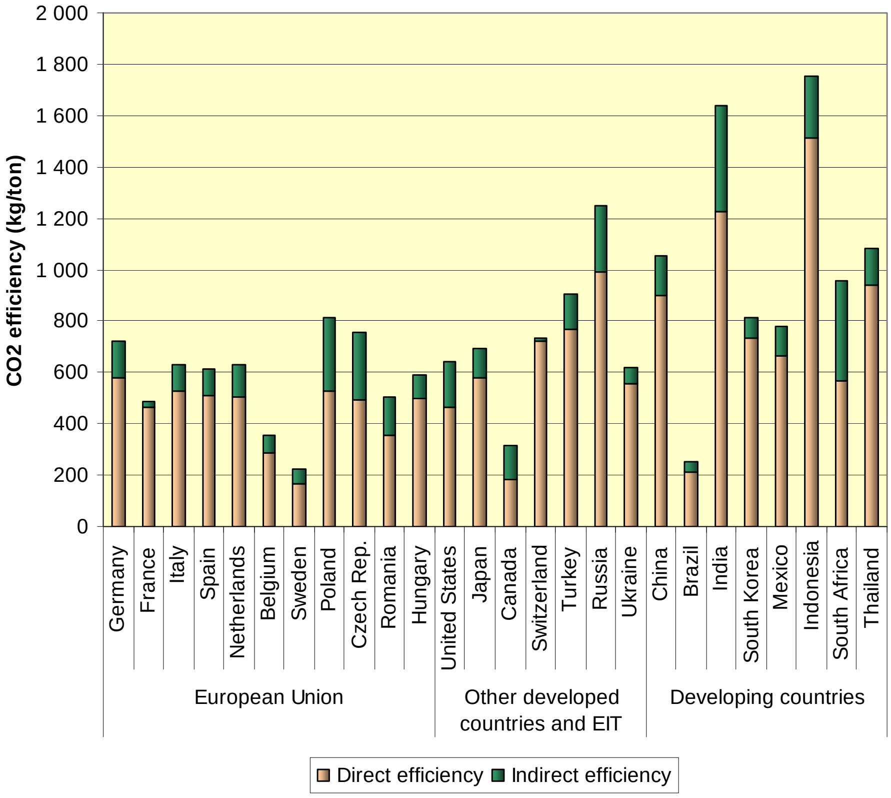


Figure 4-11 CO_2 efficiencies in the paper and pulp industry for the year 2005, account biomass emissions as zero emissions

Assuming non-zero CO_2 emissions from biomass, with regard to carbon leakage in the pulp and paper sector, it may be concluded that relocation away from western or southern Europe to main paper producing countries almost always leads to carbon leakage. Relocation from Sweden, Poland, and the Czech Republic would not make much of a difference or would even lead to lower global emissions.
However, if biomass emissions are accounted as zero CO_2 emissions, the picture is completely different. Relocation away from the main paper producing countries (e.g. Sweden, Canada) would almost always lead to carbon leakage.

4.4.3 BAT and future efficiencies

Table 4-32 presents the fuel use and electricity use associated with the use of BAT. The table describes the pulping and papermaking processes separately.
Additionally, IEA (2007) provides data on the share of the relative share of the different types of paper per country. Combined with the fuel and electricity intensities of the pulp and paper industry in Table 4.33 this yields an average fuel and electricity intensity for papermaking (excluding pulping) per country. The results are shown in Table 4-34.

Table 4-32 Fuel and electricity intensities associated with the use of BAT.

Process	Fuel intensity (GJ / ton)	Electricity intensity (GJ / ton)
Mechanical pulping	0	7.5
Chemical pulping	12.25	2.08
Waste paper pulping	0.5	0.36
De-inked waste paper pulp	2	1.62
Coated papers	5.25	2.34
Folding boxboard	5.13	2.88
Household and sanitary paper	5.13	3.6
Newsprint	3.78	2.16
Printing & writing paper	5.25	1.8
Wrapping & packaging paper and board	4.32	1.8
Other paper and paperboard	4.88	2.88

Source: IEA, 2007.

Table 4-33 Weighted energy efficiency of paper production for various countries.

Country	Fuel intensity (GJ / ton)	Electricity intensity (GJ / ton)
Brazil	4.7	2.1
Canada	4.5	2.1
China	4.6	2.1
Finland	5.1	2.2
France	4.7	2.2
Germany	4.8	2.2
Italy	4.8	2.3
Japan	4.7	2.2
South Korea	4.6	2.2
Norway	4.5	2.0
Spain	4.7	2.2
Sweden	4.6	2.2
United Kingdom	4.6	2.3
United States	4.7	2.1
Average	4.7	2.2

Source: IEA, 2007.

Since the variation in fuel and electricity efficiency between countries is relatively small and the countries listed include the major pulp and paper producers in the world, the average is assumed to be valid for all countries. Using this average in combination with fuel and electricity intensities in Table 4-33, the BAT energy efficiencies for pulp and paper production can be determined. These are shown in Table 4-34.

Table 4-34 BAT associated energy intensities for the pulp and paper industry compared to the intensities with the use of current practice

	BAT		Current practice	
	Fuel intensity (GJ / ton paper)	**Electricity intensity (GJ / ton paper)**	**Fuel intensity (GJ / ton paper)**	**Electricity intensity (GJ / ton paper)**
Sulphate (Kraft) uncoated fine paper	17.0	4.3	17.5	4.4
Sulphite uncoated fine paper	17.0	4.3	21.0	4.9
Mechanical paper	4.7	9.7	5.5	10.7
Recycled paper	5.2	2.6	9.2	1.9

Using the same procedure as in Section 4.4.2, CO_2 efficiencies per country with the use of BAT can be calculated, again assuming biomass emissions as regular non-zero emissions of CO_2. The result is shown in Table 4-35.

Table 4-35 CO_2 efficiency in the pulp and paper industry in 2005 associated with the use of BAT, accounting biomass emissions as regular emissions of fuel use.

	Production (kton)	**Direct efficiency (kg/ton)**	**Indirect efficiency (kg/ton)**	**CO_2 efficiency (kg/ton)**	**Difference (direct)**	**Difference (indirect)**	**Diff. (total)**
European Union							
Germany	17 292	365	168	533	37%	-16%	26%
France	8 204	559	29	588	30%	-13%	28%
Italy	5 907	307	123	430	42%	-23%	32%
Spain	6 269	625	124	749	25%	-16%	21%
Netherlands	2 579	290	164	455	43%	-27%	29%
Belgium	2 647	629	80	709	33%	-18%	30%
Sweden	13 239	1 316	57	1372	8%	5%	8%
Poland	2 151	960	311	1271	21%	-10%	15%
Czech Republic	1 233	1 094	271	1365	19%	-1%	16%
Romania	428	654	167	821	27%	-13%	21%
Hungary	368	325	124	450	43%	-37%	33%
EU Average	88 093	726	157	883	24%	-6%	20%
Other developed countries and EIT							
United States	95 515	987	188	1174	17%	-7%	14%
Japan	33 008	812	127	939	25%	-14%	21%
Canada	27 472	1 053	119	1172	9%	6%	9%
Switzerland	1 462	502	13	515	39%	-16%	38%
Turkey	1 241	516	166	682	33%	-20%	25%
Russia	8 548	884	255	1139	12%	2%	10%
Ukraine	339	315	83	398	43%	-37%	36%
Developing countries							
China	24 079	562	191	753	38%	-26%	28%
Brazil	13 649	1 402	40	1443	9%	-2%	9%

	Production (kton)	Direct efficiency (kg/ton)	Indirect efficiency (kg/ton)	CO_2 efficiency (kg/ton)	Difference (direct)	Difference (indirect)	Diff. (total)
India	2 736	1 067	411	1478	13%	0%	10%
South Korea	7 597	516	106	622	39%	-29%	33%
Mexico	1 104	440	138	578	34%	-21%	26%
Indonesia	6 368	1 404	245	1649	7%	-1%	6%
South Africa	2 316	481	399	880	15%	-3%	8%
Thailand	2 318	733	164	898	22%	-14%	17%

The last three columns show the efficiency gained with the use of BAT compared to the efficiencies with the use current practice (as shown in Table 4-31). It can be seen that the use of BAT results in lower direct emissions through the use of fuels, however the use of electricity would increase. Overall a 20% gain in efficiency when using BAT is found for EU27.

Applying BAT on the whole does not change much in the conclusion on potential carbon leakage. However if some countries, such as China, South Korea and Mexico would apply BAT, then they would get lower CO_2 efficiencies than several European countries without BAT. Applying BAT has less affect on developing countries with high intensities such as Brazil, India and Indonesia. Relocation to these countries always causes carbon leakage.

4.5 Non-metallic minerals

4.5.1 Analysis of available statistics

The non-metallic minerals industry consists of cement and lime production, and the production of glass, ceramics and other non-metallic mineral products. For applying the standard methodology as described in Section 0 the main problem is the diversity of the sector. Since the non-metallic minerals sector consists of the production of a large range of products with different production characteristics, the availability of production data determines the outcome of this exercise.

Production data are available from the USGS Minerals Yearbooks (USGS, 2009) for cement and lime production. For other processes production data are scarcely available. For glass and ceramics, some data can be extracted from the UN statistical databases (UN, 2009). Although cement and lime are the two most important production processes within this sector, it is not possible to calculate the CO_2 efficiency on the basis of these products only. In addition, the available energy statistics for the non-metallic minerals may not include the same products for all countries. Hence, outcomes on the aggregate level are not useful for understanding potential carbon leakage.

The focus in the remainder of this section will be on the cement production process, since more detailed data are available for this sector to provide insight in greenhouse gas efficiencies. Process data are provided for lime, glass and ceramics production.

4.5.2 Cement production

Both the cement and the lime industry make products with a large amount of lime (CaO) and their production processes are rather similar. The main difference is in the application of the final product. Cement is almost exclusively used in construction, while lime is mainly consumed in the iron and steel industry, agricultural and environmental sector and construction sector (Bergman et al., 2007). Total global production of cement in 2005 was 2292 Mton. By far the largest producer of cement in the world is China, this country alone accounts for 46% of the global cement production in 2005. The second largest producer, India, accounts for 6% of the production in 2005.
The production process consists of the conversion of limestone ($CaCO_3$) into lime (CaO) using heat, a process in which CO_2 (non-combustion) is released. As these emissions relate to a chemical process they are the same in all parts of the world (540 kg CO_2 per ton of clinker). This step is followed by the burning of the CaO with silica, alumina and ferrous oxides at high temperature to form clinker. This is then ground or milled with by-products to form cement (Bergman et al., 2007). The CO_2 emission intensity thus depends on the amount of clinker in the cement.
Detailed production and emission data are available for the cement industry (IEA, 2007). These have been used to calculate the CO_2 efficiency per country for the cement industry. Results are shown in Table 4-37. Production data for cement have been collected from USGS (2007) and CEMBUREAU and recalculated to clinker production using country specific data on clinker content in cement from IEA (2007). Total energy use has been calculated from the distribution of the production over various cement process types (dry, semi-dry, wet and vertical shaft) and the typical energy use for these process types, as given in Table 4-36.
Then, total direct emissions have been calculated by using the distribution of the energy used in the cement industry over the fuel types (available from IEA, 2007). For each fuel type, a representative emission factor from the IPCC Guidelines (IPCC, 2006) has been taken to calculate the respective CO_2 emission. The total direct emissions are summed over all fuel types, combined with the process-emissions and recalculated to cement production using country specific data on the clinker content of cement from IEA (2007).
The electricity use per ton clinker is available on a country basis from IEA (2007). These data have been combined with the country-specific emissions per unit of electricity produced (as given in Table 3-2) to calculate the total indirect CO_2 emissions from cement production for each country.
The sum of direct and indirect emissions has then been divided by the total production to obtain the energy efficiency of CO_2 from cement production. The efficiency as in the table below includes the CO_2 from fossil fuel use and electricity use, as well as the CO_2 from the cement production process itself. The process emissions are assumed to be constant at 540 kg CO_2/ton clinker produced. Variation between countries therefore only reflects variation in the clinker content of cement.

Table 4-36 Process types and their energy use within the cement industry.

Process type	Fuel use [a)] (GJ/ton clinker)
“Dry process” with multi-stage cyclone preheater and precalciner kilns	3.5
“Semi-dry / semi-wet processes” (Lepol-kiln)	4.2
Wet process long kilns	5.7
Shaft kilns / production of special cements	4.5

Note: a) Geometric mean of the data ranges provided.
Source: JRC, 2008.

Table 4-37 CO_2 efficiencies per country for the cement industry.

	Cement production (Mton)	Clinker content (%)	Direct efficiency (kg/ton cement)	Indirect efficiency (kg/ton cement)	Process efficiency (kg/ton cement)	Efficiency (kg CO_2 / ton cement)
European Union (EU27)						
Germany	31.9	79%	293	18	427	740
France	21.7	81%	300	3	437	740
Italy	46.4	78%	289	16	421	730
Spain	50.3	80%	296	13	432	740
Netherlands	2.5	81%	300	23	437	760
Belgium	7.5	81%	300	10	437	750
Sweden	2.7	81%	300	4	437	740
Poland	12.5	80%	296	36	432	760
Czech Republic	4.0	80%	296	28	432	760
Romania	7.4	80%	296	20	432	750
Hungary	3.4	80%	296	20	432	750
Other developed countries and EIT						
United States	99.0	95%	370	25	513	910
Japan	74.0	91%	326	14	491	830
Canada	13.9	91%	336	9	491	840
Switzerland	4.0	81%	300	2	437	740
Turkey	38.0	80%	233	22	432	690
Russia	45.0	80%	272	22	432	730
Ukraine	12.2	80%	272	13	432	720
Developing countries						
China	1064.0	73%	278	28	394	700
Brazil	39.0	81%	269	4	437	710
India	130.0	86%	349	28	464	840
South Korea	50.0	89%	311	14	481	810
Mexico	36.0	86%	280	19	464	760
Indonesia	37.0	80%	275	25	432	730
South Africa	13.0	80%	251	38	432	720
Thailand	40.0	80%	289	21	432	740

Figure 4-12 shows the CO_2 efficiency in the cement production, including both the direct and indirect CO_2 emissions. These efficiencies are in line with figures generally found in the literature (Bergman et al, 2007; IEA, 2007). Partly due to the large share of process-emissions the emission intensities vary only slightly between the countries, the differences are to a large extent determined by the clinker content in the cement. The CO_2 efficiency ranges from 700 kg/ton cement for China (73% clinker content) to 910 kg/ton cement for the United States (95% clinker content). The average efficiency in the EU27 is between 730 and 760 kg/ton cement. The difference between EU countries is small, because for all European countries the distribution over the cement types (dry, semi-dry, wet, vertical) has been assumed to be identical (IEA, 2007) since no better data are available. Differences between EU countries only reflect differences in fuel mix and clinker content of cement.

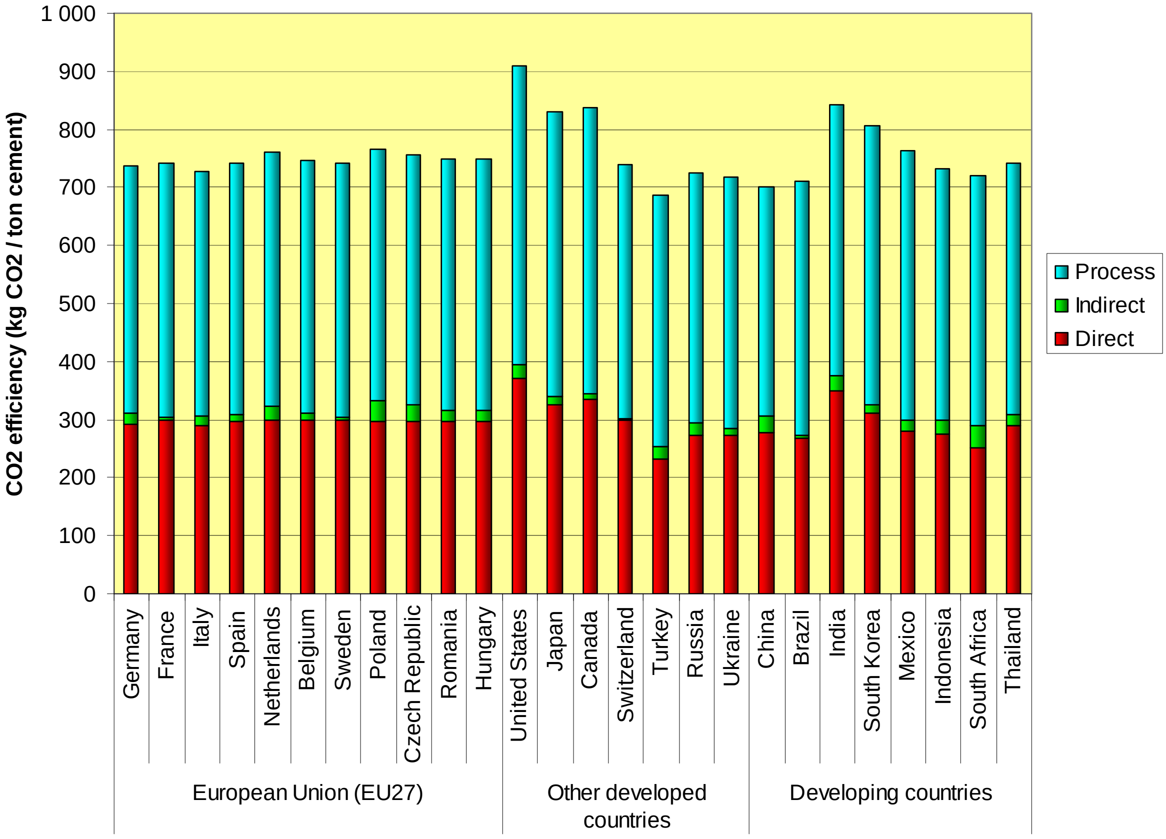


Figure 4-12 CO_2 efficiency in the cement industry per country, including direct CO_2 emissions from fuel combustion, indirect CO_2 emissions from electricity use and CO_2 from the cement production process (not combustion related).

With regard to potential carbon leakage, the conclusion is that relocation of cement production, if it would happen at all, would be more or less neutral with regard to CO_2 emissions. Only movements to countries with high coal consumption (India, USA), would contribute to a carbon leakage of about 100 kg CO_2 per ton cement.

BAT, future efficiencies and implications for carbon leakage

With regard to energy consumption in the cement industry, the draft BREF document for the Cement, Lime and Magnesium Oxide Industries (JRC, 2008) states: “For new plants and major upgrades, BAT is to apply a dry process kiln with multistage preheating and precalcination. Under regular and optimized operational conditions, the associated BAT heat balance value is 2900 – 3300 MJ/tonne clinker.”
Assuming that the average clinker content in cement is 80%, the total energy requirement for cement production with the use of BAT is ~ 2400 MJ/ton cement. Assuming the electricity use will remain constant at ~ 0.4 GJ/ton cement, around 2000 MJ of fossil fuel energy is consumed per ton of cement produced with the use of BAT. Table 4-36 shows that the present-day energy use is around 4000 MJ/ton cement (total energy use divided by total production), so the use of BAT at a global scale could reduce the primary energy use by ~ 50%.
IEA (2007) estimates the energy saving potential of all production using BAT as well as the increased use of clinker feedstock substitutes in the kiln to be around 2.5 – 3 EJ (30-36 % of the total energy use) given the current cement production. However, the economic costs of a full implementation would be high and the full reduction may not be realistic.
Applying BAT in countries with current high emissions per ton of cement and keeping the current fuel mix, however, could nullify the carbon leakage in case of movements to these countries.

4.5.3 *Lime production*

There are no detailed statistics on global lime production. Total global production is estimated to be around 120 Mton (IEA, 2007), however since a lot of lime is produced inside other facilities (e.g. iron and steel plants), the European Lime Association (EuLA) estimates the total global production at 300 Mton. As for cement, China is the largest producer and estimated to account for ~ 50% of the global production. Other large lime producers are the United States, Japan, Russia, Germany, Mexico and Brazil.
The lime production process is largely related to the cement production. Process emissions are the dominating source of CO_2 emissions in both sectors. As lime is only one component of cement, CO_2 process emissions from cement production are smaller than for lime. Fuel related CO_2 emissions for lime production in Europe are estimated to be 0.2 – 0.45 ton CO_2 per ton lime produced, while CO_2 emissions from the production process itself are estimated at 750 kg CO_2 per ton lime in Europe (IEA, 2007).
Typical energy uses nowadays are 3.6-7.5 GJ/ton in the European Union, 7.2 GJ/ton in Canada and up to 13.2 GJ/ton for small mills in Thailand (IEA, 2007).
Electricity consumption in Europe is 40-140 kWh/ton lime, depending on the type of kiln and the required fineness of the lime (IEA, 2007).
The minimum energy requirement for lime production is 3.2 GJ/t, which equals about 0.21 ton CO_2 per ton lime (IEA, 2007). Table 4-38 lists the common fuel and electricity use in lime kilns in the European lime industry (data taken from Bergman et al., 2007). The last column gives the total CO_2 intensity from energy and process, where the value between brackets indicates the process emissions.

Table 4-38 Process types and their energy use within the European lime industry.

Process type	Fuel use (GJ/ton lime)	Electricity use (GJ/ton lime)	Total energy use (GJ/ton lime)	CO_2 intensity (kg CO_2/ton lime)
Lime production in shaft kilns	4.2	0.16	4.4	1100 (750)
Lime production in rotary kilns	5.5	0.16	5.7	1200 (750)

Note: process emissions between brackets
Source: Bergman et al., 2007.

No data are available on the distribution of lime kilns and specific energy use in individual countries.

BAT and future efficiencies

For lime production, BAT is to reduce/minimize thermal energy consumption by applying a combination of measures/techniques. The thermal energy consumption levels associated with the use of BAT vary per type of kiln and range from 6.0-9.2 GJ/ton lime for long rotary kilns to 3.2-4.2 GJ/ton for parallel flow regenerative kilns. CO_2 emission reduction can therefore be achieved through replacing of old kilns by new efficient kilns, such as the parallel flow regenerative kiln. In the United States, the National Lime Association has agreed to a 9% reduction of CO_2 from combustion by 2012. In China, more than 50% of the lime kilns are outdated and an energy saving of up to 21% is achievable (Cui, 2007; IEA, 2007). Further reduction of CO_2 emissions may be achieved by switching to low carbon fuels.

4.5.4 Glass production

The glass industry distinguishes four main glass categories: container glass, flat glass, glass fibre and special glass. The first two dominate the glass industry (60% and 30%, respectively) and are used for packaging and windows/glazing, respectively. Global glass production in 2005 was around 130 Mton, of which 34.8 Mton was produced in the EU25. Together, the European Union, United States and China account for 60% of the global glass production. Glass demand has grown faster than the economy over the last decades and is nowadays growing at around 4% per year (IEA, 2007).

The production of primary glass is a very energy intensive process. About 75% of the energy used in the glass production process is used in the melting process (JRC, 2001d). Most plants are heated with natural gas or fuel oil. To reduce emissions and increase efficiency, combustion air is increasing replaced by the oxy-fuel technology. Furthermore, excess heat may be used to generate steam in a waste-heat recovery boiler or to preheat cullet. Both these measures can increase the overall efficiency of the glass furnace from 40-50% to 50-65% (Whitemore, 1999; IEA, 2007).
The recycling of glass results in lower energy consumption. As a general rule, each 10% of cullet (recycled and melted glass) results in a 2.5-3.0% reduction in energy consumption (JRC, 2001d).
The glass industry worldwide uses 0.5-0.8 EJ of energy. The actual energy requirements vary widely (3.5-40 GJ/ton), depending heavily on the furnace design, scale and operation method. However, the majority of glass is produced in large furnaces where the energy requirement for melting is generally below 8 GJ/ton. Assuming that half of the fuel used is natural gas and half fuel oil, combined with an assumed average energy intensity of 7 GJ/ton glass, the CO_2 efficiency of glass production is 450 kg/ton glass

(from energy only) (IEA, 2007) for these large facilities. However, another important part of the CO_2 emissions in the glass industry is process related and results from the release by carbonates at high temperatures and range from 30 to 250 kg CO_2 per ton glass produced, depending on the amount of carbonates used (IPCC, 2006).

Table 4-39 presents the fuel, electricity and total energy use per ton of glass produced, as well as the CO_2 efficiency. Shares of the fractions of fuels (natural gas and oil) are not reported, it has been assumed that the distribution is 50-50%.

Table 4-39 Process types and their energy use within the glass industry (from Bergman et al., 2007).

Process type	Fuel use (GJ/ton glass)	Electricity use (GJ/ton glass)	Total energy use (GJ/ton glass)	CO_2 intensity (kg CO_2/ton glass)
Container glass	6.5	0.8	7.3	700 (200)
Flat glass	7	1	8	750 (200)
Special glass	12	0.9	12.9	900 (200)
Mineral wool	17		17	1300 (200)

Note : between brackets average process emissions.
Source: JRC, 2001d; Bergman et al., 2007.

No data are available on the share of the various processes per country and hence no country analysis has been undertaken.

BAT and future efficiencies

For glass production, the theoretical minimum energy use is 2.8 GJ/ton for soda-lime glass and 2.35 GJ/ton for borosilicate and crystal (IEA, 2007). In practice nowadays, average energy use varies between 5.75 and 9 GJ/ton (Levine et al. 2004 in IEA, 2007), a factor 2 to 4 higher. Structural heat losses account for 0.85 GJ/ton of the energy input and losses due to the heat content of the flue gases for 1.18 GJ/ton of the energy use (Beerkens and Limpt, 2001 in IEA, 2007).

4.5.5 Ceramic industry

Ceramic materials are used in high volumes in the construction sector as bricks and tiles, but also as refractory materials, sanitary ware, household and other technical ceramics (Bergman et al., 2007). The ceramic industry is an energy intensive sector, the most energy is consumed during the drying and kiln firing to 800-2000°C. The fuels used are mainly natural gas, fuel oil and LPG.
Table 4-40 provides the energy and CO_2 efficiencies for 8 ceramic processes. No data are available on the share of the various processes per country.

Table 4-40 Process types and their energy use for the ceramic industry (from Bergman et al., 2007).

Process type	Share (%) [a)]	Fuel use (GJ/ton glass)	Electricity use (GJ/ton glass) [b)]	Total energy use (GJ/ton glass)	CO_2 intensity (kg CO_2/ton glass)
Brick and roof tiles	25	2.3	0.35	2.7	1700
Wall and floor tiles	39	5.6	0.84	6.4	400
Refractory products	12	5.6	0.84	6.4	420
Sanitary ware	7	22	3.3	25.3	1600
Vitrified clay pipes		5.2	1.2	6.4	430
Expanded clay aggregates		2.3	0.15	2.5	150
Household ceramics [c)]	7	45.2	6.8	52.0	3400
Technical ceramics	9	50.4	7.6	58.0	3750

Notes: a) Refers to share of production value. b) Assumed to be 20% of the thermal energy for all sectors (no better data available). c) Refers to table- and ornamental ware made of porcelain, earthenware and fine stoneware.

Source: JRC, 2007; Bergman et al., 2007.

5 Overall results

The main conclusion from this study is that international statistics are a non reliable data source for comparing greenhouse gas efficiencies between countries, and thus to arrive at any sensible conclusion on carbon leakage. The main difficulties in using international official statistics reasons are:

- insufficient detail in statistics on energy and electricity use and greenhouse gas emissions; the high level of aggregation results in broad industry groupings including many different activities that preclude a sensible conclusion;
- statistical reporting; e.g. the reporting of Combined Heat and Power (CHP) generation in energy statistics makes a comparison of industrial sectors with a large share of CHP, such as the paper and pulp industry impossible. Another example: Japan stands out in many tables in this report due to differences in sector definition.

For official statistics to develop as a reliable source for comparing industrial efficiencies, further detailing the production, energy consumption and emission statistics would be needed. For the paper and pulp industry attention would be needed for a consistent treatment of CHP and biomass feedstock. At the same time, initiatives of industry organizations to gather similar data from their members, probably with more attention for process specificities, should be encouraged.

As an alternative to the available statistics, this study has produced proxy data based on the carbon efficiencies of fuel consumed in some main sectors (on NACE 2 or 3-digit level) , and on the average carbon intensity of electricity per country, combined with general process information. These resulting figures are not useful as absolute numbers, because detailed information on the different production processes in the countries is lacking and the results are therefore based on assumptions. However, the results highlight a few important principles in the discussion on carbon leakage:

- Electricity consumption is a very important variable. The way electricity is generated in the various countries and the resulting carbon intensities determine for many industries the CO_2 efficiency of their processes;
- It is not possible to conclude that a relocation of industry from the EU to other countries will automatically result in a rise in global greenhouse gas emissions. The potential carbon leakage depends heavily on the energy provision in the country of origin and of destination and on the specific production process. Coal based countries like China have generally relatively high CO_2 intensities, but so have Poland and the Czech Republic. This characterization holds for almost all industrial sectors.
- This also works out in another way: industries that have a high share of electricity consumption in countries with “dirty” electricity generation (with high CO_2 emissions/kWh, e.g., coal based electricity), are under an unilateral regime of climate policies more exposed to financial burdens than similar industries in countries with “clean” electricity generation. That means that IF relocation would happen under the ETS, that the movement in the first place would be away from economies that are largely coal based. IF that is true, than the carbon leakage would be zero or limited.
- In case of a relocation from an efficient country to an inefficient country, the potential carbon leakage ranges from very small (cement industry) to a two or even threefold increase of emissions depending on the type of industry. Large differences between low and high intensity countries exist for the steel, copper and paper industry.

- The question if carbon leakage occurs and the absolute amount of leakage thus strongly depend on the country of origin and the country of destination of a re-allocated industry. Not every re-location of industry from the EU to a developing or another OECD-country will bring about carbon leakage. Equally it is not possible to state that a certain amount of carbon leakage is a consequence of the EU-ETS without performing a detailed country specific study (assuming that some industries would indeed re-locate as a consequence of introducing the EU-ETS).
- From the industrial processes for which proxy data could be calculated, the nickel and aluminium production stand out because of their high CO_2 intensities (4000-9000 kg CO_2/ton product). Cement has the lowest intensities (750-850 kg CO_2/ton product). Although a comparison of different products based on weight is less useful than for instance on value added, it still highlights the vulnerability of very energy intensive sectors to unilateral climate policies.
- The influence of the fuel mix used in industrial processes and of the fuel mix for electricity generation on national efficiencies is far larger then the potential efficiency gains by employing Best Available Technology or by any efficiency gains that can be achieved in industrial processes in the coming years. This means that the size of potential carbon leakage is of course influenced by choices in production technology if one considers a given pair of countries (a country of origin and a destination country), but that for a general conclusion on carbon leakage the fuel mix in the country of origin and destination is the main determining factor.

6 References

[1] Althaus, H.J., R. Hischier, M. Osses, A. Primas, N. Junghbluth, M. Chudacoff, 2007. Life Cycle Inventories of Chemicals Data v 2.0, Ecoinvent rapport No.8

[2] Alvorado, S., P. Maldonado, A. Barrios and I. Jacques, 2002. Long term energy related environmental issues related to copper production. *Energy* 27, pp.183-196.

[3] Barker, T., I. Bashmakov, A. Alharti, M. Amman, L. Cifuentes, et al., Mitigation from a cross-sectoral perspective. In: *Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Mayer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[4] 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.

[5] Bergman, Manfred; Andreas Schmitz, Mark Hayden, Katri Kosonen, 2007. *Imposing a unilateral carbon constraint on energy-efficient industries and its impact on their international competitiveness – Data and analysis*. European Economy, Economic Papers, no 298. European Commission, DG for Economic and Financial Affairs, Brussels, Belgium.

[6] Birat, J.P., 2005. The UCLOS Programme <http://cordis.europa.eu/estep/events-infostp_en.html>

[7] Council, 2009. *Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community.* Brussels, 26.3.2009, 2008/0013 (COD), PE-CONS 3737/08. .

[8] 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.

[9] Dresher, William H., 2001. *How Hydrometallurgy and the SX/EW Process Made Copper the "Green" Metal*. Copper Applications in Mining & Metallurgy. <http://www.copperinyourhome.org/publications/newsletters/innovations/2001/08/hydrometallurgy.html>

[10] Energetics Inc. 1999. Energy and Environmental Profile of the U.S. Metalcasting Industry. Prepared for U.S. Department of Energy Office of Industrial Technologies. <http://www1.eere.energy.gov/industry/metalcasting/pdfs/profile.pdf>

[11] Eurostat, 2009. Eurostat PRODCOM database for production of manufactured goods. <http://epp.eurostat.ec.europa.eu/portal/page/portal/prodcom/introduction>.

[12] FAO, 2009. United Nations Food and Agricultural Organisation. FAOSTAT Statistics <http://faostat.fao.org>.

[13] IAI, 2008. *The. International Aluminium Institute report on the aluminium industry's global perfluorocarbon gas emissions reduction programme: Results of the 2006 anode effect survey.* International Aluminium Institute, London, United Kingdom.

[14] IEA, 2007. *Tracking Industrial Energy Efficiency and* CO_2 *Emissions, Energy indicators*. International Energy Agency, Paris, France.

[15] IEA, 2007b., *Energy Statistics for OECD and non OECD countries, 2007 edition.*. International Energy Agency, Paris, France.

[16] IEA, 2008. *Energy technology perspectives, 2008, scenarios and Strategies to 2050*. International Energy Agency/OECD, Paris, France.

[17] IPCC, 2006. *Guidelines for National Greenhouse Gas Inventories, Volume 3 Industrial Processes and Product Use.* Intergovernmental Panel on Climate Change.

[18] JRC, 2001. *Reference document on Best Available Techniques in the Non Ferrous Metal Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[19] JRC, 2001b. *Reference document on Best Available Techniques in the Paper and Pulp Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[20] JRC, 2001c. *Reference document on Best Available Techniques in the Iron and Steel Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[21] JRC, 2001d. *Reference document on Best Available Techniques in the Glass Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[22] JRC, 2003. *Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[23] JRC, 2006. *Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals, Ammonia, Acids and Fertilisers*, 2006. Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[24] JRC, 2007. *Reference document on Best Available Techniques in the Ceramic Industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain.

[25] JRC, 2008. *Reference document on Best Available Techniques in the Cement, Lime and Magnesium Oxide industry*, Integrated Pollution Prevention and Control (IPPC), European Commission, JRC, Seville, Spain (draft version).

[26] Graichen, Verena; Katja Schumacher, Felix Chr. Matthes, Lennart Mohr, Vicky Duscha, Joachim Schleich, Jochen Diekmann, 2008. *Impacts of the EU Emissions Trading Scheme on the industrial competitiveness in Germany*, Federal ministry of the Environment, Nature conservation and Nuclear safety, Research Report 3707 41 501; Dessau-Roßlau, Germany. <http://www.umweltdaten.de/publikationen/fpdf-l/3625.pdf>

[27] 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.

[28] Moors, Ellen H.M., 2006. Technology strategies for sustainable metals production systems: a case study of primary aluminium production in The Netherlands and Norway. *Journal of Cleaner Production* 14 (2006) 1121-1138. Elsevier. doi:10.1016/j.jclepro.2004.08.005.

[29] Neelis, M.L., M.K. Patel, P.W. Bach, W.G. Haije, 2005. Analysis of energy use and carbon losses in the chemical and refinery industries. ECN report. Energy Study Centre, Petten, The Netherlands.

[30] Norgate, T.E. and W. J. Rankin, 2000. *Life Cycle Assessment Of Copper And Nickel Production*. CSIRO Minerals, Clayton, Victoria, Australia. Proceedings, Minprex 2000, International Conference on Minerals Processing and Extractive Metallurgy, September 2000, pp133-138. <http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_CuNi.htm>

[31] Pimentel, Sarita, 2009. *Energy consumption and greenhouse gas emissions in the Chilean Copper Industry, 2001-2008.* ICSG/ILZSG/INSG, Energy/Climate change seminars, Lisbon, April 22, 2009.

[32] Renaud, Julia, 2008. *Issues Behind Competitiveness and Carbon Leakage: Focus on Heavy Industry*, OECD, Paris, France.

[33] UN, 2009. Industrial Statistics. United Nations Statistical Division, <http://unstats.un.org/unsd/industry/ics_intro.asp>.

[34] UNFCCC, 2009. Emission and activity data as reported by Annex I countries. Available from <http://unfccc.int/national_reports/items/1408.php>

[35] USGS, 2009. USGS Minerals Yearbook. <http://minerals.usgs.gov/minerals/>. Senter Novem 2008, European Roadmap for Process Intensification. Senter Novem, The Netherlands

[36] Vargas David N., 2008. Chile: *The Copper Mining Country & The Clean Development Mechanism Opportunities.* Powerpoint presentation. <http://www.meti.go.jp/policy/energy_environment/global_warming/pdf/Chile_private.pdf>

[37] Whitemore, O.J. 1999. Energy use and Efficiencies in Firing Ceramics, Melting Glass. *American Ceramic Society Bulletin*, July 1999. pp.69-71.

[38] Worrell E., D. Phylipse, D. Einstein, N. Martin (2000), Energy Use and Energy Intensity of the U.S. Chemical Industry.

7 Authentication

Name and address of the principal
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DG Environment

Names and functions of the cooperators
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-

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1 Carbon dioxide efficiency of fuel use in industry

Carbon dioxide efficiency of fuel use per industry branch per unit of energy consumed

	Chemical industry	**Iron and steel**	**Nonferrous metal**	**Nonmetalic minerals**	**Paper and pulp**
	kg CO_2/TJ				
EU					
Germany	56100	117690	66941	71895	61903
France	56100	117918	60626	70440	75097
Italia	59319	82087	59338	75664	58416
Spain	56100	85272	72173	72633	72049
The Netherlands	71900	122523	56100	59452	56087
Belgium	56100	101192	66102	86319	93738
Sweden	77400	104613	82230	84005	106170
Poland		109803	84152	78206	100166
Czech republic		109654	56100	73504	94554
Romania	56100	114534		61970	81710
Hungary		118226	56466	79239	62535
Other developed countries and EIT					
USA	56100	66638	57632	74559	90552
Japan	70384	113678	95930	89978	94735
Canada		95591	71356	97472	100596
Switzerland		61410	63280	103732	87774
Turkey	56100	117638	68118	63963	74539
Russia		101676		59095	72306
Ukraine		98432	59614	58194	60524
Developing countries					
China	71088	139591	89411	91746	92592
Brazil	56100	106614	79923	95293	103289
India		131326	91088	93738	95420
South Korea		117321	85042	91722	88426
Mexico	56100	70196	56339	68427	65295
Indonesia		75431		88585	94600
South Africa		101378		89054	44400
Thailand		81545		95753	76685

Source: based on IEA statistics and IPCC (2006) emission factors